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Charmonium Physics at a Tau-Charm Factory

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Charmonium Physics at a Tau-Charm Factory [1]

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Abstract

This talk summarizes the status of the charmonium system, with particular emphasis on outstanding problems in QCD spectroscopy which a tau-charm factory can address.

1 Introduction

Since its discovery in 1974 the charmonium system has served hadron physics as an important arena for the investigation of many aspects of QCD and hadron spectroscopy. In this summary we briefly review some of these and discuss several of the important outstanding issues in hadron spectroscopy and their relation to the spectrum and couplings of resonances in the charmonium system. The topics we discuss are charmonium spectroscopy, electromagnetic couplings (γ, $\gamma\gamma$ and e^+e^-), strong decays and unusual states (charm molecules and charmonium hybrids), and in each case we note areas in which experiments at a tau-charm factory could make valuable contributions.

2 Charmonium Spectroscopy

The spectrum of experimental charmonium states [1, 2] is shown in Fig.1, together with the energy levels predicted by the relativized $c\bar{c}$ potential model of Godfrey and Isgur [3], complete to $\approx$ 4.2 GeV. The experimental states have $J^{PC} = 0^{-+}, 1^{--}, 2^{++}, 1^{++}, 0^{++}$ and 1^{+-}. Many 1^{--} levels are known since this channel is immediately accessible through e^+e^- annihilation. One can see that all the experimental resonances have expected theoretical levels nearby, with the largest discrepancy being 50 MeV between the observed $\psi(3770)$ and the theoretical $^3D_1(3820)$. The overall scheme of levels clearly supports the presence of a long-range confining interaction with an asymptotic behavior which is approximately linear. This allows radial excitations with a slowly decreasing level spacing; note the masses of the $^3S_1$ candidates, $J/\psi(3097), \psi(3685), \psi(4040)$ and $\psi(4415)$. The details of the multiplet splittings support the presence of short range one-gluon-exchange interactions, in the L=0 spin-spin interaction and the splittings of the L=1 multiplet. The L=1 splittings also show evidence for contributions from an additional, negative, spin-orbit term, which is expected if the confining interaction acts as a Lorentz scalar. Finally, the absence of a significant long-range spin-spin force, as seen in the near degeneracy of the S=1 χ_j multiplet c.o.g. and the S=0 $h_c(3520)$, is consistent with scalar confinement and argues against any important vector term. This L=1 multiplet structure remains the clearest experimental evidence in support of scalar confinement.

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[1] Summary talk for the Charmonium Working Group at the Third International Workshop on a Tau-Charm Factory, Marbella, Spain (1-6 June 1993).

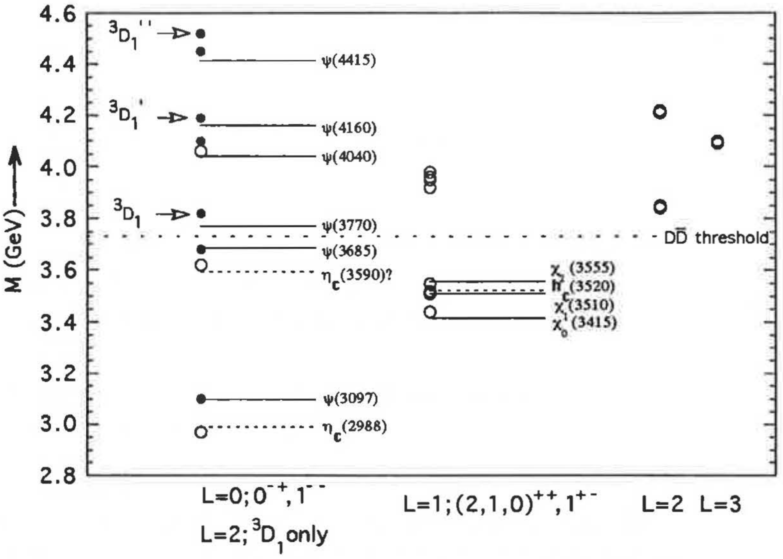

Figure 1: Charmonium spectrum; experimental resonances [1,2] (lines) and theoretical $c\bar{c}$ levels [3] (circles); filled=1^{--}, other J^{PC}=open.

Of course many theoretical levels are predicted which have not been conclusively identified to date, such as the non-1^{--} members of the L=2 multiplet at $\approx$ 3.8 GeV, the radially excited L=1 multiplet near 3.9 GeV, and other excited-L levels. The L=2 states $^1D_2$ and $^3D_2$ are especially attractive experimentally since they cannot decay strongly to $D\bar{D}$ and hence should be rather narrow. The non-1^{--} states are directly accessible in $P\bar{P}$ annihilation; indeed, one of the narrow L=2 states may have been observed recently by the E705 collaboration at Fermilab [4]. An L=0 $\eta_c(3590)$ was previously reported in $\psi(3685)$ radiative decay [5], but as this state is not seen by E760 [6] it may not exist at this mass and should certainly be searched for in $\psi' \to \gamma\eta_c'$ with better statistics. Although these are interesting experimental targets, the generally good agreement between experimental and theoretical masses leads one to ask whether anything profound can be learned from future studies of the charmonium system.

