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Particle Physics Experiments Report 1994

B A Roberts (Compiler)

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PARTICLE PHYSICS EXPERIMENTS

1994

COMPILED BY: B A ROBERTS

INTRODUCTION

This report describes work carried out in 1994 on experiments approved by the Particle Physics Experiments Selection Panel. The contents consist of unedited contributions from each experiment.

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PARTICLE PHYSICS EXPERIMENTS

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2	157	**Search for the Neutron Electric Dipole Moment using Ultracold Neutrons** Harvard University; Institut Laue-Langevin Grenoble; Rutherford Appleton Laboratory; Sussex University; University of Washington.
3	231	**Photoproduction in the energy range 70-180 GeV** Bonn University; CERN Laboratory; Lancaster University; Manchester University; Rutherford Appleton Laboratory; Sheffield University; Yerevan Physics Institute.
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24	254	**An Exposure of the Hybridised 15' Bubble Chamber with a Neon-Hydrogen Mixture to a Quad-Triplet Neutrino Beam from the Tevatron** Birmingham University; Brussels University; CEN, Saclay; CERN Laboratory; Fermi National Accelerator Laboratory; Hawaii University; IHEP Serpukhov, USSR; Illinois University; Imperial College, London; ITEP-Moscow; Jammu University; MPI-Munich; Moscow State University; Oxford University; Panjab University, Chandigarh; Rutgers University; Rutherford Appleton Laboratory; Tufts University; University of California, Berkeley.

Accelerator	Year of Running	Status (Dec 1994)	Spokesman	Experiment Code
SPS	1983	Analysis	G Myatt	WA21
Reactor ILL	1980-1994	Running and Analysis	K F Smith	PN5
SPS	1983-1986	Analysis	E Paul	WA69
	1987-1994	Running and Analysis	D H Perkins	SOUDAN II
ISIS	1988-1994	Running and Analysis	J Kleinfeller	KARMEN
SPS	1982-1994	Running and Analysis	J B Kinson	WA76/WA91
SPS	1985-1990	Complete	K Peach	NA31
FNAL	1985-1988	Analysis	G T Jones	E632

Page Number	Proposal Number	Title and Collaboration
25	263	**The SLD Collaboration at the SLAC Linear Collider** Bologna University; Boston University; Brunel College, London; California Institute of Technology; California State University, Northridge; Columbia University; Ferrara University; INFN, Frascati; INFN, Sezione di Pisa; Massachusetts Institute of Technology; Nagoya; Northeastern University; Oregon; Rutgers University; Rutherford Appleton Laboratory; Stanford Linear Accelerator Center; Tohoku University; University of California, Santa Barbara; University of Cincinnati; University of Colorado; University of Illinois; University of Padova; University of Perugia; University of Tennessee; University of Washington; University of Wisconsin; Vanderbilt University; University of Yale.
41	265	**The Study of CP Violation in the Neutral Kaon System at LEAR** Athens University; Basel University; Boston University; CERN Laboratory; Coimbra University; Delft University; ETH; Fribourg University; Ioannina University; Liverpool University; Lubljana University; Marseille University; Orsay University; PSI University; Saclay University; Stockholm University; Thessalonika University.
55	268	**The Crystal Barrel: Meson Spectroscopy at LEAR with a 4π Neutral and Charged Detector** Centre of Nuclear Research, Strasbourg; CERN Laboratory; Queen Mary & Westfield College, London; Rutherford Appleton Laboratory; University of Bochum; University of Bonn; University of Budapest; University of California, Berkeley; University of Hamburg; University of Karlsruhe; University of Mainz; University of Munich; University of Zurich.
63	270	**Dark Matter Experiments** Imperial College (A, PP), London; Birkbeck College, London (CRP); Rutherford Appleton Laboratory (PP, A, T); University of Nottingham (CRP); University of Sheffield (PP).
69	273/278	**An Exploratory Study of Heavy Ion Collisions** Aichi College; Aichi University; Bari University; CERN Laboratory; Gifu University; Nagoya University; Nagoya Institute; Rome University; Salerno University; Tohoku University; Turin University; University College Dublin; University College, London; Utsunomiya University; Yokohama University.
70	275	**Relativistic Heavy Ion Interactions** Athens University; Bari University; Bergen University; Birmingham University; CERN Laboratory; CIEMAT, Madrid; Collège de France, Paris; Kosice; Legnaro; Padova; Serpukhov; Strasbourg; Trieste University.

Accelerator	Year of Running	Status (Dec 1994)	Spokesman	Experiment Code
SLAC	1994	Running and Analysis	M Breidenbach	SLD
LEAR	1991-1994	Running and Analysis	E Gabathuler	PS195
LEAR	1989-1994	Running and Analysis	H Koch	PS197
	1994	Running	P F Smith	
SPS	1990-1994	Analysis	G Romano D H Davis	NA34/P213 EMU09
SPS	1987-1994	Running and Analysis	J Kinson	WA85/WA94

Page Number	Proposal Number	Title and Collaboration
79	276	**Sudbury Neutrino Observatory** Birkbeck College, London; University of Oxford.
82	277	**A search for the H-particle in Ξ^-d and $K^-{}^3$He reactions** Birmingham University; Brookhaven National Laboratory; Carnegie-Mellon Institute; Freiburg University; Kyoto University; Kyoto-Sangyo University; Los-Alamos National Laboratory; TRIUMF; University of Manitoba; University of New Mexico; University of Pittsburgh; Vassar College.
90	279	**Radiative weak decays of Σ^+ and Ξ^- Hyperons** Beijing (IHEP); Bristol University; Fermi Lab; Iowa University; St. Petersburg (LNPI); Moscow (ITEP); Rio de Janeiro (CBPF and CNPQ); Sao Paola; SUNY-Albany; Yale University.
92	280	**Measurement of Beauty Particle Lifetimes and Hadroproduction Cross-Section.** Bologna University; CERN; Genoa University; Imperial College, London; Moscow University; Pisa University; Rome University; Southampton University.
93	282	**A Precision Calorimetric Measurement of the 17 KeV Neutrino with a new type of Detector** Oxford University.
95	283	**A Precision Measurement of ε'/ε in CP Violation $K^0 \rightarrow 2\pi$ Decays** Caglia; Cambridge; CERN; Dubna; Edinburgh; Mainz; Perugia; Pisa; Saclay; Siegen; Torino; Vienna.
96	285	**Study of Lead Lead Interactions** Athens; Bari; Bergen; Birmingham; CERN; Paris; Genoa; Kosice; Legnaro; Padua; Rome; Salerno, Serpukhov; Strasbourg; Trieste.
98	286	**Angular and Polarization Correlation Coefficients in Neutron Decay** Glasgow University; ILL; Rutherford Appleton Laboratory; Sussex University.
99	287	**Charmed Baryon Studies in the CERN Hyperon Beam** Bristol; CERN; Genoa/INFN; ISM Grenoble; Max Planck Institute, Heidelberg; Heidelberg University; Mainz; Lebedev Institute, Moscow.
101	289	**BABAR: Physics at the SLAC B-Factory** Bristol; Brunel; Edinburgh; ICSTM; Lancaster; Manchester; Queen Mary and Westfield College; Rutherford and Appleton Laboratory; Royal Holloway and Bedford New College.

Accelerator	Year of Running	Status (Dec 1994)	Spokesman	Experiment Code
		Preparation	N W Tanner	SNO
	1991 - 1994	Running and Analysis	J Lowe	AGS E813, 836, 886
FNAL	1990	Analysis	V Smith	E761
SPS	1992 - 1994	Running and Analysis	D M Websdale	WA92
	1993 - 1994	Running and Analysis	N E Booth	
SPS	1993 - 1994	Preparation	K Peach	NA48
SPS	1994	Preparation	J B Kinson	WA97
ILL	1993-1994	Running	K Green	
SPS	1993	Running and Analysis	V Smith	WA89
	1994	Preparation	J Fry	BABAR

Page Number	Proposal Number	Title and Collaboration
104	710	**Study of e+e- Annihilation Phenomena with the ALEPH Detector** Annecy; Barcelona; Bari; Beijing; CERN; Clermont-Ferrand; Copenhagen; Deomkritos; Ecole Polytechnique; Edinburgh; Firenze; Florida; Frascati; Glasgow; Heidelberg; Imperial College; Innsbruck; Lancaster; Mainz; Marseille; MPI Munchen; Orsay; Pisa; Royal Holloway & Bedford New College; Rutherford Appleton Laboratory; Saclay; Santa Cruz; Sheffield; Siegen; Trieste; Wisconsin.
118	720	**OPAL - An Omni-Purpose Apparatus for LEP with 4π Coverage** Aachen; Alberta; Birmingham; Bologna; Bonn; Brunel; California (Riverside); Cambridge; Carleton; CERN; Chicago; CRPP Canada; Duke; Freiburg; Hamburg/DESY; Heidelberg; Indiana; Manchester; Maryland; Montreal; Oregan; Queen Mary and Westfield College, London; Rutherford Appleton Laboratory; Saclay; Technion; Tel Aviv; Tokyo; University College/Birkbeck College, London; Vancouver (UBC); Victoria; Weizmann Institute.
136	740	**DELPHI - A Detector with Lepton, Photon and Hadron Identification** Ames ; Antwerp; Athens; Bergen; Bologna; Bratislava; College de France; CERN; CRN (Strasbourg); Demokritos; Genova; Grenoble; Helsinki; IIHE (Brussels); JINR Dubna; KFK (Karlsruhe); Krakow; LAL (Orsay); Lisbon; Liverpool; Ljublajana; LPNHE (Paris VI); Lund; Lyon; Marseille; Milano; Mons; NBI (Copenhagen); NIKHEF (Amsterdam); Oslo; Oxford; Padova; Prague; RAL; Rio de Janeiro; Saclay; Sanita (Rome); Santander; Serpukhov; Stockholm; Tech Univ Athens; Torino; Trieste; Udine; Uppsala; Valencia; Vienna; Warsaw; Wuppertal.
155	750	**H1 - A Detector for HERA Experiments** Birmingham University; Glasgow University; Lancaster University; Liverpool University; Manchester University; Rutherford Appleton Laboratory; Queen Mary & Westfield Colleges; in collaboration with I and III Inst Aachen; Brussels University; Cracow Inst Nucl Phys; Davis University; DESY; Dortmund University; Ecole Polytechnique; Hamburg University; Heidelberg; ITEP Moscow; Kiel; Kosice Inst of Physice; LAL Orsay; Lebedev Phys Inst Moscow; Lund University; MPI Munich; Paris University; Prague Inst of Physics; Prague Charles University; Rome INFN and University; Saclay; SLAC; Wuppertal Ges Hochschule; Zeuthen Inst f HEP and Zuerich Imp d ETHZ.

Accelerator	Year of Running	Status (Dec 1994)	Spokesman	Experiment Code
LEP	1989-1994	Running and Analysis	J Steinberger J C Thompson	ALEPH
LEP	1989-1994	Running and Analysis	A Michelini R M Brown	OPAL
LEP	1989-1994	Running and Analysis	U Amaldi W Venus	DELPHI
HERA	1992-1994	Running and Analysis	F Eisele J Dainton	H1

Page Number	Proposal Number	Title and Collaboration
161	760	**ZEUS - A Detector for HERA** Argonne National Laboratory; Bologna; Bonn; Bristol; Brookhaven National Laboratory; Calabria; California Santa Cruz; Columbia; Cracow; DESY; Firenze; Frascati; Freiburg; Glasgow; Hamburg; Imperial College, London; Iowa; Juelich; Louisiana State University; Madrid; Manitoba; McGill; Moscow State University; NIKHEF: Ohio State University; Oxford; Padova; Pennsylvania State University; University College, London; Rome; Rutherford Appleton Laboratory; Seoul; Siegen; Tel Aviv; Tokyo Institute of Technology; Tokyo Metropolitan University; Torino; Toronto; Virginia Polytechnic; Warsaw; Weizmann Institute; Wisconsin; York; Zeuthen.
175		**The ATLAS Project** Alberta; Alma-Ata; Amsterdam (NIKHEF); Annecy; Argonne; Arizona; Arlington; Athens; Baku; Barcelona; Berkeley; Bern; Birmingham; Bonn; Boston; Brandeis; Bratislava; Brookhaven; Bucharest; Cambridge; Carleton; CERN; Chicago; Clermont-Ferrand; Columbia; Copenhagen; Cosenza; Cracow; Dortmund; Dubna (JINR); Duke; Edinburgh; Florence; Frascati; Freiburg; Fukui; Geneva; Genoa; Glasgow; Grenoble; Haifa; Hamburg; Harvard; Hawaii; Heidelberg; Helsinki; Hiroshima; Indiana; Innsbruck; Irvine; Istanbul; Jena; KEK; Kobe; Kosice; Kyoto; Lancaster; Lecce; Lisbon; Liverpool; London (QMW); London (RHBNC); London (UCL); Lund; Madrid; Mainz; Manchester; Mannheim; Marseille; Melbourne; Milan; Montreal; Moscow (ITEP); Moscow (Lebedev); Moscow (MEPHI); Moscow (MSU); Michigan; MIT; Minsk; Munich; Munich (MPI); Naples; Naruto; Nijmegen; Northern Illinois; Novosibirsk; Orsay; Oslo; Oxford; Paris (P & M) Curie and Paris VII); Pavia; Pennsylvania; Pisa; Pittsburgh; Prague; Protvino (IHEP); Rio de Janeiro; Rochester; Rockefeller; Rome (Sapienza); Rome (Tor Vergata); Rutherford Appleton Laboratory; Saclay; Santa Cruz; Sheffield; Shinshu; Siegen; Southern Methodist University; Stockholm; St Petersburg; Sydney; Tbilisi; Tel-Aviv; Thessaloniki; Tokyo; Toronto; Triumf; Tufts; Uppsala; Urbana; Valencia; Vancouver; Victoria; Washington; Weizmann; Wisconsin; Wuppertal; Yerevan.
188		**The Compact Muon Solenoid (CMS) Detector** Bristol; Brunel; Imperial College, London; Rutherford Appleton Laboratory.
201	780	**Measurements of the spin structure of the nucleon at HERA** Alberta; Argonne; Caltech; Colorado; DESY; Erlangen; Frascati; Illinois-Urbana; INFN-Rome; Liverpool; Mainz; Marburg; MIT; MPI-Heidelberg; München, NIKHEF; New Mexico State; Pennsylvania; St Petersburg; TRIUMF; Wisconsin; Yerevan.

Accelerator	Year of Running	Status (Dec 1994)	Spokesman	Experiment Code
HERA	1992-1994	Running and Analysis	G Wolf R J Cashmore	ZEUS
LHC		Development	F Dydak P Jenni P Norton	ATLAS
LHC		Development	M Della Neggra T Virdee R M Brown	CMS
HERA		Development	C Court	HERMES

Page Number	Proposal Number	Title and Collaboration
203	802	**Integrated Transition Radiation and Tracking Detector for LHC** Aachen; CERN; Dubna; Duke; Glasgow; Indiana; Kracow; Lund; Moscow (Lebedev); Moscow (MEPHI): Munich (Max-Planck); Pennsylvania; Rutherford Appleton Laboratory; Siegen; St. Petersburg.
205	803	**R & D on Optoelectronic Readout from Detectors for LHC** Birmingham; Rutherford Appleton Laboratory.
209	804	**GaAs Detector Development CERN DRDC/RD8** Aachen; Bologna; CERN; Florence; Frieburg; Glasgow; Lancaster; Vilnius, Lithuania; Modena; Moscow, IHEP; Rutherford Appleton Laboratory; Sheffield; ANSTO, Sydney.
220	805	**Solenoid Detector Collaboration (SDC)** Bristol; Liverpool; Oxford; Rutherford Appleton Laboratory. (Plus 112 Institutes World Wide).
221	807	**Development of High Resolution Silicon Strip Detectors for Experiments at High Luminosity at LHC** NCSR, Demokritus, Athens; Bonn University; Brunel; Cambridge; Comenius, Bratislava; CERN; INP Cracow; INPT Cracow; MPI Heidelberg; Liverpool; Imperial College, London; CPPM Marseille; Oslo; SI Oslo; INFN Padova; INFN Roma; Rutherford Appleton Laboratory; LEPSI Strasbourg; INFN Torino; Uppsala; IHEP Vienna; PSI Würenlingen.
228	809	**Gas Microstrip Detectors R and D** Birmingham; Liverpool; Manchester; Rutherford Appleton Laboratory; University College, London.
235	811	**A Calorimeter-Based Level-One Electromagnetic Cluster Trigger for LHC** Birmingham; CERN; Queen Mary and Westfield College, London; Rutherford Appleton Laboratory.
241	812	**Diamond Detectors** Bristol; Imperial College, London; Kings College, London.
242	895	**Laser/Plasma Particle Acceleration Experiments** Imperial College, London; Rutherford Appleton Laboratory.

Accelerator	Year of Running	Status (Dec 1994)	Spokesman	Experiment Code
		Development	D H Saxon	RD-6
		Development	I Kenyon	RD-23
		Development	K M Smith	RD-8
		Terminated	R J Cashmore	SDC
		Development	G Hall	RD-20
		Development	J C Thompson	RD-28
		Development	J Garvey	RD-27
		Development	J Hassard	
		Development	C Danson C B Edwards	-

THE STUDY OF ν AND $\bar{\nu}$ INTERACTIONS WITH PROTONS USING THE BEBC BUBBLE CHAMBER

WA21 PROPOSAL 004

Birmingham University, CERN, Imperial College, MPI-Munich, Oxford University, University College London.

Data taking for this experiment was completed in December 1983. The samples include approximately 19.000 ν and 11,000 $\bar{\nu}$ charged current events. These constitute the largest data set of interactions on free protons. Work published to date includes studies of inclusive structure functions and final state properties, exclusive final states, neutral current cross sections and production of strange and charmed particles.

During the past year results have been published on the charged current structure functions of the nucleon and the ratio of d-type to u-type valence quarks. A new feature was the inclusion of results from an exposure of BEBC with a deuterium filling. This was a powerful new tool since, being taken in the same neutrino and antineutrino beams, combination of the two sets of data could be done with small relative normalisation uncertainties. The assumption of charge symmetry of the quark distributions then allows more sensitive determinations of the distributions of the individual quark species. It is found that the BEBC data alone show significant scaling violations and a value of the QCD parameter Λ is obtained. The ratio d_v/u_v of valence quark distributions can be determined with better precision than previous neutrino analyses. The result shows a clear violation of SU(6) symmetry and is consistent with dominance of the isospin zero spectator diquark state at $x = 1$.

Work continues on the neutral current to charged current cross section ratios.

Publications in 1994

Determination of parton distributions and structure functions of the proton from neutrino and antineutrino reactions on hydrogen and deuterium, G. T. Jones et al., Z. Phys. C 62 (1994) 575.

Determination of the ratio $r_v = d_v/u_v$ of the valence quark distributions in the proton from neutrino and antineutrino reactions on hydrogen, G. T. Jones et al., Z. Phys. C 62 (1994) 601.

Electric Dipole Moment of the Neutron

TGV at the ILL

Proposal 157

University of Sussex, RAL, ILL, Harvard, Washington

For particles to have electric dipole moments (EDM's), the forces concerned in their structure must be asymmetric with regard to space-parity (P) and time (T). P-violation is a well known intrinsic feature of the weak interaction and CP-violation (and hence T-violation through the CPT theorem) has been found in the K-meson system. As yet, however, T-violation has not been identified anywhere else. Such limited information leaves open a wide range of possibilities for the understanding of T-violation. Experimental measurements of particle EDM's and in particular that of the neutron, are providing some of the strongest additional constraints on theories of T-violation. The Standard Model of the electroweak interaction gives a contribution to the neutron EDM of the order of 10^{-31} to 10^{-33} e cm. This value is second order in the weak interaction coupling constant and is very small. Extensions to the Standard Model, such as adding extra Higgs fields, right handed currents or supersymmetric partners, any of which amounts to 'new physics', invariably gives rise to dipole contributions which are of first order and as such are much larger(of order 10^{-25} to 10^{-27} e cm). Large dipole moments might also come from CP-violation in the QCD sector of the strong interactions.

The experiment reported on here, is carried out using the research reactor at the ILL in Grenoble and is a continuation of work carried out by our group for nearly two decades. The reactor itself has been out of action for three years now whilst necessary repairs to its structures were carried out. This work is now finished and it is expected that the facility will resume full operation by the end of 1994. With our new experimental apparatus and the reactor at full power it is hoped to reduce the limit on the neutron EDM by a further order of magnitude over the next 3 years. The neutron storage cell has been enlarged and further increases are also planned for later this year. At the same time provision has been made to incorporate an atomic mercury magnetometer in the same storage volume as the neutrons and hence reduce the systematic errors associated with magnetic field variation which was a major problem in all the previous experiments.

The magnetometer system has been run in its final configuration on the experiment for several periods of continuous operation this year. Experience has been gained of its performance with and without high voltage on the neutron storage cell and its performance has been measured. At the same time a new PC based data acquistion system has been for implemented for both high voltage control and magnetometry. The figure shows the results from this new system. The drift in the magnetic field in the region where the neutrons will be stored, with data points taken every three minutes, is plotted. The short term noise, excluding the drift, is 1.2 nanogauss and is dominated by the actual noise in the magnetic field. The noise internal to the magnetometer signal is only 0.4 nanogauss. The nett effect of this is that systematic measurement effects to the dipole moment sensitivity should now be reduced to the level of 10^{-27} e.cm.

Photoproduction in the energy range 70-180 GeV

WA69 Proposal 231

Bonn, CERN, Lancaster, Manchester, RAL, Sheffield, Yerevan

The WA69 experiment has been carried out by the Omega Photon Collaboration, using the Omega Spectrometer in the West Hall at CERN. Data taking was completed in 1986.

An important aim of the experiment is the study of the production of single particles and clusters of particles as a function of P_T up to P_T of 5 GeV/c, with the object of isolating the direct processes which should be present in photoproduction from the generally softer background due to hadronic processes. The photon interacts by both soft and hard processes, but the hard QCD Bethe Heitler and QCD Compton scattering processes which contribute to the latter should not be present in hadron induced reactions.

Charged particles produced by interaction of the beam with a proton in the Hydrogen target are detected and reconstructed in the Omega Spectrometer. These charged particles are identified in the downstream RICH (Ring Image Cherenkov) and TRAD (Transition Radiation) detectors, which have been constructed by the WA69 collaboration and CERN. This combination allows π and K to be efficiently separated over a wide momentum range, and provides important information on the flavour content of high P_T events. Neutral particles are detected and reconstructed in the main Omega Electromagnetic Calorimeter and a special inner Plug Calorimeter constructed for WA69 using lead/scintillating fibres.

About 20M events, with an open trigger, have been obtained with photon beams in 1985 and a further 20M with hadron beams (75% π, 25% K) at corresponding energies in 1986. Comparison of these data, which were taken using essentially identical trigger and hardware and have been analysed with the same software, has allowed a measurement of the hard QCD component due to the 'point like' interaction of the photon without the usual systematic uncertainties involved in the comparison of data from different experiments.

Results from analysis of these data have been published (a) and show an excess of photoproduced charged particles at high P_T which is in reasonable agreement with the QCD predictions, both in magnitude and dependence upon X_F. A more detailed analysis of the 'energy flow' within such high P_T events (b) and of the contribution from 'Higher Twist' (d) provide additional confirmation of the QCD model predictions. A study of forward charge asymmetry as a function of X_F and P_T, for π and K identified using the RICH/TRAD system, has produced results (c) which can be understood in terms of a Parton Recombination Model and comparisons of the photo- and hadro-production of π^0 (e), η (f) and ρ^0 mesons (g) have shown evidence for contributions from hard parton-parton scattering.

(a) Inclusive Photoproduction of Single Charged Particles at High P_T.
Apsimon et al Zeitschrift für Physik C43 (1989) 63.

(b) A Study of the point-like interactions of the Photon using energy-flows in photo- and hadro-production for incident energies between 65 and 170 GeV.
Apsimon et al, Zeitschrift für Physik C46 (1990) 35.

(c) Forward charge asymmetry in low P_T photoproduction of hadrons.
Apsimon et al, Zeitschrift für Physik C47 (1990) 397.

(d) Separation of Minimum and Higher Twist in Photoproduction of high P_T Mesons.
Apsimon et al, Zeitschrift für Physik C5O (1991) 179.

(e) Inclusive Production of π^0 - mesons in pp, πp and gp collisions at energies around 100 GeV.
Apsimon et al, Zeitschrift für Physik C52 (1991) 397.

(f) Inclusive production of h-mesons in pp, kp and γp collisions at energies around 100 GeV.
Apsimon et al, Zeitschrift für Physik C54 (1992) 185.

(g) Comparison of photon and hadron induced production of ρ^0 mesons in the energy range of 65 to 175 GeV.
Apsimon et al, Zeitschrift für Physik C53 (1992) 581.

(h) Production of f_2 (1270) and f_0(975) mesons by photons and hadrons of energy 65-175 GeV.
Apsimon et al, Zeitschrift für Physik C56 (1992) 185.

Publications Since 1993 PPEXP Report

Photoproduction and hadroproduction of ϕ (1020), K^{*0} (892) and $\overline{K}^{*0}$ (892) mesons in the energy range 65 GeV to 175 GeV/c.
Apsimon et al, Zeitschrift für Physik C61 (1994) 383.

Soudan 2 Experiment

Argonne - Minnesota - Oxford - DRAL - Tufts Collaboration

Particle Physics experiments today divide into two classes; those that pursue the predictions of the remarkably successful Standard Model and those that strike out in search of unconventional and unexpected experimental results. The Soudan experiment belongs to this second class.

The apparatus consists of a 960-ton iron calorimeter 2700 feet down the Soudan iron mine in northern Minnesota It is composed of 4.3-ton modules, one third of which were made in the UK by the Oxford/DRAL Groups. The detector was commissionned sector by sector as each was ready; the whole was completed over a year ago. A programme of upgrades and maintenance has been funded largely by the US but with major UK contributions (funded through DRAL). This is enabling significant improvements in detector performance and efficiency and should ensure an effective life of the experiment until the end of the century, at least. At the same time further counters are being added to the active shield to improve the efficiency of the external veto. These include the redeployment by Oxford of the proportional tubes that were used as the muon counters for the TASSO experiment. They should be put in place during 1995. Two Oxford graduate students, one PPARC and one funded by the Rhodes Trust, are involved in this aspect of the experiment.

The experiment is particularly well suited to investigations on three unconventional pieces of physics; experiments on the origin of cosmic rays, on neutrino oscillations, and on nucleon decay.

The apparatus has recorded more than 20 million cosmic ray muons; sky maps of the celestial directions of these muons have been constructed and compared with background estimates. The significance of "hot spots" (and "cold" spots) has been discussed and their possible relationship with the direction of known astrophysical objects studied. The thesis of Graham Giller completed during 1994 was concerned with these questions. Further work continues and more publications are forseen.

The study of neutrino oscillations is a particularly obvious way in which to search for departures from the Standard Model. There are two reasons for this. First, as any study of elementary Quantum Mechanics reveals, degenerate states are peculiarly sensitive to *any* small interaction. A good example is the degeneracy or near degeneracy in the neutral kaon system which has become an outstanding laboratory in which to study P and CP violating effects. There are few such degenerate systems. The three-fold degenerate neutrino sector is uniquely sensitive to small unexpected effects in the problem of the relationship between the lepton generations. Second there are now well established results on neutrinos from the sun and other results from neutrinos from the upper atmosphere which may be interpreted as evidence for neutrino mixing. The Soudan detector is accumulating atmospheric neutrino data at the rate of about 100 events per year. By the summer of 1995 we hope to have some 200 events analysed according to their neutrino flavour, complete with a reliable Monte Carlo study. Previous data on atmospheric neutrino interactions detected in water Cherenkov experiments have suggested a 40% anomaly in the flavour ratio. In the Soudan experiment with the statistics and systematics properly checked by Monte Carlo (which are anyway quite different to the previous experiments) we may expect a new and definitive result from Soudan II on this important question.

Any credible result on proton decay would require a proper understanding of the background. This "fully contained event" background comes from neutrino interactions. While there remain anomalies in the background, any conclusions on the existence or otherwise of a signal can only be tentative. We are collecting fully contained event data continuously; the final analysis of the experimental data will have to be described by neutrino interactions, with or without oscillations, together with nucleon decay, or limits to it.

An important new development is the Long Baseline experiment. A new collaboration has been set up to send a beam of neutrinos from Fermilab to Soudan, a distance of 730 km. This beam which is made possible by the new Main Injector will be studied by three detectors, a near-station detector at Fermilab, the existing fine-grain Soudan2 detector and a new somewhat coarser 15 kiloton detector in a new cavern in the Soudan mine. The aim of the experiment is to study changes in the beam due to neutrino oscillation. Specifically, firstly the appearance of tau leptons from the interaction of tau neutrinos and secondly the energy spectrum of charged current and neutral current interactions. The first method is more ambitious but has all the features of a "smoking gun" result. The second method is substantially more accurate and conservative. It amounts to a study of the possible modulation of the ratio of observed to expected charged current interaction rate as a function of the neutrino oscillation phase (which goes like $1/E$).

The current position is that the Program Advisory Committee has recommended this experiment to the Fermilab management. The latter have accepted the recommendation, completed a study of the beam, called for R & D Proposals from the Collaboration and called for a letter of intent (LOI) at the start of 1995. Their program expects a completed beam and a substantial part of the new detector to be ready for Physics before the end of 2000. The existing UK groups (Oxford and DRAL) are talking with other UK groups with a view to enlarging the UK involvement. Detector designs are being studied with Monte Carlo. A new PPARC graduate student at Oxford is involved. An RO (Jenny Thomas) from Oxford is spending six months at Fermilab making a contribution as Experiment Coordinator. The new experiment is gathering speed rapidly.

KARMEN; Neutrino Physics at ISIS

KfK and University of Karlsruhe
University of Erlangen
Queen Mary & Westfield College
Oxford University
Rutherford Appleton Laboratory

The Karlsruhe Rutherford Medium Energy Neutrino experiment (KARMEN) continues to take data using the neutrino flux from pion and muon decay at rest in the spallation target at ISIS. Last year we reported on our measurement of the weak nuclear form factor and a test of universality in the neutral current sector. In this report we describe our latest results on neutrino oscillations.

Neutrino Oscillations

In the Standard Model, all neutrino flavours are assumed to be massless. However, there are no fundamental symmetries requiring this assumption and should any of them differ from zero, then oscillations will occur between these non-degenerate states with a probability determined by the mixing angle Θ and the mass difference Δm.

The oscillation probability P for a flavour transition of a neutrino with energy E_ν (in MeV) after a travel distance L (in m) is given by:

$$P(\nu_1 \rightarrow \nu_2) = \sin^2 2\Theta \times \sin^2(1.27 \times \Delta m^2 \times L/E_\nu)$$

with the mass difference $\Delta m^2 = |m_1{}^2 - m_2{}^2|$ in eV^2.
The KARMEN experiment is searching for neutrino oscillations by investigating appearance channels. As evidence of oscillations we are searching for the appearance of ν_e in the prompt time window arising from $\nu_\mu \rightarrow \nu_e$, and for $\bar{\nu}_e$ in the delayed muon decay time window arising from $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$.

The $\nu_\mu \rightarrow \nu_e$ Appearance Channel

This channel can be detected through the following reaction sequence:

$$\nu_\mu \rightarrow \nu_e + {}^{12}C \rightarrow {}^{12}N_{g.s.} + e^- - 17.3 \text{ Mev}$$
$$\downarrow$$
$${}^{12}C_{g.s.} + e^+ + \nu_e$$

For oscillations of monoenergetic ν_μ to ν_e of the same energy (E = 29.8 MeV) this means a spatially correlated delayed coincidence between a monoenergetic electron of 12.5 MeV from the inverse beta decay on ${}^{12}C$ during the prompt window and a positron of up to 16.3 MeV from the beta decay of ${}^{12}N_{g.s.}$ during the subsequent beam pause. Figure 1 shows the parameters of this signature in more detail, the Monte Carlo simulations assuming 100% oscillation probability.

Analysing the data corresponding to 6021 coulomb of protons on target we find a total of 3 such coincidence events, compared to the 158.4 events to be expected for full oscillation $P(\nu_\mu \rightarrow \nu_e)=1$. Cosmic ray induced background measured in the pre-beam period amounts to only (0.10±0.02) events. More significant is the contamination due to ν_e from early μ^+ decay in the ISIS target. From our measured ν_e interaction rate in the muon decay window we extrapolate a signal of (4.5±0.2) events due to this background in the prompt time window. Following the recommendations of the Particle Data Group we calculate an upper limit of 3.7 events due to $\nu_\mu \rightarrow \nu_e$ transitions (90% Confidence Level). This corresponds to an oscillation probability P of:

$$P(\nu_\mu \rightarrow \nu_e) < 2.4 \times 10^{-2} \text{ (90\% Confidence Level)}$$

In Figure 3 we show the region of $\sin^2 2\Theta - \Delta m^2$ parameter space excluded by this result.

The $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ Appearance Channel

Electron antineutrinos can be detected by the inverse beta-decay reaction on free protons in the liquid scintillator:

$$\bar{\nu}_\mu \rightarrow \bar{\nu}_e + p \rightarrow n + e^+ - 1.8 \text{ Mev}$$

The neutrons are rapidly thermalised and after a mean diffusion time of 107 μs, determined by the characteristics of the detector,are captured in gadolinium contained within the walls of the optical segmentation of the detector giving rise to on average three gamma quanta with sum energy of 8 MeV.

The signature for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations then is a spatially correlated delayed coincidence between a positron in the muon decay time window carrying almost the entire $\bar{\nu}_e$ energy up to 51 MeV, and gamma-rays up to 8 MeV occuring in the neutron detection time window. The parameters of this signature are shown in more detail in Figure 2, again the Monte Carlo simulations assume 100% oscillation probability.

Analysing the same data set as before we find a total of 11 events satisfying these criteria. Cosmic ray induced background amounts to 16.2 events and there is a small background due to the charged current reaction $^{12}C(\nu_e,e^-)^{12}N_{g.s.}$ of 0.4 events, giving a total of 16.6 events. Thus our observed events can be completely explained by background processes.

Again following the recommendations of the Particle Data Group we calculate an upper limit of 5 events due to $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ transitions (90% Confidence Level), whereas for full oscillation we would have expected 1591 events. This corresponds to an upper limit for the oscillation probability of:

$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) < 3.1 \times 10^{-3} \text{ (90\% Confidence Level)}$$

Again in Figure 3 we show the region of $\sin^2 2\Theta - \Delta m^2$ parameter space excluded by this result.

Conclusion

The KARMEN detector is the only *neutrino spectrometer* in operation, and can therefore provide the most reliable limits on oscillation probabilities. Exploiting the spectroscopic quality of the data and the time structure of the source will enable us to achieve the most stringent limits on oscillation probability accessible to beam dump neutrino sources.

Currently our results are limited by statistics, hence we expect a significant enhancement of our oscillation sensitvity in both these reaction channels after more data taking, and also by improvement of our data evaluation methods.

Publications since October 1993:

The KARMEN Neutrino Experiment
Interdiscip. Science Reviews Vol.18, No.3 (1993), p.313.

Wavelength Dependent Light Attenuation in Organic Scintillators
Nucl. Instr. Meth. A 340 (1994) p.346.

Neutrino-Nuclear Interactions with KARMEN
Proc. XII Int. Conf. Ptles. and Nuc. Perugia, June 1993 p.735.

Low Energy Tests of SM with Neutrinos from Muon Decay
Ibid. p.290.

KARMEN: Neutrino Physics at ISIS
Prog. Part. Nuc. Phys. Vol.32 (1994) p.351.

KARMEN; Precision Tests of SM with Neutrinos from Muon and Pion Decay
Ibid. p. 375.

Neutrino Electron Scattering at ISIS
Ibid. p. 397.

KARMEN; New Neutrino Physics
CERN Courier, Vol.33 No.10 (December 1993) p.23.

Figure Captions

Figure 1:
Delayed coincidence signature for $\nu_\mu \rightarrow \nu_e$ oscillations. The energy spectra are GEANT3 simulations. Time spectra correspond to the prompt time window and the ^{12}N decay time window respectively.

Figure 2:
Delayed coincidence signature for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations.The energy spectra are GEANT3 simulations. The positron time spectrum corresponds to the muon decay curve and the neutron capture time spectrum was calculated using the neutron transport code MORSE.

Figure 3:
Contours of the 90% CL exclusion limits for $\nu_\mu \rightarrow \nu_e$ transitions (solid line) and for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ transitions (dotted line).

$\nu_e + {}^{12}C \rightarrow {}^{12}N_{g.s.} + e^-$
${}^{12}N_{g.s.} \rightarrow {}^{12}C + e^+ + \nu_e$
Events
100
75
50
25
0
0
5
10
15
20
Electron Energy [MeV]
Positron Energy [MeV]
125
250
375
500
Electron Time [ns]
τ = 15.9 ms
Read-Out
30
Positron Time [ms]

$\bar{\nu}_e + p \rightarrow n + e^+$
$n \rightarrow n_{therm} \rightarrow Gd(n,\gamma)$
Events
100
75
50
25
0
0 10 20 30 40 50 60
Positron Energy [MeV]
0 5 10
Capt.-γ Energy [MeV]
0 5 10
Positron Time [μs]
10^2
10
1
0 105 210 315 420
n-Capture Time [μs]

Δm^2 [eV^2]
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-2}
10^{-1}
1
$\sin^2 2\Theta$
$\nu_\mu \rightarrow \nu_e$
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

A SEARCH FOR GLUEBALLS IN THE CENTRAL REGION

WA76/WA91 Proposal 246

Athens : Bari : Birmingham : CERN : Dubna : Paris.

Experiment WA76 and its successor WA91 have been designed to study exclusive final states formed in the reaction

$$pp \rightarrow p_f(X^0)p_s \tag{1}$$

where the subscripts f and s indicate the fastest and slowest particles in the laboratory respectively, and X^0 represents the central system. The central system is presumed to be produced by double exchange processes. At high centre-of-mass energies the contribution of Double Pomeron Exchange (DPE) to such processes becomes increasingly large. The Pomeron is believed to have a large gluonic content, and as a result it is thought that Pomeron Pomeron scattering could be a good source of gluonic states, glueballs and hybrids.

The WA76 experiment was run in two stages. Data taken with π^+ and p incident beams at 85 GeV/c allowed good separation of many exclusive channels [1]. Several resonances suggested as gluonium candidates were seen with good signal to background ratios whereas well-known $q\bar{q}$ states were seen less prominently than in peripheral production. A second period of data taking using a 300 GeV/c p beam yielded 12 million triggers. The layout of the apparatus is shown in fig. 1. In addition to the Omega MWPC and drift chambers, two threshold Cerenkov counters were used for charged particle identification, and a fine grain electromagnetic calorimeter was used for neutral particles. The fast track measurement system [2], shown in fig. 2, is of particular interest. In order to achieve good momentum resolution, which is essential for the separation of exclusive channels, a system of microstrip detectors was used to measure the beam particle and the fast track. The reconstructed beam momentum distribution from the WA76 data is shown in fig. 3, and corresponds to a precision $\delta p/p = 3 \times 10^{-5}p$ (Subsequently $\delta p/p = 1 \times 10^{-5}p$ was achieved using a similar layout and finer pitch microstrips in WA91.)

The WA91 experiment aims to investigate central production at 450 GeV/c with a significant increase in statistics over WA76 [3]. The first phase of the experiment, performed in 1992, used the refurbished OLGA calorimeter brought close to the Omega magnet to improve acceptance for neutral particles. Slow protons were detected in WA76 on the left side of the target only, while the WA91 setup, shown in fig. 4, also allows for slow proton detection on the right. The right hand slow proton setup uses a new hodoscope (SPCR) built by the Birmingham group. The 1992 exposure yielded 67 million triggers. The second phase of the experiment was completed on June 8th 1994 and 42 million triggers were taken. The threshold Cerenkov counters C1 and C2 were used for charged particle identification and the same arrangement of fast and slow particle detectors was employed as for the first phase of the experiment. The GAMS electromagnetic calorimeter and OLGA were also used, placed behind the Cerenkov

counters, to study their use for a future phase of the experiment which is discussed below.

The analysis of the WA76 data is now essentially complete, while results from the WA91 data are mostly still in preparation. The principal results from the experiment programme are summarized below.

A detailed study of the $\pi^+\pi^-$ mass spectrum has been performed for the 300 GeV/c data [4]. The spectrum is shown in fig. 5, and shows clear evidence for $S^*/f_0(975)$ production. A good description of the $\pi^+\pi^-$ mass spectrum was obtained using a coupled channel (Flatté) formalism, and allowing the $S^*/f_0(975)$ to interfere coherently with the S-wave background. The $S^*/f_0(975)$ parameters were determined to be $m_0 = 979 \pm 4$ MeV, $g_\pi = 0.28 \pm 0.4$, $g_K = 0.56 \pm 0.18$, giving a pole position on sheet II at $(1001 \pm 2) - i(36 \pm 4)$ MeV.

The principal interest in the $K\overline{K}$ spectrum lies in the observation of the $\theta/f_2(1720)$ [5], the first such observation in hadroproduction. The K^+K^- spectrum is shown in fig. 6, where a peak corresponding to the $\theta/f_2(1720)$ is clearly seen. As a signal is also seen in the $K^0_S K^0_S$ mass spectrum, it is concluded that the spin of the object is either 0^{++} or 2^{++}. The decay angular distributions for the $f'(1525)$ and the $\theta/f_2(1720)$ are found to be qualitatively similar, suggesting that the $\theta/f_2(1720)$ and the $f'(1525)$ have the same spin.

The $K\overline{K}\pi$ mass spectrum in the 1.4 GeV mass region has been of long standing interest in this experiment [1,6,7]. The $K^0_S K^\pm \pi^\mp$ mass spectrum is shown in fig. 7, and shows very prominent signals for the $D/f_0(1285)$ and $E/f_1(1420)$ mesons. While the status of the $D/f_0(1285)$ is not controversial, that of the $E/f_1(1420)$ has aroused much interest in recent years. It now appears that there are three states in this mass region. The one seen by WA76 has been found to have $M = 1429 \pm 3$ MeV and $\Gamma = 58 \pm 8$ MeV. A Dalitz plot analysis has shown its J^{PG} to be 1^{++}, decaying to $K^*\overline{K}$ [5]. More recently [7], its observation in our $K^0_S K^0_S \pi^0$ data has fixed its C-parity to be +, from which we deduce its isospin to be zero. We have searched for the $E/f_1(1420)$ in our $\pi^+\pi^-\pi^+\pi^-$ [8], $\eta\pi^+\pi^-$ [9] and $\rho^0\gamma$ [10] channels. Although the $D/f_0(1285)$ is clearly seen in all channels, as can be seen from fig. 8, there is no evidence for production of the $E/f_1(1420)$ in any of them.

The $\pi^+\pi^-\pi^+\pi^-$ spectrum has been analysed at both 300 GeV/c and 450 GeV/c. The $\pi^+\pi^-\pi^+\pi^-$ mass spectrum is shown in fig. 9 for the 450 GeV/c data with superimposed fit [11]. In addition to the $D/f_0(1285)$ two further resonances are seen, the X(1450) and the X(1900), with masses and widths $M = 1446 \pm 5$ MeV, $\Gamma = 56 \pm 12$ MeV, and $M = 1926 \pm 12$ MeV, $\Gamma = 370 \pm 70$ MeV respectively. These resonances were first seen in the WA76 300 GeV/c data, but were not seen at 85 GeV/c[8]. The energy dependence and t dependence of the X(1450) show that it is not a decay channel of the $E/f_1(1420)$ seen in the $K\overline{K}\pi$ spectrum. A new spin analysis of the X(1450) [11] finds its spin parity to be $J^{PC} = 0^{++}$, decaying to $\rho(\pi\pi)_{Pwave}$. The X(1900) is found to be a $J^{PC} = 2^{++}$ object decaying to $a_2\pi$ and $f_2(1270)(\pi\pi)_{Swave}$. As the X(1900) is a broad object and the peaks in the $a_2\pi$ and $f_2(1270)(\pi\pi)_{Swave}$ channels are slightly displaced, it could be that there are two resonances present. The analysis method used was not available when the original WA76 study was performed, but a re-analysis of

these data shows that the two data samples yield the same J^{PC} assignments for these two resonances.

