Preprint
RAL-P-2022-002

Godfrey Stafford: a life in science

NA McCubbin

September 2022

A shorter version of this preprint was submitted for publication in the Biographical Memoirs of Fellows of the Royal Society

Enquiries concerning this report should be addressed to:

RAL Library
STFC Rutherford Appleton Laboratory
Harwell Oxford
Didcot
OX11 0QX

Tel: +44(0)1235 445384
Fax: +44(0)1235 446677
email: libraryral@stfc.ac.uk

Science and Technology Facilities Council reports are available online at:
https://epubs.stfc.ac.uk

ISSN 1361-4762

Photo: Rutherford Appleton Laboratory/UK Science and Technology Facilities Council

GODFREY STAFFORD: a life in science[1]

15 April 1920 - 29 July 2013

BY N.A. McCUBBIN

Particle Physics Department, Science and Technology Facilities Council, Rutherford Appleton Laboratory, Harwell Campus, Didcot, OXON OX11 0QX (norman.mccubbin@stfc.ac.uk)

Abstract

GODFREY HARRY STAFFORD's career as a physicist began with research in cosmic rays in the 1940s and he lived to see the discovery in 2012 of the Higgs boson at the CERN Large Hadron Collider. He made major contributions to the construction and exploitation of accelerators at the Rutherford Laboratory in the UK and was its Director from 1969 to 1981. During this period he oversaw the diversification of the laboratory into the multi-disciplinary centre it is today. He was Master of St Cross College, Oxford, from 1979 to 1987 and President of the Institute of Physics from 1986 to 1988. He was a major supporter of physics as an international activity: he was a founder member of the European Physical Society in 1968 and its President in 1984-86, and he had significant links with CERN that spanned 25 years. Stafford's career in the period 1950-1980 was intertwined with the development of particle physics in the UK and particularly with that of the Rutherford Laboratory, and so this memoir also covers some of that development.

Early Life

Godfrey Stafford was born on the 15th April 1920 in Sheffield, England, the second child of Henry and Sarah Stafford. Sarah (née Fletcher) came from Ilkeston in Derbyshire, and Godfrey was baptized there on 23rd May 1920. He attended primary school in Sheffield, but in 1928 the family emigrated to South Africa, where a sister of Godfrey's father lived. The main reason for leaving England was the shortage of suitable jobs at a time of economic depression. Godfrey's father was an engineer, but also a keen musician, and he applied to be principal bassoonist in the Cape Town City Orchestra. The application was unsuccessful, but Godfrey's father decided to go to South Africa without any definite prospect of employment, and the family followed a few months later. There were certainly times of concern when his father was unemployed, but he remembered his childhood in the Cape Town area as a happy one, with plenty of outdoor activity.

After primary schools, he completed his secondary schooling in 1935-36 at Rondebosch Boys' High School in Cape Town. Rondebosch was, and is, one of the best-known schools in South Africa, distinguished for its sporting and academic prowess. He admired the headmaster, W Mears, a historian who may well have inspired his initial inclination in that direction. But science became his main interest, despite it being taught by a strict disciplinarian who instilled fear but no great

[1] This article is adapted, with permission, from a shorter version published as a *Royal Society Biographical Memoir* https://royalsocietypublishing.org/doi/10.1098/rsbm.2022.0008

enthusiasm for the subject. Throughout his school days his mother, who had been headmistress of a primary school in Ilkeston before her marriage, provided much support and encouragement. University entrance required passing the Senior Certificate, which was taken in a broad range of subjects, including history, physics and chemistry, and in 1937 Godfrey entered the University of Cape Town, supported by a Council Entrance Scholarship, to study for a BSc.

At university his academic career flourished. Initially he had planned to specialize in chemistry with a view to becoming a teacher. But by the end of his second year he realized that physics suited him much better, noting that he won the class medal for best student in physics, but not in chemistry. For the third year he was one of only five physics students, so tuition was on an almost personal basis. He also found the atmosphere in the physics department both relaxed and inspiring, particularly the teaching of the Australian C.B.O Mohr, who had worked at the Cavendish laboratory, Cambridge, with H.S.W Massey. Another inspiring teacher was R.W James, who was appointed Professor at the university in 1937. James had been the expedition physicist on Shackleton's Antarctic expedition in 1914,[2] and later worked with W.L. (later Sir Lawrence) Bragg in Manchester and co-authored with him one of the early textbooks on X-rays. James built up a substantial research school at Cape Town in X-ray crystallography, and two Nobel prize winners learned crystallography from him: Sir Aaron Klug and Allan Cormack.

But for his MSc project in 1941 Stafford preferred to work with Mohr on cosmic rays and a study of the 'second maximum' in the Rossi curve. The Rossi curve concerns the interaction of high-energy particles with matter, which might be a solid target or, for cosmic rays (mainly protons), the atmosphere itself. The energy of the incident particle is converted into a shower of secondary particles that cascade down through the atmosphere. At ground level these shower particles are now known to be mainly muons (from pion decay) and electrons and positrons (from muon decay). Electrons and positrons (of sufficient energy) interact with matter to generate showers through bremsstrahlung of photons that then convert into pairs of electrons and positrons, which then continue the showering process. Such showers can be observed behind a few centimetres of lead but are contained completely by ~10 centimetres. By 1941 this so-called 'soft' component of the ground-level shower particles was fairly well understood. But there was also a 'hard' component that penetrated even metres of lead. Now known to consist of muons, this hard component was thought to be due to the 'mesotron' responsible for the force that holds the nucleus together. This confusion between the muon and the mesotron (now called the π-meson) was sorted out only some years later, after the war. A muon is 'just' a heavy electron, but, compared to an electron, this mass difference reduces greatly the propensity to radiate a photon (bremsstrahlung). That is why muons penetrate large depths of material, and electrons and positrons do not. But some observers, including Mohr and Stafford, reported the observation of an increase in shower activity after significant depths of lead or iron, and this was referred to as the 'second maximum' of the Rossi curve. With the benefit of hindsight, such observations were almost certainly due to showers initiated by the rare, but not impossible, process of radiation of a photon by a muon, thus initiating a 'soft' shower from the photon. It was becoming clear that this second maximum was somehow associated with the 'mesotron' component, as discussed by Mohr and Stafford (1)[3].

---

[2] After the expedition's ship, Endurance, got trapped in the Arctic ice, James calculated their longitude, facilitating the escape on to Elephant Island. (Bragg, 1965)

[3] Numbers in this format refer to the bibliography of Stafford's publications given at the end of the text.

The experimental techniques used were simple and direct. A high voltage of several hundred volts was needed for the ionization chamber and was produced simply by connecting a large number of ordinary batteries in series. Many years later, chatting with a group of younger colleagues[4] in the coffee lounge at the Rutherford Laboratory, Stafford recalled getting a substantial electric shock from this set-up.

His academic career continued to prosper; he was awarded first-class honours in the exams at the end of 1941 and also the prestigious Ebden Scholarship, tenable at Cambridge University. Luck played a part: the scholarship was available only once every few years, and 1941 was such a year. Furthermore, the scholarship was first offered to a chemist, who turned it down in favour of a Rhodes Scholarship at Oxford.[5] So, in normal times Stafford would have soon travelled to Cambridge to continue his academic career; but times were far from normal.

The Second World War

The outbreak of the Second World War resulted in a huge upheaval in South African politics: the Prime Minister, J.B. Hertzog, wanted South Africa to remain neutral, but that motion was defeated in parliament and he resigned. He was replaced by J.C. Smuts, and South Africa declared war on Germany on September 6th, 1939. In 1941 Stafford volunteered for the South African Navy as an Electrical Lieutenant.

In June 1940 the British Admiralty had sent a message to several of the then-Empire's major ports, including Cape Town, ordering the establishment and operation of 'degaussing'. This consisted of devising ways to measure a ship's magnetic properties and protect it against magnetic mines. The South African effort was led by Brian Goodlet, who had been the Professor of Electrical Engineering at UCT (1937-39 and again from 1941) and had earlier designed high-voltage transformers used by Allibone and by Cockcroft and Walton in the development of particle acceleration at the Cavendish.[6] Stafford joined Goodlet's team, and spent six months on Robben Island, which later became notorious as the penal settlement for political prisoners such as Nelson Mandela. He was then sent to Durban as Degaussing Technical Officer, and found himself, at the age of twenty-one, in charge of a dozen engineers and physicists who were older and more experienced (except in degaussing) than him. He later described this period as being of considerable formative significance. As an Electrical Officer, he was also responsible for the disposal of any mines that were washed up on the coast. Happily, there were only a few. He invented an optical device that greatly simplified the analysis needed for degaussing calculations, and the details were sent to the UK Admiralty, but was not, it seems, followed up.

---

[4] Of whom the author of this memoir was one.

[5] As second choice for a significant scholarship to study in the UK, Stafford was following in distinguished footsteps: in 1895 Ernest Rutherford was not the first-choice New Zealander for the scholarship from the Exhibition of 1851, but the first choice, James Maclaurin, a chemist who went on to a very distinguished career, turned down the award.

[6] Besides his distinction in electrical engineering, Goodlet had a remarkable early life. He was born in 1903 in St Petersburg to British parents who worked for the Russian Government. Accordingly, he attended the Imperial School in St Petersburg where he learned "my arithmetic in German; my algebra in Russian and my calculus in English." (Goodlet, 1956) In 1917 he had to shoot his way down Nevsky Prospect to escape the Revolution. One can imagine that a 100 kV transformer held few terrors after that. In 1950 Goodlet was recruited by Cockcroft to be Deputy Head Engineer at AERE, Harwell.

Stafford was greatly inspired by Goodlet, and Goodlet must have been impressed by his young lieutenant, for he arranged for Stafford and a former student to be seconded to the Royal Navy when Goodlet himself was called back to the UK to become Chief Scientist at Rosyth, near Edinburgh. Thus it was that Stafford arrived back in England in February 1943, some 15 years after leaving as a young boy. Goodlet had wanted his two young assistants to work with him, but this fell through, and they were assigned instead to radar work at the Admiralty Signal Establishment at WItley,[7] near Haslemere. Stafford was involved in sea trials on aircraft-warning radar. This had the consequence that soon after D-Day he was sent to Normandy to check the warning radar on all the cruisers involved in the landings, as the ships were having difficulty detecting the German bombers laying mines at night. In common with many of that generation, he spoke little of this afterwards,[8] and in his Royal Society personal record comments only that it was "more like a Thomas Cook tour than a naval operation." Perhaps, but the dangers were real. He was on board HMS Scylla when it was so badly damaged by a mine that it had to be withdrawn for repairs.

Soon afterwards Stafford volunteered for a sea-going appointment and was assigned to HMS Palomares as its senior radar officer. The Palomares was at that time being used to direct fighters, and was essentially a floating radar platform, so his role was both interesting and probably demanding. His experience at Witley enabled him to incorporate some recent developments into the ship's radar equipment before they became standard issue.   The Palomares was en route to the Pacific to take part in the landings at Malaya when it broke down in the Mediterranean, and its war, and Stafford's, came to an end.

After the war Stafford returned to South Africa, but before doing so, armed with a letter of introduction from Professor James, he visited Sir Lawrence Bragg at Cambridge and arranged to use his Ebden Scholarship to study for a PhD at the Cavendish Laboratory starting in 1946.

1946-54: Cambridge, Cape Town, Harwell, Pretoria and back to Harwell

Back in Cape Town, Stafford was offered a temporary lectureship at the university and was asked to lecture on electromagnetism to the Physics MSc students. The audience also included students of electrical engineering, who could attend some of the Physics MSc courses. Among these engineers were Franz Heymann and Mike Pentz. Heymann later became Quain Professor of Physics at UCL (1975-1987), and Pentz was a senior physicist at CERN (1957-1968), then first Dean of Science at the Open University (1969-1985), and throughout his adult life an outspoken campaigner on the dangers of nuclear weapons.

In 1946 Stafford returned to the UK and began his PhD research at the Cavendish under Denys (later Sir Denys) Wilkinson. Stafford later felt that the Cavendish years were not entirely satisfactory, partly

[7] The Admiralty took over the site of King Edward's School at Witley for the duration of the war. Code-breaking and radar are probably the best-known scientific contributions to the UK war effort, both requiring major 'theoretical' input from scientists and mathematicians. The code-breakers at Bletchley Park have been well covered in books and even films. Witley also had an impressive cast, among them Bondi, Gold and Hoyle, who spent some of their evenings discussing astrophysics. (Roxburgh, 2007)

[8] But in his late 80s, talking to his son-in-law Mark Piney in 2008, he recalled his trip to the Normandy beaches, and this can be heard at: https://indi.to/FKqR2 .

because of the time taken for the laboratory to recover from the effects of the war and partly because Wilkinson was recovering from serious exposure to radiation contracted in Canada in 1945 and was barred from the Cavendish for much of Stafford's time there. However, he was able to guide Stafford's PhD work, which began with the construction of an ionization chamber that operated at up to 90 atmospheres and 4000 volts (2), and which was then used in the study of the photo-disintegration of the deuteron and neutron cross-section measurements. The deuteron measurements led to a brief letter in Nature (3), and a substantial paper in The Physical Review (7). The work is also notable for the first use in an experiment of a 99-channel Analogue-to-Digital Converter (ADC) based on Wilkinson's then new design, which is still in use today. The neutron work comprised the total cross-section measurements of low-energy neutrons on a range of materials (4). Stafford was awarded his PhD in 1950, and he and Wilkinson became friends and colleagues for the rest of their lives.