In our discussion of transitions and decays we shall see that, despite the apparent good agreement in the energy levels, there are actually many problems in the couplings of the states above $D\bar{D}$ threshold, and much remains to be understood. It is useful to divide the charmonium system into a well-understood region near and below the $D\bar{D}$ threshold at 3.73 GeV, and a *terra animalium mirabilium* above $D\bar{D}$ [7] where very surprising results have been reported and new types of states are anticipated by theorists. In addition to $|c\bar{c}\rangle$ basis states, theorists also expect $|c\bar{c}g\rangle$ and perhaps $|c\bar{c}q_1\bar{q}_2\rangle$ to be evident in the spectrum, and physical resonances will of course be linear superpositions of these states. Hopefully in the charmonium system this mixing will not be large, so these states can be easily distinguished. In this review we will use the term "charmonium" to refer to all these experimental resonances, and theoretical assignments such as "$c\bar{c}$" or "$c\bar{c}$-hybrid" are understood to be approximate descriptions of somewhat more complicated linear superpositions in Hilbert space.

A tau-charm facility should allow us to explore this new territory above $D\bar{D}$ threshold and perhaps answer some of the most interesting outstanding questions in QCD spectroscopy, including the possible existence of charm molecules and hybrid mesons.

3 One-photon transitions

The experimentally observed single-photon transitions and their partial widths are shown in Fig.2. These transitions provide the only straightforward pathway to many of these levels in e^+e^- annihilation since only 1^{--} states are made initially. These can then decay radiatively through E1 transitions into 2^{++}, 1^{++} and 0^{++} states. Similarly we can produce the $^1S_0$, 0^{-+} levels through M1 radiative transitions starting from 1^{--} states. All the well-established non-1^{--} charmonium resonances now known except the $h_c(3520)$ were discovered through these radiative transitions.

Single-photon radiative transitions also provide sensitive tests of proposed assignments for charmonium resonances, since the rates are proportional to the squares of wavefunction overlap integrals which can depend strongly on the details of the wavefunctions.

There is generally rather good agreement between theory and experiment in the $\psi(3685) \to \gamma\chi_j$ and $\chi_j \to \gamma J/\psi$ E1 radiative transitions; nonrelativistically the amplitudes for these transitions are proportional to the overlap integrals $\int d^3x\, \Psi_i^*\, r\, \Psi_f$. Most of these E1 rates are known to an accuracy of about 15%. It would probably be unrealistic to expect greater accuracy from the quark model in the absolute scale, but the relative rates are subject to less theoretical uncertainty so it would be useful to improve these measurements. In the case of the χ_j decays much of the statistical error comes from the uncertainty in the total widths, which would be straightforward to determine more accurately and are also of theoretical interest.

A more fundamental question in QCD, the possibility of an anomalous magnetic moment in the charmed quark's electromagnetic coupling, can also be addressed by measuring the photon angular distribution in these transitions. A study of $\chi_2 \to \gamma J/\psi$ by the E760 collaboration [8] has found a result consistent with zero anomalous moment, although the errors are rather large. It would be very interesting to reduce the uncertainty in this measurement at a tau-charm factory.

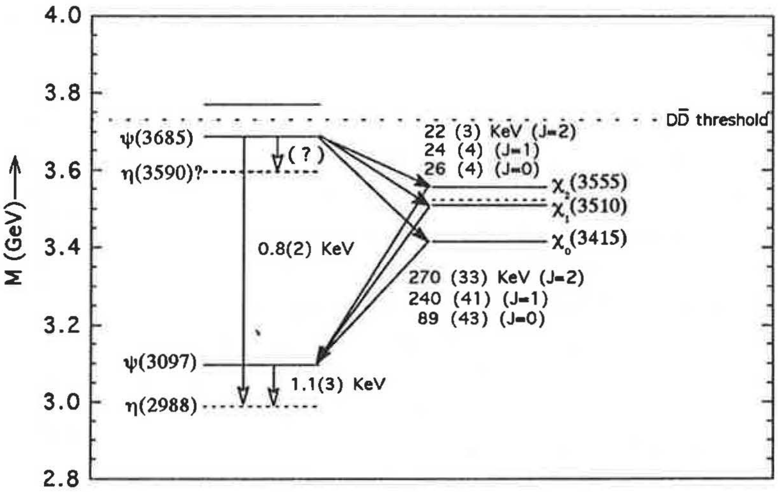

Figure 2: Observed single-photon transitions and their radiative partial widths.