FUTURE PLANS (WA91)

The $\theta/f_2(1720)$ and the $G/f_0(1590)$ represent two of the most promising non-$q\overline{q}$ candidates currently known. The $G/f_0(1590)$ has only been seen in neutral decays, while the $\theta/f_2(1720)$ has a known significant $\eta\eta$ decay mode. For this reason good acceptance for both charged and neutral particles is necessary to do a detailed study of these states. Preliminary study of the OLGA data taken in 1992 indicate that two photon resolution is an important limiting factor in the extraction of exclusive channel physics from these data. In 1993 it was proposed to install the ex-NA12 GAMS-4000 electromagnetic calorimeter at Omega in order to study neutral channels with improved acceptance. The optimum solution involves using both GAMS and OLGA together putting the higher resolution GAMS calorimeter close to the beam line and using the lower resolution OLGA blocks at larger angles. The expected rates would allow us to increase statistics on the $\eta\eta$, $\eta\eta'$ and $\eta'\eta'$ channels by an order of magnitude over currently published statistics in 120 days of running. A new proposal, requesting further running time to exploit this configuration was approved by the SPSLC in August 1994.

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11. S. Abatzis et al., Phys. Lett. **B234** (1994) 509.

PUBLICATIONS (October 1993 - September 1994)

1 Study of the vector-vector final states centrally produced in pp interactions at 300 GeV/c.
IJ Bloodworth, JN Carney, CJ Dodenhoff, JB Kinson, O Villalobos Baillie and MF Votruba with Athens, Bari, CERN and Paris.
Proceedings of Hadron '93, Como, Italy.

2 First results from experiment WA91 at the CERN Omega Spectrometer.
RP Barnes, A Bayes, JN Carney, S Clewer, JP Davies, CJ Dodenhoff, JB Kinson, O Villalobos Baillie and MF Votruba with Athens, Bari, CERN and Dubna.
Proceedings of Hadron '93, Como, Italy.

3 Observation of a narrow scalar meson at 1450 MeV in the reaction $pp \rightarrow p_f(\pi^+\pi^-\pi^+\pi^-)p_s$ at 450 GeV/c using the CERN Omega Spectrometer.
RP Barnes, A Bayes, JN Carney, S Clewer, JP Davies, CJ Dodenhoff, JB Kinson, K Norman, O Villalobos Baillie and MF Votruba with Athens, Bari, CERN and Dubna.
Physics Letters **B324** (1994), 509-514.

4 Observation of new states in the reaction $pp \rightarrow p_f(\pi^+\pi^-\pi^+\pi^-)p_s$ at 300 and 450 GeV/c.
RP Barnes, A Bayes, JN Carney, S Clewer, JP Davies, CJ Dodenhoff, JB Kinson, K Norman, O Villalobos Baillie and MF Votruba with Athens, Bari, CERN and Dubna.
Proceedings of the International Conference on High Energy Physics (ICHEP'94) Glasgow, July 1994. Presented by O Villalobos Baillie.

Fig. 1. Layout of the CERN Ω Spectrometer as used for the WA76 experiment.

Fig. 2 Layout of the μ-strips and scintillators used to measure the beam and the fast particle.

Fig. 3. Reconstructed beam momentum at 300 GeV/c.

Fig. 4. WA91 apparatus (1992) configuration.

Fig. 5. $\pi^+\pi^-$ effective mass distribution at 300 GeV/c. The fit is described in the text.

Fig. 6. K^+K^- effective mass distribution at 300 GeV/c. The fit is described in reference 4.

Fig. 7 $K_S^0 K^{\pm}\pi^{\mp}$ effective mass spectrum at 300 GeV/c.

Fig. 8. Effective mass distributions for (a) $K^0_S K^{\pm}\pi^{\mp}$, (b) $\pi^+\pi^-\pi^+\pi^-$, (c) $\eta\pi^+\pi^-$ and (d) $\rho^0\gamma$ channels.

Fig. 9. $\pi^+\pi^-\pi^+\pi^-$ effective mass spectrum for 450 GeV/c data.

A Precise Measurement of $|\eta_{00}/\eta_{+-}|^2$

CERN, Edinburgh, Mainz, Orsay, Pisa, Siegen Collaboration

The main aim of this experiment was to measure precisely the strength of CP-violation in the decay amplitude relative to the dominant CP-violation in the K^0 mass matrix, by comparing the ratio of decays into two charged and two neutral pions for K_S and K_L. Data taking took place between 1986 and 1989, obtaining a sample of more than 300 000 $K_L \to 2\pi^0$ events.

The analysis of the data for ϵ'/ϵ is complete [1], and the results indicate a small, positive value for the parameter $\epsilon'/\epsilon = 1 - \frac{1}{6}|\eta_{00}/\eta_{+-}|^2$ of 0.0023 ± 0.00065.

The excellent energy and spatial resolution of the liquid argon electromagnetic calorimeter allowed measurements of a variety of rare, purely electromagnetic decays. Observation of the decay $K_L \to e^+e^+e^-e^-$ was reported three years ago, based upon two events with negligible background. Further analysis with more data yields another six events. Furthermore, it is possible to analyze these data, using the angle between the decay planes of the two e^+e^- pairs, to show [2] that K_L is a $CP = -1$ state. There have also been searches for other rare decays, which have an important bearing on certain interesting channels; for example, new bounds [3] have been placed on the decay $K_L \to \pi^0\pi^0\gamma$.

There is also a new measurement of the common branching ratios $\Gamma(K_L \to 3\pi^0)/\Gamma(K_L \to \pi^+\pi^-\pi^0)$ and $\Gamma(K_L \to 3\pi^0)/\Gamma(K_L \to \pi e\nu)$, which have hitherto been rather poorly determined.

The experiment is complete.

Publications

1. GD Barr *et al*
   A New measurement of direct CP violation in the neutral kaon system
   Phys.Lett.B317 (1993) 233-242

2. GD Barr *et al*,
   Measurement of the Branching Ratio of the Double Dalitz Decay $K_L \to e^+e^+e^-e^-$ and the CP Parity of the K_L Meson
   to be published in Z.Phys.C

3. GD Barr *et al*
   Search for the decay $K_L \to \pi^0\pi^0\gamma$
   Phys.Lett.B328 (1994) 528-534

4. A Kreutz *et al*
   Determination of the branching ratios $\Gamma(K_L \to 3\pi^0)/\Gamma(K_L \to \pi^+\pi^-\pi^0)$ and $\Gamma(K_L \to 3\pi^0)/\Gamma(K_L \to \pi e\nu)$.
   to be published in Z.Phys.C

An exposure of the 15-foot bubble chamber filled with a Ne/H_2 mixture to a quad-triplet beam from the TEVATRON running at 800 GeV/c.

FNAL E632 Proposal 254

Berkeley - Birmingham - Brussels - CERN - Chandigarh - FNAL-
Hawaii - IHEP(Serpukhov) - Illinois - Imperial College London - ITEP (Moscow) -
Jammu - MPI Munich - Moscow State University - Oxford -
RAL - Rutgers - Saclay - Tufts

For the majority of the original groups of the experiment, data-processing finished during 1992. However, IHEP(Serpukhov), ITEP(Moscow) and Moscow State University are in the process of measuring a large unbiassed sample. A considerable increase in statistics has already been obtained, which should provide sufficient data at the highest-ever neutrino energy for many comparisons to be made with experiments at lower neutrino energies - fragmentation studies, energy dependences in strange particle production, neutral currents, etc.

Several new analyses are under way and the results should be published in the near future.

E632 and BEBC Publications since 1 October 1993

1. Bose-Einstein correlations in neutrino and antineutrino interactions with nucleons
   Zeitschrift für Physik C60 (1993) 37-51
2. Observation of $D_s^{**}(2536)$ meson production by neutrinos in BEBC
   Zeitschrift für Physik C61 (1994) 563-565
3. Determination of the parton distributions and structure functions of the proton from neutrino and antineutrino reactions on hydrogen and deuterium.
   Zeitschrift für Physik C62 (1994) 575-600
4. Determination of the ratio $r_v = \frac{d_v}{u_v}$ of the valence quark distributions in the proton from neutrino and antineutrino reactions on hydrogen and deuterium.
   Zeitschrift für Physik C62 (1994) 601-607

Public Understanding of Science/Education Paublication using E632 film

1. The Bubble Chamber and the Public Understanding of the Physical Sciences
   Nuclear Physics B (Proc. Suppl.) 36 (1994) 467-474.
2. A remarkably rich bubble chamber picture (the competition!).
   Nuclear Physics B (Proc. Suppl.) 36 (1994) 475-478.

SLD Collaboration at SLC

Proposal 263

Bologna, Boston, Brunel, Caltech, Cincinnati, Colorado State, Columbia, Ferrara, Frascati, Illinois, Massachusetts, MIT, Nagoya, Northeastern, Northridge, Oregon, Padova, Perugia, Pisa, Rutgers, RAL, Santa Barbara, Santa Cruz, SLAC, Tennessee, Tohoku, Vanderbilt, Washington, Wisconsin, Yale.

1994 is the third year of running for SLD. The SLC performance continues to improve. Numerous important physics papers have emerged from the 1993 data. The general picture is that despite the luminosity disadvantage with respect to LEP, the availability of a highly polarized electron beam (with accurately measured longitudinal polarization) allows a physics programme which is complementary to and competitive with that of the LEP experiments.

I SLC Performance and Plans

The main limitations to the SLD luminosity (as explained in last year's report) were the presence of sawtooth instabilities at high currents in the damping rings, and chromatic aberrations in the Final Focus. The first problem was eliminated by rebuilding the damping ring vacuum chambers during the 1993/4 shutdown and the second by redesigning the Final Focus. The first of these upgrades has been partially successful. There remain some current instabilities which though considerably reduced in magnitude, are still limiting the luminosity. Work on understanding these continues. The second upgrade has been a great success. At low currents, SLC runs with 400 nm high flat beams that collide to give far higher specific luminosities than ever before. The evolution of SLC luminosity is shown in Fig. 1.

While the present luminosity situation is still less than we would like for SLD physics, it is extremely encouraging for the Future Linear Collider, where the essential requirement is the stable collision of a high rate of low current bunches of extremely small vertical size. The present SLC demonstrates that many of the conditions required for this operation can indeed be met.

Regarding the electron polarization, SLC continues to make great progress. With yet further improvements in the strained lattice cathode, it regularly runs with polarization in excess of 80%; see Fig. 2. In addition, the measurements of the polarization are far more precise than in 1993. Sources of systematic uncertainty have been eliminated or greatly reduced, so that the determination of the weak mixing angle from the 1994 data will be even more precise.

II SLD Status and Plans

The SLD Detector continues to run smoothly with minimal maintenance. At the end of this section, we report on an important upgrade now under way. But the most significant developments this year have been in the area of physics analysis. The 1993 data sample of 1.8 pb^{-1} of Z^0 decay data has led to a wealth of new physics results, many of which (profiting from the electron beam polarization and the high precision vertex detector) are unique.

In the area of QCD physics, we have completed an extremely comprehensive range of measurements of α_s based on event shapes, jet rates, particle correlations and angular energy flow. The analysis is based on two approaches, one a calculation to $O(\alpha_s^2)$, and one resummed plus $O(\alpha_s^2)$ calculation.

Results shown in Fig. 3 are internally consistent, with the dominant remaining uncertainty coming from the uncalculated higher order contributions.

SLD is reaching the conclusion of a study of the flavour independence of strong interactions, using a new method based on impact parameter/lifetime tagging of jets. Already this provides the most precise test of flavour independence for *uds* events.

SLD has published results of a study of the charge multiplicity in $Z^0 \rightarrow b\bar{b}$ events. By comparison with measurements made at lower centre-of-mass energy, we have established that $\bar{n}_b - \bar{n}_{uds}$ is independent of energy, in agreement with a precise prediction of perturbative QCD.

An important unresolved question in high energy physics is whether the polarization of a parton can be observed in its hadronic jet. The process $Z^0 \rightarrow q\bar{q}$ provides an ideal testing ground for this question, since the Z^0 preferentially decays to left-handed fermions; $\langle P_q \rangle = -0.67$ for u type quarks and -0.94 for d type quarks. Of course to search for jet-handedness, it is necessary to know which jet is the q and which the $\bar{q}$. For left-handed electrons the forward hemisphere will be populated preferentially by quark jets, and vice versa for left-handed electrons. The associated jets are labelled as left or right-handed according to the sign of a triple product formed between the directions of the two highest momentum tracks in the jet and the thrust access. The data are subdivided into light and heavy quark event types. The latter category mostly hadronised via D, B of spin zero and hence cannot give a signature. The light quark sample does not show a significant signal on our present statistics, but the contribution of a larger event sample and electron beam polarization in the 1994 run may be decisive.

We have studied differences between quark and gluon jets using three-jet events in hadronic Z^0 decays. Gluon jets were identified in symmetric 3-jet events containing one jet tagged as a heavy quark jet and compared with a mixed sample of quark and gluon jets, and also with a mixed sample of light quark (u, d and s) and gluon jets. Our preliminary results show that the particle multiplicity in gluon jets is higher than that in light quark jets. These results are in qualitative agreement with QCD expectations. Differences are also observed in particle energy spectra and in jet widths, consistent with QCD expectations.

Multiplicity distributions can be described by moments e.g. factorial moments and the related cumulant moments. Next-to-leading order QCD predicts distributions for these moments which we compare with data. The observed features (see Fig. 4) are in qualitative agreement with the theoretical expectations.

Turning to heavy flavour physics, here we were greatly helped by the clean data from the pixel-based vertex detector, resulting in excellent agreement between impact parameter-related data and Monte Carlo (Figs 5 and 6). The first study has been of the measurement of R_b, the b fraction in hadronic events, evaluated by a number of different procedures. The use of a 2-d impact tag, 3-d impact tag and 3-d displaced vertex tag all give consistent results. However, the systematic errors associated with these single tag approaches are not competitive, and work is currently in progress on a double tag measurement. The statistics of the 1993 data are not sufficient, but the systematic errors associated with this measurement are extremely encouraging. It is expected that a fully competitive measurement will emerge from the 1994 data sample. This will be of considerable importance, given the window on physics which is associated with a precise R_b measurement.

Some of the most interesting physics emerging from SLD is the direct measurement of the magnitude of parity violation in the Zbb and Zcc couplings. There are two independent approaches to such measurements, both of them based on the study of the forward-backward left-right asymmetry for heavy quarks. In the first approach, the signals are determined from the momentum and transverse momentum distributions of charged leptons. The second approach is based on an analysis of the hadronic structure of the events.

For the measurement of A_b, an impact parameter tag is used to select an enriched sample of $Z^0 \rightarrow b\bar{b}$ events, and the net momentum-weighted track charge to identify the sign of the charge of the underlying b quark. In this way we have measured the left-right forward-backward asymmetry for b quark production as a function of polar angle. For the charm analysis we have used three approaches to obtaining the charm signal. Firstly the usual D^* kinematic analysis, secondly a D^* decay length analysis, and thirdly a $D^{\pm}$ decay length analysis. Essentially, these are various methods combining kinematics and decay length to obtain a clean charm signal.

Results are shown in Figs 7 and 8. Combining the leptonic and hadronic analyses we obtain the following preliminary values

$$A_b = 0.89 \pm 0.09 \text{ (stat)} \pm 0.06 \text{ (syst)}$$

$$A_c = 0.60 \pm 0.16 \text{ (stat)} \pm 0.08 \text{ (syst)}.$$

Our results are in good agreement with the Standard Model predictions of $A_b = 0.94$ and $A_c = 0.67$ (for $\sin^2 \theta_w^{eff} = 0.23$).

We have measured the average B lifetime by an impact parameter approach. This essentially consists of a bench-mark measurement, currently being prepared for publication. The future effort is going into vertexed events in which higher precision is possible and in addition the separation into different charge states. This area is of particular interest because the global averages for these quantities are not yet stable.

The tau lifetime has been measured by three independent methods. Results are not yet of sufficient statistical significance, but the excellent systematic precision associated with the small beam spot and high precision vertex detector is particularly valuable in this analysis.

As a result of new initiatives by young physicists who have recently joined the Collaboration, SLD is now on course to topological vertexing that should yield the best possible partitioning (i.e. assignment of tracks to physical vertices).

Finally, in terms of new physics, we report on the new results on electroweak parameters from this experiment. The precision measurement of A_{LR} from the 1993 data has recently been published. It yields the most precise single determination of $\sin^2 \theta_w^{eff}$ yet performed. The $\sin^2 \theta_w^{eff}$ determination is smaller by 2.3 standard deviations than a recent LEP average value extracted from measurement of the forward-backward asymmetries of leptonic, hadronic, b-quark and c-quark final states and those of the polarization of tau lepton final states (assuming universality of the weak neutral current couplings). It will be interesting to follow the evolution of all these measurements as further data come in.

The cross-section for Bhabha scattering ($e^+e^- \rightarrow e^+e^-$) with polarized electrons has been measured. The first measurement has been made of the left-right asymmetry in Bhabha scattering, $A_{LR}^{e^+e^-}(|\cos\theta|)$. The effective electron vector and axial vector coupling to the Z^0 are extracted from a combined analysis of the polarized Bhabha scattering data and the left-right asymmetry in the hadronic cross-section (A_{LR}). The effective electron couplings are measured to be

$$v_e = -0.0414 \pm 0.0020$$

and

$$a_e = -0.4977 \pm 0.0045$$

The SLD Collaboration is now engaged in the production of a new vertex detector, which will greatly enhance the physics possibilities. See Fig. 9. The main motivation for the upgrade is the potential to make a definitive measurement of B_s^0 mixing. The UK groups are responsible for CCD design and procurement, and other aspects of the new detector. The UK company EEV again proved themselves to be world leaders in the design of custom CCDs for scientific applications. They were awarded the contract by SLAC on the grounds of low bid and technical superiority, in spite of some very hot competition to secure the contract, which is worth approximately $1M. These CCDs are of a very challenging design, and will allow the construction of a detector of unprecedented precision. Most remarkable is the readout rate (10 MHz, compared with 10 KHz for similar noise performance when work with CCDs as particle detectors began, 15 years ago).

These devices will form the basis of the ultimate vertex detector capability at the future Linear Collider. Now that the world is planning to build just one hadron collider, the timescale on which the USA and Japan will be ready to invest substantially in this new project looks to be quite favourable (e.g. starting in 1997). We therefore see the SLD upgrade vertex detector as a timely pre-prototype for the new machine. Given the rich structure of heavy flavour that will be encountered at the much higher collision energies, and the copious e^+e^- pair background at small radius, the physics prospects for the machine depend crucially on the availability of a suitable low mass, pixel-based vertex detector, such as is now being built for SLD.

Publications Since Last Year's Report

1. e^+e^- Collisions at the SLC: The Left-Right Asymmetry.
SLD Collaboration (C Y Prescott, et al.), SLAC-PUB-6355, Sep 1993.
Invited talk at International Conference on Neutral Currents: Twenty Years Later, Paris, France, 6-9 Jul 1993.

2. A Study of Jet Handedness at the Z^0 Resonance.
SLD Collaboration (H Masuda, et al.), SLAC-PUB-6362, Oct 1993.
Presented at International Europhysics Conference on High Energy Physics, Marseille, France, 22-28 Jul, 1993.

3. Measurement of the Charged Multiplicity of $Z^0 \rightarrow b\bar{b}$ Events.
SLD Collaboration (K Abe, et al.), SLAC-PUB-6372, Oct 1993.
Phys. Rev. Lett. 72 (1994) 3145.

4. On the Applicability of Finite Order Perturbative QCD Calculations of Jet Rates in e^+e^- Annihilation.
P N Burrows (MIT, LNS), H Masuda (SLAC), SLAC-PUB-6394, Nov 1993.

5. A Measurement of $R_B = \Gamma(Z^0 \rightarrow b\bar{b}) / \Gamma(Z^0 \rightarrow \text{Hadrons})$ at SLD.
SLD Collaboration (H A Neal, Jr., et al.), SLAC-PUB-6398, Dec 1993.
Presented at International Europhysics Conference on High Energy Physics, Marseille, France, 22-28 Jul, 1993.

6. e^+e^- Collisions at the SLC: The Left-Right Asymmetry.
SLD Collaboration (G Shapiro, et al.), SLAC-PUB-6444, Feb 1994.
Presented at 5th Workshop on High Energy Spin Physics, Protvino, Russia, 20-24 Sep 1993.

7. Status of A_{LR} Measurement at SLD.
SLD Collaboration (W W Ash, et al.), SLAC-PUB-6401, Nov 1993.
Presented at International Europhysics Conference on High Energy Physics, Marseille, France, 22-28 Jul, 1993.

8. Precise Measurement of the Left-Right Cross-Section Asymmetry in Z Boson Production by Electron - Positron Collisions.
R E Frey (Oregon U.), SLAC-PUB 6470, Mar 1994.
Presented at 21st Annual SLAC Summer Institute on Particle Physics, Stanford, CA, 26 Jul-6 Aug 1993.

9. Measurement of α_s from Energy-Energy Correlations at the Z^0 Resonance.
SLD Collaboration (K Abe, et al.), SLAC-PUB-6451, Mar 1994.
Submitted to Phys. Rev. D.

10. Precise Measurement of the Left-Right Cross-Section Asymmetry in Z Boson Production by e^+e^- Collisions.
SLD Collaboration (K Abe, et al.), SLAC-PUB-6456, Mar 1994.
Phys. Rev. Lett. 73 (1994) 25.

11. Precise Determination of the Weak Mixing Angle from a Measurement of A_{LR} in $e^+e^- \rightarrow Z^0$.
SLD Collaboration (M Woods, et al.), SLAC-PUB-6493, May 1994.
Presented at 29th Rencontres de Moriond: Electroweak Interactions and Unified Theories, Meribel, France, 12-19 Mar 1994.

12. Measuring A_b with Polarized Beams at SLC.
SLD Collaboration (T R Junk, et al.), SLAC-PUB-6513, May 1994.
Presented at 29th Rencontres de Moriond: QCD and High Energy Hadronic Interactions, Meribel, France, 19-26 Mar 1994.

13. A Study of Jet Handedness in Hadronic Z^0 decays.
SLD Collaboration (D Muller, et al.), SLAC-Pub-6511, May 1994.
Presented at 29th Rencontres de Moriond: QCD and High Energy Hadronic Interactions, Meribel, France, 19-26 Mar 1994.

14. QCD of Different Quark Flavors with the SLD Detector.
SLD Collaboration (M D Hildreth, et al.), SLAC-PUB-6505, May 1994.
Presented at 29th Rencontres de Moriond, QCD and High Energy Hadronic Interactions, Meribel, France, 19-26 Mar 1994.

15. Recent Electroweak Results from SLD/SLC.
S Suzuki (Nagoya U.), DPNU-94-22, Mar 1994.
Talk presented at the 22nd INS International Symposium on Physics with High Energy Colliders, Tokyo, Japan, Mar 8-10, 1994.

16. Measurement of the Left-Right Charge Asymmetry in Hadronic Z Decays and A_e Determination.
SLD Collaboration (G J Baranko, et al.), COLO-HEP-342, Aug 1994.
Presented at 1994 Meeting of the American Physical Society, Division of Particles and Fields (DPF 94), Albuquerque, NM, 2-6 Aug 1994.

17. A Measurement of Quark and Gluon Jet Differences at the Z^0 Resonance.
SLD Collaboration (Y Iwasaki, et al.), SLAC-PUB-6597, Aug 1994.
Presented at 1994 Meeting of the American Physical Society, Division of Particles and Fields (DPF 94), Albuquerque, NM, 2-6 Aug 1994.

18. A Test of The Flavor Independence of Strong Interactions.
T W Markiewicz (SLAC), SLAC-PUB-6659, Sep 1994.
Presented at QCD Workshop, Montpellier, France, Jul 7-13, 1994

19. A Test of the Flavor Independence of Strong Interactions.
SLD Collaboration (M D Hildreth et al.), SLAC-PUB-6598, Aug 1994.
Presented at 1994 Meeting of the American Physical Society, Division of Particles and Fields (DPF 94), Albuquerque, NM, 2-6 Aug 1994.

20. Multiplicity Moments in e^+e^- Annihilation into Hadrons at the Z^0 Resonance.
SLD Collaboration (Jing-chen Zhou, et al.), SLAC-PUB-6600, Aug 1994.
Presented at 1994 Meeting of the American Physical Society, Division of Particles and Fields (DPF 94), Albuquerque, NM, 2-6 Aug 1994.

21. Electroweak Coupling Measurements from Polarized Bhabha Scattering at the Z^0 Resonance.
SLD Collaboration (K T Pitts, et al.), SLAC-PUB-6639, Aug 1994.
Presented at 1994 Meeting of the American Physical Society, Division of Particles and Fields (DPF 94), Albuquerque, NM, 2-6 Aug 1994.

22. Measurement of the Charged Multiplicity of $Z^0 \rightarrow b\bar{b}$ Events.
SLD Collaboration (P N Burrows, et al.), SLAC-PUB-6602, Aug 1994.
Presented at 1994 Meeting of the American Physical Society, Division of Particles and Fields (DPF 94), Albuquerque, NM, 2-6 Aug 1994.

23. Polarized Bhabha Scattering; a Precision Measurement of the Electron Neutral Current Couplings.
SLD Collaboration (K Abe, et al.), SLAC-PUB-6605, Sep 1994.
Submitted to Phys. Rev. Lett.

24. Measurement of α_s from Hadronic Event Observables at the Z^0 Resonance.
SLD Collaboration (Y Ohnishi, et al.), SLAC-PUB-6599, Aug 1994.
Presented at 1994 Meeting of the American Physical Society, Division of Particles and Fields (DPF 94), Albuquerque, NM, 2-6 Aug 1994.

25. A Search for Jet Handedness in Hadronic Z^0 Decays.
SLD Collaboration (Y Hasegawa, et al.), SLAC-PUB-6647, Aug 1994.
Presented at High Energy Physics: QCD Workshop 94, Montpellier, France, 7-13 Jul 1994.

26. A Search for Jet Handedness in Hadronic Z^0 Decays.
SLD Collaboration (K Abe, et al.), SLAC-PUB-6550, Jul 1994.
Presented at Int. Conf. on High Energy Physics, Glasgow, Scotland, Jul 20-27, 1994.

27. Measurement of α_s From Hadronic Event Observables at the Z^0 Resonance
SLD Collaboration (K Abe, et al.), SLAC-PUB-6549, Jul 1994.
Presented at Int. Conf. on High Energy Physics, Glasgow, Scotland, Jul 20-27, 1994.

28. A Preliminary, Precise Measurement of the Average B Hadron Lifetime.
SLD Collaboration (K Abe, et al.), SLAC-PUB-6586, Jul 1994.
Presented at Int. Conf. on High Energy Physics, Glasgow, Scotland, Jul 20-27, 1994.

29. Measurement of the Average Lifetime of B Hadrons at SLD.
SLD Collaboration (G Punkar, et al.), SLAC-PUB-6595, Sep 1994.
Presented at 1994 Meeting of the American Physical Society, Division of Particles and Fields (DPF 94), Albuquerque, NM, 2-6 Aug 1994.

Fig. 1. Evolution of the SLC Luminosity. First SLD physics run was in 1992.

Fig. 2. SLC Electron Beam Polarization during the early part of the 1994 run.

Fig. 3. Summary of α_s measurements from SLD.

Fig. 4. Ratio of cumulant to factorial moments in an analysis of Z^0 hadronic decays, with an eye-guiding curve.

Fig. 5. Signed normalized flight decay lengths for secondary vertices found in SLD; comparison between data and Monte Carlo.

Fig. 6. Number of significant tracks per event having impact parameter to the IP greater than 3 standard deviations.

Fig. 7. SLD's direct measurement of the parity violation parameter for *b* quarks, and comparison with other measurements.

Fig. 8. SLD's direct measurement of the parity violation parameter for *c* quarks, and comparison with other measurements.

Fig. 9. Comparison between the coverage of the SLD's existing vertex detector VXD2 (drawn below the beam-pipe) and the upgrade detector, VXD3 now being built (drawn above the beam-pipe). Note the great improvement in solid angle coverage and in lever arm for extrapolation to the IP in the new design. VXD3 also contains only half the material of VXD2.

THE STUDY OF CP VIOLATION IN THE NEUTRAL KAON SYSTEM AT LEAR

PS195 Proposal 265

Athens, Basel, Boston, CERN, Coimbra, Delft, ETH Zurich, Fribourg, Ioannina, Liverpool, Lublijana, Marseille, Orsay, PSI, Saclay, Stockholm, Thessalonika.

Introduction

Traditionally CP violation has been investigated using beams of high energy K°_L and K°_S, and has only been detected in the 2 pion and semileptonic decay modes of K°_L and their interference with the corresponding decay of K°_S. CPLEAR adopts a fundamentally different approach where CP violation is detected by observing the asymmetry between the decays of initially pure K° and $\bar{K}^\circ$ states.

The initial neutral kaon is produced in a state of definite strangeness by antiproton annihilation at rest in a high pressure [16 bar] gaseous hydrogen target via the reactions

$$\bar{p}p \rightarrow K^+ \pi^- \bar{K}^\circ, \qquad \bar{p}p \rightarrow K^- \pi^+ K^\circ$$

The strangeness of the neutral kaon is tagged by observing the sign of the charged kaon. This method has the considerable advantage of simultaneous and symmetric production of K° and $\bar{K}^\circ$ and symmetric detection of their decay products. Thus systematic corrections and uncertainties are reduced to a very low level.

This method also enables, at least in principle, CP violation to be detected in all possible decay modes of the neutral kaon. Of particular importance in this experiment are the following:

$$K^\circ \rightarrow \pi^+\pi^-, \pi^\circ\pi^\circ \qquad (1)$$

$$K^\circ \rightarrow \pi^\pm \ell^\mp \nu \qquad (2)$$

$$K^\circ \rightarrow \pi^+\pi^-\pi^\circ \qquad (3)$$

Study of [1] in the $\pi^+\pi^-$ channel will enable a determination to be made of the magnitude and phase of η_{+-} with a precision significantly better than the present world average. In the $\pi^\circ\pi^\circ$ channel the phase ϕ_{oo} of η_{oo} should be determined to better than 1°. These channels will also enable a precise measurement of the K°_S lifetime to be made. Study of [2] will enable a precise test of the $\Delta S = \Delta Q$ rule to be made, as well as the first measurement of direct T violation. It will also provide an accurate determination of $\Delta m = m_L - m_s$. Finally analysis of the three pion decay mode [3] will provide the first direct measurement of CP violation in the decay of K°_S.

Status of the Detector and Trigger

The detector is shown in fig. 1. It has cylindrical geometry and is mounted inside a solenoid of 3.6 m length which produces a magnetic field of 0.44 T parallel to the $\bar{p}$ beam. Tracking of the annihilation products is performed by two layers of proportional chambers, 6 layers of

drift chambers and two layers of streamer tubes. The proportional and drift chambers provide rapid on-line r-φ co-ordinates while the streamer tubes provide on-line axial [z] co-ordinates, all of which are used by the event trigger. More precise off-line z co-ordinates are provided by cathode strip readout from the drift chambers. Particle identification is provided by a 32-sector scintillator - threshold Cerenkov - scintillator sandwich [the PID], while an 18-layer gas-sampling electromagnetic calorimeter provides high spatial resolution detection of photons and electrons. The desired "golden channels" [$K^{\pm}\pi\mp K^{\circ}$] represent only about 4×10^{-3} of the total $\bar{p}$ annihilation rate. Hence, to achieve the physics goals of this experiment in a reasonable length of time, it is necessary to run at a $\bar{p}$ annihilation rate of about 1 MHz. In order to pick out the desired events from the large unwanted background, a sophisticated multi-level trigger has been designed based on several sequential decisions provided by fast trigger processors. Since the start of data taking, additional stages of this trigger processing have gradually been added, and the complete system has been operational since the start of 1992. This consists of

[i] the pre-trigger. This demands a coincidence between an incoming $\bar{p}$ and at least two hits in the inner scintillator, with at least one kaon candidate [an SĈS pattern from the PID].

[ii] the HWPI processor. This imposes a minimum P_T cut on the kaon candidate, demands a charged track multiplicity of 2 or 4 after on-line tracking, determines track parameters such as momentum, and places cuts on the event kinematics.

[iii] the HWP2 processor. This confirms particle identification using energy loss and TOF information from the inner scintillator and pulse height information from the Cerenkov detector.

[iv] the HWP2.5 processor. This determines the number of neutral showers in the calorimeter and enables a cut to be placed on this parameter.

The complete trigger system gives an overall data reduction factor of about 1000.
During 1994 further reductions in the event read-out time, brought about by both software and hardware improvements, have increased the maximum number of events which can be written to tape per second to about 450.

For some of the experimental data taking in 1994 the spherical, 7cm radius, 16 bar gaseous hydrogen target was replaced by a cylindrical target, 10cm long, 1.2cm radius, at 30 bar pressure. This was surrounded by a 1.5 cm radius proportional chamber [PCO]. It is intended to incorporate PCO into the trigger by demanding that, for events with 4 charged tracks, only 2 of the tracks should have hits in PCO, i.e. the neutral kaon should decay outside the radius of this chamber. For neutral kaons with the average momentum seen in this experiment, this places a minimum cut on their lifetime of about 0.6 τ_S. This will significantly reduce the trigger rate by rejecting very short lifetime $\pi^+\pi^-$ decays, which are not used, and also by rejecting "non-golden" annihilation events involving 2 charged kaons where all 4 tracks originate from the primary vertex. Use of the hit in PCO will also significantly improve the online momentum measurement of primary tracks, enabling a cleaner selection of golden events to be made.

Due to problems with the new target and PCO only a small amount of data with the new system was taken, none of it with PCO actively incorporated into the trigger. However the data taken will be sufficient to enable the effect of incorporating this into the trigger to be determined offline. This should then be in place for all data taking in 1995.

Status of Data Analysis

Significant progress has been made in the analysis of all accessible decay channels of the neutral kaon

These are as follows:

[a] $\pi^+\pi^-$ Decays

The lifetime distribution for K° and $\bar{K}^\circ$ decays combined, after acceptance correction using Monte Carlo data is shown in fig. 2. A 3-parameter fit to these data [solid curve] yields a K°_S lifetime of [0.999 ± 0.003] τ_S and a K°_L level at long lifetimes which is 1.76 ± 0.09 times greater than that expected from CP violating $K^\circ_L \rightarrow \pi^+\pi^-$ [dashed curve] showing that some residual 3-body decays remain.

The asymmetry parameter

$$A_\pm(t) = [R(\bar{K}^\circ \rightarrow \pi^+\pi^-) - R(K^\circ \rightarrow \pi^+\pi^-)] / [R(\bar{K}^\circ \rightarrow \pi^+\pi^-) + R(K^\circ \rightarrow \pi^+\pi^-)]$$

is shown as a function of K° lifetime in fig. 3. A fit of these data for the magnitude and phase of η_{+-} assuming the background contamination determined from fig. 2, is shown and gives the following results:

$$|\eta_\pm| = [2.163 \pm 0.045 \text{ (stat.)} \pm 0.030 \text{ (sys.)}] \times 10^{-3}$$

$$\varphi_\pm = [44.7 \pm 0.9 \text{ (stat.)} \pm 0.5 \text{ (sys.)}]^\circ$$

which is in excellent agreement with the present world average values.

There is an additional uncertainty of ± 0.7° an ϕ_{+-} due to the current precision with which $\Delta m = m_L - m_s$ is known. There are presently also uncertainties of ± 0.060 x 10^{-3} on $|\eta_{+-}|$ and ±1.0° on ϕ_{+-} due to the dependence of the normalisation correction on various geometrical and physical parameters. The levels of these uncertainties are limited by lack of Monte Carlo statistics and are expected to become negligible when sufficient statistics are available.

[b] $\pi^\circ\pi^\circ$ Decays

This analysis is still at a preliminary stage but has advanced considerably in the past year. Fig. 4 shows the reduced asymmetry

$$A_{00}^{red} = (A_{00} - 2\mathrm{Re}(\varepsilon_L))\, e^{-0.5(\Gamma_s - \Gamma_L)t}$$

as a function of K° lifetime using events with 4 detected photons. A fit to this gives ϕ_{00} to a statistical accuracy of 10° assuming the PDG value of $|\eta_{00}|$. The precision of this result is still limited by the measured K° lifetime resolution. Much progress on improving this has been made and work is continuing to make further improvements. The value of ϕ_{00} can be determined to a similar precision using an independent sample of events where use of the neutral pions has undergone a Dalitz decay or where one of the decay photons has

converted. Because such events contain two charged secondary tracks the K° lifetime resolution is much better but the statistics are more limited compared to the 4 photon event sample. Combining these two results gives the preliminary value.

$$\varphi_{00} = 56.0° \pm 7.5° \text{ (stat.)}$$

[c] Semileptonic Decays
Four independent decay rates can be measured in semileptonic decays:

$$R^+ = R(K° \rightarrow \pi^- e^+ \nu)$$

$$\overline{R}^+ = R(\overline{K}° \rightarrow \pi^- e^+ \nu)$$

$$R^- = R(K° \rightarrow \pi^+ e^- \overline{\nu})$$

$$\overline{R}^- = R(\overline{K}° \rightarrow \pi^+ e^- \overline{\nu})$$

Various asymmetries can be constructed from these four decay rates, which are sensitive to different physics parameters.
The asymmetry

$$A_1(t) = \frac{(\overline{R}^- + R^+) - (\overline{R}^+ + R^-)}{\overline{R}^- + R^+ + \overline{R}^+ + R^-}$$

is sensitive to $\Delta m = m_L - m_S$ and to Re[x], where x measures any violation of the $\Delta S = \Delta Q$ rule. This is shown in fig.5.

The asymmetry

$$A_2(t) = \frac{(\overline{R}^- + \overline{R}^+) - (R^+ + R^-)}{\overline{R}^- + R^+ + \overline{R}^+ + R^-}$$

is sensitive to Im[x] and Re[ε_S], assuming Re[x] = 0. It is shown in fig.6.

The asymmetry

$$A_T = (\overline{R}^+ - R^-) / (\overline{R}^+ + R^-)$$

is a direct measure of T violation, assuming x=0. If T is violated along with CP, so that

CPT is conserved, then the expected value of A_T is 4Re[ε]. This is shown in fig. 7.

The asymmetry

$$A_{CPT} = (\overline{R}^- - R^+) / (\overline{R}^- + R^+)$$

$$= 4 \text{ Re } (\delta_{CPT}) \text{ for } t \geq 5\tau_s$$

where δ_{cpT} is a measure of CPT violation. This is shown on fig. 8. Fits to these asymmetries give the following results:

Δm	=	$(534.7 \pm 3.2 \text{ (stat.)} \pm 1.0 \text{ (sys.)}) \times 10^7\ \hbar s^{-1}$
Re(x)	=	$(4.3 \pm 7.6 \text{ (stat.)} \pm 4.0 \text{ (sys.)}) \times 10^{-3}$
Im(x)	=	$(10.1 \pm 4.1 \text{ (stat.)} \pm 1.1 \text{ (sys.)}) \times 10^{-3}$
Re(ε_s)	=	$(0.9 \pm 0.7 \text{ (stat.)} \pm 0.3 \text{ (sys.)}) \times 10^{-3}$
A_T	=	$(4.5 \pm 2.1 \text{ (stat.)} \pm 2.0 \text{ (sys.)}) \times 10^{-3}$
Re (δ_{CPT})	=	$(-0.1 \pm 0.5 \text{ (stat.)} \pm 0.5 \text{ (sys.)}) \times 10^{-3}$

As in the $\pi^+\pi^-$ channel, there is an additional uncertainty on each of these parameters which is about the same size as the statistical uncertainty at the moment, due to lack of Monte Carlo statistics. This should become negligible when more Monte Carlo statistics are available.

Many of these results are already comparable with, or better than, the current PDG values, and in some cases are the first measurements of that parameter.

[d] $\pi^+\pi^-\pi^\circ$ Decays

By analysing the decays of K° and K° mesons to 3 pions in different regions of the Dazliz plot, the CP violating parameter η_{+-0} can be determined, and also the CP conserving part of $K^\circ_S \rightarrow \pi^+\pi^-\pi^\circ$ can be measured:

$$A = R\ (\overline{K}^\circ \rightarrow \pi^+\pi^-\pi^\circ) \quad \text{for} \quad M_{\pi^-\pi^\circ} < M_{\pi^+\pi^\circ}$$

$$B = R\ (\overline{K}^\circ \rightarrow \pi^+\pi^-\pi^\circ) \quad \text{for} \quad M_{\pi^-\pi^\circ} > M_{\pi^+\pi^\circ}$$

$$C = R\ (K^\circ \rightarrow \pi^+\pi^-\pi^\circ) \quad \text{for} \quad M_{\pi^-\pi^\circ} < M_{\pi^+\pi^\circ}$$

$$D = R\ (K^\circ \rightarrow \pi^+\pi^-\pi^\circ) \quad \text{for} \quad M_{\pi^-\pi^\circ} > M_{\pi^+\pi^\circ}$$

The asymmetry [(A+B) - (C+D)]/[A+B+C+D] is shown in fig. 9. The results of a fit to these data are

$$\text{Re } (\eta_{\pm 0}) = (5 \pm 22 \text{ (stat.)} \pm 7 \text{ (sys.)}) \times 10^{-3}$$

$$\text{Im } (\eta_{\pm 0}) = (16 \pm 24 \text{ (stat.)} \pm 18 \text{ (sys.)}) \times 10^{-3}$$

The statistical precision of these results is already considerably better than the current PDG values. Figs. 10[a] and 10[b] show the asymmetries (A-C)/(A+C) and (B-D)/(B+D) which are sensitive to the CP conserving decay $K_S^\circ \rightarrow \pi^+\pi^-\pi^\circ$ [CP = +1]. From simultaneous fits to the two asymmetries we get:

$$\Gamma(K_S^\circ \rightarrow 3\pi(CP = +1)) / \Gamma(K_L^\circ \rightarrow 3\pi(CP = -1))$$

$$= (2.6 \pm 1.6 \text{ (stat.)} \pm 2.0 \text{ (sys.)}) \times 10^{-3}$$

which is the first measurement of this quantity.

Conclusion

The detector and trigger system are working well and considerable progress has been made in the data analysis. Data already taken during 1994 should enable us to approximately double our present statistics so that significant further progress should be made in all physics channels.

Ph.D. Theses [University of Liverpool]

September 1994

E. L. Cawley - CP Violation in the Decay $K^\circ \rightarrow \pi^+\pi^-\pi^\circ$

Publications - 1994

CPLEAR Collaboration

1. Bose-Einstein Correlations in $\bar{p}p$ Annihilations at Rest.

   Submitted to Z. Phys. C.

2. Inclusive Measurement of $\bar{p}$ annihilation at rest in gaseous hydrogen to final states containing and f_2.

   Submitted to Z. Phys. C.