The war had ended, but it was still a period of great uncertainty. In Europe, increasing tensions with the Soviet Union led to the Berlin airlift (1948-9), and in South Africa the Smuts government lost the 1948 election to the Nationalist Party, ushering in the start of the apartheid era. Before this defeat, Smuts had asked Basil (later Sir Basil) Schonland to lead the new South African Council for Scientific and Industrial Research (CSIR). Schonland, who had studied at the Cavendish in the 1920s with Rutherford, recruited Stafford, but arranged for him to work first at the Atomic Energy Research Establishment (AERE) at Harwell to study what was known about civilian defence against atomic weapons. Stafford described this work as "very dull", but in his second year at Harwell he met up again with Jim Cassels, whom he had known at Cambridge, and Gerry Pickavance, who was the group leader for the experimental programme at the Harwell 175 MeV synchrocyclotron, which had been completed in 1949. With the agreement of Schonland, Stafford joined the Pickavance and Cassels group, and they carried out several experiments on nucleon–nucleon scattering. These included total and differential cross-sections for proton–proton and proton–deuteron scattering (5,6,8). In remembering this period, Stafford commented: "Gerry was splendid in organising everything and making sure that we had all the equipment that we needed. When it came to data taking and analysing the results we all took part and I found it a very happy and stimulating period." (Holt, 1994) More significantly, the association with Pickavance shaped his long-term career. It was also a time of big changes in his personal life: he married Helen Goldthorp Clark (known as 'Goldy') in 1950 (see Figure 1), and their son Toby was born in 1951.

Cockcroft, then Director at Harwell, wanted Stafford to extend his stay there to continue working with Pickavance and Cassels, but South African politics intervened. One of the senior CSIR scientists, Tikvah Alper,[9] had to leave South Africa because of her opposition to apartheid, and Stafford was required to return there in 1952 to replace her as head of the CSIR Biophysics Subdivision. (By chance, he met Franz Heymann again on the ship back to South Africa.) In professional terms this was not such a big change from the work at Harwell, as the main function of the unit at the time concerned radio isotopes, imported from England, to develop techniques for their use, mainly in medicine. Two of the papers published in this period are listed in the bibliography (9,10). The stay in South Africa did not last long: in 1954 Pickavance offered him a job at Harwell in the cyclotron group. The family had now increased with the birth of twin daughters, and there was a desire not to bring

[9] Tikvah Alper had a distinguished career as a radiobiologist. She was one of the first to suggest that the infectious agent in scrapie did not contain DNA, which contradicted the orthodox view at the time.

up a young family under the apartheid regime. Professionally, the offer was certainly attractive, with the prospect of getting back to high-energy physics research. The family moved back to the UK and Godfrey and Goldy lived in the Oxford area for the rest of their lives.

Figure 1: Goldy and Godfrey in London (near Piccadilly Circus) around the time of their marriage in 1950. Photo: the Stafford family.

1954-1957: Harwell, the synchrocyclotron, and the birth of the Rutherford Laboratory

For the next 27 years Stafford was based first at Harwell and then at the next-door Rutherford Laboratory, which was founded in 1957. For the first half of this period he was engaged in high-energy physics research and involved in its development in the UK. For the second half he was Deputy Director and then Director of the Rutherford Laboratory, and he led the laboratory's transition into the multi-disciplinary centre that it is today. Before describing his career in this period, it is appropriate to summarize briefly the situation of high-energy (or 'particle') physics in the UK in 1954, almost ten years after the end of WW2.

Particle physics has two main ancestral threads: the use of naturally occurring radioactivity to probe matter and the atom, and the study of cosmic rays. It was soon appreciated that energy was the key to probing matter more deeply, and both electrostatic (Cockcroft and Walton, 1932; Van de Graaff et al., 1933) and combined electric and magnetic (Lawrence and Livingston, 1931) techniques to accelerate particles were invented in the 1930s. The former is limited, by breakdown in air, to energies of a few Mega-electron Volts (MeV).[10] The latter uses a magnetic field to guide particles round through the same relatively small electric field, which alternates in phase with the passage of the particles, and can reach far higher energies than a Van de Graaff. Lawrence was inspired by the idea (Ising, 1924) and demonstration (Widerøe, 1928) of a linear 'string' of alternating electric fields in phase with the passage of the particles: a linear accelerator. Lawrence's original 'cyclotron' design was developed (Veksler, 1944; McMillan, 1945) to cope with relativistic effects ('synchrocyclotron'). Further developments in the late 1940s and 1950s led to the 'synchrotron' in which a variable magnetic field is used to confine the particles to a relatively small volume throughout the acceleration cycle. The basic idea of the synchrotron is still in use today, notably in the Large Hadron Collider at CERN.

In the wake of the scientific contribution to the UK war effort, funding for particle physics was relatively generous, even in a period of post-war austerity. Much of this funding went into building accelerators. By 1954, Harwell had the 175 MeV synchrocyclotron mentioned above and plans for a 600 MeV proton linear accelerator, which is discussed further below. In addition, the universities had a 1000 MeV proton synchrotron at Birmingham, a 350 MeV electron synchrotron at Glasgow, a 380 MeV proton synchrocyclotron at Liverpool, and a 125 MeV electron synchrotron at Oxford. Sir George Thomson (son of the discoverer of the electron, and himself discoverer of the electron's wave-like properties) was heard to observe that perhaps it was time to stop engineering and start doing some physics (33). And then there was CERN.

Thu UK was one of the 12 signatories to the convention establishing CERN in June 1953, and formal UK ratification followed at the end of the year. However, behind that simple statement of fact lies the usual drawn-out mating ritual that seems to characterize all UK engagement with projects involving continental Europe. A relatively brief but informative account can be found in Stafford's Biographical Memoir for the Royal Society of John (later Sir John) Adams (33). Suffice to note here that the UK had not signed the provisional CERN convention in 1952, and indeed the UK *was* different. Pre-war, UK scientists had been among the leaders in the science that became particle physics, UK scientists had figured significantly in the Manhattan project, and the UK was now embarked on a major programme of domestic accelerators, as outlined above. Small wonder then that the UK, both its government and many of its scientists, wished the fledgling CERN well, but good wishes tinged perhaps with a certain paternalistic air, and this continued throughout the 1950s and into the 1960s. But CERN also had strong UK supporters, crucially Cockcroft: already in 1952 CERN set up a group to study a possible synchrotron design, and this group had its headquarters at Harwell. Soon afterwards several key Harwell accelerator experts, John Adams, Frank Goward and

[10] An electron Volt (eV) is a convenient unit of energy in the physics of atoms and sub-atomic particles. One electron Volt is equal to 1.6 10^{-19} Joules. To ionize a hydrogen atom requires 13.6 eV. A proton with kinetic energy of 100 MeV is moving with a speed of 43% of the speed of light. Protons in the CERN Large Hadron Collider have energy of 6.5 TeV and move with 99.99999% of the speed of light.

Mervyn Hine, moved to CERN in Geneva, and Adams later led the construction of the CERN 28 GeV synchrotron and in the 1970s its successor, the Super Proton Synchrotron (SPS).

Stafford also had an opportunity to go to CERN at this time, but he preferred to take the post in the cyclotron group at Harwell as this offered the prospect of getting on with experiments straight away. The study of nucleon–nucleon scattering at relatively low energies provides essential input into the understanding of the nucleon–nucleon force and thus of how the nucleus is held together. Phase shifts are a way of characterising scattering in a model-independent way, and both constrain and test proposed theories. It is very helpful in extracting phase shifts from the experimental data to have scattering information using polarized beam and/or target particles.

Stafford and co-workers set about studying neutron–proton scattering using a (partially) polarized neutron beam. Their first paper from this period (11) reported on polarization effects in neutron–proton scattering at 98 MeV. Exploiting the beam polarization required taking the difference between the differential cross-sections at two different orientations of the beam polarization vector with respect to the normal to the scattering plane. In this first paper this change of orientation was carried out by the direct but mechanically delicate process of moving the 'counter telescope' (which detects the scattered particles) so that it was, in effect, rotated around the line of the neutron beam by 180 degrees. However, this method is beset with systematic errors (11), and Richard (Dick) Wilson, who worked at the Harwell cyclotron in the 1950s before moving to Harvard, suggested that the equivalent change of orientation could instead be achieved by rotating the neutron polarization vector by precession in a suitable magnetic field. For a 98 MeV neutron beam with polarization perpendicular to its line of flight, this precession can be achieved by a solenoid with field integral of 1.33 Tesla-metres (0.4 T x 3.3m). Improved results using this new method soon followed (12, 13, 15). It worked well, was simpler to implement (once the magnet was built) and led to smaller errors. The technique was copied quite widely. (For example: Barschall 1964; Beghian et al., 1963; Walker et al., 1965)

As well as the polarization measurements, Stafford and his team devised and built a neutron time-of-flight spectrometer. The energy of a neutron can be determined (for kinetic energies up to a few hundred MeV) from its time-of-flight over a distance of several metres. A neutron produced by an interaction in the target has a 'start' time defined by the proton beam hitting the target and a 'stop' time by its detection in a neutron detector at a suitable distance. But the timing structure of protons extracted from the Harwell cyclotron in the standard way meant the 'start' times were not sufficiently well defined to give a good measurement of neutron energy. The solution was to modify the usual extraction method by using electrostatic deflection to kick all the protons on to a target at the 'same' time (to within a few nanoseconds), which then defined the 'start' time sufficiently precisely to give neutron energy resolution of about 4% at 15 MeV rising to 14% at 140 MeV. This dynamic kicker was not a simple device, requiring a deflecting voltage of ~60 kV to be applied with a rise time of less than ~20 nanoseconds, and precisely phased with respect to the radio-frequency (RF) cycle of the cyclotron (14). Using it, Stafford and his colleagues made a detailed and precise measurement of the total cross-section for neutron scattering on several materials (from hydrogen to uranium) at energies from 15 to 120 MeV (16). The spectrometer was used by other teams over a period of several years. (For example: Bowen et al., 1961, 1962, 1963; Riddle et al., 1965; Marshak et al., 1968.)

By 1957 CERN had completed its first accelerator: a synchrocyclotron (CERN SC) capable of accelerating protons to a kinetic energy of 600 MeV. This was significantly above the Harwell top energy (175 MeV), and, importantly, above the threshold for pion production. Together with Franz Heymann, by then a lecturer at UCL, Stafford proposed two experiments. One was to repeat the neutron polarization experiment using the same magnetic technique to rotate the polarization detector as developed at Harwell. The second was to exploit the higher energy of the CERN SC to study pion production. But major developments at Harwell and in the UK organization of particle physics intervened.

Firstly, on the grounds that work on atomic energy was moving towards an era of industrial-scale exploitation, the responsibility for all such work (civil and military) was moved from a Department within the Ministry of Supply to a stand-alone, publicly funded organization at arm's length from government: the UK Atomic Energy Authority (UKAEA), established in 1954.[11]

Secondly, it was becoming abundantly clear that providing every interested university physics department with its own accelerator was completely impractical, both financially and operationally. Despite having (eventually) joined CERN, there was much discussion and contemplation of the need for a national laboratory, equipped with a state-of-the-art, national-scale accelerator and facilities. This discussion was not without some agonizing on the part of the university community, concerned that such a development would at least subvert, if not destroy, university research in particle physics. An interesting and informative perspective on this period and the flavour of the deliberations can be found in the recollections of Wilkinson at the Nimrod Commemoration Evening, held in 1978 (Wilkinson, 1978a).[12]

It was also recognized that such a national laboratory, with its focus on fundamental research and primary aim of providing facilities for the university community (despite their misgivings), would not sit easily within the framework of the UKAEA, which often required, for example, some level of security and vetting of personnel.

Finally, there had been a major advance in accelerator science. As mentioned above, by 1954 Harwell had well-advanced plans for the construction of a 600 MeV proton linear accelerator (PLA). The 'official' reason for building such an accelerator, as presented by Cockcroft to the Atomic Energy Board in 1953, was that it would be an excellent source of neutrons to make fissile material.[13] But Cockcroft certainly also had in mind its use by the university community: the energy was above the threshold for pion production, and, as a linear accelerator, one could extract a high-intensity beam.

[11] The Harwell laboratory began in 1945 as the research establishment for atomic energy, hence the Atomic Energy Research Establishment (AERE). As such, it was one of several such establishments, with differing roles. (For example, the Atomic Weapons Research Establishment, AWRE, at Aldermaston.) The change in organization in 1954 to bring all atomic-energy activity under the UKAEA was by no means the last such change: the name UKAEA survives to this day (2021), but its responsibilities have changed more than once since then.

