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Theoretical Predictions for Exotic Hadrons

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Abstract. In this contribution we discuss current theoretical expectations for the properties of light meson "exotica", which are meson resonances outside the $q\bar{q}$ quark model. Specifically we discuss expectations for gluonic hadrons (glueballs and hybrids) and multiquark systems (molecules). Experimental candidates for these states are summarized, and the relevance of a TCF to these studies is stressed.

I. INTRODUCTION

The most exciting developments in QCD spectroscopy involve searches for resonances which are external to the conventional $q\bar{q}$ quark model of mesons. There are two general classes of such states, which are those with dominant gluonic excitations "gluonic hadrons" and states with more quarks and antiquarks than the familiar $q\bar{q}$ states.

Since QCD is a theory which contains both quarks *and* gluons as dynamical degrees of freedom, we would expect to see evidence of both these building blocks in the spectrum of physical color-singlet hadrons. It is remarkable, however, that of the hundreds of hadronic states now known, most can be described as states made only of quarks and antiquarks in the nonrelativistic quark model, and none of the remaining problematic resonances have been established as having dominant gluonic valence components. The best evidence for the presence of gluons at low energies is indirect, for example in the Breit-Fermi one-gluon-exchange Hamiltonian used in potential models and in the $q\bar{q} \leftrightarrow s\bar{s}$ configuration mixing evident in the η and η'.

In addition to these gluonic states, one may also form color singlet combinations from multiquark systems of quarks and antiquarks, beginning with $q^2\bar{q}^2$.

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Although these have been quite controversial, it now appears that light multiquark resonances do exist in nature, *albeit* as bound meson pairs "molecules" rather than single four-quark clusters.

Experimental studies now in progress may alter the status of hadronic exotica considerably, since there are now several resonances that, if confirmed, appear to be likely candidates for glueballs, hybrids and additional molecules. As we shall see, these states share several common features with theoretical expectations for these unusual hadronic states.

In this contribution we will review current theoretical expectations for gluonic hadrons and molecules, and briefly discuss some of the experimental candidates for these states.

II. GLUEBALLS

A. Introduction

A priori one would expect glueballs to be the most attractive gluonic hadrons experimentally, since they might be expected to differ most noticeably from $q\bar{q}$. In practice this naive expectation may not be realized; studies of the light glueball spectrum using lattice gauge theory have found that the lowest-lying glueball is a scalar, and its coupling to two-pseudoscalar final states suggests a typical hadronic width. The next glueballs encountered at higher masses are predicted to be 0^{-+} and 2^{++}, and states which couple to two transverse gluons (presumably the lightest glueballs) do not contain exotic J^{PC}.

Although there have been many studies of the spectrum and quantum numbers expected for glueballs [1], the results of lattice gauge theory should be treated as the most relevant to experiment, since they bear the closest resemblance to full QCD. The assumptions of quenched lattice gauge theory are that decay channels do not modify glueball masses significantly (since the neglect of quarks implies stable light glueballs) and that the extrapolations to small lattice spacing and large lattice volume do not introduce important biases. If glueballs are not very broad objects, the assumption of stable glueballs should not introduce large mass errors.

There are lattice predictions for the masses of glueballs with various J^{PC} [2]; the most reliable is presumably for the scalar glueball ground state, which is predicted to have a mass of

$$M(0^{++}) = \begin{cases} 1.550(50) & \text{GeV [3]} \\ 1.740(71) & \text{GeV [4]} \end{cases} . \tag{1}$$

The corresponding mass estimate for the tensor glueballs is in the 2.2-2.4 GeV range,

$$M(2^{++}) = \begin{cases} 2.270(100) & \text{GeV [3]} \\ 2.359(128) & \text{GeV [4]} \end{cases} ; \tag{2}$$

with the pseudoscalar glueball at a similar mass.

There are obvious problems associated with the identification of a scalar state near 1.5 GeV. The f_0 sector is the most complicated of all meson sectors, with at least six problematical states, $f_0(980)$, $f_0(1300)$, $f_0(1365)$, $f_0(1500)$ $f_0(1590)$ and $f_0(1710)$. Since this sector contains broad and overlapping resonances, the problem of identifying unusual states against the $q\bar{q}$ and $s\bar{s}$ background, and the related problems of separating individual resonances from interference and threshold effects are daunting ones. If the scalar glueball does have a typical hadronic width, as suggested by the work of Sexton *et al.* [5], it may be quite difficult to identify this state convincingly. Amsler and Close [6] note that the near degeneracy of the pure (quenched) LGT glueball and the $L = 1$ $q\bar{q}$ and $s\bar{s}$ multiplets may lead to complicated mixing effects, so the physical states may be nontrivial combinations in flavor space, as in the η-η' sector.