Figure Captions

1. Schematic plan view of the CPLEAR detector. Also shown is a typical event decaying at long lifetime with the track fit superimposed.

2. Lifetime distribution for the sum of K° and $\bar{K}^\circ$ events decaying to $\pi^+\pi^-$. The solid curve is our best fit. The dashed curve is what we would expect to get in the absence of background.

3. The asymmetry $A_{+-}(t)$ between initial K° and $\bar{K}^\circ$ states decaying to $\pi^+\pi^-$. The curve is a fit assuming the background determined from fig. (2).

4. The reduced asymmetry A_{00} (t) between initial K°, and $\bar{K}^\circ$ states decaying to $\pi^\circ\pi^\circ$ when 4 photons are detected.

5. K°, $\bar{K}^\circ$ semileptonic decay, the asymmetry A_1 as a function of the decay time.

6. K°, $\bar{K}^\circ$ semileptonic decay, the asymmetry A_2 as a function of the decay time.

7. K°, $\bar{K}^\circ$ semileptonic decay, the asymmetry A_T as function of the decay time.

8. K°, $\bar{K}^\circ$ semileptonic decay, the asymmetry A_{CPT} as a function of the decay time.

9. K°, $\bar{K}^\circ$ decay to $\pi^+\pi^-\pi^\circ$, the asymmetry [(A + B) - (C + D)]/[(A + B) + (C + D)], see text, as a function of the decay time.

10. K°, $\bar{K}^\circ$ decay to $\pi^+\pi^-\pi^\circ$, (a) the asymmetry (A - C)/(A + C) and, (b) the asymmetry (B - D)/(B + D), see text, as a function of the decay time.

PID
Scintillator 2
Čerenkov
Scintillator 1
3 S 388
Calorimeter
4 S 407
Streamer tubes
Target wall
Proportional chambers
Drift chambers
2 P 503
Scale : 1 m

Figure 1.

Figure 2

Figure 3

Preliminary
A_{00}^{red}
0.004
0.002
0
-0.002
-0.004
-0.006
0
2
4
6
8
10
12
14
16
18
20
(t/τ_s)
$\varphi_{00} = 54° \pm 10°$ (stat)

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8

$A_{+-0}(t)$
CP Violating Amplitude $K_S \rightarrow \pi^+\pi^-\pi^0$
0.25
0.2
0.15
0.1
0.05
0
−0.05
2
4
6
8
10
12
14
16
18
20
$t/[\tau_S]$

Figure 9

$A_x(t)$
CP Conserving Amplitude $K_S \rightarrow \pi^+\pi^-\pi^0$
$x > 0$
$t/[\tau_S]$
0.25
0.2
0.15
0.1
0.05
0
−0.05
2
4
6
8
10
12
14
16
18
20

a)

$A_x(t)$
CP Conserving Amplitude $K_S \rightarrow \pi^+\pi^-\pi^0$
$x < 0$
$t/[\tau_S]$
0.25
0.2
0.15
0.1
0.05
0
−0.05
2
4
6
8
10
12
14
16
18
20

b)

Figure 10

CRYSTAL BARREL EXPERIMENT

PS197 **PROPOSAL 268**

Queen Mary & Westfield College, London; Rutherford Appleton Laboratory; Lawrence Berkeley Laboratory; UCLA; University of Bochum; University of Bonn; University of Budapest; CERN; University of Hamburg; University of Karlsruhe; University of Mainz; University of Munich; CRN Strasbourg; University of Zurich.

The main physics aim of the crystal barrel experiment is a detailed study of light quark spectroscopy with a particular emphasis on the search for glueballs, hybrids and multi-quark states produced in $\bar{p}p$ (and $\bar{p}n$) annihilations. Subsidiary aims are studies of radiative and rare meson decays and a study of $\bar{p}p$ annihilation dynamics from atomic S and P states.

The experiment uses antiproton beams from the LEAR facility at CERN over the momentum range 0.2 to 2.0 GeV/c. Since many of the exotic states are expected to decay to neutrals such as π^0 and η, good detection and measurement of photons over a large solid angle is essential. The apparatus has "4π" geometry and is mounted inside a solenoidal magnetic field of 1.5 T. The $\bar{p}p$ (or $\bar{p}d$) interactions take place in a liquid hydrogen target which is surrounded by two cylindrical multiwire proportional chambers (PWC) which provide a trigger for outgoing charged particles. A cylindrical jet drift chamber (JDC) is used to measure the momenta of charged particles and ionization sampling gives discrimination between π's and K's for momenta below 500 MeV/c. Nearly all neutrals and charged particles are detected in a 1380 element, barrel shaped CsI detector covering 97% x 4π solid angle. A silicon strip detector is being constructed to give improved vertex measurements and to significantly increase the efficiency for detecting neutral kaons decaying to charged pions.

The RAL group is responsible for the ADC and discriminator systems associated with the CsI detector and for the beam defining and veto counters. The group has also been involved in the design of a H_2 gas target operating at 10 atm pressure. The use of this gas target, which is scheduled to run in the next few weeks, will considerably enhance the rate of P-wave annihilations for antiprotons interacting at rest.

During 1994 the experiment had data taking runs at 0.2 GeV/c and then at 1.2 and 1.94 GeV/c. This latter run used special hardware constructed by the RAL group to give a fast trigger on the total energy deposited in the CsI crystals. Data was taken with both 0-prong and 2-prong triggers; for much of the time it was possible to run with these two triggers simultaneously. This was a new feature for the experiment and significantly increased the rate of effective data taking. The RAL group is also responsible for the maintenance of the software used in both the crystal readout and online data monitoring.

Analysis of $\bar{p}p \rightarrow \pi^0\pi^0\pi^0\eta$ at 1.9 GeV/c.

The analysis of data for the reaction $\bar{p}p \rightarrow \pi^0\pi^0\pi^0\eta$ at 1.94 GeV/c was described in last years report. A spin-parity analysis has now been made to search for predicted but

previously unobserved members of the pseudotensor ($J^P = 2^-$) nonet and also the $J^{PC} = 2^{-+}$ glueball for which no candidates exist. The data were fitted using the maximum likelihood method and two new isospin I = 0, $J^{PC} = 2^{-+}$ states are observed.

A resonance with mass (1650 ± 15) MeV and width (180 ± 75) is observed to decay into $a_2(1320)\pi^0$. (See Fig. 1). The second new resonance has mass (1850 ± 30) MeV and width (225 ± 75) MeV with an $f_2(1270)\eta$ decay mode. (See Fig. 2a). The resonance with 1650 MeV mass is a natural candidate for the η_2, the I = 0 partner of the π_2 (1670). The assignment of the second new resonance to the pseudotensor nonet is more difficult. A possible assignment is the η_2', a state claimed to have been observed by the Crystal Ball collaboration. However, the Crystal Ball resonance does not exhibit the same decay modes as the 1850 MeV state found in this analysis. An alternative interpretation is that the resonance is the same as that found in the MARK III data on $J/\psi \to \gamma(\eta\pi\pi)$ which shows a clear peak at 1850 MeV. If these two resonances were found to be consistent, then the 1850 MeV state must be considered as a strong glueball candidate.

A third resonance with $J^{PC} = 2^{++}$ is observed with a (2135 ± 50) MeV mass and a (250 ± 50) MeV width; it is observed with decay modes into both $a_2(1320)\pi^0$ and $f_2(1270)\eta$. (See Figs. 1 and 2a). This resonance is consistent with the $f_2(2175)$ claimed by GAMS. A tentative signal for a $J^{PC} = 0^{-+}$ resonance with a (1625-1650) MeV mass decaying into $f_0(975)\eta$ is also observed.

$\bar{p}p \to \pi^0\pi^0\pi^0\eta$ (annihilation at rest)

Confirmation of the candidate $\eta_2(1650)$ decaying to $a_2(1320)\pi^0$, ($a_2 \to \pi^0\eta$), discussed above, has been sought from data for $\bar{p}p$ annihilation at rest where the annihilation vertex is better determined. The analysis of 17×10^6 $\bar{p}p \to$ (all neutral) triggered events is nearing completion and the results from a subset of 5×10^6 events are shown in figure 3. There is evidence for some enhancement at approximately 1640 MeV/c^2 with a much smaller width than that suggested from the in-flight data. More striking features due to the $f_1(1295)/\eta(1295)$ and the $f_1(1420)/\eta(1440)$ can be clearly seen. A full partial wave analysis of these data is underway.

Analysis of $J/\psi \to \gamma(\pi^+\pi^0\pi^+\pi^-)$

The 0^+ nonet seems to be filled by $f_0(1365)$, $a_0(1450)$, $K^+(1430)$ and G(1590). This leaves the state $f_0(1505)$, observed in Crystal Barrel data, as an outstanding state, hence a glueball candidate. It appears strongly in two other sets of data shown in Figure 4: (a) E760 data from Fermilab on $\bar{p}p \to \pi^0(\eta\eta)$ at 3.1 GeV, (b) Mark III data on $J/\psi \to \gamma(\pi^+\pi^-\pi^+\pi^-)$. However, the published analysis of the Mark III data assigns all three peaks at 1500, 1770 and 2100 MeV as 0^- states. The appearance of peaks in E760 data at precisely the same masses, led us to question the spin-parity assignments, since $\eta\eta$ can have only $J^P = 0^+, 2^+$ or 4^+. The original Mark III analysis fitted the 4π final state only with $\rho\rho$. The data have been re-analysed (in collaboration with T Burnett, S Sutlief from the University of Washington, Seattle and V Anisovich and A Sarantsev from St. Petersburg), adding $\sigma\sigma$ final states, where σ stand for the $\pi\pi$ S-wave.

This results in a substantial improvement to the fit and completely different assignments of quantum numbers; namely 0^+ at 1505 MeV, 2^+ at 1770 MeV and 0^+ at

2100 MeV. The 0^+ peak at 2100 MeV is particularly striking. It seems hardly likely to be a $q\bar{q}$ radial excitation. In the past, decays to η's have been proposed as a signature of glue. This leads us to speculate that the seven states shown in Fig. 5 are the lowest lying glueball states. This spectrum is qualitatively similar to that proposed in 1976 by Jaffe and Johnson, except that all states are raised by about 600 MeV in mass. The 1^{-+} state at 1910 MeV is not yet convincingly established. It is an open theoretical question whether a 1^{-+} state can be formed from massless gluons. Its absence would not therefore invalidate the spectrum proposed for the remaining 6 states.

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7 $\eta\eta'$ threshold enhancement in $\bar{p}p$ annihilations into $\pi^0\eta\eta$ at rest.
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Figure 1 (a) Invariant Mass of $\pi^0\pi^0\eta$ for decays to $a_2(1320)\pi^0$ but not $f_0(975)\eta$ or $f_2(1270)\eta$. Peaks due to the $\eta_2(1650)$ and X(2135) are seen. The histogram shows the fit to the data.

(b) Log likelihood of the fit to the data as the mass used for the η_2 is varied.

Figure 2 (a) Invariant mass of $\pi^0\pi^0\eta$ for decays to $f_2(1270)\eta$ but not $a_2(1320)\pi^0$. Peaks due to the X(1850) and X(2135) are seen. The histogram shows the fit to the data.

(b) Invariant mass of $\pi^0\pi^0\eta$ for decays to $a_0(980)\pi$ but not $f_2(1270)\eta$ showing a clear signal due to the $f_1(1285)$.

Figure 3 The effective mass distribution for the $\pi^0\pi^0\eta$ system from the reaction $\bar{p}p \rightarrow \pi^0\pi^0\pi^0\eta$ (3089 events with 3 combinations per event). For the events having $\pi^0\pi^0\eta$ combinations falling within the shaded area (i.e., around the possible enhancement at 1640 MeV/c^2) the lower inset shows the $\pi^0\eta$ effective mass derived from the relevant $\pi^0\pi^0\eta$ combination, indicating $a_0(980)$ and $a_2(1320)$ peaks. Alternatively, the upper inset shows events selected from $\pi^0\eta$ combinations forming an $a_2(1320)$ where the hatched area indicates the position of the candidate for $\eta_2(1650)$.

Figure 4 (a) E760 data for $\eta\eta$ invariant mass from $\bar{p}p \rightarrow \pi^0\eta\eta$ at 3.1 GeV.

(b) Mark III data for the 4 pion invariant mass from the decay $J/\psi \rightarrow \pi^+\pi^-\pi^+\pi^-\gamma$.

Figure 5 Possible scheme for seven lowest lying glueball states.

DARK MATTER EXPERIMENTS

Proposal 270

Particle Physics/Astrophysics collaboration
Imperial College London (Astrophysics)
Imperial College London (Particle Physics)
University of Sheffield (Particle Physics)
Birkbeck College London (Cosmic Ray Physics)
University of Nottingham (Cosmic Ray Physics)
RAL (Particle Physics)

A major unresolved problem at the interface of particle physics and cosmology is the identity of the non-luminous matter which is known to comprise 90% of the mass of our own Galaxy and up to 99% of the universe as a whole. There is also evidence that much of the dark matter may be non-baryonic, and could thus consist of relic stable elementary particles. Candidate particles include low-mass neutrinos, axions or weakly interacting massive particles such as the neutralino.

An experimental programme to search for WIMPS was funded jointly by NP and APS Boards, initially for the period 1991-95. These experiments will search for nuclear recoil events from the interaction of dark matter particles. The UK programme is based on scintillating targets, in particular NaI and liquid Xe, but with the addition of new techniques to discriminate nuclear recoil from background. The experiments are carried out in an underground facility established in the Boulby salt mine (near Whitby UK).

The low energy threshold and background achieved in a 'stage 1' detector of 1kg high-purity Tl-doped NaI enabled dark matter limits for spin-dependent interactions to be improved by a factor 5 compared with those previously deduced from underground Ge detectors (running as double beta decay experiments). Similar limits result for a 6kg NaI detector, currently running continuously in the Boulby Mine. Pulse shape discrimination will enable the limit to be reduced by at least a further factor 2. Sensitivity is limited by the intrinsic radioactivity of the target materials, and methods of improving purity are being pursued.

However, the principal objective of this programme is to obtain substantially improved sensitivity by discriminating nuclear recoil events from radioactive background. The first experiment of this type is now running and is based on the emission of both uv and visible light from sodium iodide crystals at reduced temperatures, the ratio differing for nuclear and electron recoil events. This new 'UVIS' technique is now running underground, initially with 0.3kg and 1.2kg crystals. With this technique, the dark matter limits reduce as (mass x running time)$^{-0.5}$ and a new proposal has now been submitted to construct and run a 25kg experiment for at least two years to gain at least an order of magnitude improvement in limits. Improvements in light collection and energy threshold are also proposed.

The new proposal also includes a new type of liquid xenon detector based on proportional scintillation in an electric-field-defined fiducial region, with an outer self-shielding zone. This is named the 'ZEPLIN' configuration. Work on liquid xenon was suspended during 1994, in order to bring the UVIS detector into operation, but it is proposed to restart this in collaboration with the UCLA particle physics group.

The current funding period ends in March 1995, and a proposal to achieve at least two orders of magnitude gain in sensitivity in a new four-year programme has been submitted jointly to astronomy and Particle Physics Committees.

Recent publications

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Liquid xenon as a dark matter detector
G J Davies et al. Phys.Lett B 320 (1994) 395

Latest limits from the UK underground NaI detector
T J Sumner et al., Proc XXIX Rencontre de Moriond (1994)

Results from stage 1 of a Galactic dark matter search using low background sodium iodide detectors
J J Quenby et al., Phys. Lett B (to be published)

Measurement of nuclear recoil response of dark matter detectors using neutron scattering
G J Davies, Proc Conf Sources of Dark Matter (UCLA 1994)

Strategies for the detection of particle dark matter
P F Smith, Proc Conf Sources of Dark Matter (UCLA 1994)

Searches for particle dark matter: progress, future prospects, ideas
N J C Spooner, 6th Int Workshop on neutrrino telescopes (Venice 94)

Fig 1 Stage 1 low background NaI detectors

Fig 2 First new dark matter limits from a 1.3kg (room temperature) NaI detector. Upper plot shows the limiting rates from Na and I compared with those for ^{73}Ge in Ge. The unit is per kg of the individual element. The normalising quantity $r = 4M_DA/(M_D+A)^2$. The two pairs of curves are with and without subtraction of the ^{210}Pb background normalised to the ^{210}Pb peak. Lower plot shows coherent limits from Na and I relative to Ge limits assuming a heavy neutrino-like cross section proportional to $(A-Z)^2$. To convert to cross section, note σ (pb) = 0.002 $M_DA\ r\ (R_o/r)$

Fig 3 Designs for first cooled NaI 'UVIS' detectors.
The 1.2kg system is fully sealed for immersion in water shielding.
The 0.3kg system is easily demountable for testing alternative crystals.

Fig 4 Estimated limits (spin-dependent) versus mass x running time for cooled "UVIS" NaI detectors showing anticipated improvements over the stage 1 limits. Units and normalisation are as in Fig 2

A target mass 0.3 kg began underground operation in July 94, with a 1.2 kg system to follow in Oct 94. It is expected that a total of > 100 kg.days will be reached in the funding period to March 95. Exact dark matter limits will depend on energy threshold and background levels, and are currently uncertain by a factor 2. Further reduction in limits can be achieved by scale up to larger target masses and improved light collection.

Studies of Heavy Ion Collisions

NA34/P213/EMU 09 **Proposals 273, 278**

Aichi College - Aichi University - Bari - CERN - University College, Dublin - Gifu - University College London - Nagoya University - Nagoya Institute - Roma - Salerno - Toho - Torino - Utsonomiya - Yokohama.

Work continues on the various facets of the CERN experiments on heavy ion interactions.

The analysis of various electromagnetic dissociation events produced in Ag, Cu and Pb foil targets is progressing. The measurement of the etch pits in CR39 plastic detectors, placed fore and apt of the target foil - emulsion system, is efficient in determining those events where the incident ion loses charge on transit and the location of the associated events in the emulsion is efficient if slow. Scrutiny of the emulsions then readily separates EMD candidates from hadronic interactions and subsequent measurements of curvature of the secondary particles in the 2.5T magnetic field enables the discrimination of protons from deuterons to be made. Several hundred events have been measured and work continues to identify exclusive EMD channels in each of the targets. Preliminary results suggest that the great majority of events where the projectile ion loses one unit of charge are indeed due to proton stripping in the region of the giant dipole resonance.

A paper is in preparation which outlines the procedure of detecting charmed particle production by heavy ion collisions using synchronised emulsion tapes. The method is successful but the present analysis speed precludes a high statistics experiment. The possiblity of complete automisation of the analysis chain is being investigated by our Japanese colleagues.

A paper is also in preparation concerning a detailed investigation of transverse energy flow in ^{32}S central interactions using the HELIOS - emulsion set-up.

WA85/WA94 Proposal 275

Athens; Bari; Bergen; Birmingham; CERN; Collège de France; Košice;
Legnaro; Madrid; Padova; Serpukhov; Strasbourg; Trieste.

The study of strange baryon spectra in heavy ion collisions is a useful probe of the dynamics of hadronic matter under extreme conditions. The relative abundances for different baryon and antibaryon species allow the degree and nature of flavour equilibration to be studied, while the transverse mass (m_T) spectra provide independent information on the temperatures achieved in the collision [1]. In particular, the onset of a Quark-Gluon Plasma (QGP) phase during the collisions is expected to enhance the antihyperon yield with respect to normal hadronic interactions and to give rise to a large $\overline{\Xi^-}/\overline{\Lambda}$ ratio [2]. The WA85 experiment has high statistics data on strange baryon and antibaryon spectra ($\Lambda, \overline{\Lambda}, \Xi^-, \overline{\Xi^-}, \Omega^-, \overline{\Omega^-}$), and is the only experiment to have obtained results on Ω^- production in heavy ion interactions.

The WA85 experiment [3] is a dedicated experiment aimed at studying strange particle production at $p_T > 1$ GeV/c and central rapidity. It was performed using the CERN Omega Spectrometer with a ^{32}S beam at 200 GeV/c per nucleon incident on a tungsten target. The Omega Multi Wire Proportional Chambers (MWPCs) were modified to select only high p_T tracks; only a few tracks are recorded out of the several hundred produced in a central collision, making reconstruction of both strange and multi-strange baryons possible. The apparatus and trigger, designed to select central collisions, have been discussed previously [4].

The methods for reconstructing Λ [4] and Ξ^- [5] decays have already been described. Fig. 1 shows a fully reconstructed $\overline{\Xi^-}$ candidate. Results from our 1987 data (10 million triggers) have already been presented [4,5,6,7,8]. In this report we concentrate on new high statistics results based on 60 million triggers recorded in 1990. The results were presented at the Quark Matter '93 Conference in Borlänge, Sweden [9].

The number of reconstructed Λ, $\overline{\Lambda}$, Ξ^- and $\overline{\Xi^-}$ candidates are given in Table 1. The m_T distributions are shown in fig. 2. They were fitted in the rapidity interval $2.3 < y_{lab} < 2.8$ using the expression

$$\left(\frac{1}{m_T}\right)^{\frac{3}{2}} \frac{dN}{dm_T} = A \exp(-\beta m_T).$$

The inverse slopes ($1/\beta$) are given in Table 2, where the errors are statistical only. The systematic error has been estimated, by simulation, to be about $\pm$ 10 MeV.

Using these values, it is possible to calculate the relative production rates for hyperons in the rapidity interval $2.3 < y_{lab} < 2.8$. The results for $m_T > 1.9$ GeV and for $1 < p_T < 2$ GeV/c are given in Table 3 . The $\overline{\Xi^-}/\overline{\Lambda}$ ratio in the p_T interval $1 < p_T <$

2 GeV/c is over three times greater than that observed in pp interactions [9,10], a four standard deviation effect. Ω^- and $\overline{\Omega^-}$ hyperons have been observed for the first time in heavy ion interactions [11]. In order to isolate the small number of Ω^- candidates from background, more stringent selections are required than for Ξ^-s [12]. Fig. 4 shows the final ΛK^- (and c.c.) effective mass spectrum for events unambiguous with Ξ^-. The dotted lines show background generated by mixing V^0s with non-V^0 tracks from different events. We obtain an uncorrected $\overline{\Omega^-}/\Omega^-$ ratio of 0.57 $\pm$ 0.41 in the phase space region $2.5 < y_{lab} < 3.0$ and $p_T >$ 1.6 GeV/c [12]. More recently[13], the fully corrected $\Omega^- + \overline{\Omega^-}$ yields have been caluculated, allowing the production ratio $R_{\Omega\Xi} = (\Omega^- + \overline{\Omega^-})/(\Xi^- + \overline{\Xi^-})$ to be calculated in the region $2.5 < y_{lab} < 3.0$ and $p_T >$ 1.6 GeV/c; we obtain 0.8 $\pm$ 0.4, or $R_{\Omega\Xi} > 0.79$ at 95% confidence level. The values obtained for the Ξ/Λ, $\overline{\Xi^-}/\overline{\Lambda}$ and $(\Omega^- + \overline{\Omega^-})/(\Xi^- + \overline{\Xi^-})$ ratios are compared with those obtained in pp interactions by the AFS collaboration in fig. 3. The kinematic regions for the AFS results, shown on the figure, are similar to those used for the WA85 results. Both the $\overline{\Xi^-}/\overline{\Lambda}$ ratio and the $(\Omega^- + \overline{\Omega^-})/(\Xi^- + \overline{\Xi^-})$ ratio show a clear enhancement in multistrange production ratios with respect to pp collisions.

The WA94 experiment [14] is a successor to WA85, in which a sulphur target is used. In the first phase of the experiment the Omega MWPCs were used to measure hyperon decays in SS interactions. 100 million triggers were obtained in November 1991. Event reconstruction for these data is complete, and analysis is underway. The Ξ^-, $\overline{\Xi^-}$, Λ and $\overline{\Lambda}$ spectra have been fully corrected for acceptance, reconstruction efficiency and feed-down, allowing the m_T spectra and the relative production ratios to be determined [15]. Fig. 5 shows the m_T spectra for Ξ^-, $\overline{\Xi^-}$, Λ and $\overline{\Lambda}$ in the rapidity interval $2.5 < y_{lab} < 3.0$. The distributions have been fitted using expression (1). The values obtained for the inverse slope are shown in Table 2. In general, the values obtained are some 15 MeV lower than those obtained in SW interactions in an equivalent centre-of-mass rapidity interval. The particle production ratios are given in Table 4. As can be seen, the ratios are very similar to those obtained by WA85, and therefore again the $\overline{\Xi^-}/\overline{\Lambda}$ ratio is considerably higher than the pp value[10].

A second period of data taking took place in April 1992, using the Omega RICH in conjunction with a silicon telescope built from the existing WA82 charm decay detector, an array of silicon microstrips. The aim of this phase of the experiment is to use the Omega RICH to obtain identified proton spectra to compare with the hyperon spectra already obtained. The operation of the silicon telescope also provides valuable experience for the purpose-built silicon telescope to be used in the WA97 experiment [16]. New reconstruction code is required to find tracks in the telescope in a high track density environment. Analysis of these data is in progress.

Reference data using the Omega MWPCs was obtained from an incident proton beam at 200 GeV/c in October and November 1993. 60 million triggers were recorded. The event reconstruction was completed early this year using the RAL IBM system.

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7. Strange Particle Production in Sulphur-Sulphur Interactions at 200 GeV/c per nucleon.
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   Proceedings of the International Conference on Strangeness and Quark Matter, Crete, September,1994. Presented by D. Evans.

9. Strange Baryon and Antibaryon Production in Sulphur-Sulphur Interactions at 200 GeV/c per nucleon.
   R.P. Barnes, A.C. Bayes, I.J. Bloodworth, J.N. Carney, S. Clewer, J.P. Davies, C.J. Dodenhoff, J.B. Kinson, R. Lietava, O. Villalobos Baillie and M.F. Votruba + Athens, Bari, Bergen CERN, Collège de France, Košice, Legnaro, Madrid, Padua, Protvino, Strasbourg and Trieste.

   Proceedings of the International Conference on Strangeness and Quark Matter, Crete, September,1994. Presented by J.B. Kinson

Table 1. V^0 and cascade yields from the 1990 SW data and 1991 SS data.

Candidate	Events WA85 SW	Events WA94 SS
Λ	51 600	56 000
$\overline{\Lambda}$	13 600	18 000
Ξ^-	500	602
$\overline{\Xi^-}$	200	313

Table 2. Inverse slopes of hyperons in SW Interactions (MeV).

Particle	Inverse slope (MeV) SW	Inverse slope (MeV) SS
Λ	232 ± 3	214 ± 3
$\overline{\Lambda}$	230 ± 6	206 ± 6
Ξ^-	239 ± 11	227 ± 10
$\overline{\Xi^-}$	234 ± 15	209 ± 13

Table 3. Relative hyperon production rates in SW interactions.

Ratio	$m_T > 1.9$ GeV	$1 < p_T < 2$ GeV/c
$\overline{\Lambda}/\Lambda$	0.20 ± 0.01	—
$\overline{\Xi^-}/\Xi^-$	0.42 ± 0.05	—
Ξ^-/Λ	0.19 ± 0.01	0.09± 0.01
$\overline{\Xi^-}/\overline{\Lambda}$	0.40 ± 0.04	0.20± 0.03

Table 4. Relative Hyperon production rates in SS Interactions.

Ratio	$1.2 < p_T < 3.0$ GeV/c $2.5 < y_{lab} < 3.0$
$\overline{\Lambda}/\Lambda$	0.23 ± 0.01
$\overline{\Xi^-}/\Xi^-$	0.51 ± 0.06
Ξ^-/Λ	0.094 ± 0.006
$\overline{\Xi^-}/\overline{\Lambda}$	0.22 ± 0.02

Fig. 1. Fully reconstructed $\overline{\Xi}^-$ candidate.

Fig. 2 Transverse mass distributions for (*a*) Λs and Ξs, and (*b*) $\overline{\Lambda}$s and $\overline{\Xi}^-$s.

Fig. 3. Ξ^-/Λ, $\overline{\Xi^-}/\overline{\Lambda}$ and $(\Omega^- + \overline{\Omega^-})/(\Xi^- + \overline{\Xi^-})$ ratio for pp and SW interactions.

Fig. 4. Effective mass distribution of Ω^- and $\overline{\Omega^-}$ candidates. The dotted line is a background estimate described in the text.

Fig. 5 (*a*) Λ and Ξ^-, and (*b*) $\bar{\Lambda}$ and $\bar{\Xi}^-$ transverse mass distributions. WA94 data.

The Sudbury Neutrino Observatory (SNO)

The Sudbury Neutrino Observatory (SNO) is a joint Canadian, US and UK venture designed to study neutrinos from the sun and other astrophysical sources using a 1000 ton heavy water (D_2O) Cerenkov detector. All four existing solar neutrino experiments, Homestake, Kamioka, Sage and Gallex, report a deficiency of electron neutrinos relative to the standard solar model. A non-zero neutrino mass and neutrino oscillations could explain the observations but that is only a speculation without the positive evidence that SNO will be able to provide.

The unique advantage of the SNO detector is that the use of D_2O as a detecting medium enables not only the flux and energy spectrum of electron neutrinos but also the total flux of all neutrino types above an energy of 2.2 MeV to be measured. With these two measurements it will be possible to show clearly whether neutrino oscillations are occurring and independently test solar models by determining the production rate of high-energy electron neutrinos in the solar core.

The planned SNO detector consists of an acrylic vessel containing 1000 tons of D_2O immersed in 7000 tons of high purity light water. Surrounding the acrylic vessel are some 9600 photomultiplier tubes (PMTs) and the whole detector is located 2000m underground. In order to improve the light collection, and hence the signal to noise of the detector, the Oxford group has developed non-imaging concentrators to mount around the PMTs. They have the twin virtues of increasing by 65% the number of photons from the D_2O (thus increasing the signal), while simultaneously keeping each PMT from seeing the PMTs adjacent to it. This greatly reduces the probability of a radioactive decay near one of the PMTs being misidentified as an event in the D_2O, which is a major source of background at low energies. These advantages have made the concentrators central to the design of the detector.

Besides the design and manufacture of the concentrators, the UK is also involved in developing techniques for producing very pure water; in particular, in removing thorium whose decay photons can photodissociate deuterium and so mimic the neutral current neutrino induced reaction: $v + d \rightarrow n + p + v$, which is equally sensitive to <u>all</u> types of neutrino. In particular, Oxford is reponsible for demonstrating a technique for producing very pure anhydrous magnesium chloride. [$MgCl_2$ is added to the heavy-water to enable the neutrons produced by neutrino-induced disintegration of deuterium to be observed.] The technique involves dissolving $MgCl_2$ in ultra-pure water and then putting the solution in contact with an absorber to remove contaminants - in particular the thorium. The originally proposed absorber, MnO_2, has been shown not to provide an adequate removal of thorium. This has meant developing the technique of "seeded ultrafiltration", using hydrous titanium oxide as the absorber, from which the absorbed Ra, Pb, and Th can be eluted and counted via beta-alpha coincidences in liquid scintillator. This has proved a very effective way of monitoring and will be used to monitor the 1000 ton heavy-water detector. Prototypes of this scintillator monitor have been made.

The SNO group at Oxford plays the leading role in the development of software for the optimisation of the running of the experiment and for the analysis of data via the programme SNOMAN: <u>S</u>udbury <u>N</u>eutrino <u>O</u>bservatory <u>M</u>onte Carlo and <u>AN</u>alysis code. The core of the programme has been written and documented and is now being implemented throughout the collaboration.

Project Status Report (Dec. 1994)

The excavations of the underground detector cavity (Fig.1) and ancillary laboratory space are complete, sealed off from the rest of the mine, and are clean to the necessary degree, the walls having been previously coated with poly-urethane for the H_2O vessel and epoxy paint elsewhere. The upper half of the geodesic structure is currently being assembled and will be fitted with the panels carrying photomultipliers, concentrators, and cables early in the New Year.

The next stage is the delicate job of assembling the spherical acrylic vessel of 12m diameter, first the upper then the lower hemisphere. This is the most difficult piece of engineering of the project. By contrast assembling the lower half of the support structure and its equipment is but a trifle.

The H_2O and D_2O water systems are being assembled in the utility room in parallel with the work in the detector cavity.

Completion of the various parts of the detector ready for the first water fill is now expected in 1996.

Oxford Status Report (Dec. 1994)

Three quarters of the 9600 concentrators have been manufactured and shipped to Sudbury. The remaining quarter have been delayed (without time penalty to the project) by unsatisfactory coating of the aluminium sheets by OCLI. The problem has now been resolved and production will be resumed in the New Year in comfortable time for the assembly of the lower half of the support frame.

The seeded ultra filtration system for water purification, illustrated schematically in Fig.2, has now reached the design stage for the 200 l/min. D_2O throughput required. The filter is a polysulphone hollow fibre type made by Amicon and other manufacturers for biological work. Hydrous titanium oxide (abbreviated HTiO) deposited on the membrane surface with about 0.5 g per m^2 (roughly a micron thickness) is a highly efficient absorber for Th, Pb and Ra. The latter can be eluted with acid, subjected to a secondary concentration stage, and counted via beta-alpha coincidences. The technique is now well established and is now being translated into an engineered form for (a) the assay aand purification of the 1000 tons of D_2O, (b) a plant for the purification of $MgCl_2$ as 10 four ton batches of 5% solution in D_2O, and (c) a small system for determining the cleanliness of the parts of the purification plants. The cooperation of the manufacturer Amicon for the solution of technical problems of our unusual applications of their filters is gratefully acknowledged.

N.W. Tanner

Figure 1. A drawing of the SNO Cherenkov counter showing the cavity 22 m diameter by 30 m deep 2000 m below the surface, the support structure 17.5 m diameter for 10000 photomultipliers, and the acrylic vessel for D_2O, 12 m diameter.

Figure 2. Schematic diagram of the system for seeded ultrafiltration using *ca.* 10 p.p.m. of finely divided hydrous titanium oxide (abbreviated HTiO) to absorb Ra and Th in water and extract via a filter of pore size *ca.* 10 nm.

A search for the H-particle and other strange matter

Birmingham University, Brookhaven, Carnegie-Mellon, Freiburg, Kyoto, Kyoto-Sangyo, Los Alamos, Manitoba, New Mexico, Pittsburgh, Triumf, Vassar College

This project comprises several related experiments on systems with multiple strangeness. Two of these (E813, E836) are searches for the S=-2, B=2 H-particle[1]. The third, E886, is a search for other forms of strange matter.

A. E813 - A search for the H-particle in $\Xi^- d$ interactions

Brookhaven E813 is a search for the H-particle, a strangeness-2 dibaryon, by Ξ^- interactions at rest in deuterium. In E813, K^- at 1.8 GeV/c enter a liquid hydrogen target, producing Ξ^- by the reaction

$$K^- p \rightarrow K^+ \Xi^-.$$

The K^+ are detected in a magnetic spectrometer. The Ξ^- pass through a tungsten degrader and a Si surface-barrier detector, and stop in a liquid D_2 target, where they form $\Xi^- d$ atoms which produce H-particles via the process

$$\Xi^- d \rightarrow Hn.$$

Thus the signal of H-particle production is a K^+ in the magnetic spectrometer, a signal from the slow Ξ^- in the Si detector, and a monoenergetic neutron in the neutron TOF spectrum. A schematic diagram of the layout of the apparatus is given in fig. 1.

No new data were taken for this experiment in 1994. Instead, our effort was concentrated on analysis of data from our production runs in 1992 and 1993. We have become aware that, owing to several unanticipated losses, the sensitivity of the experiment is less than we originally thought. Therefore, out efforts have been directed towards maximising the sensitivity, by recovering lost events and by background reduction, and also to direct experimental tests of the acceptance of the apparatus. The first of these is mainly a question of careful tuning of all cuts in the analysis, and also finding ways to salvage events that were rejected because of missing hits in chambers and scintillators. In addition, several cuts to remove background events are being tested.

The possibility of direct experimental tests of our sensitivity was mentioned in last year's report. There are two possible "calibration" processes which have known yields and which have many kinematic properties similar to the H-particle production mechanism. These are
(i) The process

$$K^- p \rightarrow \pi^- \Sigma^+, \qquad \Sigma^+ \rightarrow n\pi^+,$$

with observation of the 18-MeV neutron, tests all aspects of the experiment except the tagging of the slow Ξ^- in the silicon detectors.
(ii) The process

$$\pi^- p \rightarrow K^+ \Sigma^-, \qquad (\Sigma^- p)_{atom} \rightarrow \Lambda n$$

tests, in addition, the operation of the Ξ tagging in the Si detectors. In this process, the beam momentum is reduced to 1.2 GeV/c, and the top section of the target, which normally contains deuterium, is filled with hydrogen. Thus the slow Σ^- passes from one half of the target to the other before forming an exotic atom.

Process (i) shows a clean neutron peak and, with improved analysis techniques, the resolution is as expected. This is shown in fig. 2. At the moment, process (ii) does not show a clean peak. Although this gives some concern about the efficiency of our Ξ tagging, the absence of a peak is probably consistent with the statistical accuracy, and we plan to do more running on this calibration process in 1995.

B. E836 - A search for the H-particle in $K^-\ {}^3He$ interactions

This experiment searches for H-particle production in the process

$$K^-\ {}^3He \rightarrow HK^+n.$$

Only one target is involved, a liquid ${}^3He$ target, and there is no slow Ξ to tag in Si detectors. Apart from these differences, the experimental apparatus is very similar to that for the H_2/D_2 version, E813. The ${}^3He$-target experiment is sensitive to a wider range of H-particle binding energies than is E813.

Data taking for E836 took place during the 1994 run. In spite of a late start, resulting from troubles with the liquid ${}^3He$ target, the run turned out to be quite productive.

Data analysis is at an early stage, but a preliminary momentum spectrum for the outgoing K^+, from a fraction of the data, was accumulated during the first-pass data reduction, and is shown in fig. 3. The broad distribution at the left ($p_{K^+} \leq 1.4GeV/c$) results from quasi-free Ξ production, $K^-\ {}^3He \rightarrow \Xi^- K^+ pn$. H-particle production would give a peak in the region $p_{K^+} \geq 1.4GeV/c$. There is no evidence yet for such a peak; the broad peak at $p_{K^+} \sim 1.5GeV/c$ probably results from mis-identified π^+s. It is reassuring that the background in the H-particle region is already very low, even in this very preliminary spectrum.

The next stages in the analysis involve careful calibration of the K^+ spectrometer, to improve its momentum resolution, and study of the neutron TOF spectra and of the Čerenkov pulse-height spectra.

C. E886 - A search for new strange particles in nucleus-nucleus collisions

Experiment E886 is a search for strangelets and other exotic forms of matter in relativistic heavy ion collisions, which are expected to have anomalously large mass-to-charge ratios (M/Z). After a test run in 1992, (which produced results which were published in 1993 and 94), the main data run took place during 1993.

The apparatus was again similar to that for experiments E813 and 836, but the H-particle production target was removed and replaced by 4 scintillation counters [2,3]. The AGS D6 beamline was used as a focusing spectrometer, producing a M/Z measurement, which was repeated in the associated open geometry spectrometer. The charge (Z) of the particles was deduced from pulse height measurements in four plastic scintillators placed in

the region between the beamline and the open spectrometer. Requiring agreement between the two M/Z measurements resulted in very clean spectra and good particle identification capabilities, see Fig. 4(a).

During the 1993 run, we collected the data necessary to identify the secondary particles produced by an estimated 1.3×10^{13} Au ions on the Pt target at a momentum of $\sim$ 10.8 GeV/c per nucleon. Three main results have been produced by this experiment : Production cross sections for ordinary nuclear isotopes, limits on strangelet production, and limits on the production of (H dibaryon)-nucleus systems. These results have been presented at the 1994 Vancouver conference [4].

Production cross sections for p, d, t, ^{3}He, and ^{4}He were measured. These data extend those derived from the 1992 run. A coalescence model fit to the 1992 data [3] was extended to include other nuclear isotopes and shown to be in good agreement with the cross section measurements for ^{6}He, ^{8}He, ^{6}Li, ^{7}Li, ^{8}Li, and ^{7}Be, all extracted from the 1993 data set. The cross sections are plotted against M/Z in Fig. 4(b). The upper and lower limits for these cross sections are indicated by pairs of horizontal lines. The symbols mark the values obtained from the coalescence model fit mentioned above.

From Fig. 4(a) we deduce that no strangelet candidates were seen. The 90% C.L. cross sections obtained after correction for data aquisition livetime, detection and analysis efficiencies, estimated absorption in the production target, and experimental acceptance, are plotted in Fig. 5, against M/Z. These numbers represent an improvement of about 100 over the limits obtained from the 1992 data.

Based on some recent predictions of double-lambda hypernuclear production rates in Au+Au collisions at AGS energies [5], we made an estimate of the expected cross section for two such objects, produced and detected by our experimental setup. Viewing these objects as "doorway" systems to the formation of H-nucleus systems, we set out to look for them in our data set from the 1993 run. The null result of this search can be used to set a limit on the lifetime of the H-nucleus system, which, under certain assumptions is interpreted as a limit on the lifetime of the H itself. Our result constrains the lifetime of the H-nucleus systems to ≤ 20 ns. A more complete discussion of this effort along with the presentation of the results and their interpretation are currently being compiled into a paper for publication in the near future.

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Composite particle production in relativistic Au + Pt, Si + Pt and p + Pt collisions, N. Saito, B. Bassalleck, T. Buerger, M. Burger, R.E. Chrien, G.E. Diebold, H. Enyo, G.B. Franklin, J, Franz, T. Iijima, K. Imai, J. Lowe, R. Magahiz, A. Masaike, F. Merrill, J.M. Nelson, K. Okada, P. Pile, B.P. Quinn, E. Roessle, A. Rusek, R. Sawafta, R.A. Schumacher, H. Schmitt, R.L. Stearns, I.R. Sukaton, R. Sutter, F. Takeuchi, D.M. Wolfe, S. Yokkaichi, V. Zeps, R. Zybert, Phys. Rev. C49, 3211 (1994).

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Searches for the H-dibaryon at the AGS, B. Quinn, A Berdoz, G. Franklin, R. Magahiz, R. McCrady, F. Merrill, C. Meyer, R. Schumacher, R. Sukaton, V. Zeps, J. Lowe, J. Nelson, R. Zybert, R. Chrien, P. Pile, R. Sawafta, R. Sutter, M. Athanas, N. Hamann, T. Bürger, M. Burger, J. Franz, E. Rössle, H, Schmitt, J. Syzmanski, T. Iijima, K. Imai, A. Masaike, K. Okada, F. Takeutchi, P. Barnes, C. Davis, L. Gan, M. Landry, S. Page, W.D. Ramsay, V. Sum, W. van Oers, B. Bassalleck, H, Fischer, A. Rusek, R. Stotzer, D. Wolfe, D. Gill, R. Stearns, G. Diebold, Intersections conference, Florida, 1994.

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Fig. 1. Layout of the main components of the apparatus for E813/836. The perspective view, (a), shows the general layout, while the side view, (b), shows more detail. The neutron counters, some of which are not shown for clarity, surround the target on both sides. Several Cerenkov and scintillation counters are also omitted from this drawing. For the strangelet search, E886, the apparatus is essentially the same except that the liquid H_2/liquid D_2 target is replaced by 4 scintillation counters.

Fig. 2. Neutron kinetic energy spectrum from $K^-p \rightarrow \pi^-\Sigma^+$, $\Sigma^+ \rightarrow n\pi^+$ showing the expected peak at 18 MeV.

Fig. 3. Outgoing K^+ momentum spectrum from $K^-\,{}^3He \rightarrow HK^+n$. The spectrum is a preliminary one, from a fraction of the data. A peaks corresponding to bound H-particle production would appear in the region $P_{K^+} \geq 1.4GeV/c$.