[12] Sir Denys Wilkinson's recollections were sufficiently 'interesting and informative' that the published proceedings of the Nimrod event were held up for some 18 months while clearance was obtained from the Cabinet Office. (Litt, 2014)

[13] The potential for the production of fissile material rested on then recent results that a 600 MeV proton incident on a heavy nucleus would produce about 30 neutrons. This turned out to be wrong; the true number is more like 10 from a heavy nucleus, a little more from uranium.

The prospect of this machine was one of the reasons that had attracted Stafford back from South Africa to Harwell. Pickavance was appointed to lead the PLA project, which meant that, almost as soon as he arrived back at Harwell, Stafford was acting group leader of the cyclotron group. Then, in 1955, the intensity argument in favour of a linear accelerator vanished: following a suggestion by Tuck on how to extract a beam from a synchrocyclotron with much higher intensity, Le Couteur (Le Couteur, 1955) worked out the detailed theory and it was successfully demonstrated at the Liverpool synchrocyclotron (Crewe and Gregory, 1955). And higher energy could be produced more economically than by a linear accelerator. So, with the argument based on neutron production also no longer valid, Cockcroft convened a series of meetings in 1955 and 1956. Eventually the decision was made to build a 7 GeV proton synchrotron, but, as is well known in the community and much discussed thereafter, using 'weak focusing' and not the recently proposed 'strong focusing'.[14]

The result of all this organizational and technical upheaval was that by mid-1957 the National Institute for Research in Nuclear Science (NIRNS) had been set up to provide the universities with facilities and equipment that were beyond the scope of an individual university. NIRNS was to be funded through UKAEA, and the Rutherford Laboratory[15] was established next door to the Harwell site as the first NIRNS laboratory. Pickavance was appointed as the Rutherford's first Director with the primary responsibility for the construction of the 7 GeV accelerator, later named Nimrod.[16] Stafford followed Pickavance on to the NIRNS staff, and took over responsibility for the PLA, which was no longer the next accelerator of choice, but the first stage of 50 MeV was already under construction before further work on the project was halted in 1955. The PLA building was, conveniently, situated on the periphery of the Harwell site, and could therefore be transferred to the Rutherford Laboratory outside the (Harwell) fence. There was also the possibility of transferring the Harwell synchrocyclotron to NIRNS, but this was viewed by the universities as a (further) sign of an attempt to take over the universities' role in particle physics research, and, in the end, the UKAEA largesse in terms of accelerators was limited to the PLA.

Stafford's new role and responsibilities limited the time he could devote to experiments, and he was not able to follow up on his proposal for an experiment on pion production at the CERN SC. But he did manage to participate in the polarization experiment, the results of which were published in 1962 (18). Stafford's participation made him one of the first UK 'commuters to CERN', which he felt provided him with valuable insight into what university-based researchers would face when using the Rutherford Laboratory facilities later.

1957-1969: Exploiting the PLA and Nimrod at the Rutherford Laboratory

[14] At the time, the use of weak focusing, with the resultant large-aperture beam tube and large-bore magnets, was considered the more certain route to a high-intensity machine than the recently proposed, but technically less sure, strong focusing. It was considered essential that the UK machine should have a far higher intensity than the 6 GeV Bevatron at Berkeley, which started operating in 1954. With the great benefit of hindsight, the decision in favour of weak focusing was overly cautious.

[15] Schonland, at the time Cockcroft's deputy at Harwell, suggested that the new laboratory should have Rutherford in its name. Initially it was the Rutherford High Energy Laboratory (RHEL), but the name has changed many times since 1957. In this article the name 'Rutherford Laboratory' or simply 'Rutherford' is used, unless the context requires use of the contemporary name.

[16] Nimrod: after Genesis 10, verse 9 (King James Version): 'wherefore it is said, Even as Nimrod the mighty hunter before the Lord.' The choice of name occasioned repeated playing of Elgar's Nimrod variation at the official opening some years later.

Stafford's task as Head of the PLA group was to oversee the completion of the PLA, commission it, and develop and oversee a programme of experiments. The PLA would be the only working accelerator at the laboratory until Nimrod came into operation at the end of 1963. The main components of the PLA were the three 'tanks' that sustained RF electric fields, carefully phased to the passage of the accelerating proton beam. Such tanks are directly related to Ising's original idea for a linear accelerator (Ising, 1924): they are technically challenging, require very pure, smooth surfaces to maintain the electric field, and, when opened up, rather beautiful. That beauty may have been a little lost on those who worked on the commissioning of the PLA, for:

> "…. one (fault) in particular that tried the patience of the 40-strong team was the necessity of having to clean the copper guide tubes every week until an electrical design fault was permanently rectified. The top halves of the three tanks would be lifted and everyone, including non-technical support staff, each armed with a can of metal polish, had to polish away the rainbow-hued discolouration rings that appeared on the copper surfaces causing the machine to run below its best. It would take half a day of finger-aching polishing before the guide tubes gleamed again." (Hance, 2006)

But the polishing cannot have harmed the basic soundness of their construction: two of the three tanks (tanks 2 and 3) are still in use in the injector into the ISIS synchrotron at Rutherford (Thomason, 2020). The tanks are still opened up to service the innards, but now only every 5 years.

Paul Williams, who worked at the Rutherford for many years and was its Director from 1986 to 1998, recalls visiting in the late 1950s as a young graduate student. There were:

> "….a number of single storey temporary offices, and buildings that were going up quickly to house the 50 MeV Proton Linear accelerator for which Stafford was responsible under the Lab's founding Director, Dr Gerry Pickavance. I have memories of meeting this energetic physicist who showed us round the PLA buildings; his energy, his piercing eyes and his South African accent have stayed with me ever since." (Williams, 2014a)

Inspired perhaps by the success of the polarized-neutron work with the Harwell synchrocyclotron, Stafford and his team constructed a polarized-proton source for the PLA. The method required some magnetic-field gymnastics on a beam of atomic hydrogen to select atoms with one sign of magnetic moment, and subsequent ionization to produce a proton beam with 50% polarization, which was then fed into the accelerator (19). Despite his growing organizational responsibilities, Stafford was able to take part in experiments using this polarized beam (20, 23).

Also, as at the Harwell cyclotron, it was possible to modify the intrinsic 5-nsec bunch-spacing of the accelerated beam from the PLA so that 1 nsec-long bunches of protons hit the target spaced by around 180 nsec, thus enabling a measurement of the energy of produced neutrons by time-of-flight. Achieving the necessary timing structure at the Harwell machine had required substantial hardware, as described above. For the PLA, it was relatively simple: it was sufficient to deflect the proton beam at injection into the accelerator by suitable RF. This time-of-flight system was then used to study neutron production. In a series of papers, Stafford and co-workers studied reactions in which a proton from the PLA struck a target nucleus causing ejection of a neutron, thus creating an isobar of the original nucleus (22, 24, 25, 26). Such states showed up as peaks in the neutron spectrum recorded by the time-of-flight system, and the results were valuable in furthering understanding of the nucleon-nucleon force in the nucleus.

In 1963 Stafford presented a paper at a conference at CERN on the potential of proton linear accelerators for pion production. Commenting on the PLA at Rutherford, he noted that it had taken some time to get the accelerator operational:

> "This machine has a 1% duty factor and has been in use for research now for about three years. It operates on a 24-hour per day schedule and last month achieved our best reliability factor of 87% useful time. However, it has taken a great deal of effort to work up to this acceptable degree of reliability. A permanent engineering staff of 60 are required to service and operate the accelerator and to design and build the equipment for the 50 nuclear physicists who use the machine and the team of 30 who are concerned with accelerator research and RF valve development." (21)

As Stafford also noted in his conference presentation, the duty factor of only 1% resulted from the huge power dissipation in the RF tanks due to ohmic losses. This had led Stafford and his colleague A P Banford to consider, in an earlier publication (17), the possibility of superconductivity. In that paper they argued that the use of superconducting material in the RF tanks should in principle reduce the ohmic losses by a factor of ~10^4 in an accelerator like the Rutherford PLA and allow a much higher duty factor. This is probably the most influential of Stafford's scientific publications. Superconducting RF is now the subject of an international conference held every two years. It is an essential component of many linear accelerators around the world, notably the free-electron laser (XFEL) at the Deutsches Elektron-Synchrotron (DESY, Hamburg) and the planned International Linear Collider.

The 50 nuclear physicists mentioned by Stafford would have included his team from the Rutherford and some from Harwell, but were comprised mainly of physicists from the UK universities. As already noted, Cockcroft was always enthusiastic about university researchers making use of AERE facilities as much as possible. In his comments at the Nimrod commemoration event in 1978, Wilkinson was at pains to emphasize, twice, that the experience of university users with the Harwell synchrocyclotron, as run by Pickavance and then Stafford, had been very positive. (Wilkinson, 1978b) Nevertheless, there was some basis for the university community's suspicions and concerns at the prospect of a national laboratory as the major provider of facilities for universities. Collaboration between universities and Harwell had not flourished in all cases: "..partly through lack of enterprise on the part of the universities, but partly through the unwillingness of all but a few teams at Harwell to make their facilities realistically available." (Wilkinson, 1978c).

It was, therefore, essential that the interaction between the new Rutherford Laboratory and the university community should get off to as good a start as possible, and this was surely uppermost in the minds of both Pickavance and Stafford. Once operational, the PLA hosted many university groups, and Stafford felt that working with a large university community on the PLA was very rewarding. (For example: Griffith et al., 1963, Gibson et al., 1965, Ashmore et al., 1965) This approach set the tone and ethos of the Rutherford Laboratory.

Toward the end of August 1963 Nimrod accelerated protons up to 8 GeV, and beams were first extracted for experiments in December. With the construction phase over, Stafford was appointed head of the High Energy Physics Division with responsibility for the Nimrod research programme. Some of the primary proton beam extracted from the accelerator was used to strike a secondary target and produce secondary beams, particularly of pions and kaons, which then strike targets at the location of the various experiments. So right from the start Nimrod supported this so-called 'fixed-target' programme of experiments, all operational concurrently. But competition for beam time was high, and interested physicists, usually from more than one university, sometimes also working with Rutherford physicists, had to submit proposals, which were then assessed. In keeping with the emphasis on university participation, a selection panel was established with most of its membership drawn from the universities.

The proton, neutron, pion and kaon turned out be only the 'ground states' of particles involved in the strong interactions, and there was a rich and complex spectrum of excited states to be explored and explained. This exploration had begun when Nimrod switched on, but there was much still to be done. So, despite becoming operational several years after the higher-energy (strong-focusing) synchrotrons at CERN (28 GeV, 1959) and Brookhaven (33 GeV, 1960), Nimrod was able to make a major contribution to the development of particle physics, particularly in the area of the baryon resonances (excited states). In 1967 Stafford presented a summary of the first few years of Nimrod operation (32) and reported on more than 30 experiments that had been completed, or were in progress or about to take data. Initial experience of operating Nimrod had been very positive, although a failure in the power-supply system in February 1965 meant it operated at reduced energy and intensity for much of that year.

As division head, Stafford visited the 'control room' of each experiment every evening when the experiments were taking data.[17] According to Gordon Walker, an employee at the Rutherford from 1960 and later its Director 2000-2001, Stafford liked to hear good news. He was also able to take an active part in some of the early experiments, making detailed and precise measurements of the total cross-section at several energies using proton, pion and kaon beams (27, 29, 30, 31). He was now a person of considerable experience, standing and authority, and he could exercise that authority when he felt it necessary: he was on the overnight shift on a Nimrod experiment when a key piece of electronic equipment, a Laben pulse-height analyser, failed. The expert was at home and did not have a domestic telephone. So, a telegram was composed: 'Laben up spout. Come in. Godfrey', and was delivered by a GPO dispatch rider to the expert's home at half-past three in the morning, causing some local disturbance and excitement.[18]

In 1966 Pickavance presented a report written by him and Stafford on the relationship between the Rutherford Laboratory and the universities at a meeting in Pisa on European Collaboration in Physics.[19] A Nimrod Users Advisory Committee had been set up, chaired by a university physicist and with representation from all the teams and universities using Nimrod, to advise on all matters relating to the effective conduct of research on Nimrod. Hostel accommodation and furnished and unfurnished houses were available, and the cost of travel and incidental expenses were met by the

[17] When delivering beam to experiments, a particle accelerator runs 24/7, and so the physicists monitoring the data-taking and performance of the experimental equipment must organize round-the-clock shifts.
[18] A fuller account of this incident can be heard at: https://indi.to/FkkDS starting after 3 minutes 30 seconds.
[19] The Pisa meeting was one of a series that culminated in the establishment of the European Physical Society in 1968.

laboratory. In summary, they felt “We have done our best to alleviate the considerable personal inconvenience that is involved in working in a national laboratory.” (28)

University users came overwhelmingly from the southern part of the UK. This was one factor in the decision of NIRNS to establish a second laboratory at Daresbury, which is about mid-way between Liverpool and Manchester. Approval for a 4 GeV electron synchrotron was given in 1962, and the machine, known as NINA, became operational in 1966. The model and style of university usage were essentially the same as at Rutherford.