For the M1 decays the nonrelativistic transition amplitudes are proportional to the transition magnetic moment, which is e_c/m_c times the overlap integral $\int d^3x\, \Psi_i^*(1^{--})\Psi_f(0^{-+})$. This integral is unity for states with the same degree of radial excitation and zero otherwise, if we neglect hyperfine corrections to the wavefunctions and recoil effects. Since these rates are suppressed by $1/(m_c < r >)^2$ they are considerably weaker than the E1 transitions. Due to the simple overlap integral the M1 rate for the low-recoil decay $J/\psi(3097) \to \gamma\eta_c$ should be particularly reliably calculable, to the extent that we know $1/m_c^2$. The theoretical expectation for this rate, $\approx$ 2. KeV (assuming a charm quark mass of $m_c \approx 1.6$ GeV [3]) nonetheless does not compare very well with the experimental 1.1±0.3 KeV. Of course this is only a 3σ disagreement, but since there is little systematic uncertainty in the theoretical prediction, an improved measurement with better statistics is an important experimental goal. A more accurate measurement of $J/\psi \to \gamma\eta_c$ would also improve the results for $\gamma\gamma$ couplings, since the uncertainty in the background process $J/\psi \to \gamma\eta_c$ was the dominant systematic error in the recent L3 measurement of $\eta_c \to \gamma\gamma$ [9]. Similarly the radially excited η_c' should be searched for in $\psi(3685) \to \gamma\eta_c'$, since this transition must have a radiative partial width near 1 KeV, but E760 has not been able to confirm the presence of this state near 3592 MeV, as previously reported in this transition by the Crystal Ball collaboration [5].

4 Two-photon couplings

The two-photon couplings of charmonium resonances are measured at e^+e^- machines through the virtual process $e^+e^- \to e^+e^-\gamma\gamma$, with the two photons subsequently coupling to a charmonium state, which decays to the detected final state. The measurement of the cross sections for these processes allows one to infer the strength of the $\gamma\gamma$ coupling of each resonance, and in the limit of small-Q^2_γ this determines the on-shell $\gamma\gamma$ coupling and hence the $\Gamma_{\gamma\gamma}$ partial width [10]. Unfortunately the production of charmonium resonances by this $\gamma\gamma$ process is rather weak, due both to the e^4 amplitude and the rapid fall of effective $\gamma\gamma$ intensity with increasing $M_{\gamma\gamma}$. At present the detection of charmonium states in $\gamma\gamma$ is near the limit of experimental sensitivity. Only the states $\eta_c(2988)$, $\chi_0(3415)$ and perhaps the $\chi_2(3555)$ have been observed in $\gamma\gamma$ collisions at e^+e^- machines to date, and these experiments typically report $\Gamma_{\gamma\gamma}$ values of a few KeV, with errors comparable to the reported signal. Fermilab experiment E760 has reported two charmonium $\gamma\gamma$ widths with rather higher accuracy, using direct hadronic production of charmonium in $P\bar{P}$ annihilation followed by decay to $\gamma\gamma$; the small cross sections are compensated by high intensity and efficient background rejection. This approach has led to considerably improved sensitivity, and in the best case (χ_2) the statistical error in $\Gamma_{\gamma\gamma}$ is about an order of magnitude smaller than at e^+e^- machines. The experimental partial widths are shown in Fig.3; note the discrepancy between the scale of the $\gamma\gamma$ widths reported by e^+e^- facilities (albeit with rather large errors) and the E760 results.

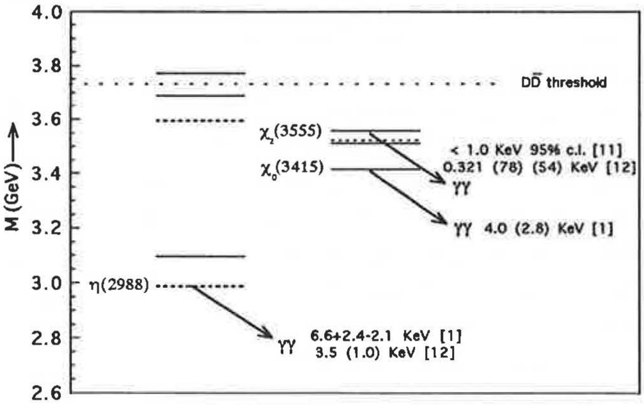

Figure 3: Observed two-photon transitions and partial widths.

These partial widths are interesting as tests of the many quark model predictions for the $\gamma\gamma$ couplings of $q\bar{q}$ states; well-known examples are the nonrelativistic ratio $\Gamma_{\gamma\gamma}(^3P_0)/\Gamma_{\gamma\gamma}(^3P_2) = 15/4$ and $\lambda = 2$ dominance of the $^3P_2$ $q\bar{q}$-$\gamma\gamma$ coupling. Recent calculations of relativistic effects [13] find important corrections in charmonium, so these couplings can serve as sensitive tests of relativistic effects if they are measured with sufficient accuracy. For example, the $\Gamma_{\gamma\gamma}$ ratio $^3P_0/^3P_2$ for the χ_j states is predicted to be reduced from 15/4 to ≈ 2.8 by relativistic corrections. This change in ratio should not be accompanied by any significant $\lambda = 0$ production of the $\chi_2(3555)$, as this is expected to be only about 0.5% of the $\chi_2(3555)$ $\gamma\gamma$ partial width. At present the statistically accurate E760 results appear to support the predictions of the relativized calculations of $c\bar{c}$-$\gamma\gamma$ couplings. An improved measurement of these two-photon partial widths and angular distributions, to an accuracy of ± 0.030 KeV or better in $\Gamma^\lambda_{\gamma\gamma}(\chi_j)$, would allow a sensitive test of these relativistic amplitudes and their helicity structure.