Fig. 4. (a) Pulse height vs. M/Z for particles from Au + Pt interactions at 10.8A GeV/c. The dotted lines separate regions where the fraction of particles detected was changed by a prescale in the trigger.

(b) Production cross sections for isotopes up to ^8He from Au + Pt interactions at 10.8A GeV/c.

Fig. 5. Limits on strangelet production cross sections at 90% CL, as a function of M/Z and Z.

RADIATIVE WEAK DECAYS OF Σ^+ & Ξ^- HYPERONS

Fermilab E–761 **proposal 279**

Rio de Janeiro (CBPF & CNPQ), São Paulo, *Brazil* **Beijing (IHEP), *PRC*** **Bristol, *UK***
Fermilab, Iowa, SUNY–Albany, Yale, *USA* **Moscow (ITEP), St. Petersburg (PNPI), *Russia***

This experiment took data in the fixed target run at Fermilab in 1990. Figure 1 shows the experimental layout : details of the experiment are given in last year's Report. The majority of our results have been published : as an example, figure 2 summarises our results on the Σ^+ and $\overline{\Sigma}^-$ magnetic moments. Work is continuing on a comprehensive set of measurements of hyperon polarisation and production cross-sections.

Publications since October 1993:

A Morelos *et al.*,
Measurement of the Magnetic Moments of Σ^+ and $\overline{\Sigma}^-$ Hyperons
Physical Review Letters, **71**, 3417 – 3420 (1993)

T Dubbs *et al.*,
Measurement of the Branching Ratio for the $\Xi^- \to \Sigma^-\gamma$ Radiative Decay
Physical Review Letters, **72**, 808 – 811 (1994)

V V Baublis *et al.*,
Measuring the Magnetic Moments of Short–Lived Particles
Using Channeling in Bent Crystals
Nuclear Instruments and Methods, B **90**, 112 – 118 (1994)

I F Albuquerque *et al.*,
New Upper Limit for the Branching Ratio of the $\Omega^- \to \Xi^-\gamma$ Radiative Decay
Physical Review D 50, R18 – R20 (1994)

Conference Report:

June 1994 : R.A.Carrigan, Jr and V.J.Smith
'Channeling Spin Precession as a Technique
for Measuring Charm Baryon Magnetic Moments'
Published in Proceedings of the Charm 2000 Workshop, Fermilab–Conf-94/190.

Thesis:

"The $\Omega^- \to \Xi^-\gamma$ Radiative Decay", I.F Albuquerque,
PhD thesis, Universidade de São Paulo, December 1993.

FIG. 1. Plan view of the E761 apparatus in the Fermilab Proton Center charged hyperon beamline.

Figure 2 : Measurements of magnetic moment of Σ^+ and (at right) $\overline{\Sigma}^-$

Measurement of Beauty Particle Lifetimes and Hadroproduction Cross-section

WA92 Proposal 280

Bologna; CERN; Genoa; Imperial College; Moscow; Pisa; Rome; Southampton

This experiment uses a 350 GeV negative pion beam incident on tungsten and copper targets at the CERN Omega Spectrometer. Its aim is to identify a sample of B mesons, large enough to address several important physics issues, including measurements of the lifetimes of charged and neutral B mesons and the B hadroproduction cross-section.

Heavy nuclear targets are used to exploit the A^1 mass number dependence of the $b\bar{b}$ cross-section. But, even so, the B-signal to noise ratio is only 10^{-6}. Methods used successfully to isolate charm signals from fixed target experiments will not work with beauty. Fully reconstructible channels account for about 10% of charm decay vertices compared with 10^{-3} for beauty. It is hopeless to rely on reconstructing the invariant mass of B-decays. Instead, the identification uses the cascade decay topology, the identification of the daughter charm decay and the high-p_T of leptons emerging from the B-decay.

The experimental triggers emphasize characteristic features of B-decay: impact parameter, to select secondary vertices; lepton triggers, to exploit the large semileptonic branching fraction; high p_T, to select high mass decays. The detector is based around the Omega spectrometer, with muon and electron identification and a dense array of high precision ($\sigma < 3\,\mu$m) silicon microstrip detectors, acting as an electronic emulsion stack in which the cascade $b \rightarrow c$ decay chain can be observed.

During 1992-93, 150M triggers were recorded. The trigger algorithm enriches (by factors $\sim 20 - 30$) the Beauty fraction of the data while maintaining a high ($\sim 50\%$) acceptance. On reasonable assumptions for the B cross-section we estimate that more than 1000 B's are on tape, from which we expect that a few hundred will be identifiable. Analysis of 20% of the triggers has so far yielded about 20 Beauty candidates with small backgrounds. Using this sample a cross-section of $\sigma(b\bar{b}) = 7 \pm 2$ nb/nucleon has been obtained. From the full data sample we expect to measure the charged to neutral B-lifetime ratio and the $b\bar{b}$ cross-section to a precision of $\sim 10\%$.

The discriminating power of the silicon vertex detectors has allowed measurements of charm physics with very low backgrounds. An analysis of kinematic correlations in $D\overline{D}$ production and a new limit on the FCNC process $D \rightarrow \mu^+\mu^-$ have been reported at conferences during 1994.

WA92 - Theses and Publications in refereed journals: 1993 - 94

"Observation of Beauty particles in π^--nucleon interactions at 26 GeV centre of mass energy".

PhD Thesis, University of London,1994.

"The beauty contiguity trigger of the WA92 experiment: detector, readout and processor overview"

Nucl. Instr. & Methods A337 (1994) 280 - 294.

A PRECISION CALORIMETRIC MEASUREMENT OF THE 17-keV NEUTRINO WITH A NEW TYPE OF DETECTOR

Proposal 282

University of Oxford

A beta spectrometer has been developed using a new type of cryogenic particle detector. The detectors consist of series arrays of superconducting tunnel junctions (SASTJs) fabricated on single crystals of InSb operated at 100 mK. Two detectors are used to completely enclose a beta electron source and are able to make fully calorimetric measurements of beta decay, eliminating both back scattering and final state effects. Preliminary results from a precision measurement of the beta spectrum of a ^{63}Ni source are reported.

1. Introduction

We report on the preliminary results from a measurement of the beta spectrum of a ^{63}Ni source using a new type of cryogenic detector. The technique allows the direct measurement of the Ni spectrum over its entire energy range. A Kurie plot of the raw data, from a run over a period of 14 days, is shown in Fig. 1 acquired at a live count rate of 50 Hz and contains 4×10^7 counts. The FWHM resolution of the detectors for this run was 1.3 keV. The structure below 4 keV is due to trigger threshold effects. The apparent end-point energy is slightly above 67 keV. The problems associated with energy calibration are discussed in §2.

The original goal of this experiment was to confirm or disprove the existence of a neutrino of mass 17 keV/c^2 by a new calorimetric technique. The evidence for this neutrino has now disappeared, in part due to a re-analysis of the data which provided the most compelling positive evidence [1] and also from experiments which showed that this positive evidence was due to instrumental effects [2].

In the present work, we have demonstrated that this new cryogenic technique, which obviates the problems of back-scattering and final-state atomic effects, is capable of making a precision measurement of a beta spectrum at the level of order 1%. These (and other cryogenic based detectors) will be used for future investigations of some of the more pressing problems in particle physics such as a search for dark matter WIMPs. (See [3] for a review of the field.)

Figure 1. Kurie plot of the raw beta spectrum of ^{63}Ni. The plot contains 4×10^7 counts recorded over a period of 14 days.

2. Experimental Overview

The Ni source was deposited on the inside face of one of the detectors as an electroplated mono–layer and is totally enclosed by the two detector channels. This provides the ideal geometry for a calorimetric measurement. Pulses due to the beta electrons were recorded from both detectors. Further details of the detectors and detection mechanism are discussed elsewhere [4, 5]. In order to check the integrity of the data taken over long periods of time, the gain and linearity were monitored using pulses from a high stability LED which illuminated the detectors via an optical fibre.

We have found that the bias conditions of the devices can be subject to inherent instabilities. A change in the bias

points alters the dynamic resistance or the tunnelling probability associated with the tunnel junctions, and therefore the intrinsic gain.

Figure 2. Plot of the variation of the gain of the two detector channels to LED calibration pulses (~60 keV) over a period of two weeks.

For the run shown in Fig. 1 optimal bias points were chosen to minimise the instability. Figure 2 shows the variation of the detector gain over the period of two weeks. Most of the abrupt changes occur at the times indicated at the bottom of the figure when the dilution refrigerator is topped up with liquid nitrogen or liquid helium.

Figure 3. Typical plot of deviation from linearity of each of the two detector channels measured using a variable LED calibration pulse.

A plot of the deviations from linearity of the two channels is shown in Fig. 3 which was taken at a time during the run shown in Fig. 2. The details of the non-linearity were found to vary with the bias point of the detector. The monitoring system permits us to adjust the Ni spectrum data accordingly, and to discard blocks where the instabilities are beyond an acceptable limit.

External gamma sources of ^{241}Am (59.5 keV) and ^{57}Co (122 and 136 keV) which span the end-point (67 keV) of the continuous ^{63}Ni spectrum were used to attempt to calibrate the absolute energy scale of the spectrometer. We have evidence that electrons give a larger pulse height (~few %) than γ-rays of the same energy in the detectors. At present we are continuing to study these and related effects which affect the precise energy calibration of the detectors. Including a ^{109}Cd internal conversion source together with the beta source will allow us to determine a more precise energy calibration for the electron events and yield an electron response function.

3. Analysis of Kurie Plot

If we optimise the energy calibration of the two channels then it is possible to look at the shape of the Kurie plot when compared with the theoretical shape (including the effects of pile-up and background). Figure 4 shows the deviation of the Kurie plot, ΔK/K, from a straight line fit in the region 51–60 keV. Although the data taking is not yet complete, and the analysis is at a preliminary stage, it can be seen from the magnitude of the error bars that we are now at the stage where the statistics are nearly sufficient to test a neutrino admixture hypothesis at the 1% level.

Figure 4. Relative deviation of the experimental Kurie spectrum from a straight line fit (51 to 60 keV). The scale is compressed by a factor of 10 above 60 keV. The grey line is the expected deviation based on the theoretical beta spectrum combined with pile-up/background effects. The black line is the deviation assuming an additional 1% admixture of a 17-keV neutrino.

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NA48 Proposal 283

A Precision Measurement of ϵ'/ϵ in CP Violating $K^0 \to 2\pi$ Decays

Cagliari, Cambridge, CERN, Dubna, Edinburgh, Ferrara, Mainz, Perugia, Pisa, Saclay, Siegen, Torino, Vienna Collaboration

This is a new experiment, approved in 1991, whose main aim is to measure precisely the strength of CP-violation in the decay amplitude relative to the dominant CP-violation in the K^0 mass matrix, by comparing the ratio of decays into two charged and two neutral pions for K_S and K_L. The technique, while similar in some respects to that of the NA31 experiment, is very different to that of previous experiments.

There are several challenges. A new neutral kaon beam system has been built in the high-intensity experimental hall in the North Area of the SPS at CERN, which delivers nearly collinear K_L and K_S beams concurrently. The proton beam was tuned during the first test beam run in late 1993, and successfully used a bent crystal to deflect a small proportion of the protons which passed through the K_L target without interacting back onto the beam axis to produce the K_S beam closer to the detector. The two beams are now operational.

The $\pi^+\pi^-$ decays will be detected and measured in a classical magnetic spectrometer while the $2\pi^0$ decays will be detected and measured in a novel electromagnetic calorimeter using liquid krypton as the ionizing medium. The liquid krypton technique has been shown to work in a small test calorimeter, and achieves the required precision in energy, position and timing. Work is in progress to design the full-size calorimeter.

The UK responsibility is for the muon veto system. Commissioning began in the autumn of 1993, and has been largely completed during two short test periods in 1994. The final timing remains to be done, but calibration and monitoring shows that the veto plane is fully efficient. The timing precision is already close to the required resolution of less than a nanosecond.

Advanced triggering and readout systems has been developed to process the very high trigger and data rates required. Prototypes of the data acquisition were tested in the beam in September 1994. A variety of advanced computing techniques are being explored to extract maximum use of control room computing. High performance network connections could allow remote data access and remote data logging. Work has started on massively parallel processing (MPP) for the necessary montecarlo and calibration of the experiment, and preliminary results are encouraging.

STUDY OF LEAD LEAD INTERACTIONS AT 160 GeV/c PER NUCLEON

WA97 **Proposal 285**

Athens, Bari, Bergen, Birmingham, CERN, Paris, Genoa, Kosice, Legnaro,
Padua, Rome, Salerno, Serpukhov, Strasbourg, Trieste.

This experiment intends to measure the spectra of hyperons and antihyperons produced in ultrarelativistic lead-lead interactions over a wide phase space window. The experiment will make use of the 160 GeV/c per nucleon Pb beam expected to become available at CERN in November 1994. The principal aim is to compare the production of baryons carrying one unit of strangeness (Λ) with those carrying two (Ξ^-) and three units of strangeness (Ω^-). The possibility of a comprehensive study of the spectra of various hyperon and antihyperon species will constitute a unique feature of our experiment. In addition, we shall measure the spectra of protons and antiprotons in a smaller but overlapping phase space window. This will enable us to compare the spectra of baryons carrying zero, one, two and three units of strangeness under the same trigger conditions.

The ultimate goal of the heavy ion programme is to find evidence for a new state of matter, the Quark-Gluon Plasma (QGP). A transition from normal hadronic matter to the QGP is predicted to occur in head-on collisions of heavy ions because of the large energy and baryon densities obtainable over a relatively large volume.

Hyperons are expected to be a useful probe for the dynamics of hadronic matter under such extreme conditions. In particular, the onset of a Quark-Gluon Plasma phase during the collision is expected to enhance the hyperon yield [1] with respect to normal hadronic interactions. The enhancement is expected to be more marked for those hyperons (*eg* Ξ^- and Ω^-) which carry more than one unit of strangeness.

The detection of Ξ^- and Ω^- decays in heavy ion interactions is not easy because of the large event multiplicities. The WA85 experiment [2] was the first one to find Ξ^- and Ω^-; this work is being continued by the WA94 experiment [2]. The results are very encouraging. The WA85 results for S W interactions at 200 GeV/c per nucleon indicate not only that the ratios of Λ and $\overline{\Lambda}$ to pions are enhanced with respect to those in p W interactions [3], but also that Ξ^- and in particular $\overline{\Xi^-}$ production [4] are larger than is predicted by non-QGP models. Recently, the WA85 collaboration detected the Ω^- and $\overline{\Omega^-}$ signal in S+W 200A GeV/c interactions and measured the production ratio $\overline{\Omega^-}/\Omega^-$ at central rapidity and p_T>1.6 GeV/c [5].

The proposed experiment aims to extend the WA85 and WA94 studies to heavier projectiles, ie to larger reaction volumes, which should increase the likelihood for the onset of a phase transition from hadronic matter to QGP during the collision. In addition, it will use a larger phase space window than WA85, in particular covering lower transverse momenta, and will have a better acceptance for Ω^- detection..

We intend to measure the hyperon and charged particle spectra by using an array of silicon microstrips, silicon pads and pad cathode readout MWPCs located in the Omega magnet [6]. The same apparatus will also be used to measure proton and antiproton spectra in conjunction with the Omega RICH.

The principal challenge is to handle the large number of secondaries produced in central Pb Pb interactions. Our strategy is (*i*) to use a restricted kinematic window, which can be moved over the required phase space region, while retaining the advantages of low multiplicity in the detector elements and (*ii*) to have a setup capable of high event rates to get good statistics in our kinematic window.

The apparatus consists of a number of elements all currently under development, which will be tested prior to the start of the lead beam programme in October 1994 using 160 GeV/c proton beams. We expect the apparatus to be ready to take good physics data from the startup date for lead beams in November 1994.

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ANGULAR AND POLARIZATION CORRELATION COEFFICIENTS IN NEUTRON DECAY

Proposal 286

ILL, Sussex, Glasgow, Rutherford Appleton Laboratory

According to the Standard Model the weak decays of nucleons and pions derive from the coupling of a weak (V–A) hadronic current to the charged gauge bosons $W^{\pm}_{\mu}$, and are governed by two real coupling constants G_V (polar vector) and G_A (axial vector). A standard notation for the ratio of these coupling constants is $G_A/G_V = \lambda$. The vector current is conserved and G_V is related to the muon decay coupling constant via the CKM matrix element V_{ud} with appropriate radiative corrections. The axial current is not conserved and G_A is renormalized by the strong interactions. To determine G_A and G_V experimentally from nuclear beta–decay it is essential to eliminate the dependence on nuclear matrix elements. This requirement limits consideration to superallowed beta transitions within isospin multiplets. These are of two types; pure Fermi $0^+ \rightarrow 0^+$ transitions and decays of mirror nuclei of which the neutron proton doublet is by far the most important.

The current experimental situation is that G_A and G_V have been determined by combining data on pure Fermi decays (giving $G_V{}^2$) and the neutron lifetime (giving $G_V{}^2 + 3G_A{}^2$).[1] However only one of the two competing values for λ determined from measurements of the electron momentum/neutron spin asymmetry in polarized neutron decay is consistent with these data.[2] It is the objective of the present programme to resolve this conflict of evidence by measuring two other correlations in neutron decay which are functions of λ. These are (a) the electron–neutrino angular correlation 'a' which may be determined from both the one and the three dimensional spectrum of decay protons[3], and (b) the proton momentum/neutron spin asymmetry in polarized neutron decay. To measure the proton spectrum we propose to use a modified version of the Penning Trap used to measure the neutron lifetime[4]. The principal change in the trapping technique employed is the use of the apparatus as a proton spectrometer, applying the method of adiabatic collimation to determine the three–dimensional spectrum. To determine the proton asymmetry we use 99% polarized neutrons from a supermirror polarizer in combination with a spin flipper.

The present situation is that most of the required modifications of the original system have been completed, including the construction of a complete new trap and data–handling system, and detailed measurements of the magnetic field distribution for the measurement of the one–dimensional proton spectrum have been carried out. Because of delays in delivery the permanent magnet needed for adiabatic collimation in measuring the three–dimensional proton spectrum has yet to be installed. Both the new neutron counter and the on–site supermirror will be completed by the time the neutron beams became available at the ILL at the end of 1994. Two cycles of beam time (12 weeks) have been allocated to the programme over the period May–August 1995. To fit in with scheduling arrangements at the ILL, which mean that a polarized neutron beam will already have been installed and calibrated, it is anticipated that the proton asymmetry experiment will be performed first.

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CHARMED BARYON STUDIES IN THE CERN HYPERON BEAM

CERN WA89 proposal 287

Bristol University – CERN Geneva – Genova University/INFN – ISN Grenoble
Max-Planck-Institut Heidelberg – Heidelberg University – Mainz University
Lebedev Institute Moscow

Although considerable progress has been made in recent years, the study of baryons with charm has lagged behind the much greater wealth of data on charmed mesons. WA89 is designed to collect data on the production, the decays and the spectroscopy of charmed baryons.

WA89 uses the Omega spectrometer in the CERN West Hall, with a special hyperon beam. This provides 10^5 Σ^- and 2.5×10^5 π^- per spill (2.5 s) at 330 GeV/c. The experimental layout is shown in figure 1. The incident Σ^- are selected on-line by 10 modules of transition radiation detectors. The beam strikes targets of copper and diamond (and the silicon detectors). The vertex detector consists of 29 planes of either 25 or 50 μm pitch. Since we are interested in charmed baryons, we must recognise hyperons and also protons and neutrons in the final state. The decay region is equipped with 40 planes of drift chambers and 32 planes of MWPC. This allows the identification of the $\Lambda \to p\pi^-$ decay. Protons, kaons and pions are recognised in the RICH detector, after the Omega spectrometer. Finally, there is a lead-glass calorimeter for π^0 and γ measurement and a hadronic calorimeter for neutrons.

Data are recorded on 6 exabyte drives ($\approx$ 1400 triggers/spill) and analysed offline on a farm of DECstation computers. In 1993, we recorded 1.8×10^8 events and in this year's run we took another 3×10^8 events in the same experimental configuration. Data analysis is underway and is expected to be completed during the next year.

Some preliminary results, showing evidence for various decay channels of the Ξ_c and Ω_c baryons, are shown in figures 2 and 3.

Figure 1:

Figure 2

Figure 3

BABAR: PHYSICS AT THE SLAC B_FACTORY

High Energy Physics groups from 10 UK institutes[1] have joined the BABAR Collaboration at the SLAC B_Factory, and 30 PhD physicists from these institutes are looking to play a full role in the experiment. The UK involvement is targeted at the CsI calorimeter, where we are taking major responsibility for electronics, the mechanical construction of the endcaps and overall prototype evaluation, and the physics, where our simulation studies have made a significant contribution to optimising the detector for CP reach.

The primary aim of the experiment is to make precision measurements of CP violation in the weak decays of the B^0 meson with the specific target of measuring the angles α and β, and the side length V_{ub}, of the CP Unitarity triangle. Since the CKM matrix, from which the unitarity triangle results, has its origin in the coupling of the Higgs boson to the quark sector, this substantive test of the Standard Model goes beyond the measurements of the electroweak coupling constants made at LEP and complements the direct search for the Higgs boson, which forms the central plank of the future research programme for LHC. Should the predictions of the CP unitarity triangle in the Standard Model be falsified, our measurements will probe the new source of CP violation and may even shed light on the fundamental astrophysical question of the baryon-antibaryon asymmetry in the universe.

Three features of the SLAC experiment are crucial to these goals. First, the collision of the electrons and positrons is asymmetric in energy which results in a Lorentz boost to the produced Y(4S), with a measurable average separation between the vertices of the two decaying B mesons. Secondly, the detector is hermetic, covers a large fraction of the solid angle and gives rather complete information on all final states of interest. In particular, several independent measurements of the angles α and β will be made from the many decay channels studied, so that vital consistency tests are possible, thereby eliminating systematic errors and enabling a reduction in the overall statistical uncertainties on the measured parameters. Thirdly, the very high luminosity of the machine, crucial to the measurement of the CP-violating B decays, will allow the pursuit of a very detailed programme to study rare decays of Beauty, Charm and Tau mesons.

The decay of the Y(4S) produces a $\bar{B}^0 B^0$ pair in a coherent quantum state, and the symmetry of the wavefunction is only broken when one of the B's decays. Because of CP-violation, the decay distribution to a CP eigenstate is modified from its otherwise exponential form by the factor $\{1 \pm \sin(2\theta) \sin[\Delta m(t_1 - t_2)]\}$, where θ is an angle of the CP triangle. Measuring the asymmetry between the appropriate decays of the B^0 and $\bar{B}^0$ as a function of time thus allows a measurement of the angles of the CP triangle. Measurement of the relative decay time, or distance, is vital since the time-integrated asymmetry is zero.

One of the most important features of the detector, shown schematically in Fig 1, is the low-mass, silicon vertex detector. This comprises five planes of double-sided silicon wafers arranged in "lampshade" geometry to enable precise determination of the decay points of the B vertices along the direction of the Lorentz boost. The average separation between the vertices is about 250 μm, and the typical uncertainty in this distance is 100 μm. Because the information from events increases with vertex separation, the effect of this smearing of the

[1] Bristol, Brunel, Edinburgh, ICSTM, Lancaster, Liverpool, Manchester, QMW, RAL and RHBNC

decay distance is to reduce the precision on the measurement of CP angles by only 10 per cent. Given the relatively low momenta of the charged particles, minimisation of multiple Coulomb scattering is necessary to obtain high precision on the measurement of momenta, and hence great efforts are being pursued with regard to helium-based gases and aluminium, or metal-coated carbon, wires. The drift chamber will comprise 40 planes over a radial distance of 60 cm, and is situated in a uniform magnetic field of 1.5 T.

Charged-particle identification is necessary both for tagging one B, using $K^{\pm}$ and $\mu^{\pm}$, and also for identifying the final state from the decay of the other B. In this latter case it is particularly important to distinguish pions from kaons and identify the final states $\pi^+ \pi^-$ and $\rho^{\pm} \pi^{\mp}$ for the measurement of the CP angle α. The technique adopted by BABAR is novel, and uses a barrel made up of quartz bars, where Cerenkov light propagates down the bar by total-internal reflection to be detected at an array of photomultiplier tubes. The Cerenkov angle, directly related to the speed of the particle, maps onto the position of the PM detector.

A high quality electromagnetic calorimeter is of great importance not only in widening the channels available to measure β, but, more fundamentally, for the analysis of the $\rho\ \pi$ channel, crucial to the measurement of the angle α. Furthermore, in enabling the measurement of the $\pi^0\ \pi^0$ cross-section the Penguin contribution to the channel $\pi^+\ \pi^-$ can be calculated, thereby enabling a second high quality measurement of α. It is also essential for the analysis of the final states $\rho\ l\ \nu$ and $\omega\ l\ \nu$ for precision determinations of the CKM matrix element V_{ub}. The main feature of a calorimeter made from pointing towers of CsI(Tl) crystals is its excellent energy resolution; this is the key to good mass resolution of the reconstructed B final state, which is essential to discriminate against background. The experience of CLEO, and their reason for upgrading to CsI, is the improvement in the analysis of all rare decay channels which results from the high efficiency in detecting π^0's, and the precise energy measurements, which translate into the ability to obtain clean, well understood data samples.

Finally, a segmented flux return is necessary both for good muon identification for tagging and K_L identification to increase the CP reach of the detector. Resistive plate chambers are both efficient and relatively cheap to build and install, and fine segmentation will enable particle identification down to low momentum which will contribute greatly to the overall programme of physics.

The design of the detector is nearing completion, and it is hoped that approval will be obtained from the various funding agencies in the Spring of 1995. The target date for for beam into the detector is Spring 1999.

John R Fry
Liverpool 22/12/1994

88 CM RADIUS
DRIFT CHAMBER
-ELEVATION-
4653.31
1696.468
2395.0
IFR
IFR
1578.75
76.587
COIL CRYOSTAT
CAL CRYSTAL BARREL
0.526
1200.0
1480.0 CAL OR
1000.0 CAL IR
880.0 D.C. OR
225.0 D.C. IR
865.0
0.257
DRIFT_CHAMBER
980.0
900.0
365.0
210.8
0.262
0.494
Q6
Q4
Q2
Q1
Q1
Q2

The ALEPH Experiment

Annecy; Barcelona; Bari; Beijing; CERN; Clermont-Ferrand; Copenhagen; Demokritos; Ecole Polytechnique; Edinburgh; Firenze; Florida; Frascati; Glasgow; Heidelberg; Imperial College; Innsbruck; Lancaster; Mainz; Marseille; MPI Munchen; Orsay; Pisa; Royal Holloway College; Rutherford-Appleton Laboratory; Saclay; Santa Cruz; Sheffield; Siegen; Trieste; Wisconsin.

1 Introduction

This year a record number of Zs have been observed in the ALEPH experiment, thanks to a superb performance by the LEP machine and the smooth operation of the detector. To date this year, approximately 1.8M Z decays have been reconstructed from a delivered integrated luminosity of 61.6pb^{-1}, all at the peak of the resonance. The detector has operated at 90 % efficiency overall, with downtime due to apparatus failure being less than 5%. The remaining losses are due to 'dead time' in the data acquisition system and poor beam background conditions from LEP.

These statistics almost double the data sample accumulated since the beginning of LEP in 1989 to the end of running in 1993. These earlier data, after reprocessing, comprised 1.94M hadronic decays and 226K $\ell^+\ell^-$ decays of the Z and were made available to all analyses presented to the International Conferences at La Thuile, Moriond and Glasgow this year. For the latter, ALEPH contributed 48 written papers of which 19 contained completely new results, the remainder being updates of work presented or published earlier. Highlights of these analyses were prominent in the Conference summary talk given at Glasgow and some of them, where UK participation is significant, are described in this report.

2 Experimental Commitments

As in previous years, all the UK groups have continued their apparatus maintenance responsibilities, namely for the Electromagnetic Calorimeter Endcaps, the Inner Tracking Chamber, the Second Level Trigger, and parts of the TPC Laser System. More of this commitment is carried out by commuting physicists and technical personnel than before, but 6 physicists are based at CERN heavily involved in supporting this commitment and running the experiment. In addition, 5 senior UK physicists have acted as Run Coordinator during the year.

2.1 VME upgrade to the Data Acquisition System

On schedule before running commenced this year, high performance VME 68040 processors (FICs) were installed in place of the original customised Fastbus processors. The front-end signal digitisers remain in Fastbus, but all downstream data acquisition has been configured in VMEbus (Fig 1). Substantial software modifications had been prepared in advance, but the inevitable shakedown at the start of running in April caused some loss in data taking efficiency. However, the benefits of higher performance (deadtime halved) and reliability are already very apparent. All 'on-line' experts in the UK groups spent a major fraction of their time on this project in the past year. It is now expected that the DAQ and monitoring systems can be maintained with a smaller commitment of resources to the end of LEP.

2.2 New Vertex Detector (Glasgow, Imperial, Lancaster, RAL, Royal Holloway)

Primarily for LEP200 physics, the new VDET is designed to (a) improve the angular coverage for inner tracking, (b) reduce material thickness and improve its uniformity, and (c) enhance the radiation hardness of the on-detector electronics compared with the existing detector which was installed in 1990. The construction of this detector is now underway, with the UK groups being responsible for the readout and front-end electronics, the wire bonding of half of the 48 Silicon modules, and the upgrading of the DAQ software. The detector is due for completion in March 1995. After careful evaluation, the RAL designed MX7 multiplexer chip was chosen in favour of the 'Viking' from MPI, Munich on the grounds of the proven radiation hardness of the selected HARRIS processing. Results from the test beam at CERN and radioactive source measurements at Imperial show that the signal to noise performance is satisfactory reaching 18:1 even on the z side of the detector where the strip capacitance is larger. However, most of the early wafers , delivered from HARRIS, suffered from poor process control of the gate oxide layer leading to unacceptable variations in the threshold voltages required. This problem is now being corrected, and is not expected to significantly delay the project. Two automatic bonding machines have been upgraded at RAL for this and other work to proceed in parallel, and preparations have been made for extensive tests of the completed modules at Imperial and Glasgow prior to their incorporation into the final detector at CERN.

3 Physics Analyses at LEP100

These analyses are organised in 5 areas, namely electroweak physics (couplings of the Z), τ physics (decays and polarisation), QCD including $\gamma\gamma$ interactions, Searches and Heavy Quark physics. The latter topic has been subdivided into (i) properties of the b hadrons and (ii) the electroweak couplings of b quarks to the Z. Two senior UK physicists have been involved in the coordination of these groups for several years. In addition, one of them is a member of the Editorial Board which oversees the publication of all papers. Selected results are described below where there has been significant UK involvement:

3.1 Heavy Quark physics

Experimental determination of the electroweak couplings of the heavy quarks (b and c) to the Z enable some of the most sensitive tests to be made of the Standard Model. The basic experimental observables are the partial widths for decay of the Z to $b\bar{b}$ and $c\bar{c}$ and their respective forward-backward asymmetries. Accurate identification (tagging) of the heavy quarks from the uds quarks is required as well as unambiguous discrimination of the quark from the anti-quark direction. Unlike the light quarks, semileptonic decays of the hadrons containing b and c quarks produce prompt electrons and muons of high momentum, and also in the case of the b with high transverse momentum to the parent hadron. Although semileptonic branching ratios are only 10% per leptonic species, this property has been exploited extensively at LEP from the beginning. During the year ALEPH has published an in-depth study of the prompt lepton tagging method. This demonstrates quantitatively the excellent disciminating power of the detector against misidentifying hadrons as electrons or muons (typically 0.1% and 1% respectively) and the value of an accurate determination of the direction of quark jets using both charged and neutral particles in a balanced energy flow analysis. These methods have been applied to the analysis of hadronic events with either single or double-tagged prompt leptons, the results of which have also been published this year. In a global approach, it has been possible to extract from simultaneous fits to the (p, p_t) spectra, the branching ratios of the direct semileptonic decay of the b, the cascade decay via a charmed daughter , and the integrated mixing parameter χ, as well as the basic electroweak observables above. The Imperial group have played a major part in both of these publications.

The pseudoscalar B meson is not necessarily primordial in the fragmentation of the b quark to B hadrons. It can be produced by de-excitation of excited vector B mesons. The production rate of B^*s from Z decays is unknown, but might be expected to follow spin counting arguments which suggest that the fraction $F_{B^*} = V/(P+V) = 0.75$. Measurements from CLEO show that the mass difference $\Delta m(B^* - B)$ is less than the π mass and is thus detected only by its radiative decay. In a Lancaster analysis, an enriched sample of $b\bar{b}$ decays of the Z are selected by tagging events with charged tracks having significant impact parameters at the interaction point (called 'lifetime' tagging). Produced B^*s are flagged by the detection of low energy photons via their pair conversions where both the e^+ and e^- are reconstructed to obtain the best possible energy resolution. The candidate γ energy is then determined in the rest frame of the b-jet with which it is associated. This gives Δm directly. Fig 2 shows such an energy spectrum accumulated from all available data. A peak is clearly visible on top of the background which is well simulated from known hadronic decays. The resulting value of Δm is $46.5 \pm 7.5 MeV/c^2$ in good agreement with the CLEO value. From the yield of B^*s found , the fraction F_{B^*} is $85 \pm 6\%$ consistent with the simple arguments above. A search is also being made, with the participation of an Imperial student, for B^{**}s decaying to $B\pi$; where the B is observed via the exclusive channel $D^*\ell\nu$. Structure is seen in the mass distribution of the $B\pi$ system with a narrow peak at 5.9 GeV and a broader peak at 5.6 GeV; which can be explained as arising from single π and double π decays of the B^{**} respectively where one π is missing in the latter case. However, soft πs from D^*s may be a significant background. This problem is under study.

A new result presented to the Glasgow conference by an Imperial physicist, who has led the analysis, is a more precise measurement of the Λ_b lifetime. It is based on event

by event reconstruction of its decay vertex into $\Lambda_c^+\ell^-\bar{\nu}_l$ followed by $\Lambda_c^+ \rightarrow pK^-\pi^+$ decay. From a data sample of 1.6M hadronic Z decays, 31 $\Lambda_c^+\ell^-$ candidate combinations are found of which 23.8 ± 5.6 are attributed to the above decay chain. Fig 3a shows the $pK^-\pi^+$ effective mass for opposite sign Λ_c^+ lepton combinations from which the mass is found to be $2.280 \pm 0.003 GeV/c^2$. Fig 3b shows a Maximum Likelihood fit to the proper time distribution of these opposite sign events in the peak region from which the lifetime is determined to be $1.06^{+0.40}_{-0.27}(stat.) \pm 0.07(syst.)ps$.

3.2 QCD and $\gamma\gamma$ physics

The range of physics topics in this area has grown appreciably within ALEPH in the last two years, such that it accounted for approximately 1/3 of all papers submitted to the Glasgow conference from the Collaboration. All UK institutes participate in this field and five of them played leading roles in six of the papers submitted to the conference. In most cases, the results presented are close to publication and represent the culmination of several years work.

One of these, a first in $\gamma\gamma$ physics, was the measurement of the inclusive rate of D^{*+} production performed by the Lancaster group. For this process at high energy, QCD predicts that charm quarks are produced mainly by photon-gluon fusion where the gluon comes from a 'resolved' photon. Thus the fraction of time that a photon contains a gluon can be determined from the differential cross section . The measurement technique exploits the fact that the strong decay of the $D^*(2010)$ to a $D^0(1864.5)$ is just possible kinematically by the emission of a single pion. Thus, the reconstructed mass difference (ΔM) should show a narrow peak 6MeV above the π mass for correctly signed $D^0\pi$ combinations. Fig 4 shows a clear peak at $\Delta M = 0.15$ GeV as expected, from which the cross section and energy spectrum of the produced D^*s can be derived. The predictions of a QCD model which includes the effect of the gluon content of the photon compare well with the data. Further studies of $\gamma\gamma$ interactions are in progress led by Lancaster and Sheffield using new untagged and tagged triggers.

Although the properties of hadronic Z decays to quark pairs are well understood , the dynamics of the consequent multi-particle production are not. One particularly simple observable which contains information on this hadronisation process is the charged particle multiplicity distribution. Subdivided into intervals of rapidity, the restraints of kinematics and charge conservation are reduced and the distributions then become more sensitive probes of the different models. Such a study was submitted to the Glasgow Conference in which the Royal Holloway group have played a significant part. Using a sample of 300,000 hadronic Z decays, three rapidity intervals were selected, corresponding to narrow ($\mid Y \mid \leq 0.5$, medium ($\mid Y \mid \leq 2.0$, and full unrestricted intervals. In each case, the data are compared with (a) two parton shower models: JETSET and HERWIG and (b) two parametrisations : the negative binomial distribution (NBD) which originated in the UA5 Collaboration and the log-normal distribution (LND) which is derived from the assumption that particles are produced by a parton branching process which is stochastic. Fig 5 shows their comparison with the data in each interval. The NBD consistently fails everywhere, whereas the LND has difficulty only in the medium interval case in accounting for a 'shoulder' observed near multiplicities of 15. This is thought to be due to multi- jet effects (ie: hard gluons) which are non-stochastic. The parton showers models do better, with JETSET providing the most detailed agreement.

These studies are continuing with the aim of measuring the charged multiplicities of the $Z \rightarrow uds$ and $Z \rightarrow b\bar{b}$ events separately using the microvertex detector (VDET).

The remaining four topics presented have been described in previous annual reports, but have been worked on extensively in the past year to produce new results with improved systematic errors. In the first of these, the Edinburgh, Glasgow and Imperial groups have continued to refine their study of the comparison of jets originating from either primary quarks or hard gluon emission. The Imperial group concentrated on using 'lifetime' tagging with the microvertex detector to identify b quark jets in events consisting of three jets in a symmetric topology. This pattern ensures that the most energetic jet is a quark jet with very high purity, simplifying the identification of the other two almost equal energy jets with the tagging algorithm. The remaining untagged jet is defined to be a gluon jet. Final results presented show that gluons fragment into more, less well collimated particles than quark jets, a trend accurately followed by the parton shower models. The second topic has been a long standing study of the fragmentation functions of identified charged particles carried out by a Glasgow Research Associate alone. His analysis now includes, for pions, kaons and protons separately, a demonstration of the coherence of soft gluon emission manifested as a peak in their so-called $\xi = ln(1/z)$ distributions. The location of this peak can be calculated in perturbative QCD and will vary with CM energy and particle mass. An effective scale parameter Λ is extracted for each particle type after fitting the evolution of the peak position in the data from this experiment and others to the QCD calculation. The third topic presented was the first measurement of the quark-to-photon fragmentation function carried out at LEP. This work has been a collaboration between the Glasgow and RAL groups alone. Hard photons, radiated from the final state quarks in Z decays, are separated from non-prompt hadronic backgrounds to produce a photon fragmentation function ($D(z)$), where z is the fractional energy of the photon within its own hadron jet. Using a QCD formalism at lowest order developed by Glover et al at Durham University, the non-perturbative component in the D function is extracted and found to be a simple constant independent of z when the mass cut-off for the perturbative evolution term is set to 200 MeV, close to $\Lambda_{\overline{MS}}$. This simple ansatz for the non-perturbative component is not understood, but it does provide a better prescription for quark bremmstrahlung within this LO QCD formalism. The fourth topic was an updated measurement of the inclusive production of η and η's performed by an RAL physicist. The final result for η's confirms that the JETSET prediction is too large by a factor of four.

In addition to these submissions to the Glasgow conference, work is progressing on other studies. The Sheffield group have been focussing on the inclusive production of light vector mesons (ω and ϕ) in hadronic Z decays as well as quark and gluon jet properties. The vector meson cross sections cannot be predicted by perturbative QCD, but resonant states such as the ϕ are quite interesting since they are produced more often than the lighter hadrons directly from the parton 'string' rather than decays of hadrons. The multiplicity of ϕs per event is found to be 0.122 ± 0.009 in the range $0.005 < x_\phi < 1.0$ in good agreement with HERWIG predictions, whereas JETSET is high by 50%. Fig 6 shows preliminary results from ALEPH compared with other experiments and these parton shower models.

3.3 Searches at the Z

The Royal Holloway group continue to lead the UK effort in this area of physics. Following on from a long standing search for excited quarks and leptons by radiative decays, a search has been made for the radiative decay of the Z to a scalar particle, S, which would occur if both particles consisted of the same preonic constituents. If the effective constituent mass is in the Tev range and they are colourless, then the width of the S with a mass below the Z would be a few MeV. In these circumstances, the theoretical width is less than the experimental invariant mass resolution of the detected fermion pair into which it would decay. Based on a sample corresponding to 1.1M Z decays, branching ratio product limits: $Br(Z \rightarrow S\gamma) \times Br(S \rightarrow f\bar{f})$ were given to the Glasgow conference for masses up to 88 GeV/c^2. They are less than 10^{-5} in the leptonic channels and less than 10^{-4} in the hadronic channels, over most of this range, which is a substantial improvement over earlier published results.

In another search for compositeness in leptons, the Sheffield group have led a new study of the reaction $e^+e^- \rightarrow \gamma\gamma$ with all the statistics available up to the end of 1992. This process is expected to be pure QED with negligible weak corrections even at the Z mass. If the electron is composite , then there would be a form factor correction to the QED predicted cross section of the form:

$$F(q^2) = 1 \pm q^4/\Lambda_\pm^4$$

where the Λs are the so-called QED cut-off parameters which set the limits of the theory. Using 1552 good events, a fit is made to the polar angular distribution from which limits at 95% confidence level can be set on the minimum values of Λ_+ and Λ_- separately. Fig 7 shows (a) the observed angular distribution and (b) its ratio to the predicted cross section for the limiting values of these parameters of about 145 GeV.

The Lancaster group have been searching for the decay of the Z to virtual W pairs. The purpose is to look for anomalous bosonic couplings of the Z which would be a signature for new physics. The highest possible statistics are required, so final results will not be quoted until the 1994 data is included.

4 ALEPH Publications since last year's report:

1. Correlation measurements in $Z \rightarrow \tau^+\tau^-$ and the τ neutrino helicity
   Phys. Lett. B321 (1994) 168-176

2. Production of charmed mesons in Z decays
   Z. Phys. C62 (1994) 1-14

3. Measurement of the B_s^0 lifetime
   Phys. Lett. B322 (1994) 275-286

4. An investigation of B_d^0 and B_s^0 oscillations
   Phys. Lett. B322 (1994) 441-458

5. Heavy flavour production and decay with prompt leptons in the ALEPH detector
   Z. Phys. C62 (1994) 179

6. Heavy quark tagging with leptons in the ALEPH detector
N. Inst. Methods A346 (1994) 461-475

7. Z production cross sections and lepton pair forward-backward asymmetries
Z. Phys. C62 (1994) 539

8. One-prong τ decays into charged kaons
Phys. Lett. B332 (1994) 209-218

9. K_0 production in one-prong τ decays
Phys. Lett. B332 (1994) 219-227

10. Search for contact interactions in the reactions $e^+e^- \to \ell^+\ell^-$ & $e^+e^- \to \gamma\gamma$
Z. Phys. C59 215-229 (1993)

11. A measurement of A^b_{FB} in lifetime tagged heavy flavour Z decays
Phys. Lett. B335 (1994) 99-108

12. Observation of monojet events and tentative interpretation
Phys. Lett. B334 (1994) 244-251

5 International Conference Presentations by UK Physicists

M Cattaneo	'Hadronic decays'	Sept '93	Pavia Conf. on HFs
JC Thompson	'$Q\bar{Q}\gamma$	Mar '94	QCD, Moriond
L Moneta	'Λ_b lifetime	July '94	ICHEP94, Glasgow
A Moutoussi	'QCD at LEP'	Sept '94	τ workshop, Montreux

6 Ph Ds awarded in the past year:

Edinburgh

M. Parsons ' Quark and Gluon Jets at LEP'

Glasgow

W. Maitland 'Quark and Gluon Jets from Z Decays produced by e^+e^- Interactions at the LEP Collider'

Lancaster

D. Jackson 'Lepton Flavour Violation and Charm Production in Gamma- Gamma collisions'

Sheffield

M. Griffiths 'Weak Boson Interactions and the Effect of Compositeness'

TPDs
FVSBI
STPC
TSR
TPC
ECAL
HCAL
ITC
SAMB
BCAL
SCAL
BOM
VDET
LCAL
LVL1
LVL2
SD
µVax
Q
Key to symbols
VIC
FIC+LDA implies FVSBI
FIC
FIC+TS
HVR+ODI
underground
400m fibre optics
surface
BI
BI
VAX8700
VAX6510

Fig 1

(a)
Data
MC background
350
300
250
200
150
100
50
0
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
$M_{B^*} - M_B$ (GeV/c²)

(b)
χ²/ndf 32.39 / 33
P1 489.6 ± 43.91
P2 0.4646E−01 ± 0.7497E−03
P3 0.6791E−02 ± 0.5856E−03
150
100
50
0
−50
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
$M_{B^*} - M_B$ (GeV/c²)

Fig 2

Fig 3a

The $pK^-\pi^+$ effective mass for (a) same sign and (b) opposite sign Λ_c^+ lepton correlation.