In 1966 Stafford was appointed deputy Director of the Rutherford but continued to head the High Energy Physics Division. It was again a time of significant change in the arrangements for the administration and funding of UK particle physics. In 1965, the role of NIRNS was taken over by the new Science Research Council (SRC), with a remit covering a much broader area of science.[20] The official reason for this change was to harmonize the public funding of all branches of science. Reading the House of Lords debate in Hansard (Hansard, 1965), it is possible to discern the notion that perhaps the particle physicists had also had it too good. The responsibility for particle physics, including the Rutherford and Daresbury laboratories and matters related to CERN, now came under the Nuclear Physics Board (NPB), which reported upward to the SRC. The first chairman of the NPB was Cecil Powell. One of its first problems was CERN.

By the early 1960s both CERN and Brookhaven were contemplating the construction of accelerators of a few hundred GeV. The CERN Council was initially in favour of establishing a second laboratory at a new site to host this new accelerator, with a design energy of 300 GeV.[21] This proposal struggled to attract sufficient support from the CERN member states, and in June 1968 the UK government announced at the CERN Council that it would not be able to participate for financial reasons, even though the SRC and NPB had proposed a major cut amounting to roughly a third of the SRC domestic expenditure to address the financial concerns.[22] Brian (later Lord) Flowers, then Chairman of the SRC and chief UK delegate to the CERN Council, had to inform the Council of the UK decision, followed immediately by a statement in a personal capacity expressing his deep regret at the official decision he had just announced.

---

[20] The abolition of NIRNS was much lamented by the physicists. The new arrangements implied a longer, and therefore more tortuous, process for decision making. An additional cause for lament was that the NIRNS Governing Board had been chaired from its inception by Lord Bridges. Few, if any, outsiders involved in academic science can have evoked a similar scale of admiration, even reverence, from the scientists themselves. Thus, Wilkinson:

> “..Bridges had recently retired from being head of the Treasury and of the Civil Service – he was the last person to combine those appointments in one person. He knew Whitehall upside-down and back-to-front and when he coughed discreetly, mandarins blanched. He had earlier, I was given to understand, won World War II by being Secretary to the War Cabinet and recording in its minutes what Churchill ought to have said – but that is another story. Bridges… was a tremendous chairman of the Governing Board of NIRNS. He never permitted a vote and he always brought home the bacon.” (Wilkinson, 1978d)

Bridges, who read Greats at Oxford, was elected to the Royal Society on the basis of his great distinction. Such was the scope and scale of his service to the nation that his work for NIRNS occupies but one sentence in his Royal Society biographical memoir. (Winnifrith, 1970)

[21] The UK proposal was a site at Mundford in Norfolk. When the author of this memoir was first at CERN in the early 1970s, he heard, often, that this site did not rate highly in terms of weather, local cuisine and topography.

[22] The proposed cut amounted to about £6M out of an annual budget of about £18M. It would have required the closure of at least one and probably both of the domestic accelerators, Nimrod and NINA.

The UK particle physics community was dismayed at the decision, in particular the leadership, which had endeavoured for several years to come up with a financially acceptable package that would allow UK participation. If such a group of scientific leaders can be said to emit howls of anguish, then they did so now, and immediately set to work to get the decision reversed.[23] It was clear that financial savings in the domestic expenditure similar to the NPB proposals of summer 1968 would be required. In March 1969 Flowers addressed the Rutherford staff and informed them that the SRC proposal was to reduce Nimrod operation starting in 1970 and close it in 1975. The Rutherford Laboratory would become a 'staging post' for the preparation of experiments to be mounted at CERN and elsewhere, and the laboratory would also start up other

SRC-sponsored research. In parallel, the UK particle physics community would have to be reduced in number. At Daresbury, the development of a synchrotron radiation facility was being considered, as well as the possible upgrade of the electron synchrotron to 15-20 GeV.

In September 1969 Pickavance, who had already been spending a fraction of his time working on policy matters in the SRC's London office, was appointed to be SRC's full-time Director of Nuclear Physics, thus becoming responsible for both the Rutherford and Daresbury laboratories, as well as for matters related to CERN. A primary task was to get the UK decision on the 300 GeV project reversed. Stafford was the obvious successor as the Rutherford Director and he was duly appointed.

1969-1981: Rutherford Director

The circumstances of Stafford's start as Director in September 1969 were hardly auspicious. In October he attended the party for the closure of the PLA, though this had been announced two years before. (And, as already noted, two of the RF tanks live on.) Far more significant were the SRC's proposals for the future of Nimrod and the laboratory. Not surprisingly, he considered these proposals logistically and logically flawed on the grounds that Nimrod still had good physics to offer and that Rutherford was the natural site for a future national accelerator. Furthermore, he felt it would not be sensible or practical to have the staging post for the preparation of experiments at one laboratory, Rutherford, and the national accelerator at another, Daresbury.

An important component of these future prospects of Nimrod and the laboratory came from the possible application of superconductivity to accelerators. Accelerator designers in the 1960s were fully aware that the high field possible with superconducting magnets held out the prospect of significantly higher energy than could be achieved with room-temperature magnets, but at roughly similar cost. However, no one had a practical solution to the problem of 'flux jumps' and the associated transition of the superconductor back to the normal, resistive state. This changed in 1968 at a conference at Brookhaven, where a report:

> ".. a watershed event in applied superconductivity – was delivered by Peter F. Smith, of the Rutherford Laboratories in Oxfordshire, Great Britain, the premier British accelerator laboratory. Smith announced that his group had found a way to eliminate flux jumping and

[23] A remarkable, and remarkably interesting, account of the machinations that lay behind the UK decision was published in 1969 by the science journalist Robin Clarke. (Clarke, 1969) It is not possible, more than 50 years later, to check the story Clarke tells in every detail, but he must have been briefed very thoroughly by at least one of the interested parties.

> reduce AC losses entirely, giving rise to superconductors that were *intrinsically stable*." (Crease, 2005)

Peter Smith, Martin Wilson and colleagues had succeeded in developing a cable made up of many superconducting filaments, each of diameter comparable to a human hair, and twisted together in such a way as to minimize the inter-filament coupling (Smith et al., 1968). This is crucial for the use of superconductivity in accelerator magnets, which have to be 'pulsed', i.e. cycled regularly between low and high magnetic fields.

The work of the group had been strongly supported by Stafford. Many years later he confided to Wilson that getting the necessary funding from the NPB had not been easy, not least because some of the money would be paid to outside industry (Imperial Metal Industries, UK) to develop the super-thin filament (Wilson, 2014).

Smith had also suggested that, if suitable superconducting magnets could be developed, then Nimrod's energy could be increased relatively inexpensively to 25 GeV or more. In one of his first acts as Director, Stafford launched a major programme to develop the cable further and build prototype superconducting magnets suitable for a synchrotron. Recalling this decision some 50 years later, Smith wrote:

> "However, the early 'breakthrough' moment in this arose from the far-sightedness of Dr Stafford, who believed in my suggestion for upgrading Nimrod in this way and authorized a major expansion (staff and money) of the superconductor R&D program at RAL (Rutherford), initially for the possible energy upgrade at RAL, but also with the aim of developing very high current-carrying superconducting cables and prototype guide field magnets. So it was this key decision to fund an expanded program that can be attributed to Dr Stafford, who also recognized that at that time we had a world lead, which in turn led to an expansion of world interest." (Smith, 2020)

In his Foreword to the 1969 Annual Report, Stafford wrote that the development of superconducting magnets was now the laboratory's main technical work. The use of superconducting magnets for the CERN 300 GeV project was considered carefully in the early 1970s, but eventually rejected as too risky at the time.[24] Since its development, this superconducting cable, later named Rutherford Cable, has been used in all successful superconducting accelerator magnets, including those at the CERN Large Hadron Collider.

SRC's drastic proposals for the Rutherford Laboratory were directly coupled to the 300 GeV issue, and work to get that decision reversed continued at the SRC/NPB level. As Rutherford Director, Stafford was now *ex officio* a member of the NPB, as was the director of Daresbury, who was probably as concerned about the possible repercussions as Stafford was. Both directors presumably argued their corner. Official papers and memoranda from the period make clear that the decision as to which accelerator (Nimrod or NINA, or even both) would have to close was rather fluid and subject to change.[25] At this point national politics intervened.

---

[24] In his Biographical Memoir of John Adams, Stafford wrote: "My opinion now is that Adams was correct in not succumbing to …. the possibility of building the world's first superconducting accelerator." (33)

[25] This observation is based on the papers of Sir Denys Wilkinson in the archive at Churchill College, Cambridge. https://archivesearch.lib.cam.ac.uk/repositories/9/resources/1899

Somewhat against expectation, the Conservatives won the UK general election in June 1970, and the new prime minister, Edward Heath, appointed Margaret Thatcher to be the Secretary of State for Education and Science. One of her first acts was to visit CERN on September 24th, 1970, arranged no doubt by Pickavance and the SRC. The CERN Courier (CERN's internal monthly magazine) described the visit as 'informal', but the CERN management no doubt took it very seriously. By this time, John Adams had been appointed Director for the CERN 300 GeV programme,[26] which was still struggling to get the go-ahead from the member states, and the UK withdrawal from the project in 1968 had not helped. Adams had developed a 'Project B' version, which involved siting the accelerator on Swiss and French territory adjacent to the existing laboratory and making significant use of existing CERN infrastructure. This proposal was significantly cheaper than establishing a new laboratory and finessed the vexed question of where a new laboratory should be. Project B had been given strong encouragement by the CERN Council in June 1970 and was also supported strongly by the European Committee of Future Accelerators (ECFA), which was chaired at the time by Pickavance. As well as being shown the various CERN facilities,[27] Mrs Thatcher's visit included discussion with the CERN senior management, and Pickavance, accompanying the visit, was probably also present. No publicly available record of the discussions seems to exist. However, it is surely the case that the savings possible from the Project B proposal and the importance of UK involvement were laid out in some detail, and Mrs Thatcher always appreciated a discussion of detail presented by those who were on top of their material.

On December 4th 1970, Mrs Thatcher informed the House of Commons in a written answer that:

> "We have decided that the United Kingdom should participate with the other European countries which are members of the European Organization for Nuclear Research (C.E.R.N.) in building a 300 GeV accelerator near the existing C.E.R.N. site at Geneva. A careful appraisal of priorities within the civil science budget has made it possible for the cost to be found without additional public expenditure." (Hansard, 1970)

It is probable that her visit to CERN was significant in the UK decision, and it may even have been pivotal.

At the CERN Council meeting just before Christmas 1970, Flowers reported the new UK decision. Happily, Pickavance, in his capacity as the chairman of ECFA, was also present: just a few months later, on a trip to Italy with the Stafford family for vacation and a conference, he suffered the debilitating stroke that ended his career.

The 'careful appraisal of priorities' mentioned by Mrs Thatcher had, of course, to be carried out and implemented. The earlier SRC proposal to run down Nimrod and focus on Daresbury for the national accelerator was re-visited and by the end of 1972 there was a significant change: Nimrod would run to the end of the decade and be equipped with a new injector (to increase its intensity), and NINA

[26] John Adams led the construction of the 28 GeV synchrotron at CERN, and was, briefly, interim Director-General of CERN in 1960 after the death in an aeroplane crash of the Director-General, C J Bakker. Adams then returned to the UK and was Director of the UKAEA laboratory at Culham until 1966. He was invited back to CERN to lead the 300 GeV project at the end of 1968.

[27] UK particle physicists at CERN were regaled by tales of Mrs Thatcher's visit for some time afterwards. At the bubble chamber facility the CERN expert began, "I don't suppose you know what a bubble chamber is…", but was interrupted: "Of course I know what a bubble chamber is!".

would close in 1977.[28] Furthermore, planning for a new national accelerator for the 1980s was also undertaken, with participation from across the UK community and major involvement of Rutherford staff. By the end of 1973 a very ambitious project had been conceived for the Rutherford site: a first phase would consist of an electron-positron collider of energy 14+14 GeV,[29] to be followed some years later by a proton ring, of up to 200 GeV if superconducting magnets were available, for electron-proton collisions. The plan had a suitably ambitious acronym: Electron-Positron/Proton Intersecting Complex, EPIC. Stafford must have been pleased at the turn-around in the Nimrod and Rutherford prospects that had been achieved. He was also probably aware that the wheel of change does not always stop where one wants it to.

A costed proposal for the electron-positron (e+e-) phase, making maximum re-use of Nimrod and NINA components, was submitted to the SRC in November 1974. This was the same month as the 'November revolution' in particle physics: the simultaneous discovery of the J/ψ particle in e+e- collisions at the Stanford Linear Accelerator Center (SLAC) in California and in the e+e- final state in p-Be collisions at Brookhaven. Almost overnight, this discovery vaulted the e+e- collider into the machine of choice for particle physics. So, the physics case for the e+e- collider was readily accepted by the SRC, and further work to develop the proposal was approved. But the SRC also stated that full approval (at a cost of over £20M) would require a significant contribution, perhaps around a third, from European partners.