In addition to relativistic effects, calculations of $O(\alpha_s)$ QCD radiative corrections to these $\gamma\gamma$ widths and other $c\bar{c}$ transitions have been reported in the literature. Unfortunately these radiative corrections are renormalization-prescription dependent, so their numerical importance depends on an unphysical parameter. Various methods for dealing with this prescription dependence have been proposed [14], which involve calculating higher order corrections and then choosing the renormalization prescription for fast convergence in α_s or to minimize sensitivity to the choice. Typically a large coefficient of α_s is an indication of an inappropriate choice of prescription. A more serious problem is that confinement may modify these gluonic corrections in a nonperturbative manner, for example through the infrared behavior of the gluon propagator; this could invalidate conclusions regarding radiative corrections which depend strongly on the assumption of perturbative gluons at small-Q_g^2.

The accuracy of these corrections at a given order in α_s in a given renormalization scheme can easily be tested experimentally. As an example, the $O(\alpha_s)$ radiative corrections to the $\gamma\gamma$ width ratio ${}^3P_0/{}^3P_2$ in the scheme advocated by Kwong *et al.* [15] give $\Gamma_{\gamma\gamma}(\chi_0)/\Gamma_{\gamma\gamma}(\chi_2) = R_0 \cdot (1+0.2\alpha_s/\pi)/(1-16\alpha_s/3\pi)$, which for $\alpha_s = 0.3$ changes the nonrelativistic ratio of $R_0 = 15/4$ to about 7.8, corresponding to $\Gamma_{\gamma\gamma}(\chi_0) = 2.5$ KeV using the E760 $\Gamma_{\gamma\gamma}(\chi_2)$ width. In contrast, with only relativistic corrections we expect $\Gamma_{\gamma\gamma}(\chi_0) = 0.9$ KeV; obviously it is straightforward to test these two theoretical results through accurate measurements of $\Gamma_{\gamma\gamma}(\chi_0)$ and $\Gamma_{\gamma\gamma}(\chi_2)$. The total width ratio $\Gamma(\chi_0)/\Gamma(\chi_2)$ can be used similarly. These tests of QCD radiative corrections at the charmonium mass scale can obviously have wide implications regarding the range of applicability of perturbative QCD.

The L>1 $c\bar{c}$ states are expected to have very weak $\gamma\gamma$ couplings, so they may remain experimentally inaccessible in this process. For example, in recent calculations the ${}^1D_2$ expected at ≈ 3.8 GeV is predicted to have $\Gamma_{\gamma\gamma} \approx 30$ eV [13]. Earlier nonrelativistic calculations gave a somewhat larger estimate of $140-200$ eV [16], although this reference overestimates $\Gamma_{\gamma\gamma}(\chi_2)$ relative to the accurate E760 result. Production of radially excited $c\bar{c}$ states from $\gamma\gamma$ is not expected to be suppressed significantly, so $\gamma\gamma$ may serve as a filter for L=0 0^{-+} and L=1 0^{++} and 2^{++} $c\bar{c}$ states above $D\bar{D}$ threshold, given adequate statistics. Radial excitations are especially interesting because none have yet been identified in $\gamma\gamma$ production of light $q\bar{q}$ systems, despite predictions of unsuppressed $\gamma\gamma$ couplings. It is not clear if this is a problem for theory, because light radials with these quantum numbers are poorly understood, and their branching fractions to the final states reconstructed to date are unknown and may be small.

Previous e^+e^- experiments have exclusively used the radiative process $e^+e^- \to e^+e^-R$ to determine $\gamma\gamma$ couplings. Another possibility [6] which might be exploited at a tau-charm facility is the annihilation process $e^+e^- \to \psi(3685) \to \gamma\chi_j$, $\chi_j \to \gamma\gamma$. These $\psi' \to \gamma\gamma\gamma$ branching fractions are $\sim 10^{-5}$, so for a plausible sample of 10^8 ψ' events at a tau-charm factory we would have about 10^3 $\chi_j \to \gamma\gamma$ decays, and could then determine $\Gamma_{\gamma\gamma}(\chi_j)$ to an accuracy of a few %. This is sufficient to allow sensitive tests of the relativistic and radiative corrections cited above.