Fig 3b

Result of the extended maximum likelihood fit to the proper-time distribution of opposite sign $\Lambda_c^+ l^-$ events in the Λ_c^+ peak region

. On the top is shown the distribution of ΔM for the data compared to Monte Carlo events and background events. The peak in the data at $\Delta M = 0.15$ is evidence of D^* production. The lower plot shows the energy of the D^* divided by the total energy in event. The shape is well described by the QCD model which includes the effect of the gluon content of the photon.

Fig 4

Unfolded charged particle multiplicity distributions for the small ($|Y| \leq 0.5$), medium ($|Y| \leq 2.0$) and full rapidity window compared to the prediction from JETSET and HERWIG (left side) and best fits to the negative-binomial and log-normal distributions (right side).

Fig 5

Comparison of overall ϕ rate with other experiments.

Fig 6

Fig 7a

Predicted and observed Born cross-section as a function of $\cos\theta$

Fig 7b

95% confidence level limits on the QED cut-off model

THE OPAL EXPERIMENT AT LEP

PROPOSAL 720

Aachen; Alberta; Birmingham; Bologna; Bonn; Brunel; California (Riverside); Cambridge; Carleton; CERN; Chicago; CRPP Canada; Duke; Freiburg; Hamburg/DESY; Heidelberg; Indiana; Manchester; Maryland; Montreal; Oregon; Queen Mary and Westfield College, London; Rutherford Appleton Laboratory; Saclay; Technion; Tel Aviv; Tokyo; University College/Birkbeck College, London; Vancouver (UBC); Victoria; Weizmann Institute.

INTRODUCTION

The LEP machine has operated very successfully during 1994, delivering an integrated luminosity of more than 1pb-1 in a 24 hour period on several occasions, and 5pb-1 in a 7-day period. An important development has been the measurement of beam polarisation under the conditions of physics collisions. This will enable the already impressive precision on the knowledge of the beam energy, and hence the Z^0 mass, to be further improved.

OPAL has made full use of the excellent accelerator performance, and by mid-October more than 1.8M Z^0 events had been recorded in 1994, adding to the total of 2.3M accumulated in the previous 4 years. In June OPAL celebrated the submission for publication of its 100th physics paper, becoming the first of the LEP experiments to reach this milestone.

DETECTOR OPERATION

Barrel Muon Detector

The Muon Barrel chambers, for which Manchester is responsible, have run efficiently throughout the OPAL data taking periods. Virtually all the chambers are working well, and the designed 4-layer redundancy takes care of the handful that are not. Keeping the hardware running smoothly and efficiently requires continual monitoring of the HV and gas systems and readout diagnostics. A crucial task for the succeeding years is to ensure that this record of reliability and high performance is maintained.

End Cap Muon Detector

The University of Birmingham streamer chamber arrays at the two ends of OPAL have continued to operate with good efficiency at LEP during 1994.

During the 1993/1994 shutdown some significant upgrades were made to the Data Acquisition System. To improve the monitoring capability and to reduce the readout deadtime, more powerful processors (MVME 167s) were added to all of the three Readout System Crates, and a new front-end VME interface was installed. At the same time the software was translated from assembler into C code. This will simplify any

future software modifications and simplifies interaction with the system. As a result of these changes the readout deadtime has been reduced from 5.5 msec to about 4.2 msec.

There seems to be no indication of any fall off in detector efficiency after 5 years of operation, and no streamer units have had to be disconnected during this year. In all only 1% of the streamer units have been disabled and this occurred mainly during the commissioning stages. Some of these have been reconnected and run at a lower HV.

Vertex Drift Chamber & Track Trigger

The precision Vertex Drift Chamber and the Track Trigger, both responsibilities in the UK of the Cambridge, QMW and RAL (Electronics) groups, have continued to operate with good efficiency. The chamber provides (r-ϕ) co-ordinates with a precision around 50 μm, as well as z co-ordinates with $\sigma(z)$ around 700 μm from stereo wires. The track trigger processor forms an essential part of the OPAL event trigger for both 8 bunch and bunch-train operation of LEP.

End Cap Electromagnetic Calorimeter

The End Cap Electromagnetic Calorimeter, consisting of 2264 instrumented lead glass blocks, is the responsibility of RAL together with Cambridge and QMW. The calorimeter is a crucial component of OPAL, both at the trigger and reconstruction level. It has continued to perform extremely reliably throughout the 1994 run.

During the 1993/94 LEP winter shutdown the opportunity was taken to perform maintenance on one of the endcaps. In the course of this work a long standing problem which caused the gain of a few channels to drift with time (albeit tracked by the monitoring system) was identified and cured.

This year, as in previous years, Bhabha scattering events have been used to check and, where necessary, improve the calibrations of individual detectors. Results from this work show that the absolute calibration of the calorimeter has been stable to within $\pm 0.1\%$ over the last four years, indicating that ageing effects (such as radiation damage of the glass) are negligible.

LEP operation with 4-trains of 4 bunches spaced by 250 ns, foreseen for 1995, will result in the calorimeter response falling by up to 5% depending on which bunch in the train is responsible for a given event. The necessary correction factors will be established using the LED and laser monitoring systems well before the start of the 1995 run.

Forward Detector

The Forward Detector, components of which are the responsibility of UCL, Brunel and Birkbeck, has continued to run as a tagger for two photon physics and to contribute to the selection of hadronic events. The performance of the Gamma-Catcher, which covers the gap between the Forward Detector and the End Cap Electromagnetic Calorimeter, has improved and better calibrations have been obtained, now that earlier noise problems have been diagnosed and cured.

UPGRADE PROJECTS

The Silicon Microvertex Detector

The Silicon Microvertex Detector project was the first upgrade of OPAL and has since 1991 (Phase I) provided the highest precision component of the OPAL inner tracking. The project was initiated and led by the Cambridge and QMW groups. The two university groups developed the OPAL silicon microstrip devices, which use a new FoxFET biasing technique, in association with Micron Semiconductors Ltd (UK), who have manufactured them.

The improved detector (Phase II), installed in March 1993, again uses FoxFET biased single-sided microstrip wafers, 250 μm thick, but in an orthogonal back-to-back configuration to provide both (r-ϕ) and z co-ordinates, with precisions of between 5 and 10 μm. Excellent signal to noise ratios of better than 20:1 are again obtained.

Cambridge and QMW physicists continue to be responsible for the necessary DAQ software, off-line reconstruction of data, Monte Carlo simulation and software alignment. More than half the OPAL publications in the last year have been dependent on data from the detector and Cambridge and QMW physicists have played a major role in many of these analyses.

A final upgraded detector (Phase II) was approved last year. This involves using the present devices, where each detector ladder consists of 3 daisy-chained silicon wafers, joined end to end with new 2-wafer ladders of similar construction. The microstrip readout is then taken from both ends of the complete system, and the new geometry therefore has an extended θ coverage, coming from the increased length (180 mm to 300 mm), and almost complete ϕ coverage, achieved by overlapping ladders of the detector through including one more in each layer (inner from 11 to 12, outer from 14 to 15).

This system is now under construction, and the UK contribution to the project has been strengthened by the addition of electronic engineering and technical support from Birmingham, and technical support from UCL. Work is also underway to repair damage caused to the present detector by a failure of the cooling system in October 1994.

Silicon-Tungsten Luminosity Monitor

The UK groups (UCL, Birmingham, RAL) all contributed to the construction and commissioning of the Silicon-Tungsten Luminometer. Its performance in 1993 was markedly better than that of the existing Forward Detector, with experimental systematic errors of 0.7 parts per thousand on absolute luminosity. This feeds directly into measurements of the number of neutrino types, and is an important part of the measurement of the total and partial widths of the Z^0. Calibration data obtained from test beam running in 1994 will allow a further reduction in the systematic error on the luminosity measurement. This is now dominated by the uncertainty on the theoretical calculation of the Bhabha Scattering cross section.

PHYSICS ANALYSIS

The UK groups have maintained their central position in the physics analyses of OPAL data across a broad range of topics, and some highlights are summarised below.

Precision Electroweak Physics

The OPAL results from the 1993 data taken in the high precision scan around the Z^0 were submitted to the Glasgow ICHEP conference and will be published shortly. Including data taken in previous years, these results are based on a total number of 227,000 leptonic and 1,840,000 hadronic Z^0 decays. Significant improvements in the accuracy of measurements of $M_Z = 91.1862 \pm 0.0054$ GeV/c^2 and $\Gamma_Z = 2.4946 \pm 0.0061$ GeV/c^2 are obtained. The lineshape and lepton pair forward-backward asymmetries are consistent with the predictions of the Standard Model and within this model yield the constraints $M_t = 144^{+24}_{-28}{}^{+18}_{-17}$ GeV/c^2 and $\alpha_s(M_z^2) = 0.133 \pm 0.008 \pm 0.002$.

The Manchester group has maintained its strong activity in the analysis of the Z^0 lineshape and lepton pair forward-backward asymmetries. In the past year, members of this group have contributed to the estimation of the systematic errors in the selection of $Z^0 \rightarrow \mu^+\mu^-$ and $Z^0 \rightarrow \tau^+\tau^-$ events, the inclusion of endcap $e^+e^- \rightarrow e^+e^-$ events into the electroweak fits, studies of events consisting of four final-state fermions and the work of the LEP energy working group. A Brunel student was responsible for a large part of the analysis of the $Z^0 \rightarrow \mu^+\mu^-$ channel and, in particular, provided many detailed checks of systematic errors and biases in the asymmetry analysis.

$\Gamma_{b\bar{b}}$ has now become one of the important components in Standard Model fits. The 'double tagging' technique combining both vertex and lepton tagging has been shown to be a powerful method for selecting $Z^0 \rightarrow b\bar{b}$ events. The vertex tagging component which dominates the precision is the responsibility of the Cambridge group. Using both 1992 and 1993 data, OPAL has published the result $\Gamma_{b\bar{b}}/\Gamma_{had} = 0.2171 \pm 0.0021 \pm 0.0021$, which is currently the most precise determination at LEP (see Figure 1).

The UCL group has continued its involvement in the OPAL electroweak work by providing an independent fit analysis, whereby the cross-sections, asymmetries and important correlations are fully taken into account when extracting the electroweak parameters. New fits to the lineshape and asymmetry data have been used to measure the ε parameters which separately parametrise the corrections to the lowest order electroweak diagrams due to Standard Model effects (primarily top quark and Higgs) and effects from beyond the Standard Model. Work done at UCL has established this technique on the 1993 data, where no significant violation of the Standard Model is seen, and it is ready for use on the larger quantities of data from 1994 and 1995 running. The UCL and Brunel groups have also developed a new analysis to search for the possible presence of an extra high mass neutral gauge boson. A Z' could manifest itself through direct exchange, interference with the standard Z^0 or by mixing, resulting in a modification of the values extracted from the fits. Mixing angles of the order of 10 mrad have so far been excluded and this represents a substantial improvement over previous results.

b Quark Physics

The UK groups have continued to play a leading role in b quark physics. A number of new results were presented at the ICHEP conference in Glasgow and the DPF conference in Albuquerque.

QMW has been entirely responsible for measurements of charm meson production in semileptonic B hadron decays. The following branching ratios were obtained :

$$B(b \to D^+\ell X).B(D^+ \to K^-\pi^+\pi^+) \qquad (1.93 \pm 0.22 \pm 0.14)10^{-3}$$
$$B(b \to D^0\ell X).B(D^0 \to K^-\pi^+) \qquad (2.49 \pm 0.14 \pm 0.18)10^{-3}$$
$$B(b \to D^{*+}\ell X).B(D^{*+} \to D^0\pi^+).B(D^0 \to K^-\pi^+) \qquad (7.41 \pm 0.46 \pm 0.61)10^{-4}$$

Combining these results with those from the Y (4s) implies that $0.83 \pm 0.07 \pm 0.10$ of all b quarks fragment to a B^0 or B^+ meson.

The QMW group also searched for narrow P-wave charmed mesons in semileptonic B decays. Using the decay channels $D_J^0 \to D^+\pi^-$, $D_J^0 \to D^{*+}\pi^-$ and $D_J^+ \to D^0\pi^+$, total signals of $44 \pm 8^{+3}_{-7}$ D_J^0 and $48 \pm 10^{+3}_{-6} D_J^+$ events were observed (see Figure 2). This is the first evidence for semileptonic B decays to charged P-wave charm states and the first measurement separating the pseudovector and tensor components. Together, these modes are estimated to make up $34 \pm 7\%$ of charmed semileptonic B^0 and B^+ decays.

In addition, the QMW group has observed a signal of 423 ± 71 events in the channel $\Lambda_c^+ \to pK^-\pi^+$. First measurements of the production rates

$$f(b \to \Lambda_c^+X).B(\Lambda_c^+ \to pK^-\pi^+) \quad (0.48 \pm 0.12 \pm 0.05)\%$$
$$f(c \to \Lambda_c^+X).B(\Lambda_c^+ \to pK^-\pi^+) \quad (0.33 \pm 0.15 \pm 0.08)\%$$

have been obtained. When combined, these give a total rate of:

$$\Gamma(Z^0 \to \Lambda_c^+X).B(\Lambda_c^+ \to pK^-\pi^+)/\Gamma_{had} = (0.322 \pm 0.049 \pm 0.039)\%.$$

QMW is extending the study of charm hadron production in Z^0 decays by including the D_s^+ final state.

Searches for rare decays of B hadrons into two charged particles have been performed by Cambridge using 2 million hadronic Z^0 decays. Such decays include contributions from flavour changing neutral-current processes such as hadronic penguin decays. No excess of events has been observed in the invariant mass distributions and upper limits (90% C.L) have been set on branching ratios as follows :

$$B(B_d^0 \to \pi^+\pi^-) < 4.7 \times 10^{-5} \quad \text{and} \quad B(B_d^0 \to K^+\pi^-) < 8.1 \times 10^{-5}$$
$$B(B_s^0 \to \pi^+K^-) < 2.6 \times 10^{-4} \quad \text{and} \quad B(B_s^0 \to K^+K^-) < 1.4 \times 10^{-4}$$

The B_s^0 limits are the first obtained. Other topics under study in Cambridge include the measurement of $b \to J/\Psi$ decays and the tagging of B_s mesons using D_s-lepton correlations.

The Cambridge and QMW groups have updated their measurements of the B^+ and B^0 lifetimes to include data collected in 1993, giving preliminary results of $1.62 \pm 0.10 \pm 0.10$ ps and $1.53 \pm 0.14 \pm 0.11$ ps respectively. The measured ratio of $0.94 \pm 0.12 \pm 0.07$ confirms expectations that the lifetimes are similar.

Manchester is contributing to the measurement of the forward-backward asymmetries for b-quarks. In particular, the use of a neural network for determining jet charges has been investigated. The Birmingham group is measuring the inclusive Λ production rate in $Z^0 \to b\bar{b}$ events identified by a vertex tag.

A Birmingham physicist leads the working group on $B^0 - \overline{B}^0$ oscillations. Observations have been made of the time-dependence of B_d^0 oscillations in three independent channels (see Figure 3), of which two are published and the third is preliminary. Combining the three channels, we obtain $\Delta m_d = 0.520 \pm 0.054 ps^{-1}$, where Δm_d is the mass difference between the two B_d^0 mass eigenstates. In addition, a preliminary lower limit on the B_s^0 oscillation frequency has been obtained, $\Delta m_s > 1.3 ps^{-1}$ at 95% confidence level, using dilepton events.

τ Physics

The RAL group continues to be active in the measurement of τ branching ratios. The work on the topological branching ratios performed in collaboration with Birmingham and on the exclusive branching ratio $\tau \to 3h\nu_\tau$ is now complete. A first measurement within OPAL of the τ polarisation in the difficult $\tau \to a_1\nu$ channel is well underway.

The τ leptonic branching ratios have been measured by the Birmingham group. Using 1991 and 1992 data, they obtained the preliminary results $B(\tau \to e\nu\bar{\nu}) = (18.14 \pm 0.20 \pm 0.28)\%$ and $B(\tau \to \mu\nu\bar{\nu}) = (17.48 \pm 0.18 \pm 0.23)\%$ as presented at the 3rd Workshop on Tau Physics in Montreux. These have been used together with other properties of the μ and τ to demonstrate lepton universality at the 1% level.

The QMW group in conjunction with Canadian colleagues updated the OPAL measurement of the τ lifetime using both 1992 and 1993 data. The new published result is $\tau_\tau = 288.8 \pm 2.2 \pm 1.4$ fs and represents the most precise determination of the τ lifetime to date. Assuming e-μ universality and combining with measurements of the τ semileptonic branching fractions, this gives the ratio of charged-current couplings, g_τ/g_μ, as 1.005 ± 0.007. This is in agreement with the hypothesis of τ - μ charged-current universality.

QCD

The longitudinal and transverse fragmentation functions for the process $e^+e^- \to h + X$ have been separated and measured by Cambridge using 1.17 million events (22 million charged tracks). Comparisons have been made with QCD predictions and the measured value of the longitudinal cross-section $\sigma_L/\sigma_{tot} = 0.067 \pm 0.008$ lies about one standard

deviation above the expectation of the JETSET parton shower model. This is considerably above the $\vartheta(\alpha_s)$ QCD prediction of 0.038 ± 0.002 due to hadronization and higher-order perturbative effects. The gluon fragmentation function has been extracted from the transverse and longitudinal functions. This offers a complementary approach to other methods.

A cone-based jet finding algorithm has been developed and applied to hadronic events by the Cambridge group. This has enabled comparisons to be made with jets from $\bar{p}p$ collisions as well as the more conventional jetfinders in e^+e^- physics. New measurements of $\alpha_s(M_{Z^0})$ have been made which are both compatible and competitive with previous techniques. Jets in e^+e^- collisions were found to be significantly narrower than those observed in $\bar{p}p$ collisions. The main contribution appears to arise from differences between quark and gluon induced jets.

In another study, at Cambridge, the dependence of event shape cross-sections on the QCD structure constants has been investigated. The measured values of the structure constants extracted from the fits were found to be consistent with standard QCD based on SU(3) and five active quark flavours (see Figure 4). This new technique complements the conventional method based on 4-jet events, and has the advantage of accounting for some higher-order effects.

The RAL group has extended the study of isolated energetic photons in hadronic events to include the end-cap regions of the detector. Monte-Carlo models based on matrix elements have shown good agreement with data in predicting event shapes. The extraction of the quark electroweak couplings from the measured photon yields remains a longer term goal. An analysis of photons produced within jets in hadronic events has also been started at RAL.

In the field of non-perturbative strong interactions, Manchester is responsible for the co-ordination within OPAL of measurements of inclusive particle production and fragmentation. Measurements made in Manchester of the production of the strange vector mesons $\phi(1020)$ and $K^*(892)^0$ in hadronic Z^0 decays have been updated to use data from 1990-1992, were submitted to the Glasgow conference, and will be published shortly. A measurement of the production rate of the tensor meson $K_2^*(1430)^0$ was also presented and this represents the first observation of a strange tensor meson at LEP. The position ξ of the peak in the distribution of $\ln(1/x_p)$ for $\phi(1020)$ and $K^*(892)^0$ has been measured and compared with measurements from other species of hadrons (Figure 5). In the framework of the modified leading log approximation, the ξ values are expected to depend only on the mass of the produced hadron, but OPAL measurements have suggested that baryons and mesons lie in two separate bands. It has been shown that this apparent discrepancy is probably due to the production and decay of higher mass resonances.

In Manchester, the production of $\phi(1020)$ and $K^*(892)^0$ in gluon jets is also being investigated. Another long standing interest has been the residual effects of Bose-Einstein correlations on the mass spectra of unlike-signed pairs of hadrons. An understanding of these effects is necessary before a reliable measurement of the production of the ρ^0 meson can be performed.

$\gamma\gamma$ Physics

The UCL analysis of the photon structure function for OPAL was the first to be performed at LEP. As a second stage to the analysis, the unfolding of the true Bjorken x distribution has now been done on a logarithmic scale which refines the measurement at low x values - extending into a region which lower energy experiments could not reach. Down to x values of 0.01, there is no sign of any rise in the photon structure function. This has already ruled out a number of theoretical models. Results from LEP II are eagerly awaited, where the reach in x will be sufficient to see whether the photon has a rise in the same region of x as the rise seen in the proton structure function at HERA.

Work is also in progress at RAL to measure F_2^γ using end-cap tags and thereby extend the Q^2 range to 150 GeV^2.

Higgs Searches

UCL have been in charge of the search for Higgs events with a recoiling muon or electron pair. They have found what is probably the best candidate yet seen at LEP (Figure 6); an event which passes the $Z^* \rightarrow \mu^+\mu^-$ selection criteria with one well resolved beauty decay vertex. However, four-fermion production gives rise to an irreducible background in this channel which, for masses above 50 GeV/c^2, is estimated to be 0.3 ± 0.1 events.

LEP2 Physics

Preparations for LEP2 physics have started, with work in Cambridge on the measurement of the $W^\pm$ mass based on both the $W^+W^- \rightarrow q\bar{q}q\bar{q}$ and $W^+W^- \rightarrow q\bar{q}\ell\nu_\ell$ channels.

OPAL PUBLICATIONS

1 Multiplicity and Transverse Momentum Correlations in Multihadronic Final States in e^+e^- Interactions at $\sqrt{s} = 91.2$ GeV
The OPAL Collaboration, R Akers et al
Phys Lett **B320** (1994) 417

2 Measurement of the $\tau^- \rightarrow h^-\pi^0\nu_\tau$ and $\tau^- \rightarrow h^- \geq 2\pi^0\nu_\tau$ Branching Ratios
The OPAL Collaboration, R Akers et al
Phys Lett **B328** (1994) 207

3 Measurement of the Time Dependence of $B_d^\circ \leftrightarrow \overline{B_d^\circ}$ Mixing Using a Jet Charge Technique
The OPAL Collaboration, R Akers et al
Phys Lett **B327** (1994) 411

4 QCD Studies Using a Cone-based Jet Finding Algorithm for e^+e^- Collisions at LEP
The OPAL Collaboration, R Akers et al
Zeit Phys **C63** (1994) 197

5 Measurement of the Production Rates of Charged Hadrons in e^+e^- Annihilation at the Z^0.
The OPAL Collaboration, R Akers et al
Zeit Phys **C63** (1994) 181

6 A Study of Mean Sub-jet Multiplicities in Two- and Three-jet Hadronic Z^0 Decays
The OPAL Collaboration, R Akers et al
Zeit Phys **C63** (1994) 363

7 Search for the Minimal Standard Model Higgs Boson
The OPAL Collaboration, R Akers et al
Phys Lett **B327** (1994) 397

8 Measurement of the Time Dependence of $B_d^o \leftrightarrow \overline{B_d^o}$ Mixing using Leptons and $D^{*\pm}$ Mesons
The OPAL Collaboration, R Akers et al
Phys Lett **B336** (1994) 585

9 Observation of Exclusive Decays of B Mesons at LEP
The OPAL Collaboration, R Akers et al
Phys Lett **B337** (1994) 196

10 Search for Rare Hadronic B Decays
The OPAL Collaboration, R Akers et al
CERN-PPE/94-98 (28 June 1994)
Submitted to Phys Lett **B**

11 Search for a Scalar Top Quark Using the OPAL Detector
The OPAL Collaboration, R Akers et al
Phys Lett **B337** (1994) 207

12 Search for Neutral Higgs Bosons in the Minimal Supersymmetric extension of the Standard Model
The OPAL Collaboration, R Akers et al
Zeit Phys **C64** (1994) 1

13 Measurement of Single Photon Production in the e^+e^- Collisions near the Z^0 Resonance
The OPAL Collaboration, R Akers et al
CERN-PPE/94-105 (14 July 1994)
Submitted to Zeit Phys **C**

14 Measurement of $\Gamma(Z^0 \rightarrow b\bar{b})/\Gamma(Z^0 \rightarrow \text{hadrons})$ using a Double Tagging Method
The OPAL Collaboration, R Akers et al
CERN-PPE/94-106 (15 July 1994)
Submitted to Zeit Phys **C**

15 Measurements of the Inclusive Branching Ratios of τ–Leptons to K^0_s and Charged K^* (892)
The OPAL Collaboration, R Akers et al
CERN-PPE/94-108 (15 July 1994)
Submitted to Phys Lett **B**

16 Determination of an Upper Limit for the Mass of the τ Neutrino at LEP
The OPAL Collaboration, R Akers et al
CERN-PPE/94-107 (15 July 1994)
Submitted to Phys Lett **B**

17 Measurement of the τ-Lepton Polarization and its Forward-Backward Asymmetry from Z^0 Decays
The OPAL Collaboration, R Akers et al
CERN-PPE/94-120 (27 July 1994)
Submitted to Zeit Phys **C**

18 Determination of the Event Shape distributions and $\alpha_s(b)$ from Z^0 to $b\bar{b}$ events at LEP
The OPAL Collaboration, R Akers et al
CERN-PPE/94-123 (27 July 1994)
Submitted to Zeit Phys **C**

19 Updated Measurement of the τ Lifetime
The OPAL Collaboration, R Akers et al
CERN-PPE/94-129 (29 July 1994)
Submitted to Phys Lett **B**

20 A Measurement of the QCD Colour Factor Ratio C_A/C_F and T_F/C_F from Angular Correlation in Four-jet Events
The OPAL Collaboration, R Akers et al
CERN-PPE/94-135 (19 August 1994)
Submitted to Phys Lett **B**

OPAL-related papers by UK Authors

The OPAL Silicon Strip Microvertex Detector with Two Coordinate Readout
P P Allport et al., NIM **A346** (1994) 476

The Longitudinal Coordinate from "Double Diamond" Tapered Cathode Pad Readout.
R J Barlow, NIM **A349** (1994), 277.

The OPAL Silicon-Tungsten Calorimeter Front-End Electronics
B E Anderson et al., IEEE Trans. Nuc. Sci. **41** (1994), 845.

Conference Contributions and Review Articles by UK Physicists

Electroweak b physics results from LEP
J R Batley
DPF-94, Albuquerque, New Mexico
2 - 7 August 1994.

Charm and Beauty Hadron Production at $\sqrt{s} = M_{Z^0}$
V Gibson
ICHEP, Glasgow 20 - 27 July 1994

Properties of quark and gluon jets
D R Ward
QCD94, Montpellier, July 1994

Z^0 Lineshape Results from LEP-1993
P E L Clarke
XXIX Rencontre de Moriond, Electroweak Interactions and Unified Theories
12 - 19 March 1994, Meribel. UCL/HEP 94-03

The Status of Searches for the Standard Model Higgs Boson at LEP.
T Wyatt.
XXIX Rencontre de Moriond, Electroweak Interactions and Unified Theories
12 - 19 March 1994, Meribel.

$\gamma\gamma$ Physics at LEP2; Experimental Possibilities
D J Miller
Two Photon Physics from DAΦNE to LEP200 and beyond
College de France, Paris, 2 - 4 February 1994. UCL/HEP 94-02

Two Photon Physics with OPAL.
D J Miller
Proceedings of Workshop on Two Photon Physics at LEP and HERA, Lund, Sweden, 26 - 28 May 1994, eds G. Jarlskog and L Jonsson (Lund University). UCL/HEP 94-05.

OPAL Research Theses by UK Students

A measurement of the Mean B-Hadron Lifetime using the Central Drift Chambers of the OPAL Experiment at LEP.
G J Barker, Ph.D. Thesis, University of London, 1993 (RALT-93175).

A Determination of the Three Jet Rate for b quarks and a Test of Massive QCD at LEP.
S Barnett, Ph.D. Thesis, Manchester, February 1994 (RALT-94011).

Silicon Microstrip Detectors with Two Co-ordinate Readout
U C Dunwoody, Ph.D. Thesis, Cambridge, January 1994, (RALT-94009).

A Study of B^0s meson production in Z^0 decays at LEP
F C Grant, Ph.D. Thesis, Cambridge, September 1994.

Studies of QCD with Event Shape Variables in e^+e^+ Annihilation at the Z^0 Energy
S Kluth, Ph.D. Thesis, Cambridge, September 1994.

Photon Structure Functions from Tagged Photon-Photon Scattering.
M H Lehto, Ph.D. Thesis, University of London, 1993 (RALT-94020).

Bhabha Scattering at All Angles.
J R McNutt, Ph.D. Thesis, Brunel 1993.

Tests of QCD from Jet and Hadron Production at LEP
L del Pozo, Ph.D. Thesis, Cambridge, December 1993, (RALT-93002).

Measurement of Electroweak Parameters using the Muon Pair Charge Asymmetry at OPAL.
G E Richards, Ph.D. Thesis, Manchester, 1994 (RALT-94014).

A Measurement of Average B Lifetime and B Fraction in Multihadronic Decays of the Z at OPAL.
J P Walker, Ph.D. Thesis, Birmingham, 1994 (RALT-94012).

Figure 1 Comparison between the measured value of $\Gamma_{b\bar{b}}/\Gamma_{had}$ and the Standard Model prediction using the ZFITTER program. The hatched area shows the $\pm 1\sigma$ range of this measurement. Curves indicate the predicted values of $\Gamma_{b\bar{b}}/\Gamma_{had}$(left) and $\Gamma_{d\bar{d}}/\Gamma_{had}$(right) as functions of the top quark mass m_{top}. The widths of these black lines represent the small uncertainty due to Higgs particle masses in the range 60-1000 GeV/c^2.

Figure 2 Data distributions of Δm for $D\pi$ combinations satisfying the selection criteria for D_J charmed mesons. The variable Δm is defined as $m(D^{(*)}\pi) - m(D^{(*)})$.

Figure 3 The ratio R of mixed to total events as a function of proper decay time for $B_d^0 \leftrightarrow \overline{B}_d^0$ oscillations measured using $B_d^0 \rightarrow D^{*-}\ell^+\nu X$ decays.

Figure 4 Error ellipses with the QCD structure constants T_F/C_F and C_A/C_F or C_F and C_A/C_F as parameters in fits to OPAL event shape cross-sections. The one, two and three standard deviation ellipses are drawn, corresponding to confidence levels of 39%, 86% and 99% respectively.

Figure 5 The variation of ξ_{peak} with mass for various hadron states. Measured data points are shown as circles, with the JETSET values shown as stars. For π and K, one star represents both the charged and neutral states. The arrows show the change in ξ_{peak} for JETSET simulations if only primary hadrons are considered.

Figure 6 Display in the y-z plane of Higgs candidate accepted by the charged lepton channel selection procedure. The tracks and clusters shown pass the data quality cuts. Two jets are seen in the negative z direction. A third jet, consisting of a track and some clusters in the EM caloriometer, is visible in the positive z direction near the beam pipe. For both muons, the tracks, the associated clusters in the EM and hadron calorimeters and the track segments in the muon chambers (denoted by arrows) are visible.

Ames; Antwerp; Athens; Bergen; Bratislava; Bologna; College de France; CERN; CRN (Strasbourg); Demokritos; Genova; Grenoble; Helsinki; IIHE (Brussels); JINR Dubna; KFK (Karlsruhe); Krakow; LAL (Orsay); Lisbon; **Liverpool**; Ljubljana; LPNHE (Paris VI); Lund; Lyon; Marseille; Milano; Mons; NBI (Copenhagen); NIKHEF (Amsterdam); Oslo; **Oxford**; Padova; Prague; **RAL**; Rio de Janeiro; Rome; Saclay; Sanita (Rome); Santander; Serpukhov; Stockholm; Tech Univ Athens; Torino; Trieste; Udine; Uppsala; Valencia; Vienna; Warsaw; Wuppertal.

Physics Results in 1994:

Publications on physics topics studied with the DELPHI detector this year have again covered a wide range of topics (see publications list attached). In addition, approximately 40 further papers were presented at the International Conference on High Energy Physics in Glasgow in July and are currently being prepared for publication. The following briefly summarises some of the studies in which UK physicists have been most recently and most heavily involved:

1) Standard Model Tests :

Measurements of the mass and the partial and total widths of the Z^0 together with the forward-backward asymmetries in Z^0 decay provide a powerful test of the Standard Model. During the last year a big step forward was made by using the 20 nb^{-1} of luminosity taken in 1993 at c.m. energies 2 GeV above and 2 GeV below the Z^0 peak energy and exploiting the better knowledge of the LEP beam energy, including detailed measurement and analysis of the effects of the tides, as well as the better understanding of the detector and of the luminosity measurement. This reduced the errors on the position, height and width of the Z^0 peak by about a factor 2.

Fits to the absolute cross sections for $e^+e^- \rightarrow$ hadrons and $e^+e^- \rightarrow$ leptons and their energy dependences ('line shapes') and the forward-backward asymmetries for $e^+e^- \rightarrow$ leptons using the data taken in 1990, 1991, 1992 and 1993 yielded the following preliminary values (reported at Glasgow) for the unfolded Born cross section at the Z^0 pole and the mass and the total width of the Z^0 :

$$\sigma_0 = 41.26 \pm 0.17 \text{ pb},$$

$$M_Z = 91.1870 \pm 0.0052 \text{ GeV},$$

$$\Gamma_Z = 2.4951 \pm 0.0059 \text{ GeV}.$$

The ratios R between hadronic and leptonic decays were found to be

$$R_{\mu\mu} = 20.60 \pm 0.12$$

$$R_{\tau\tau} = 20.64 \pm 0.16$$

$$R_{ee} = 20.96 \pm 0.16$$

and the forward-backward asymmetry parameters A^0 were found to be

$$A^0_{\mu\mu} = 0.0128 \pm 0.0037$$

$$A^0_{\tau\tau} = 0.0209 \pm 0.0057$$

$$A^0_{ee} = 0.0207 \pm 0.0073.$$

The three R values and the three A^0 values are fully consistent with the universality of the coupling of the Z^0 to charged leptons expected in the Standard Model. Their averaged values are

$$R_{\ell} = 20.690 \pm 0.086$$

$$A^0_{\ell} = 0.0160 \pm 0.0029.$$

To illustrate the high quality of the 1993 data, Fig.1 shows the differential cross-sections in the $\mu^+\mu^-$ channel at the three energy values and Fig.2 shows all of the forward-backward asymmetry values measured in the $Z^0 \to \tau^+\tau^-$ channel.

Values can also be extracted for the squared vector and axial vector couplings of the Z^0 to charged leptons,

$$V_l^2 = 0.00135 \pm 0.00025$$

$$A_l^2 = 0.2510 \pm 0.0009$$

and for the invisible and hadronic widths,

$$\Gamma_{\rm inv} = 508.7 \pm 5.7 \text{ MeV}$$

$$\Gamma_{\rm had} = 1735.1 \pm 6.4 \text{ MeV}.$$

Assuming also the value of the strong coupling constant measured by DELPHI, $\alpha_s = 0.123 \pm 0.005$, and using the Standard Model to predict $\Gamma_{\nu\nu}/\Gamma_{\ell\ell} = 1.992 \pm 0.002$ gives

$$N_\nu = 3.027 \pm 0.029$$

as the number of light neutrino species. Alternatively, fixing the number of neutrino species to be 3, the value of $R_{\ell\ell}$ may be used to extract the value

$$\alpha_s = 0.119 \pm 0.010$$

A Standard Model fit to all of the cross section and asymmetry data using the measured value of α_s as a constraint yields a value for the top quark mass:

$$m_t = 170^{+21}_{-24}(\text{expt})^{+18}_{-18}(\text{Higgs}) \ \text{GeV}$$

where the Higgs mass is varied from 60 to 1000 GeV with a central value of 300 GeV.

All of the work on the $\mu\mu$ and $\tau\tau$ channels and much of the global fitting and interpretation of the results was done by the UK groups.

The mean τ polarisation $< P_\tau >$ in $Z^0 \to \tau^+\tau^-$ decay has also been measured using the data taken in 1991 and 1992 by analysing the angular distribution of the τ decay products in the τ rest frame. The polarisation P_Z of the initial Z^0 was then determined from the forward-backward asymmetry of P_τ. Fig.3 illustrates the P_τ measurement in the $\tau \to \mu\nu\bar{\nu}$ channel. The value obtained from this fit was $< P_\tau >= -0.033 \pm 0.068 \pm 0.041$. From the forward-backward asymmetry of this τ polarisation, the polarisation of the Z^0 was found to be $P_Z = 0.024 \pm 0.099 \pm 0.003$. Combining all decay channels gave

$$< P_\tau >= -0.145 \pm 0.024$$

$$P_Z = -0.140 \pm 0.028$$

2) Lifetime measurements :

Precise measurement of the inclusive B hadron lifetime is important for the study of the weak decays of the b quark and the measurement of $|V_{bc}|$. Two such measurements have been completed in the last year.

From the flight path distribution of 112 ± 12 ψ mesons decaying to $\mu^+\mu^-$ selected in the 1991-92 data, corresponding to an inclusive branching ratio of $\text{BR}(Z^0 \to \psi + X) = 0.362 \pm 0.040 \pm 0.036$ %, an average B lifetime of $1.50^{+0.24}_{-0.21} \pm 0.03$ ps was obtained. The prompt fraction was left free in the fit. This is potentially a very clean measurement, but it will always be severely limited statistically. The same events were used to demonstrate ψ' and χ_c signals in the channels $\psi' \to \psi\pi^+\pi^-$ and

$\chi_c \to \psi\gamma$ and to measure the ψ' and χ_c production rates. One was recognised as coming from $B_s^0 \to \psi\phi$ decay and contributed to the measurement of the B_s^0 mass.

The analysis using the method developed last year to measure the average B lifetime from the length distribution to reconstructed decay vertices has also been completed. The $b \to c \to s$ decay chain produces several consecutive vertices, so only the closest reconstructed vertex was used. The vertices at radii above 1.5 mm from the beam spot constructed from 4 tracks or more having an invariant mass above 1.7 GeV were found to have a B purity of 93%. Fitting their length distribution (see Fig.4) gave

$$\tau_B = 1.599 \pm 0.014 \pm 0.035 \text{ ps}$$

which is the most precise single measurement of the inclusive B hadron lifetime currently available.

The inclusive reconstruction of B decay vertices in sufficiently clean conditions that the charge of the B could be measured, in order to measure the B^+ and B^0 lifetimes separately, has been performed only in Delphi. The analysis has continued with the 1993 data. As before, jets from hadronic Z^0 decays were selected whose tracks were inconsistent with forming a single vertex but could form two vertices, the primary Z^0 decay vertex and a secondary vertex, with good probability in a unique way. Nearly all of the selected secondary vertices made from 3 tracks or more with mass above 2.2 GeV (see Fig.5) are B decays. Each such vertex was then swum back towards the primary vertex until it could no longer be distinguished from it by the criteria by which it had been selected. This gave the minimum detectable flight path for that B. The excess flight paths above that minimum for neutral and charged vertices were then fitted (Fig.6). The fit uses the multiply charged vertices to measure the charge confusion and thus to corrected for it. This is now done for 3 mass bins separately, instead of the single mass bin used before, to optimise the use of information. The fit procedure has also been further refined to allow for events in which a track is misassigned from the primary to the secondary vertex or vice versa. The need for this was established using simulated events, which were also used to validate the procedure. After correcting for the presence of B_s^0 mesons and Λ_b^0 baryons, the preliminary values for the fitted mean lifetimes of charged and neutral B mesons presented in Glasgow were:

$$\tau_{B^+} = 1.72 \pm 0.08 \pm 0.06 \pm 0.01 \text{ ps}$$

$$\tau_{B^0} = 1.68 \pm 0.15 \pm 0.10^{+0.09}_{-0.14} \text{ ps}$$

$$\tau_{B^+}/\tau_{B^0} = 1.02^{+0.13}_{-0.10} \pm 0.09^{+0.10}_{-0.05}$$

where in each case the first error is statistical, the second is systematic and largely represents due to the statistical precision to which the analysis method has been verified with Monte Carlo simulated data, and the third represents the uncertainty in the correction for B_s^0 and Λ_b^0. This is the most precise single measurement of τ_{B^+} currently available and one of the most precise ones of τ_{B^0} and the lifetime ratio τ_{B^+}/τ_{B^0}. The analysis is now being finalised for publication. The continuation of this analysis should benefit greatly from the z information available in the 1994 data from the upgraded microvertex detector (see below).

An analysis to measure the Λ_b lifetime is also in progress and work continues on the τ lifetime. In the $\tau \to 3\pi^\pm$ channel, for example, the statistical precision on the measured lifetime has now reached 1.5%. Consequently much detailed and difficult work has been invested and is continuing to be invested in order to establish systematic errors substantially below that level. The work has largely concentrated on achieving a detailed understanding of systematic effects in the tracking.

Detector performance in 1994 and upgrades implemented and foreseen:

The whole detector has continued to operate well throughout 1994. In particular, the hardware items for which UK groups have responsibility, namely the Outer Detector, Barrel Muon Detector and Micro-vertex Detector, all continue to perform excellently. For the first time, both the complete Barrel Ring Imaging Cherenkov (BRICH) Detector and the complete Forward Ring Imaging Cherenkov (FRICH) Detector have routinely taken good-quality physics data throughout the year.

At the time of writing, the statistics accumulated this year equal the total of the two previous years. This has been achieved despite a slow and inefficient start due principally to teething problems with Decnet Phase V and an unusually severe lost-particle background due to an initially poor vacuum locally in the machine resulting from outgassing from the beam pipe. On the other hand a synchrotron radiation mask system, foreseen to be necessary to protect against the higher synchrotron background expected at LEP200, was tested very successfully.

The silicon microvertex detector was upgraded during the 1993-94 shutdown. The upgraded detector uses newly-developed double-sided silicon detectors yielding precise z as well as precise RΦ coordinates both for the outer layer (radius 11 cm) and for an extended closer layer (radius 6 cm) built in the UK. The new detector has run extremely well throughout the year. Fig.7 shows an early event reconstructed both in RΦ and in z. Fig.8 shows the z resolution achieved using the initial hardware alignment. The precision in z is currently almost a factor 2 better than that shown in Fig.8 and is rapidly approaching the design performance as the z alignment is refined using tracks. The precision in RΦ is now the same as that achieved previously using the well understood detector that had taken data for the previous three years.