Given the physics potential, the UK was not alone in planning to construct a new e+e- collider: both SLAC in the USA and, more significantly, the DESY laboratory in Germany had similar proposals. The scale of such projects meant that it was impossible, even undesirable, for both the European proposals to proceed. In October 1975 the German government, engaged at the time on a major programme of investment in infrastructure, authorized the construction of the DESY machine, PETRA. In practice, this killed EPIC, and it was cancelled officially soon afterwards. Remarkably, just a few months later in 1976 Stafford and his team were able to submit a proposal for an entirely different facility that would exploit neutrons.

Neutrons

In 1932, James Chadwick, the discoverer of the neutron, said in an interview with the New York Times that, "I am afraid neutrons will not be of any use to anyone." As scientific predictions go, this is almost on a par with Rutherford's more famous prediction in 1933 about atomic power. The neutron has turned out to be a remarkably useful research tool: neutron scattering can reveal where atoms are and what they do, and the technique is used in studies ranging from the dynamics of chemical reactions to new materials for hip implants.

The story of neutron research in the UK, with its various European entanglements, has many similarities to that of particle physics. A very brief summary follows. The study of nuclear reactor technology was a key part of Harwell's work in the post-war period, and several reactors (of varying size) were constructed, primarily to test materials by 'burying' the test material inside the reactor core. But, beginning in the late 1950s, the potential of neutron scattering was becoming apparent, using neutrons that exited a reactor through small channels or 'ports', and demand for neutrons for

[28] In the early 1970s the synchrotron radiation from NINA was used as a research tool. Following the closure of NINA, a dedicated synchrotron radiation facility (SRS) was constructed at Daresbury and operated from 1981 to 2008. A brief, but comprehensive history of synchrotron radiation and its uses can be found at https://xdb.lbl.gov/Section2/Sec_2-2.html

[29] A collider, in which two beam travelling in opposite directions collide, has a huge advantage over a beam striking a stationary target in terms of the fraction of the initial energy available for the production of other particles. In the latter case, conservation of momentum 'uses up' much of the initial energy.

academic research grew. In the early 1960s Harwell designed a High Flux Beam Reactor (HFBR)[30] optimized to meet this demand. Discussions of a possible European project took place under the auspices of the European Nuclear Energy Agency,[31] but the UK withdrew from the ENEA project in 1964 in favour of a national facility. Harwell (UKAEA) submitted a proposal for an HFBR in 1966, and a revised proposal jointly with the SRC in 1968. This revised proposal foresaw a 20% contribution from Europe, which was surely optimistic as Germany and France had by then already launched their own joint project, which became the Institut Laue-Langevin (ILL) at Grenoble. In the UK the Ministry for Technology decided in early 1970 that the UKAEA should not contribute to the cost of the UKAEA-SRC project, as the proposed reactor was primarily for academic research, and the responsibility for taking any proposal forward fell to the SRC alone.[32] At which point the government changed. In 1971 the SRC had to choose between the alternatives of joining the ILL, where construction was already well advanced, and pushing for an HFBR in the UK. It decided, narrowly, for the latter, and proposed this to the Department of Education and Science, but in 1972 the government chose to pursue UK membership of the ILL instead.[33] These discussions proceeded rapidly, and the UK became an equal member (with France and Germany) of the ILL in January 1973.

Access for university physicists to the UKAEA reactors at Harwell and Aldermaston had been formalized in 1966 under an agreement between the UKAEA and the SRC,[34] and managed by the SRC's Nuclear Beam Research Committee (NBRC). Support for neutron physicists was therefore not, at first, a priority at Rutherford, although Pickavance was always very keen to broaden the areas of research supported by the laboratory.[35] In 1971, with the SRC proposal for a national HFBR under active consideration, Stafford established the Neutron Beam Research Unit (NBRU) under Leo Hobbis.

But a reactor is not the only way to produce neutrons. A heavy nucleus, for example tungsten or uranium, is neutron rich and neutrons can be shaken loose when the nucleus is struck by a sufficiently energetic particle. Starting in the 1950s, Harwell built a series of electron linear accelerators that produced neutrons in this way by photoproduction. By the early 1970s, based on the pioneering work of Jack Carpenter in the USA, the case for a spallation neutron source using a proton accelerator, with the prospect of a much higher yield of neutrons, was being developed.[36]

---

[30] The planned UK reactor was referred to in some contemporary documents and articles as the HFBR. To the neutron community of today, the HFBR means the reactor constructed at Brookhaven, and which ran from 1965 through 1996.

[31] The European Nuclear Energy Agency (ENEA) was established in 1958. Euratom (founded in 1957) was primarily concerned with the deployment of nuclear energy in Europe; the ENEA was concerned with all other aspects of nuclear energy, for example nuclear safety and nuclear science. The Dragon reactor at Winfrith, which operated from 1965 to 1976, was part of an ENEA programme. The organization exists today as the Nuclear Energy Agency, which reflects its present international membership.

[32] Though the siting of the HFBR would have been complicated by the requirement of a licence for handling enriched uranium. Harwell had such a licence; Rutherford did not.

[33] In October 1971, the UK Parliament had voted to join the European Common Market, and it is possible pro-European zeal played a part in the decision to seek to join the ILL.

[34] In the second half of the 1960s the UKAEA came under increasing pressure from central government to increase its 'external' income. From 1966 SRC had to pay for access to the Harwell and Aldermaston reactors.

[35] With his understanding of the academic community and Harwell, Pickavance was able to facilitate the academics' access to the Harwell reactors.

[36] John M 'Jack' Carpenter pioneered the use of a proton accelerator to produce neutron beams. In 1971 he proposed using the Argonne Zero Gradient Synchrotron (ZGS) to produce neutrons in this way and he went on to develop a 'moderator' that reduces the neutron energy to a range that is useful for experiment. He died in March, 2020. In its obituary, Physics Today wrote that, "… he changed the field of neutron scattering." https://physicstoday.scitation.org/do/10.1063/PT.6.4o.20200424b/full/

After the cancellation of the UK HFBR in favour of joining ILL, the work of the NBRU switched to support of research at ILL. But some work was also done on a possible accelerator-based neutron source. However, this was considered 'unofficial' as long as EPIC was the official Rutherford proposal for a major new facility. But once EPIC was cancelled in 1975, Stafford was able to act with great speed and effectiveness. He immediately convened a small working group, the Pulsed Spallation Neutron Source Working Group, which concluded very quickly that a neutron source (referred to as the SNS – the spallation neutron source) using a proton accelerator and based on existing Nimrod infrastructure was feasible and would also complement and extend the excellent results already coming out from ILL. The group proposed some preliminary studies of neutron production. Andrew Taylor, who went on to play a major role in the development and exploitation of neutrons at Rutherford, joined the burgeoning project in October 1975 and recalls:

> "Importantly we built MUSTA (Mock Up Spallation Target Assembly) using a de-tuned 800 MeV proton beam from NIMROD to generate spallation neutrons and quantify the thermal neutron performance. This later proved to be a key measurement in confirming the viability of the project. Geoff Manning was inspirational. Godfrey (Stafford) summoned me to his office to report these results, to counter arguments made against building SNS. Although as Lab Director he terrified me at the time, his support was critical to the project succeeding." (Taylor, 2020)

A complete proposal for the SNS, including scientific case, technical specification, costings and timescale, was submitted to SRC in December 1976. The SNS would be based on a (strong-focusing) 800 MeV proton synchrotron with the extracted proton beam striking a uranium target to produce the neutrons. By making extensive use of existing Nimrod and NINA components and infrastructure, the cost (~£10M) was estimated to be only a third of a completely new facility. The project had broad but not unanimous support from the academic community. As mentioned by Taylor, there were arguments against building SNS, and some believed a UK reactor was the better, surer approach. One senior university physicist felt sufficiently strongly to write to the Secretary of State (Shirley Williams) urging that the SNS should not proceed. But official government approval followed in June 1977.

The construction of the SNS required the closure of both NINA (in 1977) and Nimrod (in 1978) to enable re-use of components and infrastructure (see Figure 2). The construction took place during a period of severe pressure on public expenditure in the UK, which stretched the schedule, but the experimental programme of neutron scattering began in 1985. At around the same time as the SNS construction, spallation sources in the USA and Japan were also being developed, and Stafford was keen to foster international collaboration. Initially this was LARJ (Los Alamos, Argonne, Rutherford, Japan), but soon became ICANS (International Collaboration – not conference! - on Advanced Neutron Sources). The 23rd ICANS meeting took place in 2019.

The SNS was opened officially by the Prime Minister (Mrs Thatcher) in October 1985, at which point it was renamed ISIS.[37] Its performance and facilities have been improved and enhanced significantly since then, and it is a widely used world-class facility, which is expected to continue to operate for many years.

With the closure of NINA and Nimrod, all accelerator-based experiments carried out by UK particle physicists moved to CERN and other overseas centres, completing a trend that had been increasing

[37] ISIS is not a contrived acronym to match the local tributary of the river Thames, but rather taken from the goddess Isis of the ancient world, who was able to restore the dead to life. Thus ISIS is born from the remnants of NINA and Nimrod. Replacing the name SNS was motivated, apparently, by a desire to avoid confusion with the SRS (Synchrotron Radiation Source at Daresbury) and SPS (Super Proton Synchrotron at CERN).

for several years. At the Rutherford Laboratory close collaboration with the university particle physics community continued and continues through the design, construction and operation of particle detectors, for which the resources of the laboratory have been essential.

Figure 2: Stafford and Pickavance switching off Nimrod, July 1978. Photo: Rutherford Appleton Laboratory/UK Science and Technology Facilities Council

Further diversification: Lasers, Computing, Space

Lasers

In similar vein to Rutherford and Chadwick, the developer of the laser, Theodore Maiman, was sceptical of the device's potential, declaring that it was a "solution looking for problems".[38] By the early 1970s the potential of lasers for plasma research was becoming apparent, and with it the need for facilities on a scale that could not realistically be provided to each interested university. So, as happened for particle physics accelerators, planning began for a national facility. Following a report on the science case to its Science Board in 1973, the SRC set up the Laser Steering Committee, chaired by Dan Bradley, who was transferring from Queen's University, Belfast, to Imperial College.

[38] This remark has been attributed to various people associated with the development of the laser, probably because it was so widely repeated. The 1964 Nobel Prize was awarded to Townes, Basov and Prokhorov for their "fundamental work … which has led to the construction of oscillators and amplifiers based on the maser-laser principle". Maiman, working for Hughes Aircraft Company, was the first to demonstrate a device producing visible light (laser) rather than microwaves (maser). Maiman's PhD supervisor was Willis Lamb (of the Lamb shift) and his thesis work on measuring the fine structure in excited Helium states was important for his later development of the laser.

Bradley was initially enthusiastic for a site in Northern Ireland, which lacked any national-scale facility at the time, but the case was undermined by a deteriorating security situation.

In 2014 Paul Williams recalled that: "Godfrey (Stafford) led an initiative in the SRC and convinced the interested parties that the best solution would be for one super-laser to be built at the Lab.". (Williams, 2014b) But a further complication arose. It had been appreciated for some time that lasers might in principle be able to confine and compress a plasma to such a degree that controlled nuclear fusion occurred: Inertial Confinement Fusion, ICF. Some experimental results in the early 1970s stimulated considerable interest, so the UKAEA, with its laboratory at Culham, established in 1960 to explore fusion energy, was interested in high-power lasers. It was eventually agreed to propose a facility sited between Rutherford and Harwell and operated jointly by SRC and UKAEA, and a detailed proposal (SRC 107-74) to this effect was submitted to SRC in December 1974. However, results on laser-induced compression were considered 'sensitive' and touched on national security. So, firstly, the proposal had to be treated as strictly confidential because it contained sensitive technical data, and secondly, and more consequentially, the facility would have to be operated in a bi-polar fashion: open access for academic research, but with security restrictions for the fusion-related studies. Stafford was extremely uncomfortable at this prospect. Fortunately, it never materialized. The UKAEA withdrew from the joint proposal in September 1975,[39] and the SRC approved the Central Laser Facility (CLF) as an SRC-only facility in October 1975.

The CLF was established very quickly, and experiments began at the end of 1976. Like ISIS, it has been developed and upgraded extensively, and is recognized as a world-leading centre through its work with its university partners, industry and the international community. Its 40th anniversary was celebrated in 2017, and there are ambitious plans for major upgrades to maintain its leading position.

Computing

In the 1950s it gradually became clear that computers had potential far beyond lengthy numerical calculations. In particular, computers could handle the 'book-keeping', storage and routine analysis of scientific data. In 1961 a national laboratory for computing was established, under NIRNS. The laboratory, sited between Harwell and Rutherford, was to be equipped with a state-of-the-art 'Atlas' computer[40] developed and manufactured by the University of Manchester and the UK company Ferranti. Atlas would provide powerful computing facilities for the entire academic community and government departments, notably the Met Office. Jack Howlett had been involved with numerical

[39] At the time the reason for the UKAEA withdrawal from the laser project was reported in Physics Bulletin (Physics Bulletin, 1975) to be that the UKAEA did not wish to duplicate research being planned under a European Economic Community (EEC) framework. The EEC plans for fusion power were co-ordinated through Euratom, and discussion of the 1976-1980 5-year plan was bogged down by the issue of the site for the Joint European Torus (JET), which eventually (1977) came to Culham. But the 5-year plan also contained a relatively small programme on laser-induced fusion. However, Paul Williams' recollection is that this consideration played no significant role: rather, UKAEA withdrew after various 'sensitive' physics results from the USA were declassified in late 1974 (Williams, 2021).