5 e^+e^- couplings

The final electromagnetic process we consider is single-photon production of 1^{--} states, which is measured directly in e^+e^- annihilation. These partial widths are shown in Fig.4, and have errors of typically ±0.2 KeV. Nonrelativistically we would expect production of only ${}^3S_1$ states, since the nonrelativistic production amplitude is proportional to $\Psi(0)$. There are nonlocal relativistic corrections to this result, however, so some production of ${}^3D_1$ states is also expected, with an amplitude proportional to $\Psi''(0)$ nonrelativistically. In $c\bar{c}$ potential models this ${}^3D_1$ amplitude is much weaker than the ${}^3S_1$ coupling. For example, in the Godfrey-Isgur model one expects $\Gamma_{e^+e^-}(\psi(3770))/\Gamma_{e^+e^-}(J/\psi(3097)) \approx 0.010$, assuming that these states are dominantly ${}^3D_1$ and ${}^3S_1$ respectively.

As we can see in Fig.4, the e^+e^- coupling of the $\psi(3770)$ is indeed much weaker than that of the L=0 states $J/\psi(3097)$ and $\psi(3685)$. However the observed magnitude of the coupling disagrees with theoretical expectations; the ratio $\Gamma_{e^+e^-}(\psi(3770))/\Gamma_{e^+e^-}(J/\psi(3097))$ is about a factor of five larger than Godfrey and Isgur predict. (The $\psi(3770)$ errors are actually rather large and should be improved.) This may be due to a ${}^3S_1$ component in the $\psi(3770)$, which might be tested by a determination of its E1 transition rates to the L=1 χ_j states. Such an admixture is driven by the tensor term in the one-gluon-exchange Hamiltonian, but this effect is already incorporated in the Godfrey-Isgur model and the mixing is not large enough to explain the observed e^+e^- partial width. In earlier, closely related work Eichten *et al.* [17] found that the e^+e^- width of the $\psi(3770)$ could be explained by

$^3S_1$-$^3D_1$ mixing through virtual $D\bar{D}$ intermediate states. The size of such virtual meson-pair effects is an important and currently rather obscure issue, and studies at a tau-charm factory may clarify this issue, for example through a more accurate determination of the composition of the nominally $^3D_1$ states $\psi(3770)$ and $\psi(4160)$.

For the higher-lying 1^{--} states these e^+e^- couplings are even more problematical; the $\psi(4160)$ is usually considered a radially excited $^3D_1'$ $c\bar{c}$ state due to its mass, but it has an e^+e^- coupling comparable to those of the putative $^3S_1^{(n)}$ states $\psi(4040)$ and $\psi(4415)$. Either there is very important configuration mixing or the $\psi(4160)$ has been misidentified. A detailed scan of R from $D\bar{D}$ threshold to the highest accessible energy at a tau-charm factory should clarify the spectrum of 1^{--} $c\bar{c}$ resonances. This will also be an important contribution to the identification of non-$c\bar{c}$ 1^{--} states such as charmed-meson molecules and charmonium hybrids, since these may exist in this mass range and will only be apparent once the conventional 1^{--} $c\bar{c}$ states have been identified. The presence of these additional states may account for some of the unusual properties reported for the higher-mass ψ resonances.

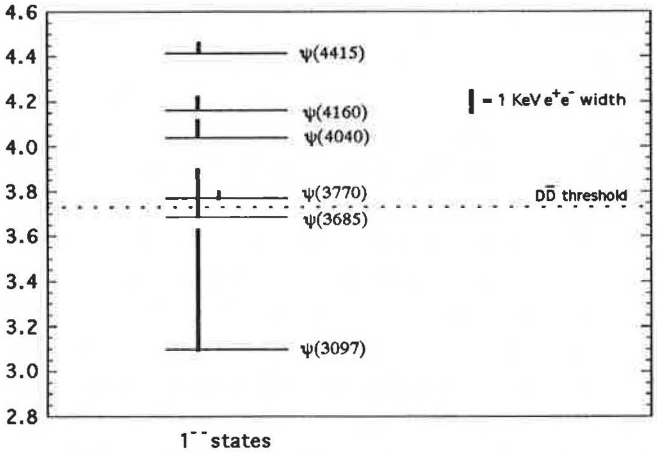

Figure 4: Experimental e^+e^- partial widths of 1^{--} charmonium resonances.

6 Strong decays: $c\bar{c}$ versus charm molecules

Below the $D\bar{D}$ threshold of 3.73 GeV most hadronic decays of charmonium states involve annihilation into light hadrons. This is usually approximated by $c\bar{c}$ annihilation into free gluons, ggg for $^3S_1$ states and gg for $^1S_0$, $^3P_2$ and $^3P_0$. (See especially [16] and [17] for these results.) The qualitative ordering of strong widths is accounted for by this approximation, although higher-order strong corrections to these rates are problematical and can appear quite large; see our discussion of radiative corrections to $\gamma\gamma$ widths in this regard. There are interesting problems in the exclusive hadronic final states, for example the $\rho\pi$ branching fraction from the $J/\psi(3097)$ is at least two orders of magnitude larger than from the $\psi(3685)$. Actually, much of the interest in these annihilation decays is not in the annihilation process itself, but is instead due to the possibility of detecting gluonic states [18] such as glueballs or light hybrids in the final state.