Other upgrades that were completed at the same time include 1) the addition (also with UK participation) of surround muon chambers ('SMC') closing the gap between the existing barrel and end-cap detectors and 2) the replacement of the principal luminosity monitor ('SAT') by one of more precise construction, a scintillating tile calorimeter ('STIC'), which also closes the small angle gap between the present luminosity monitor and the forward electromagnetic calorimeter. Fig.9 shows a hadronic event with a muon identified in the SMC.

The upgrade of the silicon microvertex detector was the first stage of a larger upgrade intended to extend the b-tagging capability to smaller angles and to augment the track reconstruction efficiency in the small-angle forward region for LEP200 physics. It is hoped that the second stage will be implemented during the 1994-5 winter shutdown. It requires also a rebuilding of the Inner Detector to extend its coverage to smaller angles too. The new jet-chamber part is being constructed at NIKHEF using the same techniques as before, but a new approach was needed for the trigger layers. These are being implemented, with participation of UK physicists but no UK funding, using straw-tube technology. Fig.10 shows test beam results illustrating the precision of track elements reconstructed in the straw tube detector.

LEP200 Studies:

Preparations continue for physics at LEP200, the upgrade of the LEP machine intended to more than double the energy of e^+e^- collisions by 1996. The opening up of this new region will intensify the search for the Higgs boson and supersymmetric particles, and will also allow observation of the reaction $e^+e^- \rightarrow W^+W^-$ for the first time. A detailed study has been made of the potential of this reaction for detecting deviations from Standard Model predictions in the angular distributions of the reaction products. Fig.11 shows the results of maximum likelihood fits of simulated events to pairs of parameters representing deviations from the expected couplings of vector bosons: the precision with which the couplings are determined, indicated by the narrowness of the likelihood peaks, is seen to improve as the amount of angular information used in the fit is increased. An interesting feature of the fit, which has been explained in terms of the amplitude structure of the W^+W^- production process, is the emergence of two peaks in the likelihood function, implying the possibility of ambiguous solutions for the parameters.

DELPHI Publications in the last year:

1. Limits on the production of scalar leptoquarks from Z^0 decays at LEP
   P. Abreu et al.
   Phys. Lett. 316B (1993) 620

2. Production of Λ and $\Lambda\bar{\Lambda}$ Correlations in the Hadronic Decays of the Z^0
   P. Abreu et al.
   Phys. Lett. 318B (1993) 249

3. Production Rate and Decay Lifetime Measurements of B_s^0 mesons at LEP using D_s and ϕ mesons
   P. Abreu et al.
   Zeit. Phys. C61 (1994) 407

4. Measurement of the $B^0 - \overline{B^0}$ Mixing using the Average Electric Charge of Hadron Jets in Z^0 -Decays
   P. Abreu et al.
   Phys. Lett. 322B (1994) 459

5. Invariant mass dependence of particle correlations in hadronic final states from the decay of the Z^0
   P. Abreu et al.
   Zeit. Phys. C63 (1994) 17

6. Interference of Neutral Kaons in the Hadronic Decays of the Z^0
   P. Abreu et al.
   Phys. Lett. 323B (1994) 242

7. Study of hard scattering processes in multihadron production from $\gamma\gamma$ collisions at LEP
   P. Abreu et al.
   Zeit. Phys. C62 (1994) 357

8. Measurements of the Lineshape of the Z^0 and Determination of Electroweak Parameters from its Hadronic and Leptonic Decays
   P. Abreu et al.
   Nucl. Phys. B417 (1994) 3

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19. Search for pair-produced heavy scalars in Z^0 decays
P. Abreu et al.
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20. J/ψ Production in the Hadronic Decays of the Z
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Submitted to **Phys. Lett. B (1994)**

21. First evidence of hard scattering processes in single tagged $\gamma\gamma$ collisions
P. Abreu et al.
Submitted to **Phys. Lett. B (1994)**

22. A Study of Radiative Muon-Pair Events at Z^0 Energies
and limits on an additional Z' gauge Boson
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Submitted to **Zeit. Phys. C (1994)**

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by Double Hemisphere Tagging
P. Abreu et al.
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25. Measurement of the Forward-Backward Asymmetry of $e^+e^- \to Z \to b\bar{b}$
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Submitted to **Zeit. Phys. C (1994)**

International conference presentations by UK physicists in last year:

Search for Higgs Bosons at LEP,
G. Gopal,
Invited review talk,
10th Aspen Winter Conference on Elementary Particle Physics,
Aspen, Colorado, USA,
January 1994.

Current Status of B-physics at the Z^0 peak and future prospects – B-hadron lifetimes,
G.J. Barker,
Invited review talk,
Beauty-94,
Mont St Michel, France,
April, 1994.

B-baryon production at LEP,
S. Tzamarias,
Invited review talk,
International Conference on High Energy Physics, Glasgow,
July, 1994.

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W.J. Murray,
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B. Franek,
Computing for High Energy Physics,
San Francisco, California, USA.
July, 1994.

Microstrip silicon detectors - present status and application at Delphi and CDF,
L. Yu,
Symposium on Medium Energy Physics,
Beijing, China,
August 1994,

Selected topics in B Physics,
W. Venus,
CERN Seminar,
August, 1994.

Talks by UK students at the Bristol IOP conference, April 1994

S. Bosworth (Oxford)
Measurement of the Λ_b lifetime using the impact parameter distribution of the Λ.

R. Campion (Liverpool)
Strange and charm particle production in $Z^0 \to b\bar{b}$ events.

J. Davies (Liverpool)
A study of the $Z^0 \to \tau\tau$ cross section and forward-backward asymmetry.

J. Richardson (Liverpool)
τ lifetime from 3-prong decay vertices using Delphi 1992 data.

R. Zuberi (Oxford)
The Delphi inclusive lepton analysis.

Theses completed by UK students in the last year:

S. Blyth,
A study of radiative muon-pair events at Z^0 energies
and limits on an additional Z' gauge boson,
Oxford (1994).

P. Collins,
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Oxford (1994).

K. Forbes,
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M. Richardson,
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using the Delphi detector at LEP,
Liverpool (1994).

R. Zuberi,
An inclusive study of the leptonic decay modes of the Z^0 boson,
Oxford (1994).

Fig.1 The differential cross sections in the $Z^0 \to \mu^+\mu^-$ channel measured from the 1993 data at the three c.m. energy values. The angular coverage extends to within 10° from the beam pipe. The curves are fits to the lowest order form of the angular distribution. The asymmetry at the Z^0 pole is found to be $A^0_{\mu\mu} = 0.0128 \pm 0.0037$.

Fig.2 The full set of forward-backward asymmetry values measured in 1990-1993 in the $Z^0 \to \tau^+\tau^-$ channel. The 1993 data set consists of some 17000 selected τ-pairs taken on the Z^0 peak and 2 GeV above and below it. Combining all the data. the asymmetry at the Z^0 pole is found to be $A^0_{\tau\tau} = 0.0209 \pm 0.0057$.

Fig.3 The determination of $< P_\tau >$ in the $\tau \to \mu\nu\bar{\nu}$ decay channel using 6600 selected events from the 1991+1992 data. The angular distribution of the muon in the τ rest frame reflects into the muon momentum spectrum in the laboratory. The solid circles show the measured muon momentum spectrum normalised to the beam energy. The solid line shows the Monte Carlo simulation for the fitted value of $< P_\tau >$. It is the sum of the hatched area corresponding to the background, coming mainly from other τ decay modes, and the dashed and dotted histograms which show the negative and positive helicity contributions respectively.

Fig.4 The inclusive B lifetime fit to the length distribution of about 11,000 reconstructed vertices (1992 data) at radii above 1.5 mm from the beam spot constructed from 4 or more tracks and having an invariant mass above 1.7 GeV. Their B purity was found to be $93.1 \pm 0.3\%$.

Fig.5 The reconstructed mass distribution from data and Monte Carlo simulation of the secondary vertices constructed from 3 or more tracks and selected for measuring the B^+ and B^0 lifetimes. The cut at 2.2 GeV is indicated by the dashed line. According to the simulation, for masses above 2.2 GeV the B purity is around 99% and the charge is estimated correctly in $80 \pm 1\%$ of charged vertices and $57 \pm 2\%$ of neutral vertices.

Fig.6 The excess proper time distributions of the neutral and charged vertices with masses above 2.2 GeV (see Fig.5) finally selected for the measurement of the B^+ and B^0 lifetimes.

Fig.7 An event with a very clear secondary B decay vertex reconstructed both in RΦ (left) and in z (right) in the upgraded microvertex detector that has been operating throughout this year. The z measurements are available from the outermost and innermost layers, the RΦ measurements are available from all three layers, as before.

Fig.8 The z resolution of the upgraded microvertex detector measured using tracks traversing overlapping silicon modules obtained using the initial alignment from the pre-installation survey of the outer layer. The lower plot shows the resolution as a function of the angle θ to the beam axis. The closed circles indicate the change to double strip spacing. The z resolution is currently being further improved by detailed alignment studies using these tracks and others.

Fig.9 Display of a hadronic Z^0 decay containing a muon identified in the 'Surround Muon Chambers' (SMC). The SMC was installed in the 1993-94 shutdown to cover the gap that had existed between the barrel and end-cap muon detectors. Its four sections are seen in the $R\Phi$ (left) and z (right) projections outside the main cylindrical body of the detector. One of the downward-going tracks can be seen to give hits in all four layers of the hadron calorimeter (box sizes indicate signal heights corresponding to a minimum ionising track) and subsequently give a hit in the SMC.

Fig.10 Difference between the known track position and the track position reconstructed in the straw tube detector. This detector has been built to replace the trigger layers of the Inner Detector and provide greater angular coverage and less material. The test beam measurements show that the trigger efficiency for single tracks is 99.1%, the track position is reconstructed within 50 μm (shown in this plot) and its angle within 3.7 mr.

Fig.11 Log-likelihood functions for fits to vector boson coupling parameters in simulated $e^+e^- \to W^+W^-$ events. κ_γ and λ_γ are the dipole and quadrupole γWW couplings and δg_Z is the deviation of the ZWW coupling from its Standard Model value $\cot\theta_W$. Proceeding from top to bottom, increasing use is made of the available angular information. The top row uses only the W-pair production angle while the second row uses also the leptonic and folded hadronic decay angles in the $jj\ell\nu$ final state. The improvement shown in the bottom row, which would require the hadronic decay angles to be unfolded, reveals the presence of an ambiguity.

High Energy Electron-Proton Physics at HERA

H1

Proposal 750

Birmingham, Glasgow, Lancaster, Liverpool, Manchester, Queen Mary-Westfield and Rutherford-Appleton Laboratory

in collaboration with

Aachen I, Aachen III, Brussels, Cracow, Davis, Dortmund, Saclay, DESY-Hamburg, DESY-Zeuthen,, Hamburg I, Hamburg II, Heidelberg, Kiel, Kosice, Lund, ITEP Moscow, LPI Moscow, Munich, Orsay, Ecole Polytechnique, Paris VI, Paris VII, Prague, Rome, SLAC, Wuppertal, ETH Zurich and Zurich

Introduction and Overview

HERA commenced operation in 1994 in April with the by now customary period of machine physics. By mid-May, steady electron-proton luminosity was achieved with 200 bunch operation, and H1 commenced data taking. Peak luminosity at the beginning of electron fills regularly reached about 10% of design often with low background conditions and thus good data taking efficiency (~ 80% per electron fill). However the accumulation of data, that is (time) integrated luminosity, was not as wished if the aim of having HERA deliver 5 pb^{-1} in 1994 was to be achieved. The electron beam lifetime was low due to a subtle problem associated with ion capture by the electron beam from "getter" vacuum pumps. After 1 pb^{-1} had been delivered in June, the decision was taken to attempt to operate HERA with positrons, and in two weeks positron-proton collisions with the same luminosity and a much longer positron lifetime were established, and data taking recommenced. The immediate effect was a dramatic increase in data collection rate by H1 due to the much higher HERA duty cycle. In the subsequent months to the beginning of November data were accumulated at a steady rate with daily integrated luminosity sometimes reaching 80 nb^{-1}. By the end of data taking in November, HERA had delivered almost 5.5 pb^{-1} almost 4 pb^{-1} of which was of a quality suitable for H1 physics analysis.

Throughout 1994 data taking, all of the H1 detector components, which were designed and built by the UK groups, were operational. These include the ***Superconducting Solenoid***, the ***Forward Track Detector*** (FTD) which extends the reconstruction of charged tracks down to within about 5° of the proton beam, the ***Time of Flight*** (ToF) scintillator counters which provide essential inter-bunch timing resolution, the H1 ***Central Data Acquisition System*** (DAQ), and the ***Forward Muon Detector*** (FμD) and ***Trigger*** which provide muon identification and reconstruction also in this forward region. During the positron running, the latter experienced much higher background conditions than hitherto which necessitated operation without the drift chambers downstream of the toroid spectrometer magnet. During the machine physics period following data taking, this was traced to synchrotron radiation generated in "beam bump" magnets upstream of H1.

Throughout 1994, analysis has proceeded apace on the data taken throughout 1993. Papers have been published [1-11] concerned with many aspects of photoproduction and electroproduction in the new kinematic regions to which HERA provides unique experimental access. The increase in statistics achieved by virtue of the continuing improvements in the delivered luminosity has meant that the unique richness of *ep* physics at HERA has continued to unfold in the form of measurements concerned with both photon and electron (positron) substructure and with fundamental tests both of electroweak theory and QCD.

Throughout 1994 the H1 upgrade program has continued on schedule for installation in the 1994-95 winter shutdown. It includes enhanced track reconstruction close to the *ep* interaction vertex for the central and backward angular regions, plus enhanced calorimetry for better measurement of electromagnetic and hadronic energy flow in the backward direction. Improvements in the DAQ and drift chamber read-out systems continue. Following an exceptionally reliable running period, first tests of the FTD drift chambers with a new gas mixture optimised for X-ray as well as charged track sensitivity were carried out to investigate the performance of the FTD in π/e discrimination in complex *ep* events.

Physics

The major thrust of our physics program is conveniently differentiated as photoproduction, deep inelastic *ep* (DIS) interactions, and searches for new and unexpected phenomena, so called "exotic" *ep* interactions. The H1 UK groups have been concerned with topics in all these areas.

Following the first measurements in 1993 of the total hadronic photoproduction cross section and the differential inclusive cross sections for jet production as a function of transverse momentum and laboratory pseudo rapidity, the latter have also been measured for charged particle production [4]. The cross section dependence on transverse momentum p_T shows a "tail" characteristic of hard partonic physics which exceeds that observed in *pp* interactions at the same energy, implying a larger proportion of such physics in γp than in *pp* interactions. A perturbative QCD calculation reproduces the data well, demonstrating that the interpretation in terms of resolved and direct partonic γp processes, first observed by H1 in 1992, is confirmed quantitatively. The identification of the diffractive component in γp interactions by means of the lack of hadronic energy flow adjacent to the proton remnant direction has been used to study the topological characteristics of diffractive hadronic photoproduction. Conclusive evidence has been found to demonstrate that such interactions also have a substantial contribution from hard partonic processes [10], thereby paving the way with increased statistics in the future to an understanding of the partonic structure of an old conundrum in soft hadronic physics, the pomeron. The first observation of heavy flavour physics has been published with a measurement of the J/ψ photoproduction cross section at HERA energies [8].

DIS *ep* physics has continued with measurements in the new kinematic region at very low Bjorken-x possible for the first time because of the immense HERA collision energy. The remarkable rise in the proton structure function F_2 with decreasing Bjorken-x has been confirmed with a tenfold increase in statistics. The kinematic reach of the measurements has been extended to larger x and to lower Q^2 to meet results from fixed target experiments. To get to lower Q^2 the HERA rings were operated successfully with the *ep* interaction vertex shifted to alter the acceptance in Q^2 of the backward electromagnetic calorimeter. An understanding of these results in terms of the QCD dynamics of proton structure shows no indication for an unusual behaviour in Q^2 [2], whereas in x the observed rise suggests that new effects may be important.

Any interpretation of proton structure in terms of partons and perturbative QCD includes an understanding of the way the proton fragments in deep inelastic *ep* scattering. The hadronic energy flow and charged particle production characteristics have been measured and compared with theoretical simulations based on QCD motivated models of such processes [5],. The results are interesting. There is no interpretation which overall gives a good description of the data. The DIS hadronic final state is a rich mixture of QCD based dynamic phenomena. However, if attempts are made to isolate the perturbative partonic processes by searching for jet production, then quite unexpectedly it seems that, even with our present uncertainty in the quark and gluon substructure of the proton, the underlying properties of QCD can be isolated - Figure 1 shows *the* signature of partonic QCD, namely the observation of a running coupling constant α_S as a function of Q^2 for the first time observed in a single experiment (H1) [11].

A portent of the future has been possible with the first observation of charged current DIS events. The total cross section for the process $ep \rightarrow \nu X$ has been measured, and its value has been shown to be consistent with expectation. The significance of this measurement is summarised in Figure 2 in which the effect of the W propagator is visible in charged current interactions for the first time [3].

More specific aspects of the DIS hadronic final state have been concerned with interesting effects associated both with the definition of QCD momentum transfer scale and with the fraction of events in which a high momentum proton, or low mass excitation, remains in the final state [6]. For the former, studies of the distribution of hadronic fragments with respect to the direction of the struck, or current,

quark indicate that the scaling violations intrinsic to any QCD dynamics evolve with $\sqrt{Q^2}$, in DIS, in a manner similar to that observed as a function of CMS energy $\sqrt{s}$ in e^+e^- interactions. For the latter an innovative use of the FμD as a detector of hadronic secondaries produced at very small angles to the proton beam has facilitated event selection in a substantially enhanced kinematic range. A measurement has been made of the proportion and characteristics of DIS events which may be interpreted as diffractive. New preliminary results show that such processes are broadly of a scale invariant nature and that they do not account for all of the rise of the proton structure function F_2 at low Bjorken-x,. A first extraction of a structure function of diffraction is now well advanced. The latter is intimately related to the pomeron mentioned above, and to an understanding of it per se and its role in proton structure.

Data Acquisition

RAL are responsible for the project leadership of the central data acquisition system. During the whole of 1994 the system performed without any breakdown or serious incident. The system consists of a dual-fibre optic ring which co-ordinates the readout of the detector sub-components in VMEbus. An array of R3000 RISC processors, equivalent to 20 IBM-3090 units, provides event filtering, data processing, event reconstruction and histogram monitoring in real-time. By embedding the full data acquisition functionality in VMEbus, the complete system can be operated from the latest generation of user-interactive workstations.

Silicon Tracker Readout

Members of H1-UK are collaborating with groups from DESY-Hamburg, DESY-Zeuthen and Zürich, to provide silicon detectors located inside the jet chamber of the Central Tracking Detector. The Central Silicon Tracker (CST) will provide high resolution tracking and vertex reconstruction in the central region, and the Backward Silicon Tracker (BST) will extend this coverage to small backward angles. RAL are responsible for providing the data acquisition readout chain. The first stage of the detector is in the final phase of preparation for operation in H1 during 1995. The final system will contribute a total of 230,000 electronic channels read out by custom-built chips into VMEbus. The architecture of the readout, shown in Figure 3, follows that of the successful central DAQ by using fibre-optics and fast integer processing within a modular framework. Parasitic monitoring and reconstruction tasks can be executed in parallel using R3000-RISC modules and graphics-oriented workstations cater for software development and operator-intervention. The final batch of amplifier-pipeline chips, working to specification, have now been delivered together with the first version OnSiRoC readout cards. The key elements of the data acquisition have all been integrated and are now executing the basic tasks in readiness for data taking in 1995.

Backward Calorimeter Upgrade

All modules for the new upgraded H1 backward calorimeter (SPACAL) are now complete and are being assembled at DESY. The device uses scintillating fibres encased in lead and viewed by mesh-dynode photomultipliers that work very well in the 1T H1 field. Prototype modules in test beams at CERN and DESY have demonstrated the expected excellent energy performance ($(7\%/\sqrt{E(GeV)}) \oplus <1\%$) as well as excellent timing (better than 1 *ns* resolution). Preparations for installation of SPACAL, following a cosmic ray test run, are well advanced and the operation should be complete before the end of the 1994-95 shutdown.

Accurate timing information is vital for adjustment of the trigger gates and this monitoring task is being implemented by H1-UK groups. The system is very compact, requiring only two VME-crates. It is based around the TMC1004 chip and is capable of handling all 1400 SPACAL channels. Each board of the 22 modules holds 16 chips and each of these can digitally record the time of arrival of four discriminated photomultiplier pulses in 1 *ns* cells. By covering only the appropriate 32 *ns* of the 96 *ns* beam crossing interval, the encoded times may be pipelined on the same chip for significantly longer than the 2.5 *μs* level 1 trigger latency period. They may then be readout after the trigger decision has been made. In addition each board contains four units, each of which can automatically prepare sixteen separate histograms, programmable by four "definition bits" fanned out from a single system control module. The modules also provide a set of 32 bit rate scalers and the contents of these as well as the 5.5 *Mb* of histogram RAM is available to monitoring software.

H1 Publications 1994:

[1] *A Measurement of multi - jet rates in deep inelastic scattering at HERA.*
H1 Collaboration (I. Abt, et al.), DESY-93-137, Oct 1993. 18pp.
Z. Phys. C61: 59-66, 1994

[2] *Scaling violations of the proton structure function F_2 at small x.*
H1 Collaboration (I. Abt, et al.), DESY-93-146, Oct 1993. 10pp.
Phys. Lett. B321: 161-167, 1994

[3] *First measurement of the charged current cross-section at HERA.*
H1 Collaboration (T. Ahmed, et al.), DESY-94-012, Jan 1994. 12pp.
Phys. Lett. B324: 241-248, 1994

[4] *Inclusive charged particle cross-sections in photoproduction at HERA.*
H1 Collaboration (I. Abt, et al.), DESY-94-030, Mar 1994. 17pp.
Phys. Lett. B328: 176-186, 1994

[5] *Energy flow and charged particle spectra in deep inelastic scattering at HERA.*
H1 Collaboration (I. Abt, et al.), DESY-94-033, Mar 1994. 32pp.
Z. Phys. C63 (1994) 377

[6] *Deep inelastic scattering events with a large rapidity gap at HERA*
H1 Collaboration (T.Ahmed at al.), DESY-94-133, Jul 1994
Nucl. Phys. B429 (1994) 477

[7] *A search for heavy leptons at HERA*
H1 Collaboration (T.Ahmed et al.), DESY-94-138, Aug 1994

[8] *Photoproduction of J/Ψ mesons at HERA*
H1 Collaboration (T. Ahmed et al.), DESY-94-153, Aug 1994
Phys. Lett. B338: 507, 1994

[9] *A search for leptoquarks and squarks at HERA*
H1 Collaboration (T. Ahmed et al.), DESY-94-154, Aug 1994

[10] *Observation of Hard Processes in Rapidity Gap Events in gamma-p Interactions at HERA*
H1 Collaboration (T. Ahmed et al.), DESY-94-198, Aug 1994

[11] *Determination of the Strong Coupling Constant from Jet Rates in Deep Inelastic Scattering*
H1 Collaboration (T. Ahmed et al.), DESY-94-220, Aug 1994

Figure 1; The result of a measurement of the QCD coupling constant α_s in *ep* DIS as a function of Q^2 from the relative rates for 2(+1) jets and 1(+1) jet production.

Figure 2; The predicted CC cross section as a function of the propagator mass M_{prop} (thin solid line). The dashed line indicates the asymptotic case $M_{prop} = \infty$. The shaded region represents the 1σ band of the measured cross section.

Figure 3; The H1 Silicon Tracker Data Acquisition architecture and components.

ZEUS – A DETECTOR FOR HERA

Proposal 760

Collaborating Institutes by Country

CANADA: MANITOBA, MCGILL, TORONTO, YORK

GERMANY: BONN, DESY, FREIBURG, HAMBURG, JUELICH, SIEGEN, ZEUTHEN

ISRAEL: WEIZMANN INSTITUTE, TEL AVIV

ITALY: BOLOGNA, CALABRIA, FIRENZE, FRASCATI, PADOVA, ROME, TORINO

JAPAN: INS + UNIVERSITY TOKYO

NETHERLANDS: NIKHEF

RUSSIA: MOSCOW

POLAND: KRAKOW, WARSAW

SPAIN: MADRID

SOUTH KOREA: SEOUL UNIVERSITY

UNITED KINGDOM: BRISTOL, GLASGOW, IC LONDON, UC LONDON, OXFORD, RUTHERFORD APPLETON LAB.

USA: ARGONNE NATIONAL LABORATORY, BROOKHAVEN NATIONAL LAB., COLUMBIA UNIVERSITY, IOWA, LOUISIANA STATE UNIVERSITY, OHIO STATE UNIVERSITY, PENNSYLVANIA STATE UNIVERSITY, UNIVERSITY OF CALIFORNIA SANTA CRUZ, VIRGINIA POLYTECHNIC INST., WISCONSIN

Introduction.

The 1993 running period provided ZEUS with twenty times as much data as that of 1992. A number of physics analyses on the 1993 data have already been published or accepted for publication and quite a few more will be submitted for publication before the end of 1994. Notable among the physics topics is the measurement of the proton structure function F_2, which has been greatly improved allowing a more detailed study of the interesting low x region. The higher statistics have also allowed studies of the gluon density in the proton; this is seen to rise strongly at low x.

The 1994 running period will end on 31 October, by which time there will be at least a factor five increase in luminosity compared to 1993. The Central Tracking Detector (CTD) has continued to perform well and significant enhancements have been made to the detector readout. Analysis of the 1994 data is in its early stages but will provide interesting results in the coming year.

HERA.

HERA delivered a total luminosity of about 1 pb^{-1} to the experiments in 1993. The performance of HERA has improved in 1994 and the end of data taking, on 31 October 1994, will see the machine having delivered more than 5 pb^{-1}. The factor of five increase over 1993 is in line with that predicted by the HERA machine group based on improvements made. The klystron power is a factor of two higher than in 1993 and the number of colliding bunches has been doubled from 84 to 168, 80% of the design value. Proton beam currents of 52mA at 820 GeV have been achieved and the maximum measured luminosity is within a factor of three of the design value of 1.5 10^{31} $cm^{-2}s^{-1}$. The maximum specific luminosity, higher than the design value, is 5 10^{29} $cm^{-2}s^{-1}mA^{-2}$.

At the start of the 1994 data taking HERA was running with beams of electrons and protons, the electron beam being at a slightly higher energy, 27.52 GeV, than in 1993. The lifetime of the electron beam was low at about three hours, and so, having delivered about 1 pb^{-1} of electron-proton collisions, it was decided to change to positrons. The necessary changes (reversing magnet polarities, etc.) were carried out in the second half of July, and since then positron running has led to lifetimes of about eight hours and improved luminosities.

Longitudinal polarisations of the electron beam of more than 60% have been reached using a pair of spin rotators in HERA – this is the first time that longitudinal polarisation has been achieved in an electron storage ring. However, spin rotators will not be installed in the ZEUS (or H1) experiment regions until the end of 1996 and therefore there will be no physics with longitudinally polarised beams until at least 1997.

The problems with the electron beam lifetime were found to be due to ion sputter vacuum pumps and the only remedy is to replace all such pumps. This will not happen before the 1995/1996 shutdown and so the 1995 running will continue with positrons to maintain good luminosities.

ZEUS data taking and detector.

The ZEUS detector has generally been working well this year even though there was much installation work and modification of hardware, electronics and trigger and readout systems during the 1993/1994 shutdown. The much improved luminosities have meant that all three levels of the trigger have had to be modified significantly. Despite this, the performance of ZEUS is better than in 1993 and nearing the end of the 1994 running we regularly see data taking efficiencies of over 90%. Recently installed detectors (eg. SRTD, FNC, LPS – see below) are beginning to provide interesting data. Approved upgrades covering the small angle and beam pipe regions will allow ZEUS to extend its physics reach to lower Q^2, higher precision and improved study of diffractive physics.

The Central Tracking Detector (CTD) and its associated electronics, trigger and readout, were designed, constructed and commissioned by the UK groups. The CTD is a large volume drift chamber, 2.4m long and 1.7m in diameter, providing charged-particle tracking and momentum analysis over the central region. The CTD trigger and track information is essential for all physics analyses in ZEUS. The UK groups continue to be responsible for all aspects of the operation of the CTD. In the last year a great deal of effort has been devoted to increasing both the speed and the functionality of the CTD data acquisition (DAQ). In the period between the 1993 running and the 1994 running, the speed at which

the DAQ can accept first level triggers without unacceptable deadtime has increased from less than 100 Hz to around 450 Hz, and recent work implies that 600 Hz should be readily attainable. Features such as automatic pedestal subtraction and improvements to the pulse timing algorithm in the Flash Analogue to Digital Converter (FADC) system have been introduced. The structure of the CTD run control program has been improved and made more efficient. Stage I of the CTD first level trigger has been commissioned and is used in a variety of physics triggers. The final design for Stage II of the trigger has been completed and prototypes of the remaining boards tested during data taking. Production of the final trigger processor boards has begun and the full system will be operational for 1995 running. The CTD second level trigger has been optimised and largely rewritten to improve speed and functionality. A great deal of work has still to be done to improve the general slow control facilities and the high voltage control of the CTD. The maintenance, understanding and improvement of the CTD electronics and DAQ is a major and long-term effort which is being successfully undertaken by a team from the UK groups.

In the last year significant progress has been made in developing the CTD reconstruction algorithms and improving the understanding of systematic effects in the chamber. The data from the chamber are essential to all physics analyses requiring determination of the position of the primary interaction. The power of the chamber is particularly important in analyses involving the reconstruction of secondary vertices. As an example, Figure 1(a) shows the result of a search for the decay $K_S^0 \to \pi^+ + \pi^-$. A clear peak is visible at the known K_S^0 mass. Figure 1(b) shows a typical event in the detector. The secondary vertex at which the K_S^0 decays is clearly seen. A second team is energetically pursuing an analysis to improve further the understanding of systematic effects in the chamber. The same team is responsible for ensuring that the quality of the data coming from the CTD is maintained during the running period.

The Transition Radiation Detector (TRD), part of the Forward Tracking Detector (FTD) is primarily a Bonn responsibility, but considerable assistance with this has been provided by the Glasgow group. Successful operation of the TRD in ZEUS has been demonstrated, with signals from both electrons and pions, and with hits positioned correctly on extrapolated tracks. However, shortage of readout electronics has led to the temporary loan of the TRD read-out to the Rear Tracking Detector (RTD), since the RTD is crucial to improving the measurement of the scattered electron at low Q^2.

Although the ZEUS detector is mostly complete and functioning, there are still some components being commissioned and there are further upgrades planned. Most enhancements reflect the need to reduce systematic errors as the amount of data increases, or to improve precision in measurements of energies, positions etc. Another area of interest is the forward and rear low angle region: the very forward region is particularly important for diffractive physics; improving the coverage for electron (positron) measurements at small angles in the rear region allows regions of low Q^2 and hence low x to explored.

The Small-angle Rear Tracking Detector (SRTD) was installed during the 1993/1994 shutdown. This scintillator strip detector placed around the beam pipe is designed to improve electron (positron) position measurement in this important low angle region, and to identify electrons that pre-shower before reaching the calorimeter. It has been taking data during 1994, and the combination of the SRTD and Calorimeter information leads to a dramatic improvement in the electron energy measurement.

A new smaller beam pipe is being designed and will be installed in the 1994/1995 shutdown. This will allow improved coverage at small angles and give less material in front of the calorimeter, thus allowing improved measurements of the scattered electron (positron) at low Q^2. The new beam pipe will also create space in the inner region for a new or additional vertex detector.

In the very forward region the Leading Proton Spectrometer (LPS) detects protons scattered at very small angles and small transverse momenta ($p_T < 1$ GeV/c). Leading protons are expected in a substantial fraction of all neutral and charged current interactions, including low x and elastic and diffractive processes. The ability to tag and measure the leading proton improves the determination of the event kinematics. In 1993 the LPS was partially equipped and data corresponding to a luminosity of 28 nb^{-1} were collected. A resolution in x_L, the fraction of the proton beam energy carried by the forward proton, of 8 10^{-4} was achieved. Studies indicate that requiring a track in the LPS allows a clean and unbiased selection of high x_L events in the whole kinematic range. For the 1994 running the LPS was 80% complete and there is now about 1 pb^{-1} for which the LPS information has been recorded. Analysis of these data is beginning.

The Proton Remnant Tagger (PRT) consists of scintillator 'paddles' surrounding the beam pipe in the forward region at distances of 5m and 24m from the interaction point. This device, which provides energy and time measurements for particles which escape through the forward beam pipe hole of the central detectors, has recently started to be read out. The PRT will help to distinguish events with diffractive dissociation of the proton from elastic scattering.

Another element of the very forward detection system in ZEUS is the Forward Neutron Calorimeter (FNC). A test FNC used in the 1993 running led to the first observation of leading neutrons in *ep* collisions. It was found that about 8% of tagged photoproduction events and of deep inelastic scattering events with $Q^2 > 10$ GeV^2 have leading neutrons with energy greater than 400 GeV. Leading neutrons at HERA are expected to be produced through reggeon or pomeron exchange. An upgraded FNC, was installed in time for the 1994 running and studies of peripheral processes in *ep* collisions are underway. The complete FNC should be available next year.

Other elements of the detector which are still to be completed or commissioned are the forward and rear tracking detectors (F/RTD), calorimeter pre-samplers and the hadron-electron separators (HES). As already mentioned, the RTD is now being read out and will be used for physics; the first data taking with part of the FTD occurred in October 1993. The pre-samplers are layers of segmented scintillator which will be placed in front of the calorimeter modules to detect showering particles and correct for energy loss. A small prototype is currently in position in front of the rear calorimeter; this is being read out. Further modules have been beam-tested during the summer. The rear HES is complete and the forward HES is under construction.

Zarah.

The success of the ZEUS collaboration in carrying out a wide range of analyses and producing an enormous wealth of physics results in the past year has been due in large part to the computing facility known as Zarah. Zarah consists of Silicon Graphics processors with disks and peripherals and was purchased by DESY in the middle of 1993. Zarah has

proved essential for UK physicists working on physics analysis, both at DESY and in the UK, as it allows access to the complete 1993 physics sample and a representative sample of Monte Carlo data. All ZEUS event reconstruction is performed centrally at DESY on a dedicated farm of processors provided by DESY. The reconstructed data in mini data summary tape (MDST) format, as used for physics analysis, are then made available on Zarah. The data volumes involved are large: the 1994 MDSTs are expected to occupy 500 Gbyte of storage. The logistics and delays in transporting this data to the UK and ensuring that it is kept up to date would have seriously restricted UK analysis efforts. Due to the increased data volume in 1994 and the increased analysis load Zarah is to be upgraded and the costs borne by the collaborators.

Physics.

The 1993 data have already provided a rich physics output for ZEUS. Many analyses are still ongoing and we expect many more publications in the coming months. The physics accessible with ZEUS at HERA covers a vast range of topics many of which were presented, in preliminary form, at the 1994 International Conference on High Energy Physics (ICHEP) held in Glasgow in August. ZEUS submitted 26 abstracts and papers to ICHEP. Below we mention some of the highlights and areas where UK physicists are heavily involved.

The twenty fold increase in the amount of 1993 deep inelastic scattering (DIS) data compared to those of 1992 allowed a much better determination of the proton structure function F_2 (see Fig.2). Both the statistical and the systematic errors were significantly reduced and the range of the measurement was extended to both higher and lower Q^2 values. Prior to experiments at HERA there were discrepant theoretical predictions of the likely behaviour of the parton densities in the proton at low x. The strong rise of F_2 with decreasing x seen for the first time last year was confirmed with the 1993 data and led to the exclusion of models predicting a flat gluon momentum distribution in the proton. Whether this is evidence of the so-called Lipatov evolution or can be explained by the normal Altarelli-Parisi behaviour is still the subject of argument amongst theoreticians.

The gluon density in the proton is related indirectly to F_2. In leading order, scaling violations at low x are dominated by effects due to the gluon density and hence this density can be extracted from the slope $dF_2/d\ln Q^2$ using approximate solutions of the perturbative QCD evolution equations. This technique has already been applied to the ZEUS data of 1992; it is now being used on the F_2 measurements from the 1993 data together with an alternative method which performs a full next-to-leading order iterative fit to the F_2 data. A large contribution to F_2 from the gluon density is seen at low x.

The increased statistics of the 1993 data have permitted a more detailed study of DIS events with a large rapidity gap (LRG) between the outgoing proton system and the remaining hadronic system. Such diffractive DIS events were first seen by ZEUS in the 1992 data. The proton, or proton system, is not detected though this will be remedied by the new detectors in the forward region (FNC, LPS, PRT). The diffractive DIS process is modeled using the exchange of a colourless object, the pomeron, between the proton and the virtual photon. There are two different models of this process. In one the beam proton emits a pomeron whose constituents take part in a hard scattering process with the virtual photon or its constituents. The other model assumes that the exchanged photon

fluctuates into a $q\bar{q}$ pair which interacts with a colourless two-gluon system emitted by the proton. Both these models fit the data reasonably well though a hard, rather than a soft, pomeron quark momentum density is needed in the former in order to reproduce the data. Several fits to the distributions of the hadronic angle and the maximum observed rapidity in the event have been used to extract the fraction of diffractive events in the DIS sample. The fraction is about 10%, the value obtained depending slightly on the model used. The diffractive cross section has also been evaluated. Jet searches have been carried out in the LRG events both in the ep system and in the $\gamma^* p$ centre of mass system. Production of LRG events with transverse energy greater than 5 GeV in the $\gamma^* p$ system is saturated by jet production; this hard scattering and jet production support the idea of a partonic structure to the pomeron.

Studies are underway into exclusive vector meson production in DIS. A clear ρ^0 signal is seen in the 1993 data and earlier this year ZEUS presented the first measurement at HERA of the diffractive production cross section for ρ^0 mesons produced by the virtual photoproduction process $\gamma^* p \rightarrow \rho^0 p$ in the Q^2 range $(7 - 25\ \mathrm{GeV}^2)$. This cross section is predicted to depend on the gluon density in the proton and so may be useful for extracting this density. The properties of the ρ^0 events have also been studied and compared to diffractive electroproduction calculations based on vector meson dominance models and calculations in perturbative QCD as well as to similar data at lower centre of mass energies. The heavy vector mesons ϕ and J/ψ are also observed in DIS.

HERA offers a large kinematic range for the study of the hadronic final state system in DIS. One particular area of study has been the measurement of the scaled momentum and charged multiplicity distributions in the current region of the Breit frame, i.e. the region of the outgoing struck quark. These can be used to study QCD coherence effects in DIS and to test the universality of quark fragmentation by comparing with e^+e^- data. The growth in the mean charged multiplicity with Q is similar to the growth in e^+e^- experiments with the centre of mass energy and the evolution of the scaled momentum indicates a coherent evolution of the parton shower. The consistency with e^+e^-data affirm the QCD cascade picture.

The gluon content of the proton is the subject of intense theoretical and experimental interest. Several methods have been proposed to measure the gluon density in the proton indirectly via the scaling violations of F_2 (as mentioned above). The production of heavy quarks at HERA is sensitive to the gluon density at first order, and as such represents a direct and sensitive probe of the gluon density. Great progress has been made this year in isolating a signal for J/ψ and D^* meson production.

The J/ψ has been observed via its decay into electron and muon pairs. As an example the invariant mass of the electron pair in the candidate $J/\psi \rightarrow e^+e^-$ events is shown in Figure 3. The events found in roughly one tenth of this year's data are shown as the points together with a fit to determine the mass, width and number of events. For comparison the mass peak observed with the full 1993 data is shown as the hatched histogram. A publication is in preparation reporting the cross section measured using the 1993 data. The five fold increase in the luminosity in the 1994 data taking means that we expect to be able to study the events in much finer detail in order to study the gluon density in the proton.

The observation of D^* mesons demonstrates that the experiment is sensitive to the pro-

duction of open charm. The most sensitive way to search for the production of the D^* is to search for events in which the D^* decays to D^0. The D^0 is observed via its decay to $K\pi$ final states and the D^*, D^0 mass difference $m_{D^*} - m_{D^0}$ is formed. Figure 4 shows a plot of the mass difference in which a clear D^* signal is observed. Once again a paper is in preparation reporting the cross section measured using the 1993 data. The higher luminosity of the 1994 data means that the gluon density may be investigated using this data.

A paper in which the ZEUS group announced the first separation of the direct and resolved processes in hard photoproduction has now been published. This has opened new areas of physics, which are now being followed up. One of the topics in which ZEUS-UK have a particular interest is the identification of heavy flavours in hard photoproduction. Signals from K^0 and Λ particles have been identified in photoproduction events containing high-p_T jets, and these particles are found to be associated largely with the jets. Studies are in progress to measure the direct and resolved components of photoproduction events of this type, which will give new handles on the partonic content of the photon and the proton.

Searches for "exotic" particles have continued. These are particles which are not known to exist, but whose existence is suggested by analogy with the patterns and properties of other particles. The much increased luminosity now available has still given no examples of leptoquarks (decaying into an electron, or ν or μ or τ, and a quark) with standard couplings. This excludes the existence of these particles with masses up to 242 GeV/c^2. Similarly searches, again negative, for excited states of electrons have placed stringent limits on coupling strengths for masses up to 250 GeV/c^2. These searches are not yet limited by background; tighter limits (or else discovery!) will be provided by more data in this and subsequent years running.

Conclusions.

The luminosity of HERA has increased substantially over the last year and can be expected to do so again next year. Further modifications to ZEUS have improved its capabilities for physics, and the reliability of its components has improved as problems are ironed out, leading to improved running efficiency. HERA is a unique facility for studying high energy lepton-quark interactions. The increased data accumulated in this last year (and foreseen for the future) will sharpen the conclusions of analyses begun with earlier data and open further facets of this fundamental physics to experimental study.

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Figure Captions.

Fig. 1(a) Invariant mass of a sample of oppositely charged track pairs showing a clear K_s^0 mass peak.

Fig. 1(b) An event containing a K^0 decay in the CTD.

Fig. 2 The proton structure function F_2 as measured by ZEUS for different values of Q^2 as a function of Bjorken x. The error bars on the data are the sum (in quadrature) of the statistical and the systematic errors. The strong rise of F_2 persists up to $Q^2 = 500$ GeV^2. Five different F_2 parametrizations are also shown on top of the data points. From the lower Q^2 points it becomes clear that the lower MRSD$'_0$ curve assuming a flat gluon at low x can be excluded.

Fig. 3 Invariant mass of the e^+e^- pair for $J/\psi \rightarrow e^+e^-$ candidates (see text).

Fig. 4 $D^* - D^0$ mass difference (see text).