[40] The Atlas computer was for a time the fastest computer in the world. It was the first machine with an 'operating system' to control and co-ordinate the flow of tasks and with 'virtual memory' to extend the available memory. 'Real' memory was based on ferrite cores (hence the reference in those days to memory as 'core') and was extremely expensive. The Atlas computer had a few hundred kilobytes of core memory. A modern (2021) smart phone has four to five orders of magnitude more. The Atlas computer was based on discrete transistors, a technology that was overtaken from the mid-1960s by designs using integrated circuits. Much interesting material about Atlas, the Atlas Laboratory and computing in the 1960s and 1970s is available at http://www.chilton-computing.org.uk/index.html .

analysis and computers since the 1940s and came over from AERE Harwell to be Director of the Atlas Laboratory, as it was named. The Atlas computer was delivered in 1964 and ran until 1973, by which time the next-door Rutherford Laboratory, Daresbury Laboratory and many of the universities had substantial computing installations of their own.

So, alongside the discussion in the early 1970s of the futures of the Rutherford and Daresbury laboratories and their facilities, the SRC also considered how to organize better its provision of computing. Prompted in part by Howlett's impending retirement in August 1975, it was finally decided that the Atlas Laboratory, which now came under the SRC, should merge with the Rutherford Laboratory, and this took place in 1975. In parallel, some of the Atlas Laboratory's computing support of the academic community, for example in atomic and molecular physics, was transferred to Daresbury. Computing has evolved hugely since then, and computing support for the academic community has flourished at both laboratories.

Space

Soon after the first World War, the British government established the Radio Research Station at Ditton Park, Slough, to investigate radio transmission and the ionosphere. The work carried out there led to the development of radar. By the mid 1970s it had become the Appleton Laboratory, named after the Nobel-prize winner Sir Edward Appleton, and its role had expanded to the support of atmospheric, solar system and astrophysics research in the universities, including the building of the instruments sent into space. As with other disciplines, the need for international co-operation became apparent in the 1950s, and several European nations, including the UK, formed the European Space Research Organization (ESRO) alongside the European Launch Development Organization (ELDO), which were based on, but not identical to, the model of CERN. By the 1970s these had merged into the European Space Agency (ESA), which has been in existence ever since. The Appleton Laboratory's role for the UK 'space science' community therefore had many similarities to the role of the Rutherford for the particle physics community, and a merger of the (smaller) Appleton Laboratory with Rutherford looked attractive.

This merger started in 1979 and went through with relatively little friction. The ex-Appleton scientists were pleased to be freer to publish their research papers, but less pleased by the Rutherford's predilection for memos. They were also concerned that there were not enough local carpenters to make the wooden models that were widely used at Ditton Park (Meadows, 2009).

Stafford welcomed this further, major diversification of the laboratory's activities. In 1979 Richard Holdaway was a young Appleton scientist joining the Rutherford Laboratory. Speaking at the 2014 event to celebrate Stafford's life, and by then head of 'RAL Space', Holdaway recalled Stafford's kindness to the arriving Appleton staff. At Ditton Park he had been accustomed to being addressed as 'Holdaway' by senior staff; at Rutherford he was pleasantly surprised at Stafford's greeting, "It's Richard, isn't it? How is your programme going?" (Holdaway, 2014).

Like ISIS and the CLF, Space Science is now one of the major components of the Rutherford Laboratory's activities, and it supports academe and industry in research that spans Earth's climate to the fundamental physics of the universe.

With the merger of the Appleton laboratory in 1979, the site was renamed the Rutherford Appleton Laboratory (RAL), a name that is still in use today. John Houghton came from Oxford to be Director of the Appleton and Geoff Manning became Director of the Rutherford, with Stafford as Director General of the combined laboratory.

In April 1980 Stafford turned 60. The general direction for the future laboratory was clear, and, though the new activities were by no means fully established, he could perhaps feel more certain of the laboratory's long-term future than when he started as Director in 1969. He would keep a watchful eye on 'his' laboratory for the rest of his life – he was appointed its first honorary scientist - but in 1981 he was ready to relinquish the reins, as there were by then other, different calls on his time.

1979-1987: Master of St Cross

By the early 1960s, a substantial fraction of Oxford University's academic staff, particularly the scientists, had no fellowship at an Oxford college, and many of the graduate students had no college 'home'. This situation led, eventually, to the establishment of St Cross (1965) and Wolfson (1966) as graduate colleges. St Cross took its name from its location on a university site in St Cross Road.[41] The college was accommodated in a refurbished school house and a purpose-built wooden hut of plain exterior but well-appointed interior. The first Master of St Cross, 'Kits' van Heynigen, was a biochemist who was keen for the college to embrace modern technology where possible, and he wondered if a computer could be accommodated on the site. He soon learned that this would require substantial and unaffordable infrastructure, but he was put in touch with Jack Howlett, then the Director of SRC's Atlas Laboratory. Howlett suggested that a terminal linked to the Atlas computer at Harwell by a telephone line could be very useful and would require only a small, ordinary room. Thus it was that St Cross became the first Oxford college to have a network connection to a mainframe computer. Howlett was elected a Fellow by Special Election in 1966 and became an active member of the college.

It seems likely that Howlett made some of his Rutherford/Harwell colleagues known at St Cross. In any case, Pickavance was elected a Visiting Fellow in 1968[42] and Stafford in 1971. Van Heynigen was due to retire as Master in summer 1979 and a selection committee was set up to consider his successor. Stafford was on the point of writing to the committee with some suggestions when he received a letter inviting him to become the second Master of St Cross. As a scientist who had come to Oxford from South Africa via Cambridge, Stafford was succeeding a scientist who had followed the same path, and at the time they both lived in the same Oxford village of North Hinksey. He took over, initially on a part-time basis, in September 1979. The college faced some interesting challenges, but the circumstances were much more propitious than those he faced when he became Rutherford Director in 1969.

The need for much larger college premises and the finances to pay for them dominated the first years of St Cross. After some ten years, a remarkable opportunity arose: Pusey House was established in 1884 as a centre for religious study and to provide spiritual counsel to members of the university. As such, it was closely associated with the university, but independent of it. Situated in the centre of Oxford, Pusey House consisted of a beautiful set of buildings, which were occupied by the university's Faculty of Theology and Religion and the Pusey chapter. In 1976 the Faculty was about to move to new quarters, and it was suggested that St Cross could move in, a suggestion that

---

[41] Similarly, Wolfson College was initially named Iffley College, after its planned location in Iffley village in north Oxford. But major benefactions from the Ford and Wolfson Foundations led to a more central site and a change of name.
[42] The same year as the film star Douglas Fairbanks, Jr., who Van Heynigen hoped would help to unlock a large benefaction from the USA. Fairbanks did not manage to do that, but he was a generous, long-term friend of the college.

was accepted readily by the college. Detailed discussion ensued as to how the college and the chapter might share the buildings and facilities. It was agreed that St Cross would purchase some of the buildings on a 999-year lease as well as the right to develop the garden area behind the main buildings. But £350,000 were needed to buy the lease and more would be required to adapt the available buildings to the college's needs. Van Heynigen had been approaching potential benefactors since the college's foundation and had established friendly links with the owners of Blackwell's, the famous Oxford bookshop. Happily, the Blackwell family were seeking an appropriate way to mark Blackwell's centenary in 1979, and a large benefaction enabled the deal to go through. So, when Stafford took over as Master, the main components for the move to Pusey House were in place.

Stafford made an early, lasting impact: a new dining hall was needed. Eric Whittaker, who became vice-Master just after Stafford took over, recalls:

> "What is now the library had been Pusey's dining room, served by a hatch from the kitchen…. This was very inadequate for our needs, but I suggested that we should initially use this for lunch, supplemented by tables in the circulation space outside the dining room door. Fortunately the Master had a much better vision and designed a steel reinforced ceiling … strong enough to support the walls of the first floor, and permit the removal of the load-bearing walls that divided up the ground floor…. Thus we were provided with a dining hall." (Whittaker, 2014)

Following further building in the 1990s, this dining hall became a spacious Common Room that continues to benefit from Stafford's idea. The college was finally able to take up occupancy of Pusey House in September 1981, just as Stafford retired from the Rutherford Laboratory and devoted himself full-time to St Cross. His principal aims as Master were to increase the number of graduate students, broaden the scope of their research and to provide more college accommodation for them. And to raise further endowments.

The college's first graduate students in 1966 numbered just five, heavily outnumbered by around fifty fellows. One result was that the college made no hierarchical distinction between the fellows and the graduate students, welcoming them rather as honoured guests. One of the 1966 intake recalls that St Cross was seen as a "grown-up institution, unlike many traditional colleges which gave the appearance of being an extension of school.". There was no 'high table' or Senior Common Room from which the students were debarred. This egalitarian approach continues as a core principle to this day (2021), when the number of graduate students exceeds 500. During Stafford's mastership the number of graduate students rose firstly to 36, the University-imposed limit as of 1982, and by 1987 was close to the revised upper limit of 75. And a significant fraction used college accommodation.

Speaking at the Founders' Feast in 1980, Stafford noted that a large single benefaction, on a scale that can lead to a change of college name, still evaded St Cross. And it continued to do so, although there was a steady flow of relatively small legacies, and, in 1987, a very generous benefaction. The first call on these funds was to build in the garden area behind the existing buildings. Plans had to pass Oxford City Council's planning committee, which proved tortuous, and work on the first building in the garden began only in 1991.

Stafford's nine years as Master spanned the move into the new home and the clear evolution of the college towards its present-day state. Many viewed his mastership as transformational. Speaking at the dinner to mark the end of his tenure, Derek Roe, then the vice-Master, noted the rate of increase of student numbers and financial capital during Stafford's term and observed that, "Were your immediate successors to continue progress at that rate, we should in a short while become the richest college in Oxford and one of the largest." (Roe, 2014)

As an Honorary Fellow, Stafford enjoyed continued links with St Cross for the rest of his life and had several close, long-term friends among the fellowship.

Community Leader

Stafford believed profoundly in co-operation and the use of shared facilities, and he was a natural supporter of international collaboration. He was enthusiastic about the idea of a European Physical Society (EPS) and was a member of the steering committee that led to its formation in 1968. He was also the scientific secretary of the organising committee for the first EPS conference in Florence in 1969. In 1984-86 he was the EPS president.

As already mentioned, Stafford was an early user of CERN and was involved with it until 1982. Once Nimrod began operating in 1964, the CERN Director-General invited Stafford to attend CERN's Nuclear Physics Research Committee, which then oversaw all CERN's research programme, in order to facilitate co-ordination between the experimental programmes at CERN and at Rutherford.

In 1973 he was invited to become a member of CERN's Scientific Policy Committee (SPC), which advised CERN's governing body, CERN Council, on major scientific policy, for example on the construction of new accelerators. Membership of the SPC was by election and on the basis of a person's scientific standing. He was vice-chair of the SPC for 1976-77 and then its chair for 1978-80. During his time as chair, the SPC had to advise CERN Council on the proposal to build a large electron-positron (LEP) collider as CERN's major new accelerator after the SPS. The physics case for such a facility was strong by the late 1970s, but it was nevertheless a major decision, taken at a time of (not uncommon) budgetary concerns, and with far-reaching consequences for CERN: the 27 km tunnel excavated for LEP was, deliberately, made large enough to accommodate a post-LEP proton machine, today's Large Hadron Collider. As SPC chair, Stafford attended CERN Council and served as one of the UK delegates to Council during that period.

In the UK, Stafford was President of the physics section of the British Association for the Advancement of Science (now the British Science Association) in 1986, and President of the Institute of Physics in 1986-88.

Figure 3: Almost all the family circa 1999. From the left: Anne Stafford (front), Godfrey (back), Max Wallis (front), Liz Stafford (back), Goldy (front), Toby Stafford (back), Alice Stafford (front), Simon Wallis (back), Rachael Wallis (front), Gabriel Wallis (back), Sam Stafford (front) and Mark Piney (front). Photo: the Stafford family.

Family life and retirement

Helen Goldthorp (Goldy) Clark was born in Adelaide, Australia, in 1920. She was an avid reader from a young age but also enjoyed outdoor activities. She majored in Zoology and Bacteriology at the University of Adelaide and came to London in 1948 to study for a PhD. Visiting Cambridge with a close friend, she met the research student Godfrey Stafford. The two friends were planning to visit Oxford soon afterwards. When they did, Godfrey somehow 'happened' to be in Oxford too, and romance blossomed. They were married in 1950; Goldy's PhD was never finished, though she was the author and co-author of published articles on cestodes in Australian birds (Harvey Johnston and Clark, 1949; Clark, 1957).