Above $D\bar{D}$ most charmonium resonances can couple to open-charm decay channels, and they have hadronic widths in the 10s of MeVs. Remarkably little is known about the branching fractions of the four charmonium resonances reported above 3.73 GeV. (See Figs.1 and 5.) The $\psi(3770)$ is reported [1] to decay dominantly to $D\bar{D}$, but "hairpin diagrams" which would allow cascade processes such as $\psi'' \to J/\psi\pi\pi$ are known to be weak (these contribute a partial width of $\approx$ 100 KeV to $\psi(3685)$ decays) so this is hardly surprising. Of the two highest levels, nothing is claimed for the strong modes of the $\psi(4160)$, and the $\psi(4415)$ is reported to decay dominantly to hadronic final states, again not a surprise.

The single resonance above $D\bar{D}$ threshold with known branching fractions is the $\psi(4040)$, and the experimental results are puzzling. The branching fractions to $D^*\bar{D}^*$: $D^*\bar{D}$+$h.c.$: $D\bar{D}$ are in the ratios $32\pm12 : 1 : 0.05\pm0.03$. Thus, the dominant mode is $D^*\bar{D}^*$, despite the proximity of the $\psi(4040)$ to the

$D^*\bar{D}^*$ threshold of 4.02 GeV. The $D^*\bar{D}^*$ mode is reported to be stronger than $D\bar{D}$ by about three orders of magnitude, despite the much smaller $D^*\bar{D}^*$ phase space, which is a surprising result indeed. These branching fractions are inferred from the assumed resonant part of the cross section $e^+e^- \to M_1M_2$, in which the ratios are less extreme due to spin multiplicity factors. The reported $\psi(4040)$ branching fractions may be biased by misidentified nonresonant production of charmed meson pairs, and should be remeasured with improved accuracy and careful determination of the nonresonant background. This nonresonant production is expected to contribute to the cross section for $e^+e^- \to M_1M_2$ in the ratio $7:4:1$ [19].

In view of these remarkable branching fractions, Voloshin and Okun [20] suggested that the $\psi(4040)$ might be a $D^*\bar{D}^*$ molecular state, similar to the $K\bar{K}$-molecule description of the $f_0(975)$ and $a_0(980)$ proposed subsequently by Weinstein and Isgur [21]. This is an obvious suggestion given the mass and branching fractions reported for the $\psi(4040)$, although it does not explain why this state has an e^+e^- coupling about equal to expectations for a $^3S_1''$ $c\bar{c}$ state, which is anticipated near this mass. In recent work Ericson and Karl [22] concluded that one pion exchange forces are sufficiently strong to bind the $D^*\bar{D}^*$ system, although they find a $^1S_0$, $J^P = 0^+$ ground state rather than 1^-. Of course both molecular and $c\bar{c}$ states may exist in this mass region.

Since the $^3S_1''$ $c\bar{c}$ assignment for the $\psi(4040)$ is a second radial excitation, there are two zeroes in the strong decay amplitude as a function of $|\vec{P}_f|$, and the $D\bar{D}$ and $D^*\bar{D}+h.c.$ modes may have been "accidentally" suppressed by their values of $|\vec{P}_f|$. This possibility was investigated in the $^3P_0$ model by LeYaouanc *et al.* [23], who concluded that the observed decay modes did indeed arise naturally from nodal suppression of the decay amplitudes. This $c\bar{c}$ model can be tested in future through measurements of the branching fractions of the other candidate radially excited $c\bar{c}$ states such as the $\psi(4415)$. Of course the $^3P_0$ and other $q\bar{q}$ pair-production decay models are very phenomenological, and a better understanding of couplings to open channels may be required to explain the branching fractions of these higher-mass states. At present, models typically find important $c\bar{c}$ mass shifts due to couplings to open channels [24], which is surprising in view of the success of naive $c\bar{c}$ potential models in explaining charmonium spectroscopy. Accurate experimental studies of strong decays should lead to considerable refinement of the models and hopefully to an understanding of why these effects appear small below $D\bar{D}$ threshold.

These branching fractions will be of great interest for studies of charm physics as well, because future experiments on charmed mesons such as the D_s will presumably use the higher-mass ψ resonances as charmed-meson factories, and the branching fractions will determine the optimum ψ-resonance source of each charmed meson.

7 Charmonium Hybrids

The search for gluonic excitations in the hadron spectrum may be the most interesting topic in QCD spectroscopy [18]. Hadrons which contain quarks and excited glue in their dominant basis states are referred to as "hybrids", and in the meson sector these can have exotic-J^{PC} quantum numbers which are forbidden to $q\bar{q}$ states. The charmonium system provides a natural laboratory for the study of hybrids because the ordinary $c\bar{c}$ spectrum is rather straightforward and, with better statistics above 3.8 GeV, can probably be clarified considerably. It should then be possible to identify any additional states such as hybrids or charm molecules against the background of $c\bar{c}$ resonances. Since charm molecules are expected to lie just below two-meson thresholds and have S-wave quantum numbers, there should be little confusion between these two types of non-$c\bar{c}$ states.