ZEUS Preliminary K_S^0 signal
mass=497.8±0.3 MeV/c²
σ=7.5±0.4 MeV/c²
K_S^0 fitted=909
Lumi=554 nb⁻¹
sec vtx candidates per 5 MeV/c² bin
300
250
200
150
100
50
0
0.4
0.45
0.5
0.55
0.6
0.65
reconstructed π⁺π⁻ mass, GeV/c²

Figure 1(a)

ZEUS
E= 30.6 Et= 11.5 pt= 0.5 pz= -15.3 E-pz= 45.8 Ef= 4.4 Eb= 7.5 Er= 18.7
Tf= 99.0 Tr= -2.5 Le= 0.0 Lg= 0.0 FNC= 8 BCN= 25 FLT=426E0000 01000000
e- x=.0003 y=.378 Q2= 10 DA x=.0004 Q2= 11 JB y=.239 phi [0.180]
Zeus Run 7239 Event 4489
11-Oct-1993 23:12:25.279 File --s/zdata/jdis2.7238_7447
π^-
K_s^0
π^+
XY
ZR

Figure-1(b)

F2
Q² = 8.5
Q² = 12
Q² = 15
Q² = 25
Q² = 35
Q² = 50
Q² = 65
Q² = 125
Q² = 250
Q² = 500
Q² = 1000
Q² = 2000
MRSD'_
MRSD'0
MRSA
CTEQ2D'
GRV(HO)
ZEUS
3
2
1
10-4
10-2
x

Figure 2

Diffractive J/Ψ
Events
35
30
25
20
15
10
5
0
2
2.2
2.4
2.6
2.8
3
3.2
3.4
3.6
3.8
4
Invariant Mass
[GeV/c²]

Figure 3

Events
35
30
25
20
15
10
5
0
χ^2/ndf 20.88 / 19
0.14
0.145
0.15
0.155
0.16
0.165
GeV
Mass Difference

Figure 4

The ATLAS Project

Alberta; Alma-Ata; Amsterdam (NIKHEF); Annecy; Argonne; Arizona; Arlington; Athens; Baku; Barcelona; Berkeley; Bern; Birmingham; Bonn; Boston; Brandeis; Bratislava; Brookhaven; Bucharest; Cambridge; Carleton; CERN; Chicago; Clermont-Ferrand; Columbia; Copenhagen; Cosenza; Cracow; Dortmund; Dubna; Duke; Edinburgh; Florence; Frascati; Freiburg; Fukui; Geneva; Genoa; Glasgow; Grenoble; Haifa; Hamburg; Harvard; Hawaii; Heidelberg; Helsinki; Hiroshima; Indiana; Innsbruck; Irvine; Istanbul; Jena; KEK; Kobe; Kosice; Kyoto; Lancaster; Lecce; Lisbon; Liverpool; QMW; RHBNC; UCL; Lund; Mainz; Madrid; Manchester; Mannheim; Marseille; MIT; Melbourne; Michigan; Milan; Minsk; Montreal; ITEP, Moscow; Lebedev, Moscow; MEPHI, Moscow; MSU, Moscow; Munich; MPI, Munich; Naples; Naruto; Nijmegen; Northern Illinois; Novosibirsk; Orsay; Oslo; Oxford; Paris (VI and VII); Pavia; Pennsylvania; Pisa; Pittsburgh; Prague; Protvino; Rio de Janiero; Rochester, Rockefeller; Rome (I, II and III); RAL; Saclay; Santa Cruz; Sheffield; Shinshu; Siegen; Southern Methodist Univ; St Petersburg (IFMO and NPI); Stockholm (Univ and KTH); Sydney; Tbilisi; Tel-Aviv; Thessaloniki; Tokyo; Toronto; TRIUMF; Tufts; Uppsala; Urbana; Valencia; Vancouver; Victoria; Washington; Weizmann; Wisconsin; Wuppertal; Yerevan.

The year 1994 has been a busy one for those working on the ATLAS project. Since the submission of the Letter of Intent [1] in 1992 the design of the detector has been further optimised and most options have been agreed. This work has culminated in the submission of the Technical Proposal [2] in December.

A significant change in ATLAS this year has been the assimilation of a large number of groups from non-member states of CERN who were formerly involved in experiments at SSC. ATLAS has been greatly strengthened by their admission, but their participation is subject to the satisfactory conclusion of bilateral agreements with CERN.

The overall detector concept remains unchanged (Figure 1). Inner particle tracking is performed in a central 'cavity' inside a solenoid. Calorimetry is in liquid argon (electromagnetic part and hadronic endcap) and scintillator tile (for the barrel and extended barrel hadronic calorimeters). Outside the calorimeters is the air-core toroid system, both barrel and endcaps, equipped with muon chambers.

ATLAS has benefitted from the extensive R&D programme detailed elsewhere in this compilation of experiments. Work is now concentrating on ATLAS-specific subdetector development and funds have been made available by the PPESP for this purpose.

The main activities undertaken by groups in the UK have been:

1. The air-core toroid endcaps, designed at RAL [3]. The proposal is for each endcap to be constructed from eight symmetrically distributed coils in a single large cryostat (Figure 2).

2. **Inner tracking [4] (Figures 3 & 4)**

   The ATLAS Inner Tracking System is designed to cover a rapidity range up to ± 2.5 with good momentum resolution, tracking efficiency and enhanced electron identification. At low luminosity the goals are to reconstruct all tracks, identify secondary vertices and K_s^0 decays and tag b-jets.

   These design aims are achieved by a combination of 'precision' tracking at low radius and 'continuous' tracking using straw tubes at large radius. The precision devices are Si pixels, Si strip detectors, GaAs detectors and MSGCs. At least six precision hits are the aim at all values of rapidity, with 36 straw tube hits on each track.

Figure 1: Three-dimensional view of the ATLAS detector installed in the underground hall.

Figure 2 : Transverse view of the ATLAS muon spectrometer in the underground hall.

Figure 3 : Three-dimensional view of the ATLAS inner detector.

a) Silicon strip detectors

This work is very extensive within the UK and forms a very substantial part of the UK activity on ATLAS. Progress has been made on silicon detectors, their associated electronics, module structure, mechanics, cooling, alignment and simulation software.

Prototype detectors (FOXFET biased) have been produced by Cambridge and QMW in collaboration with UK industry, for use in test beams and for radiation studies. RAL and Liverpool have produced prototypes of a different kind (double-metal) for evaluation.

For the electronics, a radiation hard front-end chip (APV3) has been designed at RAL and many measurements have been made in a test beam. Further developments under way include electronics for the clock and control functions and their signal distribution (Oxford - RAL), a sequencer for use in the test beam (RAL) and a readout module for ATLAS (Cambridge-RAL). Optical fibre data readout schemes are in progress at Birmingham (MQW devices) and Oxford (LEDs).

Cambridge, Liverpool, QMW and RAL have been working on the thermal and mechanical prototyping of silicon detector modules and functional prototypes for the test beam. The overall mechanics has been under careful study: various designs have been considered but most attention has been given to one based on beryllium staves (Figure 5). The overall cooling system has also received considerable attention with the evaluation of a 'binary ice' test rig for reliability. Binary ice is a two-phase system of ice and fluid which combines the advantages of high thermal capacity and constant temperature of the phase change. Work is in progress in Oxford on an alignment system for the inner tracking system using frequency scan interferometry.

Work has also continued on pattern recognition studies for the optimisation of the inner detector layout, and on physics studies of B meson decays in ATLAS.

b) GaAs detectors

GaAs detectors are much more radiation-hard than those in silicon and are being developed for those regions of the tracker (e.g. radii between 20 and 35 cm at Z = 144 cm) where the radiation dose is calculated to be highest.

Work has proceeded (Glasgow, Lancaster, Sheffield) on studies of charge collection, where earlier problems have been largely overcome and are now understood. A mechanical layout consisting of two GaAs wheels at each end of the inner tracker has been produced. Each wheel consists of a set of overlapping detectors, each detector measuring two stereo views 'u' and 'v' (the latter inclined at an angle of 1°) to give an $r\phi$ resolution of 20 μm and a radial resolution of 1.2 mm.

Further refinements and developments are in progress on details of the fabrication.

c) MSGCs

The current baseline for precision tracking in the forward region is the MSGC. It consists of 'small' annular discs between Z = 0.9 and 2.4 m from the interaction point and one 'large' disc at each end of the tracker. Each disc provides three coordinates (ϕ, u, v) to give a space point.

The natural geometry of the basic detector is a 'keystone' form of size approximately 130 x 160 mm^2 and with radial detector strips (Figure 6).

Fig 4: Details of the inner tracker layout

Fig 5: Design for a barrel Si cylinder

Fig 6: Details of the MSGC design

MSGCs have been developed over the past few years and used in current experiments. The further R&D required for ATLAS, which has been carried out by Birmingham, Liverpool, Manchester, RAL and UCL, has concentrated on the design of the keystone geometry, the developments of large area detectors of low mass, the sensitivity to neutrons and ageing (the behaviour under long-term irradiation). Many detectors have been built and tested [5], allowing a choice of design to be made. The large area has been achieved. A satisfactory substrate material (semiconducting glass) has been found which has excellent electrical properties and efforts are being made to find equally good properties in a lighter substrate. Neutron sensitivity will be measured on the Neutron Irradiation Facility at ISIS. Finally, a thorough study of the ageing of detectors as a function of gas mixture and purity, substrate material, metallization, etc. has been made and a combination of these factors has been shown to give satisfactory performance.

d) TRT

Work has continued in RAL on the front end electronics for the straw tubes. The signals are accurately shaped to cancel the ion tail and provide two levels of discrimination, a low level for minimum ionising particles to give high efficiency for track reconstruction and a high level for the identification of transition radiation photons, hence providing electron identification independent of the calorimeter.

At Glasgow, detailed analysis of test beam data has been performed to assess the behaviour of prototype straw tube arrays in beams of electron, pions and simulated jets.

3. Level-1 Trigger

Detectors at the LHC will have to handle raw data rates of order 10^{15} bytes per second. To this end, a 3-level trigger system is under study to reduce this rate by 10^7, so that only interesting event data from proton - proton collisions is recorded for subsequent physics analysis. The first level, consisting of custom designed hardware is expected to reduce the rate by a factor of 10^4, the second level by a factor of 10^2 and the third level by a factor of 10.

The ATLAS level-1 trigger system is based on calorimetry (electron, photon, jet, missing transverse energy triggers) and on muon detectors. The subtrigger processors work independently and in parallel to summarise the characteristics of the event for transmission to the central level-1 trigger processor where the overall trigger decision is taken. Birmingham, QMW and RAL are involved in the design and prototyping of a purpose-built, synchronous digital processor for the level-1 calorimeter trigger.

The main components of the calorimeter trigger (Figure 7) are the front-end digitisation and Bunch Crossing Identification (BCID) logic, a high speed transmission system, and processors identifying e.m. clusters, jets and missing-E_T. The electron/photon trigger at the heart of the system has been refined following detailed simulation work. The algorithm (Figure 8) identifies a localised deposit of energy in the ECAL, and optionally requires low energy deposit in the ring of e.m. cells surrounding the cluster and in the hadronic window behind it. The electromagnetic processing for an earlier version of this algorithm has been incorporated into an ASIC, and this was demonstrated in 1993 at the full LHC bunch crossing rate of 40 MHz.

Data Transmission

Transmission of data from approximately 8000 detector trigger cells into the trigger processor system is a major design issue for the calorimeter trigger. Assuming 8-bit FADCs with a sampling rate of 40 MHz, the total data rate is 320 Gbytes/s. Furthermore, data from each trigger cell participates in 16 copies of the trigger algorithm, and very large numbers of

connections are therefore required to ASICs, boards and crates. In earlier studies, a preliminary design had been developed in which information was sent asynchronously as a single, zero-suppressed 160 Mbits/s serial stream for each channel. However, more recent study has shown that the latency associated with the derandomizing buffers at each end of the link is unacceptably high.

In the current trigger design, optical signals from the detector are brought directly onto each module using 64 fibres, each fibre carrying information from two trigger cells at 640 Mbit/s. After optical reception, retiming and multiplexing, data enters the cluster-processing ASICs synchronously as two 160 Mbit/s streams per channel, using two I/O pins. This design is still evolving as our studies and prototype work continue and as new technology becomes available. However, it should be noted that the design has been studied in considerable detail, is based on technology available now or in the near future, and appears feasible both on cost and performance grounds.

Fig 7: Architecture of the ATLAS Level-1 calorimeter trigger

Fig 8: Electromagnetic Cluster-finding Algorithm

Bunch Crossing Identification

The signals from calorimeters proposed for ATLAS are slow compared to the 25 ns bunch-crossing interval. Hence, if the raw digitised signals are used, large energy deposits would be seen by the trigger processor for several consecutive bunch-crossings. This problem can be overcome by using signal processing techniques, which can be positioned near the FADC system. The process requires a filter in which the digitised data samples are convoluted to enhance any peaks, followed by peak finding logic.

A single-channel demonstrator module has built been [6] to allow evaluation of filtering and peak-finding algorithms.

Future Work

A new BCID demonstrator is currently being built which will consist of three 12-channel modules. The test beam work scheduled for 1995 will concentrate on BCID studies using these modules. A new FADC system is also being constructed by collaborators in Heidelberg, which will consist of nine 4-channel VME cards with diagnostic memories. The FADC system is an important component of the BCID work, as the effects of noise and pedestals can alter the performance of the BCID algorithms.

We have identified several key areas of the bit-parallel processor that require further study before a full level-1 system could be designed and constructed. We therefore plan a set of laboratory tests which will lead to a phase-2 bit-parallel demonstrator system to be used in 1996. We feel that our e.m. clustering algorithm has been adequately demonstrated by the existing prototype system, and we believe that putting more channels onto one ASIC in order to reduce the overall size of the system and its interconnections is a relatively straightforward task. Future work will therefore concentrate on high-speed optical and electrical signal handling, control of timing, and evaluation of remaining architectural options.

4. Level 2 Trigger

The level-2 system (see Figure 9) is split into local and global parts. A processor in the local system is used to process data from a specific, small region of a detector. Whilst a global processor is used to process data derived from all regions of all detectors. UK groups have been working on a demonstration system with responsibility for the local sub-system undertaken by UCL and RHBNC and for the global sub-system by the University of Manchester and RAL. Work at Oxford University, UCL and RAL is also focused on discrete event simulation of the system.

In the local part, guidance is taken from the level-1 system to extract fine grain raw data from the level-2 buffer to produce specific regions of interest (RoI) of the detector. The data is processed in feature extractors (FEX) to produce a feature (e.g. for a calorimeter this would be a cluster energy and position with some associated 'particle' classification).

The resulting features from all detectors participating in the level-2 system are then gathered together in a data concentration phase prior to passing through a network to the global sub-system. Here, features from different detectors which correspond to the passage of a particular particle or jet through the detector are combined and a probable particle identification assigned. Certain physical quantities are then evaluated for use in classification of events according to topology and likely under-lying physics processes. The end result is a decision as to whether to accept or reject the data.

The essential features to note are :-

- Localised processing of fine grain raw data.
- Reduction of required level-2 system input bandwidth by limiting processing to specified Regions of Interest.
- Parallel processing in both local and global sub-systems to achieve a design decision frequency of 10^5 Hz, but with a processing time of a few milliseconds for each event.
- System scalabilty to track the evolution of algorithms and corresponding physics goals.

Building Blocks

For the local sub-system, C40 digital signal proessors are used. Commercial units, namely DBV42 & DBV44 modules, provide a maximum of either two or four C40s per card respectively, and were used for all C40 processors. The level-2 buffer is implemented as a sister module to a C40 board and is designed to operate at up to 100 kHz.

Scalable Coherent Interface (SCI) provides a very high performance interconnect between processors and memory through a network of point-to-point links combining the advantages of backplane buses and traditional networking. SCI nodes are usually organised in a ring structure, with each SCI transaction consisting of request and response sub-actions. Since all SCI links can transfer data concurrently, there is no arbitration bottleneck.

All SCI interfaces were custom built from SCI node chips and high performance fifos. RISC, C40 and 68040 processor nodes were interfaced to the SCI ring.

Figure 9 Functional Architecture of a Level-2 System

Figure 10 Beam Test Set-up

Test Set-up

Figure 10 shows the interconnection of modules used to build the first test system. Data was derived from a HIPPI spy unit which formed part of a router system placed in the data readout path of a Transition Radiation Detector (TRD). Two channels were equipped to feed data into two level-2 buffers, each under the supervision of a C40 based buffer manager.

Data was fed through a link unit to enable routing of data to the appropriate FEX (again both C40 based). After feature extraction (a null algorithm in initial tests) the data was concentrated in the global gateway (another C40) where it was sent on to a SCI node for final processing by a global processor. Events were recorded at the global gateway by an OS9 system and at the target SCI node consisting of a DEC Alpha processor.

The whole system was self-triggered by the passage of an event on the TRD HIPPI lines.

The complete system was first successfully operated in the ATLAS test beam line at CERN during September/October 1994 using data from the TRD of the RD-6 collaboration. Parasitic operation ensured minimal disruption to other parts of the ATLAS tests and enabled the work programme to remain independent of other activities. Invaluable experience was gained in integrating with real detectors providing real data.

It is believed that this is the first time that 'live' detector data has been passed round an SCI ring at a beam line.

Simulation

Much work has gone into modelling the system using the MODSIM language and tools. Code has already been written and debugged. Performance comparisons with the test setup are now possible and proof of scalability to larger systems will be pursued.

Future Plans

It is planned to expand the scope of the project in the near future by enlarging the system to accept data from more than one detector and to field an adequate set of RISC global processors to handle the data. Proper feature extraction algorithms will be implemented, tailored to individual detectors. Features from different detectors for the same RoI must be matched and subsequently processed by a global algorithm to yield an overall Level-2 decision.

5. Software Development

Along with collaborators from Birmingham and Edinburgh, RAL has been active in the ATLAS Object Oriented (OO) group which is a major contributer to the CERN Research and Development project (RD41), known as Moose, which is studying the viability of the Object Oriented approach for software development for High Energy Physics reconstruction and analysis code at the LHC.

By working on some well defined prototypes, experience is being gained in OO analysis, design and implementation. It is planned, while constructing the prototypes, to learn from practical experience about requirements specification, project management and process control as they apply to software.

The large prototype being worked on currently is the reconstruction of electrons in the Atlas EM Calorimeter and Inner Tracker. A CASE tool is used to generate a skeleton system in Eiffel (an OO programming language). A simple object persistence scheme which should be adequate for this prototype has been constructed at RAL.

Methodologies are being studied using a small and easily modified CASE tool which was built mostly at RAL using an OO interpreted language.

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Thesis

R J Hawkings (Oxford 1994): Tracking and triggering using silicon detectors, and a study of Higgs physics at the Large Hadron Collider

THE COMPACT MUON SOLENOID (CMS) DETECTOR

UNITED KINGDOM

Bristol University; Brunel University; Imperial College, London; Rutherford Appleton Laboratory

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INTRODUCTION

The CMS (Compact Muon Solenoid) collaboration is proposing a general purpose experiment designed to run at the highest luminosity at LHC [1]. The detector has been optimized for the search for the Standard Model Higgs boson over a mass range from 90 GeV/c^2 to 1 TeV/c^2, but it will also be sensitive to a wide range of possible signatures from alternative electro-weak symmetry breaking mechanisms. Muons, photons and electrons will be identified and measured with high precision.

UK groups are involved in three main areas within CMS. Brunel, ICSTM and RAL have played a major role in the research and development of homogeneous media for electromagnetic calorimetry at LHC. As a direct consequence of this work, CMS has very recently chosen the crystal lead tungstate ($PbWO_4$) for the electromagnetic calorimeter in both the barrel and endcap regions. Brunel, ICSTM and RAL are involved in the readout electronics for the tracker. Bristol and RAL are involved in the trigger and data acquisition system.

Electromagnetic Calorimetry

Significant advances have been made over the past year in the development of crystals and glasses suitable for use at LHC. One of these materials is lead tungstate ($PbWO_4$). It has a fast scintillation emission at a wavelength of 450 nm with a yield of around 0.5% NaI(Tℓ). It has a short radiation length of 9 mm, making it very attractive as the active medium in the CMS electromagnetic calorimeter, since this is located within the magnetic field volume where space is at a premium. The crystal is radiation tolerant to 10 MRad, the level of performance required at LHC.

The UK has undertaken an appraisal of lead tungstate during the past year by constructing a prototype calorimeter and exposing it to high energy electron beams at CERN. The prototype consisted of a 6 x 6 projective array of $PbWO_4$ crystals, each with a 18 mm square front face and a length of 210 mm. The back face of each crystal was equipped with a 5 mm diameter Hamamatsu Avalanche Photodiode (APD) operating at a gain of 24. In front of the crystal array was a (demountable) preshower detector. This consisted of 16 mm of lead followed by a plane of 25 silicon strips each 2 mm wide.

The APDs were read out with preamplifiers which were custom designed and provided by RAL. They had a shaping time of 30 ns and incorporated voltage monitoring of the 280 V APD bias voltage (to ± 200 mV) and temperature monitoring (to ± 0.02°). The electronic noise per channel, determined mainly by the detector capacitance (80pF) and the APD leakage current (typically 350 nA), was approximately 3500 electrons rms, corresponding to 80 MeV.

The UK played the leading role in undertaking the lead tungstate test beam runs and in performing the subsequent data analysis. The response of the prototype array to 120 GeV electrons is shown in figure 1. The plot shows the distribution of pulse heights summed over 9 crystals, for beam particles entering a 15 x 15 mm^2 area of the central crystal. The energy resolution, taking into account the preshower information, is 0.81%.

Additional measurements made with photomultiplier readout give an energy resolution of 0.45% at 150 GeV suggesting that further improvements in the ultimate performance of a

lead tungstate calorimeter should be possible. Simulations of such a calorimeter have been carried out by ICSTM [2]. Figure 2a shows the background subtracted di-photon effective mass spectra with the peaks expected for an integrated luminosity of 2×10^4 pb^{-1} (the first 2 - 3 years of LHC running) for Standard Model Higgs particles at masses of 90, 110, 130 and 150 GeV/c^2. Figure 2b shows the (cross section x branching ratio) as a function of Higgs mass required to achieve 3, 5, 7, 10 and 15 σ signals above background, with an integrated luminosity of $2 \times 10^4 pb^{-1}$. The significance of the Standard Model Higgs signal is greater than 5σ for masses greater than 90 GeV/c^2.

The other area of electromagnetic calorimetry where the UK groups have played the leading role is in the development of scintillating glasses as a possible cost effective alternative to crystals. The most promising glasses studied so far are those based on hafnium fluoride with cerium fluoride doping. Considerable progress has been made in the past year, resulting in a material with properties close to those needed for particle physics detector applications. Furthermore, it has been established that some difficult-to-remove contaminants can be tolerated without compromising the performance, dramatically reducing the price of the raw materials.

Over 200 glass samples of various mixes have been made at Sheffield University and evaluated at RAL and Brunel. Glass samples have been exposed to neutrons using the ISIS neutron irradiation facility, and measurements of light yield and scintillation decay time have been made using the ISIS test beam. The best light yields obtained from glasses are somewhat larger than those measured for lead tungstate, and the temperature dependence of the yield (figure 3) is five times smaller.

This year has seen the production of the first large blocks of glass, $10 \times 30 \times 140$ mm^3, and these were tested with high energy electrons at CERN. The blocks have a light yield of approximately 40 photons/MeV. A PIPSS award was made to RAL, Sheffield University and Merck Ltd., to carry out further research into the production of large blocks.

Brunel has carried out radiation damage evaluation, optical annealing (after irradiation), and determination of the scintillation decay time components by correlated photon counting. The University was recently awarded a PIPSS award to continue work with the UK fine chemical company, Johnson Matthey, on the production of large quantities of cheap but appropriately purified hafnium fluoride. Staff from Brunel have taken part in test beam runs on glass at CERN, and have provided the linear photomultiplier and base assembly for pulse-height measurements.

Doping with indium has been shown to be a very effective way of improving the tolerance to radiation, but the very high degree of radiation hardness required to survive the harsh environment at LHC has not yet been achieved. This is currently one of the main drawbacks of glass compared to its crystal rivals on CMS, although further improvement in radiation resistance is anticipated.

On the other hand, excellent radiation hardness has recently been obtained with lead tungstate. This, combined with the overall rapid progress that has been made in developing and manufacturing the material, has enabled CMS to make a decision on the choice of ECAL technology much earlier than originally planned, with lead tungstate emerging as the clear winner. The UK groups will now concentrate their ECAL efforts on

lead tungstate; although the glass work will continue for a further year to complete the development for other detector applications.

The UK continues to take the leading role in the design of the barrel ECAL support structure for CMS. Finite Element Analysis for the carbon composite basket strucures, required to hold the lead tungstate crystals, has been carried out at RAL.

CMS TRACKER

The UK groups working on the CMS tracking system have based their contributions to the experiment on the R&D projects under way, mainly RD20 and RD23, in which they have been very active. Their principal interests are the silicon detectors, especially radiation damage issues, front end electronics, based on the RD20 developments, and the application of UK optical data transfer technology being developed by RD23. Work has recently begun on the design of the data acquisition interface which will allow UK groups to develop a full readout system. Work on the novel optoelectronic technology based on multi-quantum well modulators is under way in close cooperation with industry and will be strengthened from 1995 by a PPARC Industrial Support Scheme grant to Imperial College, in conjunction with GEC-Marconi.

The readout system proposed for CMS is an analogue system based on a front end chip development by RD20 and on the optical links being developed by RD23, which deliver data to a VME bus system in the experimental barracks [4]. Both gas and silicon microstrips are read out by the same overall system with minor modifications to the front end chips to accommodate the different detector characteristics. The main emphasis this year has been on demonstration prototypes of the CMS detectors and readout system. A series of double sided microstrip detectors designed for CMS at ICSTM is in fabrication, in collaboration with RD20. These use either stereo strips or pads to measure the second coordinate.

Each microstrip is read out by a charge sensitive amplifier with a time constant of 50ns, whose output voltage is sampled at the beam crossing rate of 40 MHz. The samples are stored in an analogue pipeline for 128 beam crossing intervals and, if a positive level 1 trigger signal is received, are deconvoluted by an analogue signal processor. This, in the case of the silicon, confines the analogue signal to a single beam crossing interval and enables measurement of signal amplitude and precise timing of the interaction associated with the hit. For MSGCs, the optimal signal processing is still under investigation but studies have shown that several variations of the deconvolution method (e.g. double correlated sampling) can meet the CMS requirements of high efficiency and a timing precision of two bunch crossings (figure 4).

The Preshape32 is a 32 channel version of the original RD20 preamplifier and shaper produced in a non-hardened form at MIETEC. Its principal purpose was to provide an amplifier to evaluate MSGCs at an LHC-like readout speed. In fact, once the chip was produced it was decided by groups in CMS to instrument sets of 128 channels of both silicon microstrips and MSGCs with Preshape32 chips and external line drivers to the ADCs for beam tests.

The tests were carried out successfully in July. Using 12.5 cm 50 μm pitch silicon double sided detectors, a signal to noise ratio of 27:1 was obtained, with a ratio of 22:1 on the

orthogonal 6 cm stereo surface. Measurements were made of the spatial resolution of the silicon/MSGC telescope and the behaviour of MSGCs in a 3T magnetic field. Of particular importance were direct measurements of digitised minimum ionising signal pulses from the MSGCs, which have been compared for the first time with simulations, and permit the study of signal processing algorithms optimised for MSGCs.

A silicon detector readout using a 32 channel version of the radiation hardened RD20 chip (APV3) was tested in a beam in September 1994, initially with multiplexed data transferred using coaxial transmission lines and, subsequently, using one of the 4 channel multi-quantum well modulator devices. This is the first time that such an optical data link has been used in an experimental situation and so the successful operation of both the front end chip and the link were significant milestones. The full offline data analysis is currently in progress (figure 5). Noise in the system is presently dominated by cross-talk in the pipeline which will be improved in the next version but the operation of the full readout chain, embodying several new technological developments, is a major step forward.

At Brunel, work has continued on the understanding of radiation damage mechanisms in silicon strip detectors. A clean laboratory for detector bonding and inspection has been set up. Hardware was contributed for the Si-strip beam line tests.

Physics studies have concentrated on the simulation of CP violating B decay channels, with both time independent and time dependent analyses being carried out [5] (figure 6). At present the tracking system is being re-optimised with two layers of pixels installed between 8 and 12 cm radius and some of the outer layers removed to contain the overall cost. The main goal is seen to be B tagging at high luminosity to enhance the discovery potential of the experiment [6].

CMS DATA ACQUISITION

The CMS data acquisition system (DAQ) will be required to handle unprecedented rates of data flow and event selection.

At the LHC design luminosity of 10^{34} cm^{-2} s^{-1} there will be approximately 10^9 interactions/sec. The 10^7 electronics channels of CMS will produce of the order of 100 MBytes of raw digitised information at a rate of 40 MHz. The task of the DAQ system will be to reduce this flow of data to 1 Mbyte sized events recorded at approximately 100 Hz for subsequent analysis. This will be achieved by using a combination of custom designed micro-electronics together with state of the art commerical hardware.

Figure 7 shows the key elements of the system. Data will be read out in parallel from the front-end subsystems into around one thousand fast dual port memory devices, each capable of buffering 1 kByte packets at a rate of several hundred Mbytes/second. This critical pathway from front end to DAQ memory, which will have a common architectural structure for all detector subsystems, is being designed by RAL. Data from the fast memories will be fed into an event-building matrix, and this will merge the information into an event filter based on a farm of advanced microprocessors with a combined power of 10^{12} instructions per second. Despite the extensive use of multiplexing at the front end, there will still be several hundred crates of electronics to be managed globally by workstation computers. RAL will coordinate the design and implementation of this high level control and monitoring system.

DAQ activities in the UK will be closely integrated with other UK contributions to CMS. Thus a DAQ test bench will be built around the tracker readout (see above) where the UK is already playing a leading role.

SIMULATION STUDIES AND TRIGGER

ICSTM, RAL and Bristol have undertaken simulation studies for the ECAL at CMS, particularly on the effects of radiation damage on detector performance [3].

Bristol is contributing to the design of the level 1 calorimeter trigger for CMS. The trigger logic will be based on searching for physics signals including electrons/photons, jets, isolated single hadrons and missing transverse energy. These signals will be combined with information from the muon chamber system in the global level 1 trigger logic. The electron/photon and the muon channels are expected to be the most important for LHC physics, and the electron/photon trigger is particularly challenging because of the large background from QCD jets. Currently there are two possible algorithms being considered for identifying electromagnetic showers in the calorimeter, and Bristol is carrying out simulation studies to compare their performance. Other work using a number of fast simulations has given inconsistent results, and these results will be checked against the full detector simulation. Bristol is also involved in the trigger hardware, designing a processor to collect together the results of the electron and other algorithms from different (η, ϕ) regions of the calorimeter and sort the results for use by the global trigger.

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Figure 1 The pulse height distribution obtained from a prototype array of lead tungstate crystals equipped with avalanche photodiodes, exposed to a beam of 120 GeV electrons.

Figure 2 A simulation of the sensitivity of a crystal calorimeter to the process $H^0 \rightarrow \gamma\gamma$, for an integrated luminosity of 2×10^4 pb^{-1}. (a) The background substracted mass spectrum in the presence of Standard Model Higgs particles with masses of 90, 110, 130 and 150 GeV/c^2. (b) The (cross section x branching ratio) as a function of Higgs mass, required to achieve signals with a significance of 3, 5, 7, 10 and 15σ above back ground.

Figure 3 The variation of light yield with temperature of HfF_4 glass doped with CeF_3.

Figure 4 Detection efficiency vs incident angle for MSGC signals using several signal processing schemes.

Figure 5 The signal to noise ratio for particles measured in a silicon microstrip detector read out using the first version of the complete CMS readout chain, including radiation hard front end chip and analogue optical link.

Figure 6 The time dependent asymmetry for B° decays simulated in the 1994 version of the CMS detector

L1T	Level-1 Trigger	ROC	Readout Controller
GTS	Global Trigger System	FED	Front-End Driver
TTC	Timing, Trigger and Control	RDPM	Readout Dual Port Memory
FPL	Front-End Pipeline	RDL	Readout Data Link
DER	Derandomiser	SFI	Switch Farm Interface
		EFC	Event Flow Control
		WSC	Work Station Cluster

Figure 7 CMS Data Acquisition : Key elements and communication paths

MEASUREMENTS OF THE SPIN STRUCTURE OF THE NUCLEON AT HERA

THE HERMES COLLABORATION Proposal 780

Alberta, Argonne, Caltech, Colorado, DESY, Erlangen, Frascati, Illinois-Urbana, INFN-Rome, Liverpool, Mainz, Marburg, MIT, MPI-Heidelberg, München, NIKHEF, New Mexico State, Pennsylvania, St Petersburg, TRIUMF, Wisconsin, Yerevan.

Introduction

The HERMES collaboration was set up to make high precision measurements of the spin structure of the nucleon. It will study spin dependent deep inelastic scattering from the proton and the neutron using the longitudinally polarised 27 GeV electron beam now available at HERA, in conjunction with internal polarised gas targets of hydrogen, deuterium and He-3. The scattered electrons will be detected in a magnetic spectrometer which also includes a Cerenkov detector for hadron identification. The experiment is currently being assembled in the HERA East Hall.

Experimental programme

A test experiment with an unpolarised gas target was put into operation in the East Hall during the 1994 HERA running period. It was used to investigate the possible sources of background in the detectors and also established that the gas targets can be operated at a realistic density without significantly reducing the (positron) beam lifetime. A large amount of development work was also carried out on the polarised beam. It is now possible to routinely obtain longitudinal polarisations of better than 60%.

The full electron spectrometer and the polarised He-3 target are being installed during the 1994-95 shutdown. It is planned to commission the experiment at the start of the 1995 running period and take data on the neutron spin dependent structure function during the later stages. The He-3 target will be removed and the H/D target will be installed in the electron ring at the end of this period.

Polarised Targets

The HERMES targets use a cooled thin walled storage cell, with open ends, through which the electron beam passes. The cell is fed by a high intensity source of polarised atoms. The polarisation production technologies are different for He-3 and H/D and in particular the H/D target requires a relatively high and uniform magnetic field over the volume of the target cell. The Liverpool Group is involved in the development and construction of both targets. In collaboration with the DRAL Applied Science Group, they have designed and commissioned a superconducting magnet to provide the H/D target longitudinal holding field. This magnet (fig 1) has been manufactured by a UK company and has now been delivered to DESY. The group is also responsible for the H/D target chamber (fig 2) and the cell cooling system for both targets. They are also involved in the design, development and construction of the components which minimise the effects of the wake fields, generated by the electron beam, on the target components.

Figure 1 The HERMES superconducting holding field magnet complete with external iron shield.

Figure 2 The HERMES hydrogen/deuterium target chamber with prototype polarised atom storage cell installed.

Integrated Transition Radiation and Tracking Detector for LHC

Glasgow and RAL

in conjunction with

Aachen, CERN, Dubna, Krakow, Lund, Moscow (MEPHI), Moscow (Lebedev), MPI Munich, Siegen, St Petersberg, Duke, Indiana, Pennsylvania

The RD6 collaboration has been developing a tracking detector with enhanced electron identification suitable for use at LHC. It is based on 4 mm diameter straw tubes filled with a Xe-rich gas mixture embedded in thin foils or foam to produce transition radiation X-rays from electrons. Such a detector forms an essential part of the proposed ATLAS detector [1].

RAL Electronics Division has been responsible for providing a fast, low-noise, amplifier-shaper-discriminator with two levels of discrimination; one low threshold for the tracking of all particles, one high threshold for signalling the large energy deposits of transition radiation photons. The control and threshold levels are provided by a second chip which receives the small signals from the front-end and converts them into CMOS for onward transmission. For operation at the high rates expected at LHC, the shaping of the signal is crucial in order to cancel the long tail produced from the movement of the positive ions in the chamber gas. In 1994 an improved version of the front-end ASIC was produced, as before in bipolar technology, to make better cancellation of this tail. Further evaluation of this circuit will continue in 1995. Tests have been made of the radiation resistance of this bipolar chip, for both charged particles and neutrons, and the results are very promising, indicating that this technology may be adequate for LHC needs. For the following CMOS chip, further work in specifically radiation-hard technology will be necessary. Further developments in miniaturisation are envisaged to match the small space available for the electronics in ATLAS.

Essential to the development of the detector has been an extensive test-beam programme over the past few years. Analysis of these data has been performed in Glasgow, particularly of the particle identification capability of the detector, which was exposed to beams of electrons, pions, photons (including conversions) and simulated jets. As an example, Fig 1 shows the separation between pions and electrons achieved using a threshold of 5.5 keV, and Fig 2 shows the pion rejection as a function of this threshold. Although these data were taken with no magnetic field, the results in a magnetic field are very similar.

[1] ATLAS Technical Proposal. CERN/LHCC/94-43

Figure 1: Clusters above 5.5 keV for 30 GeV electrons (full line) and 20 GeV pions (dashed line)

Figure 2: Rejection vs energy threshold for TR-clusters at B=0

OptoElectronic Modulator Readout for LHC Tracking Detectors. P803

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Introduction

Data transfer from the frontend is only feasible via optical fibre links, which reduce the volume of material by a factor of ten compared to copper twisted pairs and the number of radiation lengths of material by a factor one hundred. Ground loops, electronic pickup between channels and high power drivers are eliminated. Possible means of converting the electronic signals at the frontend to optical signals rely on either active elements (lasers or LEDs) or passive modulators. In the case of modulators the light source is a laser at the electronics barrack and the light is piped by fibre to the modulator. Electronic signals applied to the modulator affect the light level it transmits or reflects; and this modulated signal is returned to the electronics barrack via optical fibre. Of the two possible modulator technologies investigated the RD23 collaboration (1,2,3,4,5) has found that, while both are functionally satisfactory, that based on Multi Quantum Well (MQW) modulators is preferred because the device size is compact and the potential for using monolithic optoelectronic integrated circuits at the electronic barrack offers cost and manufacturing advantages. The design, construction and proving of this technology has been carried out by the RD23 Collaboration (spokesman: G. Stefanini) (1,2) which includes GEC-Marconi Defence Systems at Stanmore UK.
Compared to readout with active devices at the frontend the modulator approach offers an intrinsically radiation hard technology, whereas diodes or lasers relying on minority carrier processes are more susceptible to radiation damage. Furthermore the level of power consumption and heating is reduced to a negligible level with modulators.

Proposed System

Data transfer from the frontend will be over monomode optical fibre, with the conversion from electronic to optical signals being performed at the frontend by MQW modulators at an optical wavelength of 1530nm. At the electronic barrack, photodiodes on the readout board will recover the electronic signals. Also located at the headend (readout board) will be the lasers that pump the light to the modulators. A single fibre carries the light from the laser to the the modulator and also returns the reflected modulated beam to the photodiode. At the headend an optical splitter couples the laser and photodiode to the fibre. The lasers, photodiodes, couplers and light guides will be constructed in compact Opto-Electronic Integrated Circuits (OEICs). The optical link transfers the electronic signals from the front end to the electronics barrack with frequency independent unit gain, zero cross-talk and negligible increase in noise level. It is essentially transparent. There are several architectures being considered for the frontend requiring either analogue or digital signal transfer from the frontend; all of which can use MQW modulators for signal transfer. The link components are intrinsically radiation hard, and a full link will be tested to levels of radiation expected from 10 years of LHC operation. Several modulators are expected to be packaged together, the package having a footprint of 10mmx8mm or less and a height of 6mm or less. The whole system - modulator, packaging and fibre does not appreciably add to the radiation lengths of material or mass of the detector.

Device Characteristics

The MQW modulators have input capacitance of 1pF and input resistance of 1MΩ. Operation is at a bias of -7V currently with response being linear to 2% for signals of 1.5V amplitude. Dynamic range is currently ≈100:1 with an improved range expected from devices now being manufactured. The electric current drawn through a modulator under bias is $\approx 10\mu A$. Overall heating from all processes is only milliwatts per modulator. This includes Joulean heating, dissipation of absorbed light and light lost in couplings. Bench tests currently in progress at 40MHz analogue operation at Birmingham are encouraging. The temperature range is likely to be -5^0C to $+15^0C$ around the selected operational temperature; and should be adequate to allow low luminosity running without cooling at the detector as well as high luminosity running with cooling Studies at Birmingham (4) show that up to magnetic fields of 4T there is negligible change in the MQW characteristics. The device structure in III/IV material is inherently radiation hard. Thus far negligible change in the characteristics of MQW material reflectivity has been observed at neutron fluences of a few $10^{14}\, n/cm^2$; exposure to gamma radiation at LHC ten year levels is now in progress. Radhard fibres and connectors are available.

Architectures

Currently CMS have selected analogue signal transfer as part of their baseline technology. ATLAS are evaluating several architectures including analogue signal transfer. With analogue signal transfer from the frontend each modulator would have 128 electronic analogue levels multiplexed onto it at 40MHz. This signal train would be preceded by a header of four clock cycles with levels provided by the frontend chipset: full on, full off, then two voltage levels (the first high, the second low). The transitions from the first pulse pair would provide a initialization signal at the readout board; while the second pair would provide calibration pulses for each analogue channel. A package of 8 modulators would service one silicon module of the SCT, that is 1024 strips (electronic channels). Corresponding packaging is foreseen for the GaAs and MSGC readout. With digital signal transfer the output of ADCs on the frontend chip will be multiplexed onto modulators after sparsification. This will typically involve multiplexing from 512 or 1024 electronic channels onto one modulator. In this case there would be either two modulators or one modulator for digital signal transfer in each package mounted on a single SCT silicon module. The total number of modulator packages would be unchanged from the analogue readout case; however each package would have fewer fibres emerging.
Additional fibre connections are necessary between the frontend and the electronics barrack to bring in clock and control signals. It is possible that these lines may use MQW photodiodes at the frontend mounted in the same packages as the modulators or adjacent to them. The design of this facet of optoelectronic signal transfer is not as far advanced as that for signal transfer from the frontend.

Current Testing Programme

The programme already approved by the PPESP in the UK and by the CERN DRDC for RD23 is to have ten complete 4-optical channel links available. At this moment beam tests are due to start shortly of the first phase II 4-channel modulator package in the full analogue readout chain for CMS. In Summer 1995 a full scale ATLAS analogue readout

chain will also undergo beam tests; this chain is being built by Birmingham, Cambridge, Liverpool, Oxford, Queen Mary and Westfield College and Rutherford Appleton Laboratory. The CMS and ATLAS optoelectronic links have discrete components (lasers, photodiodes and optical couplers) at the readout board.

Future Developments

In parallel the RD23 collaboration will be designing, fabricating and testing OEICs for the headend. By the end of 1995 RD23 aim to complete all the necessary tests on prototype MQW multichannel modulator packages; including irradiation, temperature and magnetic field response; and also to have prototype OEICS. The final prototype MQW modulators and packaging incorporating experience from bench and beam test results will then be available. Thereafter, of order 50 of the final protoptype 8-channel links would need to be purchased by ATLAS and CMS for their programmes in 1996. For the full analogue readout architecture these links would have 8 fibres carrying analogue signals out. In the event that the full digital readout architecture is preferred then a similar number of links would be needed for the ATLAS BSP programme (6), each with 1 or 2 fibres carrying out the digital signals. Additional control, level 1 trigger and clock signals would be routed on optical fibre from the headend to the frontend, and one possibility being actively investigated is that MQW photodiodes (possibly on the same substrate as the modulators) could be used to convert the inboard optical signals to electronic signals. Additional modulators and fibres could be included in the modulator packages to provide spares should this appear prudent. In the next section a detailed description of a specific, but not final, analogue link is given.

Full analogue link

These are the components of a possible full analogue link for a single silicon module with 1024 strips and area 6cmx12cm:
1) 8-channel modulator and 2 channel photodiode assembly with 2 spare modulators; with 10m long radhard monomode 12way fibre ribbon cable terminated by MT 12way snap fastening connector, also radhard.
2) 90m long 12way monomode optical fibre ribbon cable with MT 12way snap fastening connectors at each end; ribbons will have protective sheathing and be merged into ~1000 fibre cables over the run from the detector to the electronics barrack,
3) Optoelectronic integrated circuit (OEIC) incorporating 8 channel photodiode receiver and transimpedance amplifier, bandwidth 300MHz, 1530nm laser source(s); 2 channel transmitter for clock and control signals transfer to frontend at 40MHz; 12way monomode optical fibre pigtail terminating in 12way MT snap connector on an optical backplane.