Family life started at Harwell, switched to South Africa in 1952, and then back to Harwell in 1954. By then the family had increased with the arrival of a son, Toby, in 1951 and twin daughters, Elizabeth (Liz) and Anne, in 1953. The family settled happily in Abingdon, a few miles from the Rutherford Laboratory. Before the children reached school age, Goldy took them (by ship) to Australia to visit her family and childhood home, but without Godfrey, who could not spare that much time away from work. Godfrey and Goldy both missed the sun and warmth of their childhoods, and, as soon as the children were old enough, summer holidays were spent camping in the south of France and, later, in Italy. Getting there took a few days in the family Jaguar and allowed time for good lunches on the way to the camp site for the night. The opening of the Mont Blanc tunnel in 1965 saved some journey time but diminished the drama of crossing the Alps.

Standards in the Stafford household were high: as they grew up the children learned that their parents expected them always to try their hardest and do their very best. All three children went on to university and to high-level professional careers. In 1971 the family moved from Abingdon to the village of North Hinksey, on the edge of Oxford, and Godfrey and Goldy lived there, in Ferry Cottage, for the rest of their lives. As the daily demands of her growing family reduced, Goldy began to have time for her wider interests. Always a believer in 'doing', she taught biology part-time and took adult classes in literature. The Soviet invasion of Czechoslovakia in 1968 prompted her, together with two friends, to establish the Abingdon branch of Amnesty International. During Godfrey's time as Director of the Rutherford, Goldy was able to accompany him on some of his official trips. And she often went to social occasions and events at St Cross during Godfrey's Mastership and afterwards.

Rachael, the first of five grandchildren, arrived in 1984, and Godfrey and Goldy both revelled in their roles as grandparents. Through St Cross, Godfrey became a close friend of the artist and sculptor Audrey Blackman,[43] who made several pieces depicting the grandchildren. There were many family gatherings, outings and trips involving the three generations (see Figure 3). This period of happy, carefree retirement was broken when Goldy's memory started to fail in the late 1990s and she required increasing amounts of care, which Godfrey gave with unstinting love and devotion. Goldy died in 2003; they had been married for 53 years.

In the last decade of his life, Godfrey enjoyed relatively good health; he would regularly cycle between St Cross and North Hinksey, although eventually succumbing to some battery power to assist pedalling. He enjoyed the company and conversation of friends, regular visits to the Rutherford Laboratory and St Cross, playing bridge, often with long-time friends and colleagues Norman Lipman and Geoff Manning, and, above all, his family, who provided support and brought him much pride and joy. His intellectual vigour was undiminished. Margaret Yee, a Senior Research Fellow by Special Election at St Cross, became a close friend during this time and remembers many delightful meals and discussions with Godfrey and visiting academics. As a researcher into the 'principles of knowing' and inter-disciplinary exchange, she found herself challenged regularly on the relative roles of science and theology.

His visits to the Rutherford often included listening to a seminar, but also checking what his successors were up to. It was his wont after such visits to provide feedback on how aspects of the laboratory could be managed better. His last visit was in 2013 (see Figure 4), and Andrew Taylor, then Director, duly received five hand-written pages full of very sensible but hard-to-implement advice. In the early summer of 2013, he became unwell and was diagnosed with aortic stenosis. He was due to have an artificial valve fitted, and emailed Margaret Yee that he expected to skip around like a newborn lamb afterwards. But there were complications after the operation, and he died in July at the age of 93. Celebrations of his life and legacy were held at St Cross and a little later at the Rutherford, with many expressions of gratitude and admiration.

[43] Audrey Blackman (née Seligman) was a well-known artist who exhibited regularly at the Royal Academy. She was married to Geoffrey Blackman, who was the professor of Rural Economy at Oxford and a Fellow of St John's. The Blackmans lent many paintings and other objects for display in St Cross. Audrey Blackman was a member of the St Cross Common Room from 1980 until her death in 1990. The Blackman Collection of Watercolours, including several by Edward Lear (d. 1888), John Cotman (d. 1942), and John Piper (d. 1992), now resides permanently in St Cross College, along with a collection of Audrey Blackman's own sculpture.

Figure 4: Visiting the ISIS facility at Rutherford Appleton Laboratory with Paul Williams, 2013. Photo: Rutherford Appleton Laboratory/UK Science and Technology Facilities Council

Conclusion

Godfrey Stafford lived a long and eventful life. He was of the generation that served in the Second World War and then enjoyed the ensuing prosperous peace. His family life brought him great happiness. His career spanned a remarkable era of discovery and development in particle physics. He contributed significantly to experiments using early accelerators and with ideas and support for their development, notably the applications of superconductivity. He was a strong supporter of international co-operation. He was Master of St Cross as the college grew towards its present state. But his principal legacy is the Rutherford Laboratory, which he joined at its inception, oversaw the exploitation of the PLA and Nimrod accelerators, and went on to be its Director, guiding its transformation in the 1970s. As Director he was quiet-spoken, approachable but not too approachable, demanding but supportive, and he had the complete respect of his staff. He understood from the start that the nature of the laboratory's interaction with the wider academic community was fundamental. There is no Stafford building or Stafford road at the laboratory, but the man himself would, I think, be quietly content that in many key respects he laid the foundations for the Rutherford Laboratory that flourishes today.

Awards and Recognition

Commander of the Order of the British Empire (1976)

Fellow of the Royal Society (1979)

Honorary DSc, University of Birmingham (1980)

Glazebrook Medal and Prize, Institute of Physics (1981)

Acknowledgements

It is a great pleasure to acknowledge and thank the many people who have helped in the writing of this article, by answering numerous questions and providing much useful information. In particular, Godfrey and Goldy's children, Anne, Liz and Toby and the wider family; many former colleagues at the Rutherford Appleton Laboratory: Chris Damerell, Martin Evans, George Kalmus, Steve Rose, Peter Smith, George Stirling, Andrew Taylor, Gordon Walker and Paul Williams; Roy Taylor from Imperial College, and Emilie Savage-Smith and Margaret Yee from St Cross College, Oxford.

The portrait photograph at the front of this memoir is with permission of the Rutherford Appleton Laboratory/UK Science Technology and Facilities Council, as are the photographs shown in Figures 2 and 4. The photographs shown in Figures 1 and 3 are with permission of the Stafford family, as is the recording of Stafford's 2008 recollection of D-Day. All are gratefully acknowledged.

It is also a pleasure to acknowledge those organizations that provide rather complete and online-accessible digital archives. They are of enormous assistance to anyone wring a memoir of this type, particularly during a time of pandemic.

References to articles and publications of which Stafford is not an author

Ashmore, A., Devine, M., Hird, B., Litt, J., Range, W.H., Shepherd, M.E., & Clarke, R.L. 1965 A measurement of the A parameter in proton–proton scattering at 47.5 MeV. *Nucl.Phys.,* **65**, 305-317. https://doi.org/10.1016/0029-5582(65)90271-3

Barschall, H.H. 1964 Neutron experiments with a tandem accelerator. 1964 *Nucl. Instr. Meth.*, **28**, 44-51. https://doi.org/10.1016/0029-554X(64)90347-7

Beghian, L.E., Sugimoto, K., Wächter, M.H., & Weber, J. 1963 Neutron polarization in the 1 MeV region by elastic scattering on C, O and D. *Nucl. Phys.*, **42**, 1-20. https://doi.org/10.1016/0029-5582(63)90709-0

Bowen, P.H., Cox, G.C., Huxtable G.B., Langsford, A., Scanlon, J.P., & Thresher, J.J. 1961 Polarization in neutron–proton scattering below 100 MeV. *Phys. Rev. Lett.*, **7**, 248-250. https://doi.org/10.1103/PhysRevLett.7.248

Bowen, P.H., Cox, G.C., Huxtable G.B., Scanlon, J.P., Thresher, J.J., & Langsford A. 1962 An investigation of the production of polarized neutron beams in the energy range 18 to 120 MeV. *Nucl. Instr. Meth.*, **15**, 31-39. https://doi.org/10.1016/0029-554X(62)90022-8

Bowen, P.H., Cox, G.C., Huxtable G.B., Scanlon, J.P., Thresher, J.J., Langsford A., & Appel, H. 1963 Small angle elastic scattering of neutrons by uranium at energies between 18 MeV and 120 MeV. *Nucl. Phys.*, **40**, 186-194. https://doi.org/10.1016/0029-5582(63)90264-5

Bragg, W.L. 1965 Reginald William James, 1891-1964. *Biogr. Mems Fell. R. Soc.* **11**: 114-125. https://doi.org/10.1098/rsbm.1965.0007

Clark, H.G. 1957 Cestodes from Cormorants from South Australia. *Trans. of the Royal Society of South Australia*, **80**, 124-134. https://www.biodiversitylibrary.org/page/41001136#page/141/mode/1up

Clarke, R. 1969 How the 300 GeV decision was made. Science Journal, March 1969, 4-6. A copy of the article can be found at https://cds.cern.ch/record/713566/files/presscut-1969-012.pdf?version=1

Cockcroft, J.D. & Walton, E.T.S. 1932 Experiments with high velocity positive ions. – (I) Further developments in the method of obtaining high velocity positive ions. *Proc. R. Soc. Lond. A* **136**: 619-630. https://doi.org/10.1098/rspa.1932.0107

Crease, R.P. 2005 Quenched! The ISABELLE Saga, I (pp347-348). *Physics in Perspective*, **7**, 330-376. https://doi.org/10.1007/s00016-004-0246-7

Crewe, A.V. & Gregory, J.W. 1955 The Extraction of the Beam from the Liverpool Synchrocyclotron. II. Experimental work. *Proc. Roy. Soc. A.,* **232**, 242-251. https://doi.org/10.1098/rspa.1955.0215

Gibson, W.R., Johnston, A.R., & Griffiths, R.J. 1965 The (p,2p) interaction for 50 MeV on carbon and calcium. *Nucl.Phys.,* **70**, 114-122. https://doi.org/10.1016/0029-5582(65)90227-0

Goodlet, B.L. 1956 Journal of the Royal Central Asian Society, **43:3-4**, 200-212, https://doi.org/10.1080/03068375608731578

Griffith, T.C., Imrie D.C., Lush, G.J., & Mehteringham, A.J. 1963 Measurement of the Depolarization Parameter for 50 MeV proton–proton scattering at 70° c.m. *Phys.Rev.Lett.,* **10**, 444-446. https://doi.org/10.1103/PhysRevLett.10.444

Hance, N. 2006 *Harwell. The Enigma revealed.* p 96. Buckland: Enhance Publishing. ISBN 978-09553055-0-4

Hansard 1965 HL Deb 23 Feb 1965 vol 263 columns 766-94. https://api.parliament.uk/historic-hansard/lords/1965/feb/23/science-and-technology-bill

Hansard 1970. HC Deb 04 December 1970 vol 807 c475W https://api.parliament.uk/historic-hansard/written-answers/1970/dec/04/300-gev-accelerator#column_475w

Harvey Johnston, T. & Clark H.G. 1949 Cestodes from Australian Birds. I. Pelicans. *Trans. of the Royal Society of South Australia*, **72**, 77-82. https://www.biodiversitylibrary.org/page/41362600#page/90/mode/1up

Holdaway, R. 2014 Space Science and Technology in *The Legacy of Godfrey Stafford: A celebration. 23 Jan 2014*. https://indico.cern.ch/event/298115/

Holt, J.R. 1994 Thomas Gerald Pickavance, 1915-1991. *Biogr. Mems Fell. R. Soc.* **39**: 303-323, p310. https://doi.org/10.1098/rsbm.1994.0018

Ising. G. 1924 Prinzip einer Methode zur Herstellung von Kanalstrahlen höher Voltzahl. *Arkiv för Matematik, Astronomi och Fysik.* **18**, 1–4.

Lawrence, E.O. & Livingston, M.S. 1931 The Production of High Speed Protons without the use of High Voltages. *Phys. Rev.* **38**, 834-834. https://doi.org/10.1103/PhysRev.38.834

Le Couteur, K.J. 1955 The Extraction of the Beam from the Liverpool Synchrocyclotron. I. Theoretical work. *Proc. Roy. Soc. A.,* **232**, 236-241. https://doi.org/10.1098/rspa.1955.0214

Litt, J. 2014 Private communication

Marshak, H., Langsford, A., Wong, C.Y., & Tamura, T. 1968 Total neutron cross section of oriented ^{165}Ho from 2 to 135 MeV. *Phys. Rev. Lett*., **20**, 554-558. https://doi.org/10.1103/PhysRevLett.20.554

McMillan, E.M. 1945 The Synchrotron – A Proposed High Energy Particle Accelerator. *Phys. Rev.* **68**, 143-144. https://doi.org/10.1103/PhysRev.68.143

Meadows, A.J. 2009. *Big Science. Fifty Years of the Rutherford Appleton Laboratory (1957-2007)* p53. ISBN 978-1-4092-5562-8

Physics Bulletin, 1975 **26**, 425 and 519. https://iopscience.iop.org/article/10.1088/0031-9112/26/9/053/pdf and https://iopscience.iop.org/article/10.1088/0031-9112/26/12/010/pdf

Riddle, R.A.J., Langsford, A., Bowen, P.H., & Cox, G.C. 1965 The neutron-neutron and neutron-deuteron total cross-section in the energy range 15-120 MeV. *Nucl. Phys*., **61**, 457-464. https://doi.org/10.1016/0029-5582(65)90104-5

Roe, D. 2014 Quoted in *St Cross College at fifty*. (ed. E. Savage-Smith), p 93. ISBN 978-0-9930099-1-4

Roxburgh, S.W. 2007 Hermann Bondi, 1919-2005. *Biogr. Mems Fell. R. Soc.* **53**: 45-61. https://doi.org/10.1098/rsbm.2007.0008

Smith, P.F., Wilson, M.N., Walters, C.R., & Lewin, J.D. 1968 Intrinsically Stable Conductors in *Proceedings of the 1968 Summer Study on Superconducting Devices and Accelerators*, Part III, p. 913 (BNL 50155 C-55). https://www.bnl.gov/magnets/staff/gupta/summer1968/0913.pdf

Smith, P.F. 2020 E-mail to the author. Quoted with permission.