The tensor glueball may be an easier experimental target, since the expected mass is far above the lowest-lying 2^{++} quarkonium states. Here the problem is that the mass region above 2 GeV is poorly explored, so it is not yet possible to distinguish a tensor glueball from the background of radial $^3P_2$ and $^3F_2$ $q\bar{q}$ and $s\bar{s}$ states. This lack of adequate information regarding the higher mass quarkonium spectrum is even more of a problem in the 0^{-+} sector.

B. Expectations for glueball properties

Since we have no confirmed glueballs and the states predicted are in channels with a complicated or poorly explored resonance spectrum, it would be useful to have reliable theoretical predictions of glueball properties as a guide. The data we are likely to have on gluonic candidates in the near future are their masses, widths and strong decay amplitudes. Here a very characteristic naive glueball signature can be given, although it is easy to imagine ways in which this signature might be violated.

As gluons at the bare lagrangian level have equal strength couplings to quarks of all flavors, one can make the assumption that flavor-symmetric couplings to hadron final states are approximately valid for physical glueballs. This gives a characteristic flavor-singlet branching fraction to pseudoscalar pairs, which is (neglecting phase space differences)

$$\Gamma(G \to \pi\pi : K\bar{K} : \eta\eta : \eta\eta' : \eta'\eta')/(\text{phase space}) = 3 : 4 : 1 : 0 : 1 . \tag{3}$$

Of course this simple pattern should at least incorporate the $|\vec{P}|$ from phase space for an S-wave decay, and there is in addition a decay form factor which depends on the unknown scalar glueball wavefunction and the decay mechanism. Experience with the $^3P_0$-model $f_0(q\bar{q})$ decay amplitude to $\pi\pi$, which has a node near the physical point [7], suggests that the naive pattern of flavor-singlet decay amplitudes may indeed be far from the physical couplings.

The accuracy of naive flavor-singlet couplings can be tested for a pure (quenched) scalar glueball in lattice gauge theory through a determination of the glueball-Ps-Ps three point function. Preliminary results for this coupling [5] indicate that flavor-singlet symmetry may indeed be badly violated at the amplitude level, and higher-mass Ps pairs are preferred in the decay. In view of the relatively large errors it is important to improve the statistics of this interesting lattice gauge theory measurement. An extension of this work to the decay amplitudes of tensor and pseudoscalar glueballs would also be a very useful contribution.

In future experimental work it may be possible to determine or limit electromagnetic couplings of glueball candidates. Measurements of one-photon ($R \to \gamma q\bar{q}$) and two-photon ($R \to \gamma\gamma$) transition rates of these resonances are extremely important because theorists can calculate these for $q\bar{q}$ states with reasonably accuracy [8]. The radiative transition rates of a relatively pure glueball would clearly be anomalous relative to expectations for the corresponding $f_J(q\bar{q})$ state. If physical glueballs are indeed strongly mixed linear combinations of gluonic, $q\bar{q}$ and $s\bar{s}$ basis states, a convincing way to identify the flavor components of these mixed states would be through a comparison of the relative rates

$$\Gamma(R \to \gamma\rho^0 : \gamma\omega : \gamma\phi)$$

since these act as flavor tags. Similarly, $\gamma\gamma$ couplings can be used to locate the scalar nonstrange f_0 $q\bar{q}$ signal, since this state should have a strong coupling to $\gamma\gamma$. Results on this reaction have already been obtained by the Crystal Ball in the reaction $\gamma\gamma \to \pi^o\pi^o$ [9]. Since a glueball should have suppressed couplings to $\gamma\gamma$, measurements of the $\gamma\gamma$ couplings of the various f_J states and other light resonances would be very important contributions to light meson spectroscopy at a TCF.

C. Summary of glueball candidates

At present the two most prominent experimental candidates for glueballs are the scalar $f_0(1500)$ and the $\xi(2230)$, which is probably a tensor. The scalar candidate has a mass and width (as reported by Crystal Barrel [10]) of

$$M(f_0) = 1520 \begin{array}{c}+20\\-55\end{array} \text{MeV} \quad (4)$$

and

$$\Gamma(f_0) = 148 \begin{array}{c}+20\\-25\end{array} \text{MeV} . \quad (5)$$

The $f_0(1500)$ seems rather too massive to be a nonstrange $^3P_0$ $q\bar{q}$ state, but is consistent with the lower mass estimates from LGT for a scalar glueball. The width is also quite narrow for a $^3P_0$ $q\bar{q}$ state at this mass. The decay pattern to pseudoscalar pairs is however inconsistent with flavor symmetry; the squared invariant couplings cited by Amsler [10] are

$$\Gamma(f_0(1500) \to \pi\pi : K\bar{K} : \eta\eta : \eta\eta')/(\text{p.s.}) =$$

$$1 \;:\; < 1/8.6\ (95\%c.l.) \;:\; 0.24 \pm 0.12 \;:\; 0.35 \pm 0.15 . \quad (6)$$