The masses of light hybrid mesons have been estimated using the MIT bag model [25], QCD sum rules [26], the flux tube model [27] and heavy-quark lattice gauge theory [28]. Although there is considerable variation in detail, all these approaches predict that the lightest hybrid mesons have masses of ≈ 1.5 − 2. GeV, and in heavy-quark systems (from the flux-tube model and lattice gauge theory) near the lightest $Q\bar{Q}$ mass plus ≈ 1 GeV. The exotic quantum numbers $J^{PC} = 1^{-+}$ are often suggested for experimental searches in light-quark systems, because all techniques find a light hybrid with these quantum numbers, and the flux tube model predicts that the I=1 1^{-+} should be relatively narrow. This model finds an especially rich lowest-lying hybrid multiplet, with $J^{PC} = 1^{\pm\pm}, 2^{\pm\mp}, 1^{\pm\mp}$ and $0^{\pm\mp}$ all approximately degenerate. The mass estimated for this lowest $c\bar{c}$-hybrid multiplet has varied between 4.19 GeV and 4.473 GeV in flux tube references [27]. Perantonis and Michael [28] find 4.04 GeV for the lightest hybrids in heavy-quark lattice gauge theory in the quenched approximation, and estimate 4.19 GeV without this approximation. Finally, Narison [26] quotes a QCD sum rule result of 4.1 GeV for the 1^{-+} exotic $c\bar{c}$-hybrid, consistent with the lattice gauge theory and lower flux-tube results. Theoretical estimates of the mass of the lightest $c\bar{c}$-hybrid multiplet are thus typically about 4.2 ± 0.2 GeV.

Theoretical models predict rather characteristic two-body decay modes for hybrids. In both constituent gluon [29] and flux tube [27] models the lightest hybrids are found to decay preferentially to pairs of one $L_{q\bar{q}}=0$ and one $L_{q\bar{q}}=1$ meson, for example πf_1 and πb_1. These unusual modes have received little experimental attention and may explain why hybrids were not discovered previously. For $c\bar{c}$-hybrids this implies that the hybrid mass relative to the S+P threshold of ≈ 4.3 GeV is an important issue; if hybrids lie below this threshold their preferred decay modes will be closed, and they will be correspondingly narrow and detection may be straightforward. Hybrids below this threshold are preferred by most models, and in this case the dominant modes will probably be $D^{(*)}\bar{D}^{(*)}$, with weaker contributions from cascade decays to $c\bar{c}$ plus light hadrons. Prospects for searching these modes for hybrids are discussed below and by Close [30].

There are several possible strategies for producing hybrid charmonium states at a tau-charm factory.

First, one may search for additional 1^{--} states directly through a high-statistics scan of R. Although hybrids are expected to appear weakly since they must couple through their $c\bar{c}$ components, they might nonetheless be evident as small, relatively narrow peaks which can be excluded as conventional $c\bar{c}$ resonances by their masses and quantum numbers. (Of course the narrow width is speculative, based on the closed S+P channel for $c\bar{c}$-hybrid masses below ≈ 4.3 GeV and the preferred-mode argument.) This experiment is straightforward since a detailed scan in R would be an early priority at a tau-charm factory in any case.

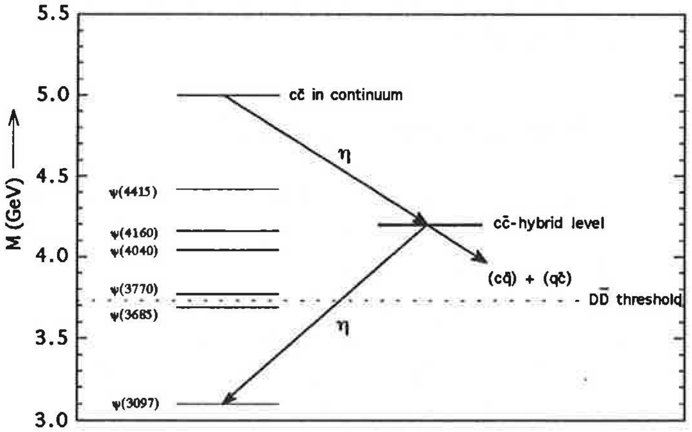

Figure 5: Production of a $c\bar{c}$-hybrid by cascade decay from the $c\bar{c}$ continuum.