Taylor, A.D. 2020 E-mail to the author. Quoted with permission.

Thomason, J.S. 2020 Private communication.

Van de Graaff, R.J., Compton, K.T. & Van Atta, L.C. 1933 The Electrostatic Production of High Voltage for Nuclear Investigations. *Phys. Rev*. **43** 149-157. https://doi.org/10.1103/PhysRev.43.149

Veksler, V.I. 1944 Concerning some new methods of acceleration of relativistic particles. *Comptes Rendus (Doklady) Acad. Sci. U.S.S.R.* **44** 393-396. (Comptes Rendus is the translation into French. The original is, of course, in Russian. Veksler refers to this paper in a brief letter to Physics Review in 1946, in which he points out that his paper(s) developed the idea of the synchrotron independently of McMillan: *Phys. Rev*. **69** 244. https://doi.org/10.1103/PhysRev.69.244)

Walker, B.D., Wong, C., Anderson, J.D., McLure, J.W., & Bauer, R.W. 1965 Polarization of Neutrons from the C^{13} (p,n) N^{13} and N^{15} (p,n) O^{15} Reactions. *Phys. Rev.*, **137**, B347-351. https://doi.org/10.1103/PhysRev.137.B347

Whittaker, E. 2014 Quoted in *St Cross College at fifty*. (ed. E. Savage-Smith), p 77. ISBN 978-0-9930099-1-4

Widerøe, R. 1928 Über Ein Neues Prinzip Zur Herstellung Höher Spannungen. *Archiv für Elektronik und Übertragungstechnik* (in German). **21** 387–406. doihttps://doi.org/10.1007/BF01656341

Wilkinson, D.H. 1978a Events surrounding the construction of Nimrod in *Nimrod: The 7-GeV proton synchrotron.* (ed. J. Litt), pp 7-20. http://purl.org/net/epubs/work/42061

Wilkinson, D.H. 1978b Events surrounding the construction of Nimrod in *Nimrod: The 7-GeV proton synchrotron.* (ed. J. Litt), pp 17-18. http://purl.org/net/epubs/work/42061

Wilkinson, D.H. 1978c Events surrounding the construction of Nimrod in *Nimrod: The 7-GeV proton synchrotron.* (ed. J. Litt), p 17. http://purl.org/net/epubs/work/42061

Wilkinson, D.H. 1978d Events surrounding the construction of Nimrod in *Nimrod: The 7-GeV proton synchrotron.* (ed. J. Litt), p 16. http://purl.org/net/epubs/work/42061

Williams, P.R. 2014a and 2014b Godfrey's Legacy in *The Legacy of Godfrey Stafford: A celebration. 23 Jan 2014*. https://indico.cern.ch/event/298115/

Williams, P.R. 2021. E-mail to the author. Quoted with permission.

Wilson, M.N. 2014 *The Legacy of Godfrey Stafford: A celebration. 23 Jan 2014*. Written contribution from Martin Wilson read out by C. Damerell, approx. 11 minutes in to the 'Contributions from the Audience' at https://indi.to/FkkDS

WInnifrith, J. 1970 Edward Ettingdean Bridges – Baron Bridges, 1892-1969. *Biogr. Mems Fell. R. Soc.* **16**: 36-56. https://doi.org/10.1098/rsbm.1970.0003

Bibliography This bibliography lists the majority of Stafford's publications. A complete list is available at: https://royalsocietypublishing.org/doi/suppl/10.1098/rsbm.2022.0008#secSuppl

(1) 1944 (With C.B.O. Mohr) The production of cosmic-ray bursts by mesotrons. *Proc. Roy. Soc. A*. **183**, 54-64. (https://doi.org/10.1098/rspa.1944.0021)

(2) 1948 A high-pressure hydrogen-filled ionization chamber. *Nature*. **162**, 771-772. (https://doi.org/10.1038/162771b0)

(3) 1950 (With C.A. Barnes & D.H. Wilkinson) Photo-electric disintegration of the deuteron at 6.13 and 17.6 MeV, *Nature*. **165**, 69-70. (https://doi.org/10.1038/165069b0)

(4) 1951 The Total Cross Section of Beryllium, Aluminium, Sulphur and Lead for Neutrons of Energies from 2 MeV to 6 MeV. *Proc. Phys. Soc. A*. **64**, 388-395. (https://doi.org/10.1088/0370-1298/64/4/305)

(5) 1951 (With J.M. Cassels & T.G. Pickavance) Proton–proton scattering at 146 MeV. *Nature*. **168**, 468- 469. (https://doi.org/10.1038/168468a0)

(6) 1951 (With J.M. Cassels & T.G. Pickavance) Scattering of 146 MeV protons by deuterons. *Nature*. **168**, 556-557. (https://doi.org/10.1038/168556b0)

(7) 1952 (With C.A. Barnes, J.H. Carver & D.H. Wilkinson) The photodisintegration of the deuteron at intermediate energies I. *Phys. Rev*. **86**, 359-372. (https://doi.org/10.1103/PhysRev.86.359)

(8) 1952 (With J.M. Cassels & T.G. Pickavance) Proton–proton scattering at 147 MeV. *Proc.Roy. Soc. A.* **214**, 262-272. (https://doi.org/10.1098/rspa.1952.0166)

(9) 1953 (With L.H. Stein) The $^{54}Fe(n,p)^{54}Mn$ Reaction. *Nature.* **172**, 1103-1103. (https://doi.org/10.1038/1721103a0)

(10) 1954 (With T. Gerritsen & H.J. Heinz) Estimation of blood loss in hookworm infestation with ^{59}Fe : Preliminary Report. *Science.* **119**, 412-413. (https://doi.org/10.1126/science.119.3091.412)

(11) 1956 (With P. Hillman) Polarization effects in neutron–proton scattering at 98 MeV. *Il Nuovo Cimento.* **3**, 633-641. (https://doi.org/10.1007/BF02744436)

(12) 1956 (With P. Hillman & C. Whitehead) A new method of measuring asymmetries in neutron polarization experiments. *Il Nuovo Cimento.* **4**, 67-74. (https://doi.org/10.1007/BF02823452)

(13) 1957 (With P. Hillman & C. Whitehead) Polarization in neutron–proton scattering at 95 MeV. *Il Nuovo Cimento.* **5**, 1589-1597. (https://doi.org/10.1007/BF02856048)

(14) 1957 (With P.H. Bowen, J.P. Scanlon & J.J. Thresher) Neutron time-of-flight spectrometer for use with the Harwell 110-inch cyclotron. *Rev. Sci. Instr.* **28**, 749-757. (https://doi.org/10.1063/1.1715717)

(15) 1960 (With S. Tornabene & C. Whitehead) The polarization in neutron–proton scattering at 77 MeV. *Proc. Phys. Soc.* **75**, 345-356. (https://doi.org/10.1088/0370-1328/75/3/303)

(16) 1961 (With P.H. Bowen, J.P. Scanlon, J.J. Thresher & P.E. Hodgson) Neutron total cross sections in the energy range 15 to 120 MeV. *Nucl. Phys.* **22**, 640-662. (https://doi.org/10.1016/0029-5582(61)90474-6)

(17) 1961 (With A.P. Banford) The feasibility of a superconducting proton linear accelerator. *J. Nucl. Energy, Part C Plasma Phys.,* **3**, 287-290. (https://doi.org/10.1088/0368-3281/3/4/308)

(18) 1962 (With C. Whitehead) The polarization in free neutron–proton scattering at 140 MeV. *Proc. Phys. Soc.,* **79**, 430-439. (https://doi.org/10.1088/0370-1328/79/2/325)

(19) 1962 (With J.M. Dickson, D.C. Salter & M.K. Craddock) A source for the production of polarized protons. *Nucl. Instr. Meth.,* **15**, 146-154. (https://doi.org/10.1016/0029-554X(62)90064-2)

(20) 1962 (With C.J. Batty & R.S. Gilmore) Measurement of the polarization in 50 MeV proton–proton scattering at 45° c.m. *Phys. Lett.,* **2**, 109-110. (https://doi.org/10.1016/0031-9163(62)90172-5)

(21) 1963 The proton linear accelerator as a pion factory. *International Conference on Sector-Focussed cyclotrons and Meson Factories, CERN, 1963.* 328-333.

(22) 1963 (With C.J. Batty & R.S. Gilmore) Excitation of isobaric states in (p,n) reactions at 30 and 50 MeV. *Phys. Lett.,* **6**, 292-293. (https://doi.org/10.1016/0031-9163(63)90480-3)

(23) 1963 (With C.J. Batty & R.S. Gilmore) Measurement of the polarization in proton-proton scattering at 30 and 50 MeV. *Nucl. Phys.,* **45**, 481-491. (https://doi.org/10.1016/0029-5582(63)90823-X)

(24) 1965 (With C.J. Batty, R.S. Gilmore & J.A.R. Griffith) States of F^{16} excited in the reaction O^{16} (pn) F^{16}. *Nucl. Phys.,* **68**, 36-48. (https://doi.org/10.1016/0029-5582(65)90368-8)

(25) 1965 (With C.J. Batty & R.S. Gilmore) Neutron energy spectra in the forward direction from the p+d reaction at 30 and 50 MeV. *Phys. Lett.,* **16**, 137-138. (https://doi.org/10.1016/0031-9163(65)90157-5)

(26) 1966 (With C.J. Batty & R.S. Gilmore) Isobaric states excited in (p,n) reactions at 30 and 50 MeV. *Nucl. Phys.,* **75**, 599-608. (https://doi.org/10.1016/0029-5582(66)90981-3)

(27) 1966 (With D.V. Bugg, R.F. George, K.F. Riley, D.C. Salter & R.J. Tapper) Nucleon–nucleon total cross sections from 1.1 to 8 GeV/c. *Phys. Rev.,* **146**, 980-992. (https://doi.org/10.1103/PhysRev.146.980)

(28) 1966 (With T.G. Pickavance) The relationship between the Rutherford High Energy Laboratory and British universities. Societa Italiana di Fisica, Meeting on European Collaboration in Physics, Pisa, April 16-17. Editors L.A. Radicati and A. ZIchichi. *Editrici Compositori, Bologna,* OCLC number 521592.

(29) 1967 (With D.V. Bugg, A.A. Carter, J.D. Davies, J.D. Dowell, R.S. Gilmore, P.M. Hattersley, R.J. Homer, K.M. Knight, A.W. O'Dell, K.F. Riley, D.C. Salter, R.J. Tapper & E.J. Wilson) Structure in the K^{-}–Nucleon total cross sections between 600 and 1400 MeV/c. *Phys. Rev. Lett.,* **18**, 62-64. (https://doi.org/10.1103/PhysRevLett.18.62)

(30) 1968 (With D.V. Bugg, A.A. Carter, J.D. Davies, J.D. Dowell, R.S. Gilmore, P.M. Hattersley, R.J. Homer, K.M. Knight, A.W. O'Dell, K.F. Riley, D.C. Salter, R.J. Tapper & E.J. Wilson) Pion–Nucleon total cross sections from 0.5 to 2.65 GeV/c. *Phys. Rev.,* **168**, 1457-1465. (https://doi.org/10.1103/PhysRev.168.1457)

(31) 1968 (With D.V. Bugg, A.A. Carter, J.D. Davies, J.D. Dowell, R.S. Gilmore, P.M. Hattersley, R.J. Homer, K.M. Knight, A.W. O'Dell, K.F. Riley, D.C. Salter, R.J. Tapper & E.J. Wilson) Kaon–Nucleon total cross sections from 0.6 to 2.65 GeV/c. *Phys. Rev.,* **168**, 1466-1474. (https://doi.org/10.1103/PhysRev.168.1466)

(32) 1968 *Hadrons and their Interactions.* A Brief Review of the Nimrod Experimental Programme February 1964 to July 1967. pp525-638. Academic Press Inc., New York. ISBN 9780323142892

(33) 1986 John Bertram Adams 1920-1984. *Biogr. Mems Fell. R. Soc.* **32**: 1-34. (https://doi.org/10.1098/rsbm.1986.0001