Table of System Characteristics

Parameter	Range/Performance
Dynamic range	≈100:1 (now)
Bias	-7V
Max voltage swing with 2% linearity	$\pm 1.5V$
Operational Temperature range	-5^0C to $+15^0C$ round selected temperature
Magnetic field range	0 to above 4T
Radiation resistance	MQW material tested to $10^{14} n/cm^2$ γ irradiation in progress
Operational wavelength	≈ 1530nm
System bandwidth	≥ 300MHz
Heating/channel	2mW
8-modulator package size	8mmx10mm footprint ≤ 6mm high

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RD-8/ Status
October 24, 1994

STATUS REPORT OF THE RD8 (GaAs) COLLABORATION

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University of Sheffield, U.K.
ANSTO, Sydney, Australia
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The main objectives of the collaboration are: -

- fabrication and testing of simple GaAs detectors for charged particles and X-rays
- understanding of the properties and limitations of these simple, pad detectors
- investigation of alternative wafer materials and detector fabrication technologies
- fabrication and testing of prototype microstrip detectors to LHC specifications
- demonstration of the radiation-hardness of GaAs detectors and understanding its limitations
- encouraging the commercial production of GaAs microstrip detectors
- developing a detailed understanding of the costs of commercial detectors
- design, fabrication and testing of GaAs pixel detectors

Charge Transport Studies

Progress has been made in the understanding of charge transport and trapping in GaAs and of the variability of performance of our first microstrip detectors. Monte Carlo models based on this improved understanding, now give a reasonably complete prediction of their response to various sources of ionising radiation. We believe that GaAs detectors are now a credible option for the proposed Large Hadron Collider and also for a wide variety of applications outside of High Energy Physics.

The industry standard LEC (Liquid Encapsulated Czochralski) GaAs wafers contain traps which adversely affect particle detectors. Material from a range of suppliers and subjected to a range of annealing techniques which vary the concentrations of trapping centres are being studied in an ongoing search for the optimum material. Epitaxial growth techniques, (LPE, VPE), have also provided very good detector material, but it is difficult at present to reach the necessary quality in the layer thicknesses of $> 100\mu m$ required for high energy physics applications at an affordable cost.

While LEC GaAs detectors suffer from incomplete collection of the charge released by traversing ionising particles, with careful surface finishing the charge collection efficiency in all of a recent sample of 80 simple Schottky diode detectors is at least 70%. *p-i-n* detectors [1] are an alternative to the Schottky diode approach. The eventual choice of fabrication technology will depend on the level and consistency of performance obtained and on cost.

Investigations have been made of the electric field distribution through the thickness of sample detectors, using an extensive range of techniques [2, 3, 4, 5]. Detailed analysis of current pulse shapes from alpha-particles in simple detectors [6, 7] has also provided information on charge trapping. Systematic characterisations of wafer material and contacts have also been carried out [8]. Taken together, these experiments support a model [9, 10, 11, 15, 14] in which the electric field is relatively uniform through a "high field" fraction of the wafer thickness and falls to rather low values for the remainder. In the first region, which increases roughly linearly in thickness with reverse bias voltage [13], the charge collection efficiency is high. In the remaining, "low field" region the field is not capable of sweeping out the electron-hole pairs released by ionising radiation. Figure 2 shows the good agreement between predicted and measured Landau distributions due to m.i.p.'s for different detector bias voltages. The experimentally-measured electric field distribution is also in reasonable agreement with the model predictions.

Ongoing attempts to understand the above behaviour in terms of the energy levels and concentrations of electron and hole traps and wafer annealing effects in the semi-insulating GaAs [6, 16, 17, 18, 11, 12], while providing some suggestive evidence, have not yet supplied a definitive explanation of the detector behaviour.

Microstrip and Pixel Detector Results

Progress has been made in reach-through biasing methods for GaAs microstrip detectors [22], as illustrated in Figure 3. Prototype microstrip detectors have also been fabricated using the technology

Figure 1: Electric field profiles across the thickness of S.I. GaAs Schottky detectors; (a-c) using a photon beam, (d) by direct voltage probing

(a) 200V (b) 400V

Figure 2: Comparison of Monte Carlo simulation of response to minimum ionising particles (m.i.p.s) and measured pulse height spectra at two bias voltages in a $350\mu m$ thick Schottky diode detector

Figure 3: Bias strip operation of GaAs microstrip detectors

(a) Profiling method

(b) Charge carrier concentration

Figure 4: Profile of Russian microstrip detectors fabricated in Tomsk

of in-diffusion of Fe or Cr deep-level donors into the semi-insulating wafer [23]. The material profile is illustrated in Figure 4. Analysis of test beam results from these detectors is in progress. Studies of the radiation hardness of microstrip detectors of this type are also under way.

The first commercially-made LHC prototype, 50 micron pitch microstrip detectors, 200 microns thick, were received from Alenia SpA on August 1st, 1994. Preliminary analysis of data collected with one of these detectors obtained a spatial accuracy of $\approx 14\mu m$, consistent with $(pitch/\sqrt{12})$, from fits to tracks through the GaAs detector under test and the four layers of the Strasbourg group's silicon microstrip telescope [25]. A set of commercial prototype microstrip detectors has also been produced recently by E.E.V. in the U.K.. These are presently being extensively studied in the laboratory before evaluation in a test beam.

Prototype GaAs pixel detectors, fabricated in Glasgow early this year, were bump-bonded to the Omega2 read-out chip by GEC-Marconi, Caswell, and tested in a CERN test beam together with two silicon pixel detectors of identical geometry [24]. The beam profile detected from coincident hits in the three detectors is shown in Figure 5.

Radiation Hardness Studies

75 detectors made in Aachen from SI-GaAs (VGF) with $3mm$ diameter (NiCr/Au) contacts were irradiated at the ISIS facility at RAL. Fig.6 shows characteristic I-V curves before and after n-irradiation with a dose of 10^{15} n/cm^2 [28]. The increase of reverse current corresponds to a "damage constant", α_n of $\approx 10^{-19} A/cm$. The signal from ^{90}Sr electrons (mips), shown in Fig.6 as a function of the neutron flux for different bias voltages, is $\sim$ 8000 electrons even at the highest radiation level, while the noise, for a shaping time of $1\mu s$, shows an increase of only 10% - 15%. The most promising results so far on neutron radiation resistance in GaAs have been obtained in tests of detectors made in Tomsk [23]. The variation in response of these detectors with neutron fluence is illustrated in Fig.7.

Gamma-ray and electron irradiation of simple pad detectors up to 1 MGy (100 MRad), as illustrated in Fig.8 [30] produces only minor deterioration in performance.

Tracking Studies for LHC Applications

The main aims of our ongoing studies are:

- to attempt to understand neutron radiation damage mechanisms and how to ensure effective operation of GaAs microstrip detectors for neutron doses up to at least $5 \times 10^{14} n/cm^2$

(a) Beam profile

(b) Discriminator threshold scan

Figure 5: Results of tests of first pixel detector in GaAs

- to determine the optimum microstrip pitch and aspect ratio for GaAs tracking elements
- to evaluate the extent of any "dead zone" between microstrip electrodes
- to determine the most effective biasing and decoupling arrangement for both single-sided and double-sided detectors
- to evaluate the performance of our GaAs detectors with prototype LHC rea-out electronics. As a first step, a simple Tomsk detector tested at CERN using the LHC prototype BIPOLTEST read-out chip [31] gave a signal above 20000 electrons, in good agreement with the 95% charge collection efficiency measured by the Protvino group [32]. The measured pulse height spectrum due to m.i.p.'s is shown in Fig.9
- to carry out further work on GaAs pixel detectors, both on semi-insulating and on LPE epitaxial GaAs layers

Conclusions

We have demonstrated that we can make GaAs microstrip and pad particle detectors routinely and reliably. For the 200 micron thickness we propose for LHC applications, GaAs microstrip detectors will work as well as 300 micron thick silicon detectors, with fewer operational complications. The material penalty to be paid is an additional $0.54\% X_0$ for GaAs layer relative to a 300 micron thick silicon layer. The read-out electronics can be identical in the two cases. Pixel detectors in GaAs offer increasingly interesting scope for applications at the LHC and elsewhere.

Figure 6: Collected signal charge and noise signal from simple, 3mm diameter electrode GaAs detectors versus neutron dose

Figure 7: Variation of collected signal charge with neutron dose for Tomsk detectors

Figure 8: Effects of irradiation of pad detectors with 1 MGy of gamma-rays and 3MeV electrons

Figure 9: Pulse height due to minimum ionising beta particles measured with an ICON preamplifier on a Tomsk pad detector

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SDC Experiment

Bristol, Liverpool and Oxford Universities, and RAL

With the demise of the SSC during 1993 work on the SDC experiment has terminated. However much of the progress in R&D in silicon detectors, electronics and gas microstrips has been transferred to the LHC experiments, ATLAS and CMS, by the scientists moving to these new collaborations. High energy *pp* physics remains their objective and the LHC will provide the opportunity to study such physics.

Development of High Resolution Silicon Strip Detectors for Experiments at High Luminosity at LHC

RD20 **Proposal 807**

NCSR Demokritos Athens, Bonn University, Comenius University Bratislava, CERN, INP Cracow , FNPT Cracow, MPI Heidelberg, Liverpool University, Brunel University, Imperial College London, CPPM Marseille, Oslo University, SINTEF Oslo, INFN Padova University ,INFN Roma Sanità , Rutherford Appleton Laboratory, LEPSI Strasbourg, INFN Torino, Uppsala University, IHEP Vienna , PSI Würenlingen

1 Introduction

The aim of this project is to develop the elements of a high spatial precision tracking detector for use in LHC experiments based on silicon microstrip detectors and radiation hard front end electronics. The main emphasis has been on:

- design, production and systematic evaluation of prototype microstrip detectors and a large range of associated test structures. The studies have included measurements before irradiation and after exposure to doses of 10-20Mrad and neutron and minimum ionising particle fluences up to ~$4\times10^{14}.cm^{-2}$
- the development of a high density, front end electronics chip with adequately low noise, precise timing and minimum power in a radiation hard form,
- studies of low mass cooling schemes and the development of light and stable mechanical support structures, including tolerance to high radiation levels.

2 Detectors

The work carried out by RD20 falls into two categories, microstrip detector design and evaluation and bulk damage studies.

Microstrip detectors

A large range of devices have been produced at SINTEF in several dedicated production runs; in addition test structures and full size detectors from CSEM, Micron Semiconductor and Tesla have been delivered. Most of the detectors have been produced using high resistivity silicon from Wacker. A wide range of strip geometries have been tested leading to the production of full size LHC prototypes using 50μm pitch strips in 64mm lengths. Single sided polysilicon biased, a.c. coupled LHC detectors have been produced and double sided detectors incorporating p-stop isolation, with stereo and pad layout of the ohmic surface, are in production.

Initial studies were on the components of junction (p-side) detectors; subsequently attention has focussed on the ohmic surface in view of its importance for double sided readout detectors. The principal conclusions from this work are that, while the detector lifetime is ultimately limited by bulk damage, the surface components used in silicon microstrips are very capable of long term operation at LHC. Polysilicon resistors and integrated capacitors are very stable and the use of silicon nitride as a dielectric can lead to improved resistance to failure from oxide pinholes during operation as well as increasing the value of coupling capacitors. This is valuable in view of the higher operating voltages foreseen at LHC. Interstrip isolation on the junction surface alters during irradiation due to substrate doping changes but the value after many years high luminosity LHC operation is within a tolerable range (fig.1).

Fig. 1. p-side interstrip resistance

Fig. 2. p-side interstrip capacitance

A comparative study has been made of other device parameters, in particular strip capacitance, which is the dominant factor in the noise of LHC readout electronics. Values of 1.2-1.4pF/cm are expected for p-side strips on 50μm pitch. Although there is an increase in this value after ionising irradiation, in the high frequency range of LHC amplifier operation the change appears to be no more than 10-20% (fig.2).

The n-side studies have compared field plate and p-stop isolation techniques. For field plate devices, interstrip isolation is achieved by holding a voltage across the field plates greater than the oxide flat band voltage. It was demonstrated that good interstrip isolation for these devices can be maintained, provided that a minimum of 60-80V is held across the coupling capacitors. Both techniques have been demonstrated to be usable but field plate detectors suffer from microdischarges at the edge of overlapping metal which creates difficulties for high voltage operation. For p-stop devices, isolation is dependent on the p-stop doping concentration; with a doping of 5×10^{13} cm^{-2} the isolation resistance remained high (fig. 3).

Fig. 3. Interstrip resistance of p-stop detectors.

For the ohmic surface before irradiation, field plate and p-stop devices of matching geometries were seen to have similar capacitances. After photon irradiation, the capacitance of field plate strips increased only marginally. P-stop strip capacitances were observed to increase by as much as 25% at 1MHz, but for devices previously irradiated with fast neutrons the increases were seen to be much smaller (fig. 4) due to an accompanying increase in p-stop voltage caused by bulk damage. A dependence on the processing technology has been observed which is under investigation; it seems possible that the nitride used in the main series of RD20 prototypes may be beneficial for interstrip capacitance.

Fig. 3. Interstrip capacitance of p-stop detectors measured at 100V bias and 1MHz.

Bulk damage

Doping changes have been observed during and after irradiation with neutrons, protons and pions and long term observations of the annealing behaviour carried out. The damage constants for different particles have been measured as well as annealing of the bulk leakage current. Preliminary results from recent pion irradiations indicate that 190MeV pions exhibit similar damage to 1MeV neutrons.

The major bulk damage effect is that the effective impurity concentration, N_{eff}, of n-type detectors reduces with neutron fluence and becomes p-type after about 10^{13} n.cm^{-2}. This is called the inversion fluence, above which N_{eff} for both p- and n-type detectors increases linearly with fluence at almost the same rate. Irradiated detectors also become more p-type with a time constant of several months at room temperature (fig. 4), which can be halted for temperatures below about 5°C. This makes it essential for the detectors to be cooled during operation. Since the doping concentration determines bias voltage, a lifetime fluence above 10^{14} cm^{-2} appears feasible with bias voltages up to 150V.

Fig. 4 Annealing of the effective doping of diodes irradiated almost to, and beyond, type inversion.

The origin of the changes in doping concentration during irradiation is still poorly understood in terms of elementary defects so Deep Level Transient Spectroscopy (DLTS) has been used to identify defects, measure introduction rates and study annealing at the microscopic level. A model of the defect kinetics has been developed and a semiconductor simulation, including defects, carried out which appears to be adequate to explain many of the observations (fig.5). It suggests that a single or small number of deep levels within the silicon band gap are the probable origin of the effects observed and that the level of oxygen and carbon in the material may influence their evolution in realistic conditions. Further tests of this are under way.

Fig. 5. N_{eff} vs 1 MeV neutron flux for n- and p-type silicon; data compared with model calculations.

3 Electronics

The RD20 front end chip is based on a 50-75nsec time constant amplifier and an analogue pipeline followed by an analogue signal processor, which implements a deconvolution algorithm, to limit the output pulse to a single beam crossing interval (fig. 6) . The pulse processing is carried out by forming a weighted sum of consecutive temporal samples of the amplifier output voltage using a switched capacitor circuit. Important specifications are low power consumption (~2mW/channel), low noise (below about 2000e for the system lifetime, including radiation damage effects) and timing resolution of a single beam crossing. The chip is being developed in two forms, as a non-hardened prototype (FElix) and in radiation hard CMOS technology (APV series), with investigations of specific RD20 designs in alternative radiation hard processes also under way.

Fig. 6 Schematic of the RD20 front end chip.

Fig. 7. Response of an RD20 amplifer, before and after the deconvolution operation.

A 32-Channel FElix chip has been tested, with a noise performance of $ENC(e) = 386 + 34/pF$, measured for an input FET drain current of 600μA and pulse peaking time of 75nsec. The full functionality of the digital control part and the analog circuits was tested in the lab with a BCO clock of 40 MHz, prior to beam tests.

The APV3 is the 32 channel radiation hardened chip produced in the Harris 1.2μm AVLSI-RA bulk CMOS process. The pipeline has a length of 128 elements plus buffers. The chip was successfully tested during summer 1994 in lab and beam. Noise from the amplifier was measured to be$ENC\ (e) = 550 + 50C_{load}(pF)$.. The weighting function, which is the effective impulse response of the filter , is shown in fig. 8. The APV5-RH is the 128 channel successor to the APV3 chip which also includes a 40MHz multiplexer. It is expected to be delivered in January 1995.

Fig. 8. The measured weighting function of the APV3.

Fig. 9

Fig.9 shows the residual distribution of tracks in detectors in a 100 GeV π^- beam. It shows the spatial resolution obtained with a detector with readout pitch of 50μm measured with the FElix chip and of a

detector with 200μm readout pitch measured with the APV3 chip, determined using the deconvoluted amplitude.

Detailed characterisations of transistors and amplifiers in the Harris process have been carried out, mainly in the range up to 10Mrad. The principal conclusions are that threshold shifts are below a few hundred mV, and for PMOS transistors transconductance and noise show very minor changes after irradiations to 10Mrad while in NMOS devices more significant changes are observed. Critical transistors in this design are PMOS so these results are very satisfactory and further irradiations of Harris transistors have demonstrated hardness in excess of 100Mrad. Similar characterisations are underway using the DMILL technology, where an amplifier of the RD20 type is in production.

4 Mechanical studies

Studies have been carried out on several solutions to the problem of constructing a silicon tracking system, using helium gas, heat pipes, evaporative and liquid based cooling schemes. A compilation of data on the properties of materials of interest has been prepared and studies on the properties of composites and adhesives have been carried out, including irradiation of samples and experimental work on the thermal resistance and lifetime of adhesives.

A section of one possible silicon tracker was tested in a gas stream of air or helium. The mechanical stability and susceptibility to vibration was studied and the cooling power of the gas was measured with an infrared thermometer for different power densities and gas flow conditions. The results indicate that gas cooling of silicon detectors is feasible and gives acceptable temperature distributions. Helium gas gives significantly better results than air, although further studies are required to understand some of the behaviour. It was also shown that, since finite element thermal modelling only takes account of heat conduction, experimental verification of results is essential.

Evaporative cooling studies have been carried out using a class of inert fluorocarbons, concentrating on fundamental aspects of the cooling process in open and closed loop cooling systems. Heat pipe experiments are also being carried out in model structures with both pixels and microstrip detectors in mind. Heat is collected from the readout electronics by the evaporation of liquid at one end of the heat pipe. The condensation of vapour takes place at the other end of the heat pipe which is cooled by water flowing in an aluminium channel. Tests have been carried out using freon or water as the heat pipe fluid.

Water cooling experiments are under way using aluminimum models of a proposed beryllium structure. A novel (Binary ice) scheme, in which a suspension of microscopic ice crystals is added to a water based fluid appears to be very promising. When this liquid comes into contact with a source of heat, there is melting of some of the ice crystals and increases the effective specific heat capacity of the water. The efficiency of Binary-Ice cooling has been demonstrated by observing the temperature difference across a source of power as the coolant changes from a conventional fluid to an ice suspension and has shown that the operation of a full scale system within the LHC environment is indeed feasible.

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UK Participants

Birmingham University, Liverpool University, Manchester University, University College London, and Rutherford Appleton Laboratory.

Introduction

The Collaboration was formed in January 1992 to carry out generic research on microstrip gas chambers (MSGCs) and to develop the technology for use at the LHC experiments. The aim has been to build detectors having similar tracking capabilities and occupancy levels as the Silicon microstrips; able to withstand the harsh radiation environment but at a cheaper price per unit area. Progress in the last two years has been substantial enough for the LHC ATLAS and CMS Collaborations to adopt them as baseline tracking detectors in their technical proposals, and to initiate studies of larger scale prototypes. Therefore, in the past year the UK RD28 Collaboration has focussed on remaining outstanding generic issues common to both LHC experiments.

The basic MSGC consists of thin anode and cathode strips, typically 10 and 100 microns wide respectively, laid or etched on an insulating substrate at a distance of typically 200 microns apart. An upper drift electrode defines the sensitive gas volume where electrons are released by ionising radiation. The back side of the substrate can also have a field defining electrode or be segmented into readout strips for two-dimensional localization. From the beginning, it was known that the choice of substrate was crucial to the performance of the detector. In the past year, much of the UK effort has been devoted to establishing the optimum materials for this part of the detector, the layout of the electrode strips and the best technology for its fabrication. This optimisation has centred upon finding substrates which allow the detector to operate at high rates (10**5 minimum ionising particles per sq mm) with minimal degradation of performance (ageing) when exposed to the equivalent of 10 LHC years of radiation.

Choice of Substrate

Early work showed that the boro-silicate glasses such as DESAG D263 or TEMPAX were apparently unsuitable because of their ionic high resistivity which causes initial large gain shifts at power-on and subsequent rate-dependent gain behaviour. These phenomena have been understood, but somewhat unexpectedly it was found by a Pisa group that the rate-dependence can be almost eliminated by running at a high value of the drift field. Although the initial gain shifts remain, this discovery is valuable because it may allow these glasses to be used in some circumstances. Their advantage is cheapness, relatively low radiation length, and excellent surface quality down to 100 microns thickness. In the past two months, the Manchester and RAL groups have started urgent programmes to verify these Pisa results, as well as investigate their ageing properties under these conditions.

The best results in terms of gain stability have been obtained with electron-conducting glases. The UK groups (except Liverpool) have focussed mainly on S-8900 commercial Schott glass with a bulk resistivity in the 10**11 ohms-cm range and to a lesser extent custom made glasses from Pestov and collaborators at the Budker Institute in Novosbirsk. The latter were given some support to develop very thin plates by a 'pulling technique' but so far this has not been successful. In the past

year, all industrial processing of S-8900 plates has been carried out at the VTT Laboratory in Helsinki where excellent reproducibility and low level of faults have been achieved. The glass is metallised with gold electrodes for example by a triple process in which the metal pattern is formed on a thin seed layer of nickel for good adhesion, and the exposed nickel subsequently removed. Alternatively, aluminium metallisation is usually carried out by conventional wet-etching. More recently in response to the search for lighter and cheaper glasses than S-8900 with the same surface characteristics, VTT have succeeded in fabricating a substrate from a base optical glass with low sodium ion content which is then coated with a 1 micron thick layer of S-8900 glass by sputtering. Metallisation then proceeds as before. Initial results are very encouraging and the extra process costs are more than offset by the savings in the base material. An alternative search for lighter semi-conducting glasses than S-8900 continues at Sheffield University and also at Schott.
The Manchester group have also made extensive use of their University electron beam lithography facilities to fabricate specialised electrode structures on S-8900 glass.

The Liverpool group have continued their study of detectors made on Silicon wafers from HMEL, Scotland. A thin surface layer of boron implanted silicon oxide is formed on top of electrodes on the wafer which act as a back-plane. Together with the surface electrodes on the oxide layer , a two-dimensional crossed microstrip or 'pixel' electrode structure can be obtained. Detailed study of the computed surface electric fields has shown that for a given gas gain the field near the cathode edges is lower and the speed of avalanche charge collection faster than a corresponding detector built with a bulk substrate. However, these detectors still exhibit gain shifts at power-on indicating that the implanted silicon oxide has still too high resistivity. Nevertheless, in the longer term this technology promises to yield true two-dimensional detectors from one gas gap.

Ageing

Degradation of the performance after extended irradiation is the most serious problem encountered with MSGCs. Earlier work showed that they are prone to faster ageing than MWPCs although the damage still appears to be due to the formation of polymers which are deposited on the substrate surfaces and electrodes. These deposits are polymeric compounds produced from the quencher gas by the action of UV light released in the avalanche process catalysed by trace impurities in the gas. These impurities seem to be an essential ingredient in the development of the deposits, but the amounts required are so small that it is very difficult to detect directly. Ten years of LHC exposure is equivalent to about 120mC of collected charge per cm of anode strip length with the avalanche size per particle traversal being 2*10**4 electrons. In practice, the tests are carried out by exposing the detectors at normal operating gain to very high fluxes of X-rays which on conversion yield typically an order of magnitude more avalanche electrons than mips particles. In this way, 10 years of LHC can be truncated to typically one month, the assumption being that this procedure does not invalidate the results!

At RAL, such studies have focussed systematically on semiconducting glass substrates with either gold or aluminium substrates, and research grade argon-DME or argon-isobutane gas mixtures. So far, the detectors have been built from standard materials but the gas delivery systems have been substantially improved to avoid known active contaminants and employ ultra-clean stainless steel components throughout. Fig 1 shows the relative gas gains observed at one irradiation site (1sq mm size) using two different argon-DME gas mixtures followed for an accumulated dose of 46mC/cm. The

substrate was S-8900 glass with gold electrodes. The results show that after an initial rise, the final deficit is only 10% after this dose, with an indication that the fall is logarithmic in time and can be extrapolated with some confidence to 100mC/cm. The 83:17 argon:DME mix appears to be a better choice. Even better results are expected when the chamber containment materials are modified. These results contrast strongly with those obtained with argon-isobutane or standard gas systems where the gain fall-off is catastrophic. However, no clear conclusion on the responsible impurities is available yet. These results and others were presented to the International Workshop on MSGCs at Legnaro in October.

Another form of ageing is damage to the metal electrodes which causes instability and sparking at high voltage. This problem occurs mainly at the edges of the substrate where the electric fields are distorted. The RAL group developed an effective solution using a subsidiary electrode named a "robber bar" thus avoiding expensive passivation processes. The Manchester group have an even more elegant solution , avoiding the high fields by redesigning the strip profiles after study of the resulting fields with a dedicated 3-D simulation program. Experimental tests show that stable operation can be extended to gas gains two times higher than before.

Beam Tests at CERN

The UK Collaboration continued the programme of tests with 100 GeV pions in the West Area H6 beam at CERN where the infrastructure had been installed the previous year. A new mounting system capable of accommodating more MSGCs and defining Silicon telescopes was built by UCL. Five 100mm by 100mm S-8900 detectors were installed from RAL and two from Manchester enabling tracks to be fully reconstructed. The intrinsic spatial resolution for quasi-perpendicular tracks was found to be 50 microns rms, with an anode spacing of 300 microns. Fig 2 shows the correlation between detection efficiency (%) and fractional noise occupancy from a run at moderate particle flux. In this case, the noise arises from the RD20 front-end amplifiers attached to each anode, but the plots indicate that applying low thresholds to achieve efficiencies near 99% are achievable if occupancies of 0.5-1.0% can be tolerated. A detailed simulation study of possible bunch tagging algorithms has been carried out which has shown that double correlated sampling of the signals is the best procedure given the relatively long collection time of the MSGC. Comparison with experiment awaits new electronics currently being developed at RAL.

Beam Tests at ISIS

The UCL group, assisted by RAL, are studying experimentally and theoretically the effect of high low energy neutron fluxes on the operation of MSGCs. The fluxes at ISIS are 100 times LHC below 10 KeV, and comparable above this energy. The study focusses on the prompt response of a MSGC to knock-on protons, elastic scattering, and nuclear reactions as well as non-prompt signals induced by radioactivity. The most significant effect to date has been the clear observation of knock-on protons in a detector running with argon-isobutane gas. These protons deposit very large amounts of energy (up to 500 KeV) on to a single gang of anode strips which must be allowed to drain away to avoid excessive occupancy levels. Fig 3 shows a preliminary comparison between the experimental and predicted energy spectra obtained, from which an estimate of the counting rate at LHC of such large signals can be obtained. Further work on induced activity in selected chamber materials is planned.

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" Results from CERN test beams"
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S8900 - Au/Ni Processing
Argon + 50%DME
eqn: y = a - b*ln(x), error²:212,
a=+1.174E+003, b=+9.385E+001
Argon + 17%DME
eqn: a - b*ln(x), error²:328e+003,
a=+1.083E+003, b=+5.145E+001
J.E.B. & J.F.C. DRAL 25-10-94
Gain
1150
1050
950
850
0.001
0.01
0.1
1
10
100
Cummulative charge (mC/cm of anode)

Fig 1

Number of Events
10^5
10^4
10^3
10^2
10
1
0
20
40
60
80
100
120
140
160
180
200
FADC Counts
Efficiency (%)
100
99
98
97
96
95
94
0
1
2
3
4
5
6
Background (%)

Fig 2

Count Rate (arbitrary units)
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
ISIS data (Nov. 94)
MC – n+p only.
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
Energy deposited on 20 strips (MeV)

Fig 3

A First-Level Calorimeter Trigger for LHC Experiments - Design Studies, and Beam Tests of a First Prototype Trigger System

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Introduction:

First-level triggering for LHC proton-proton collider experiments poses significant experimental challenges. At a luminosity of $10^{34}cm^{-2}s^{-1}$ the inelastic proton-proton collision rate will be approximately 1 GHz. With a bunch-crossing interval of 25 ns this corresponds to approximately 25 collisions per bunch-crossing. The level-1 accept rate will be limited by the readout time of the front-end electronics to less than 100 kHz, requiring a rejection factor of 10^4-10^5. Physics signatures will be based upon combinations of high-p_T leptons, photons, partons and weakly-interacting particles, and therefore the trigger must be sensitive to these particles. This paper describes tests of a first prototype calorimeter trigger processor and developments in the design of a complete first-level calorimeter trigger system.

Trigger Algorithms:

Figure 1: e/γ trigger algorithm

The choice of algorithms is based upon extensive and ongoing physics simulation studies. These have been described elsewhere [1-3]. The inputs to the algorithms are transverse-energy (E_T) sums from "supercells" in the electromagnetic and hadronic calorimeters, of transverse granularity 0.1×0.1 in

pseudorapidity-azimuth and summed in depth. The most complex algorithms are required for the electromagnetic cluster trigger (Figure 1). The trigger requires an electromagnetic cluster E_T greater than a cluster threshold as well as electromagnetic and hadronic isolation sums less than isolation thresholds. The trigger windows slide and overlap so as to cover the calorimeters fully. Studies indicate that such an algorithm gives acceptably sharp trigger thresholds and rates of a few $\times 10^4$ Hz for a range of trigger conditions satisfying the requirements of LHC pp experiments [1-5].

Trigger Prototype:

In order to investigate and demonstrate the implementation of such trigger algorithms, an ASIC has been constructed to implement the electromagnetic part of the algorithm shown in Figure 1 (hadronic processing was excluded to reduce cost). The ASIC is a 0.8μ CMOS gate array operating in pipeline mode. It takes as input 16 8-bit linear ADC values and calculates cluster and isolation sums, which are compared with two sets of thresholds. In addition the sum of the 16 input values is computed, an operation required as input to the jet trigger. The ASIC delivers the 12-bit energy sum and the two trigger decision bits with latencies of six and seven clock cycles respectively. It has been described in more detail elsewhere [3].

The ASIC was tested in a cluster processor demonstrator system using a prototype LHC calorimeter. The system contains nine ASICs and fully processes 3×3 overlapping windows, requiring inputs from 6×6 trigger cells. Two backplanes were used, one with high-density Teradyne connectors (320 signal pins plus 80 grounds) for the data and clock connections and the other using a simple control/addressing protocol to interface to VMEbus. The module contains 256-deep circular buffers to capture time-slices of the input ADC data and the ASIC processing results. Comparison of the results with the inputs enables the performance of the trigger hardware to be studied in detail.

Beam Tests:

Data were recorded in CERN test beams with both the RD-3 barrel ("Accordion") and endcap ("Spanish Fan") liquid-argon calorimeter prototypes. Analysis of the "Spanish Fan" data is still at an early stage, so the following results come from the barrel calorimeter tests. In addition other tests have been performed with the RD-33 ("TGT") liquid argon calorimeter prototype.

Trigger cells of granularity approximately 0.1×0.1 were formed by analogue summation of signals from the calorimeter cells. The signals were digitised using a linear flash-ADC system sampling at the LHC bunch-crossing frequency of 40 MHz (some data were recorded at the original LHC frequency of 67 MHz) and passed to the cluster processor operating at the same speed. Data were taken with beam energies between 10 GeV and 300 GeV and a mixture of electron and pion beams, over a wide range of beam positions. Data were recorded both stand-alone, and also through the RD-3 data-acquisition system, to enable comparison with the full calorimeter data.

Figure 2 shows the trigger threshold curve obtained with 50 GeV electrons compared with the expectations from an ATLAS Monte Carlo. Since the beam spot-size was small compared with a trigger cell (about the size of a single calorimeter cell, whereas the trigger cell was 4×4 calorimeter cells) data from a number of runs with beams in different positions within the trigger cell were combined to produce this threshold curve. A good agreement was found between the observed and expected performance of the cluster algorithm.

Figure 2: Threshold curves from test data compared with Monte Carlo

The reliability with which the trigger processor executed the algorithms was studied by comparing the ASIC results with the expectation based upon the input ADC data and the trigger and isolation thresholds.The performance of the ASICs in forming cluster and isolation sums and comparing with thresholds is illustrated in Figures 3 and 4. In Figure 3 the cluster sum, reconstructed from the input data, is plotted for events with and without the corresponding trigger bit set. Here the isolation threshold was set high to permit a clean test of the clustering. In Figure 4 the isolation sums are similarly plotted for events with clusters above the cluster threshold. In both plots it can be seen that the execution of the trigger algorithm at the full LHC clock speed was faultless.

Figure 3: Performance of the ASIC cluster threshold

Figure 4: Performance of the ASIC isolation threshold

Bunch-Crossing Identification Studies:

Figure 5 shows a pulse from the Accordion calorimeter, after digitisation by the trigger FADC. A key feature is that the pulse occupies about four LHC beam-crossings in time. For the final trigger, filtering is therefore needed to identify the peak pulse-height and timing, and to suppress off-peak data which would otherwise contribute to (or veto) triggers in other bunch-crossings.

Figure 5: Pulse shape from Accordion calorimeter

We have been studying the use of digital filtering for this purpose. Using software simulation, a range of algorithms has been studied, based upon convolution of the data from several samplings followed by peak-finding applied to the results of the convolution. Using data recorded with the Accordion calorimeter prototype as input, it was found that simple peak-finding always gave correct identification of pulses down to five counts (approximately 6 GeV), with little improvement being found from using more complicated filtering. Small pulses are the most difficult to filter, and studies in this area are continuing. Lower electronic system noise and higher-resolution ADCs would permit the performance of all algorithms to be improved.

Figure 6: Block diagram of Bunch-Crossing Identification module

A first-prototype bunch-crossing identification module has been constructed and tested with the "Spanish Fan" endcap calorimeter prototype. The module, which filters data from a single channel, consists of a five-element deep pipelined Finite Impulse Response (FIR) filter followed by a five-element programmable comparator (peak-finder). It is illustrated in Figure 6. By setting the parameters of the filter and peak-finder appropriately, a range of algorithms could be tested in real-time at the full LHC bunch-crossing rate. The next trigger prototype will include similar bunch-crossing identification capabilities for all input channels, using Xilinx FPGAs for the digital signal processing.

Towards a Full LHC Calorimeter Trigger:

The current prototype has demonstrated that algorithms with the performance needed for LHC first level triggering can be implemented using currently-available ASIC technology and operated at the necessary speed . In order to construct a full system, however, a greater degree of integration is needed [6]; the current module processes only 9 channels, so using this modularity a full-scale 4000-channel trigger would require approximately 450 such modules. It is straightforward to process a larger area of the calorimeter in a single ASIC, but the pin counts required for parallel data input quickly become prohibitive. For example, an ASIC fully processing 4×4 trigger cells would require ~800 I/O pins alone, and a module with four such ASICs would require ~2000 backplane connections for inputs.

One solution to this problem would be to use serial input of data to the ASICs. This would provide an eightfold reduction in the number of I/O connections, but would require a corresponding increase in the bandwidth per connection. Current CMOS ASIC technology could not accept data at these rates. However, after pedestal subtraction, bunch-crossing identification and applying a noise threshold to the trigger cell E_T sums (typically 1 GeV) the occupancy of the calorimeters is expected to be only a few percent. Transmission of only zero-suppressed data would therefore reduce the bandwidth, but the resulting asynchronous data would then require bunch-crossing tagging and matching. Although having a greater latency, one advantage of this technique is that it would be inherently self-synchronising.

In order to demonstrate the viability of such a solution, as second trigger prototype is being constructed. In this system the digitised calorimeter pulses are pedestal-subtracted and applied to a bunch-crossing identification filter. The non-zero data are then tagged, serialised and transmitted optically at a rate of 160 MBd.

The cluster-finding ASIC converts the incoming serial bitstreams to parallel data, matches the tags and them passes the re-synchronised data to the trigger algorithm block. Note that while data transmission is asynchronous, the trigger decision itself is fully synchronous.

Design studies for this system are well advanced. Detailed system simulations indicate that the asynchronous transmission introduces negligible data loss and no data corruption. To reduce the non-recurrent engineering costs a dual-mode ASIC is being designed, which will include all necessary system functionality. Beam tests with prototype LHC calorimeters will be performed in mid-1995.

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[4] ATLAS Letter of Intent, CERN/LHCC/92-4
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Diamond has been considered an interesting option for niche applications in particle physics for a number of years. It is known to be physically robust, have excellent thermal properties and is potentially very fast electronically. It was also thought to be very radiation hard. The key problem was the low signal possible in a material with such a large band gap and - in conventional diamonds - small carrier lifetime. The key solution to this problem has been the development of Chemical Vapour Deposition Diamond in which the carrier combination distance has been made increasingly large - from typically 100 nm in 1986 to almost 100 μm in 1994. We anticipate values in this critical quantity to be consistently above 130μm next year. This will result in signals of over 4000 electrons, and given intrinsic diamond's intrinsic low noise, we could expect this to be adequate for many LHC applications like vertex hit association[1].

Since early 1993, initially with colleagues from the USA and CERN, we have been responsible for the first successful use of diamond detectors in particle physics:

- First position sensitive diamond strip detector *(α particles detected and read out, summer 1993);*
- First use of CVD diamond in a calorimeter (accepted for publication in Nucl. Inst. Meth., 1994);
- First successful diamond strip detector in a particle beam (50 GeV pion beam, CERN, November 1993) (accepted for publication in Nucl. Inst. Meth., 1994)

The King's College/Imperial College groups have also worked on new ideas in diamond detectors:

- We have developed novel diagnostic tools in diamond characterisation: we use electron probes, Ti-Sapphire oscillators, a He-Ne sub-bandgap laser technique, as well as making extensive use of the usual characterisation techniques in Raman spectroscopy, absorption, cathodoluminescence and profilometry etc. These techniques have been used, working closely with a UK manufacturer, to allow that manufacturer to develop diamonds with carrier recombination lengths going from less than 1 micron a year ago to over 50 microns now.
- We have developed and patented new ideas in diamond detectors which have potentially exciting applications in medical and industrial imaging[2,3]. We are working in a large industrial/medical consortium aiming to bring these ideas to market.
- We are working on pixel designs which we will aim to test in particle beams in 1995.
- We have made the first studies in neutron radiation hardness in diamond. Results are so far encouraging, but not unambiguous[4].

Much of this work is summarised in the High Energy Physics talk given at the 1994 Glasgow Conference[5] and a more general talk at "The Diamond Conference 1994"[6].

Our intentions for 1995 are to continue refining our results in radiation damage, to work in pixel designs in diamonds, and to continue in industrial liaison work with this potentially exciting material.

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LASER / PLASMA PARTICLE ACCELERATION EXPERIMENTS

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INTRODUCTION

Significant progress has been made in the past year both with plasma experiments and development of the facilities on VULCAN. In a gas target interaction experiment plasma waves with electric fields of 2×10^8 Vcm^{-1} were generated. The laser was upgraded to provide in excess of 30TW in a single ultrashort pulse and target facilities improved to allow long focal length experiments to investigate the wakefield accelerator technique.

PLASMA EXPERIMENTS

The previous work was based on the beat wave scheme, where the plasma wave is generated resonantly by the beat between two lasers with frequency difference equal to the plasma wave frequency. In the August experiment the plasma wave was generated using the self modulated wakefield scheme. This scheme, recently proposed independently by theoreticians in Russia and in the USA, is based on a single frequency laser with power greater than the critical power above which self-focusing due to the relativistic mass increase of the electron in the laser field occurs. Unlike the laser wakefield, where the plasma wave is generated as a wake behind the laser pulse with duration equal to about half the plasma wave period, a long laser pulse with duration equal to many plasma periods is used. The critical power for self-focusing depends inversely on the electron density, and thus the condition for generation of a plasma wave by the self modulated wakefield scheme is relatively simple provided that a sufficiently powerful laser is available The high power capability of the CPA VULCAN laser allowed us to operate at a high density, the large electric field generated being directly due to this since

$$E_p \alpha \sqrt{n_e}.$$

where n_e is the electron density.

In the experiment the plasma was generated by laser ionisation of a hydrogen pulsed gas jet positioned at the focus. The ionisation was produced by a tunnelling process, the hydrogen being completely ionised once the laser intensity exceeds about 10^{13} W cm^{-2}. The plasma wave amplitude was measured from the intensity of the sidebands in the transmitted laser beam. These sidebands, generated by the interaction between the laser and the plasma waves, are at frequencies up-shifted and down-shifted by multiples of the plasma frequency. Because of the fall-off of the detector sensitivity at long wavelengths, only the anti-Stokes sidebands were observed.

Figure 1. Anti-stokes sidebands giving a measure of the amplitude of the plasma wave.

The strength of the plasma wave was such that sidebands up to the third were detected, as shown in figure 1.

A plasma wave with a relative electron density amplitude of ~10% was observed in the experiment. The plasma electron density, n_e, was approximately $5x10^{18}$ cm^{-3} from which we calculate a plasma wave electric field, E_n, of $2x10^8$ Vcm^{-1} This is about two orders of magnitude larger than has previously been achieved by us or reported by other workers.

In the next reporting year we shall continue our studies of the self modulated wakefield by investigating the influence of laser spot size, Rayleigh length, laser power, intensity and prepulse. We also plan to measure the decay of the plasma wave by monitoring the sideband intensities on a delayed copropagating probe beam. We are also exploring the possibility of monitoring the energy of plasma electrons which are trapped and accelerated by the plasma wave. Energies up to about 50 MeV are expected.

FACILITY DEVELOPMENT

The VULCAN Nd:glass laser in the Central Laser Facility can now deliver > 30 TW in subpicosecond pulses using chirped pulse amplification (CPA) techniques, with energies to target of 25 J and focused intensities of ~10^{19} Wcm^{-2}.

The pulses were generated in a novel Nd:LMA additive pulse mode-locked oscillator, developed at the Optoelectronic Research Centre, Southampton University, which delivers pulses of 500 fs duration and ~1 nJ in energy at 1055 nm. The pulses are stretched to ~200 ps in a double pass grating system before amplification to 50 J in phosphate glass amplifiers at a beam aperture of 150 mm diameter. The stretched pulse is recompressed using a pair of gratings (300x150 mm, 1740 lines per mm) and focused using an off-axis parabola to avoid nonlinear effects from transmissive optics. The compressed pulse is monitored using a suite of diagnostics to determine the focusability, pulsewidth and bandwidth. Best performance to date is 43.7 J from the laser system, with 22 J to target. The pulsewidth, measured using a single shot auto-correlator was 620 fs (assuming $sech^2$ profile) with a bandwidth of 15.3 nm, giving a peak power of 35 TW. The focal spot size was measured to be < 15 microns, giving a resultant peak intensity of ~ 10^{19} Wcm^{-2} to target.

During 1995 the short pulse facilities will be further upgraded with the installation of a regenerative amplifier developed at Imperial College, London. The amplifier replaces the existing multipass rod preamplifiers reducing gain narrowing effects in propagating through the system. This will allow shorter pulses to be delivered to target.

The plasma wakefield experiments require a large depth of focus which requires long focal length focusing optics (3m) mounted within the target vacuum chamber. With funding from an SERC grant the extensive chamber modifications have been engineered and optics procured to allow this option. These modifications together with the developments of the VULCAN CPA facility will allow experimental investigations of the short pulse laser wakefield scheme during the next reporting year.