Instead of producing a 1^{--} hybrid directly one can search for hybrids in the decay products of initial 1^{--} $c\bar{c}$ resonances or the $c\bar{c}$ continuum. Ideally a search for charmonium hybrids would concentrate on the J^{PC}-exotic states, to preclude confusion with $c\bar{c}$. Indeed, since several excited-L $c\bar{c}$ multiplets are expected in this mass region (see Fig.1) it may be important to identify these as well. Decay to a hybrid state H_c can occur through a strong cascade decay such as $(c\bar{c}) \to \eta H_c$ or $(c\bar{c}) \to \pi\pi H_c$. Since the branching fraction of each cascade may be $\sim 10^{-3}$, the large numbers of events expected at a tau-charm factory will be required to make detection of hybrids practical using this mechanism. In these cascade decays a selection rule may help identify hybrids; the H_c and the light hadronic system (η or $\pi\pi$) will be produced in a relative P-wave. This origin of this selection rule can be visualized in the related process of cascade decay of a flux-tube hybrid; this occurs by "pinching off" a loop of glue from the excited flux tube, which initially had an $\exp(i\phi)$ wavefunction about the $c\bar{c}$ axis. The final $c\bar{c}$ state has a ground-state flux tube, so the $\exp(i\phi)$ dependence must be transferred to the $c\bar{c}$-(light hadronic) relative orbital wavefunction, which therefore must have $L \geq 1$. We assume that the decays are dominated by the minimum value L=1. An interesting suggestion [31] is that this search can involve a continuum cascade; the initial $c\bar{c}$ system can be produced in the high mass continuum, at perhaps ~ 5 GeV, and will then cascade into a $c\bar{c}$-hybrid plus a light hadron or hadrons.

Detection of the final H_c hybrid can follow two approaches; either it can be reconstructed from conventional pair-production final states such as $D\bar{D}$ or $D^*\bar{D}$, or it can be found in a second cascade decay. These options are suggested in Fig.5. In the double cascade, which is attractive due to the simplicity of the final states involved, the H_c can cascade into J/ψ plus a hadron or hadrons. One would select events such as $\eta\eta J/\psi$ from the 5 GeV $c\bar{c}$ continuum, and search for new states in the $\eta J/\psi$ invariant mass distribution and for exotic quantum numbers in the angular distributions. The cascade selection rules discussed above suggest a search for $H_c \rightarrow \eta J/\psi$ (P-wave) and $H_c \rightarrow (\pi\pi)_S J/\psi$ (P-wave, with the $\pi\pi$ system in S-wave). This $\eta J/\psi$ system can have $J^{PC} = 2^{--}, 1^{--}$ and 0^{--} (0^{--} is predicted to be an excited-state exotic hybrid in the flux tube model), and $(\pi\pi)_S J/\psi$ in P-wave can have $2^{+-}, 1^{+-}$ and 0^{+-}; 2^{+-} and 0^{+-} are ground-state exotic hybrids in the flux tube model. We would also expect conventional $c\bar{c}$ states to be made in cascade, albeit dominantly in S-wave combinations with the light hadrons; one could search for the $h'_c(\approx 3960)$ for example in the $\eta J/\psi$ S-wave in the same experiment.

8 Summary and Conclusions

In this review we have discussed the experimental status of charmonium and listed interesting topics for experimental investigation at a tau-charm factory. The general areas for charmonium-related experiments and what we might learn from them are as follows:

1) *Spectroscopy above $D\bar{D}$ threshold.* Are gluonic excitations evident in the charmonium spectrum? Models predict additional hybrid-charmonium states starting at about 4.2 GeV, some with exotic quantum numbers. These states may stand out clearly in a scan of R or in cascade decays (from high-mass $c\bar{c}$ states or the $c\bar{c}$ continuum). Is there evidence for charm-meson molecules, or can all observed levels be attributed to $c\bar{c}$ states or perhaps $c\bar{c}$-hybrids?

2) *Strong decays of resonances above $D\bar{D}$ threshold.* Little is known about these, and the reported branching fractions for the $\psi(4040)$ are remarkable. Measurements of the branching fractions of higher-lying resonances will allow tests of decay models, which will clarify the status of possible charm molecules. These measurements will also suggest optimum sources for production of the various charm mesons (such as the D_s) which may be of interest in weak interaction physics.

3) *Electromagnetic couplings of charmonia.* The γ, $\gamma\gamma$ and e^+e^- couplings of charmonium resonances can discriminate between a wide range of theoretical predictions in the literature, and can test the validity of relativistic correction formalisms and the applicability of perturbative QCD radiative corrections at the charmonium mass scale. There are many open questions in these electromagnetic couplings which can be resolved through accurate measurements at a tau-charm factory. Especially interesting are the M1 decays $J/\psi \rightarrow \gamma\eta_c$ and $\psi' \rightarrow \gamma\eta'_c$ and E1 transitions such as $\chi_2 \rightarrow \gamma J/\psi$ (which can test for

an anomalous c-quark magnetic moment), $\gamma\gamma$ couplings of the $\{\chi_j\}$ and η_c', and the e^+e^- couplings of candidate $^3D_1$ $c\bar{c}$ states.

Clearly, a very rich program of charmonium physics is possible at a tau-charm factory, and many problems in spectroscopy which have been unresolved since the 1970s can be addressed at this facility. We strongly advocate its approval.

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