A priori this argues against a pure glueball interpretation, and subsequent work by Amsler and Close [6] has investigated the possibility that these decays may be consistent with a scalar glueball that has important $q\bar{q}$ and $s\bar{s}$ components, leading to an $\eta\eta'$ mode and suppressing the $K\bar{K}$ mode. The limit on the coupling to $K\bar{K}$ is actually inferred from another experiment, and a more careful study of this coupling including interferences at the Crystal Barrel appears to find a much larger $K\bar{K}$ coupling [11]. This state has also been reported in a recent reanalysis of the MarkIII data on $\psi \to \gamma\pi^+\pi^-\pi^+\pi^-$ by Bugg *et al.* [12]; in this channel the $f_0(1500)$ appears dominantly in the "$\sigma\sigma$" mode of two S-wave $\pi\pi$ pairs.

The second glueball candidate, which might be the $\xi(2230)$ previously reported by MarkIII [13] in ψ radiative decays, is reported by BES [14] to have very anomalous properties for a tensor above 2 GeV. The mass and width BES cite for this state in K_SK_S are

$$M(\xi) = 2232 \begin{array}{c}+8\\-7\end{array} \pm 15 \text{ MeV} \quad (7)$$

and

$$\Gamma(\xi) = 20 \begin{array}{c}+25\\-16\end{array} \pm 10 \text{ MeV} , \quad (8)$$

with similar results in $P\bar{P}$, K^+K^- and $\pi^+\pi^-$. If this narrow state is confirmed it is a remarkable discovery indeed. The mass is consistent with LGT expectations for the lightest tensor glueball (2), and the narrow width implies that this is certainly not a tensor quarkonium state. Since the couplings to $\pi\pi$ and $K\bar{K}$ appear to be approximately flavor symmetric [14], this appears to be a natural glueball candidate.

Although Godfrey, Kokoski and Isgur [15] previously suggested that the $^3F_2$ and $^3F_4$ $s\bar{s}$ states expected near this mass could be relatively narrow, subsequent work by Blundell and Godfrey [16] has shown that other modes such as $K_1(1270)K$ are large, so $\Gamma(f_2(s\bar{s})) \geq 400$ MeV. Similarly for the $^3F_4$ Blundell and Godfrey now find a broader state given these additional modes, $\Gamma(f_4(s\bar{s})) \geq 130$ MeV. Thus the $s\bar{s}$ assignments now appear implausible if the $\xi(2230)$ does indeed have an experimental width of < 50 MeV.

Several of the properties reported for this narrow $\xi(2230)$ are disturbing. It has surprisingly small branching fractions to pseudoscalar pairs in view of the available phase space [14]; branching fractions of only a few percent are implied by the PS185 limit on $P\bar{P} \to \xi \to K\bar{K}$. A more important concern is that the reported statistical significance in each of the four channels studied by BES is rather small, $\approx 3\sigma$. A caution is appropriate because some previously reported narrow effects were subsequently found to be artifacts (for example the $\zeta(8.3)$). In view of the remarkable properties reported for this state, measurement of these channels with higher statistics is an extremely important task for any e^+e^- facility operating at the ψ mass.

Although we have only discussed the $f_0(1500)$ and $\xi(2230)$ glueball candidates, this is largely because they have attracted considerable attention recently. Several other states with similar masses and the same quantum numbers, notably the $f_0(1710)$, should also be considered glueball candidates [5]. Measurements of strong branching fractions and electromagnetic decays of this and other glueball candidates should be considered high priorities at a TCF.

III. HYBRIDS

A. Introduction

Hybrid mesons may be defined as resonances in which the dominant valence basis state is $q\bar{q}$ combined with a gluonic excitation. Hybrids are attractive experimentally because, unlike glueballs, they span complete flavor nonets and hence provide many possibilities for experimental detection. In addition, the lightest hybrid multiplet is expected to include at least one J^{PC}-exotic (forbidden to $q\bar{q}$). In the bag model, for example, the lightest gluon mode has $J^P = 1^+$, so the lowest-lying $q\bar{q}g$ multiplet contains the quantum numbers

$$J^{PC_n}(q\bar{q}g) = \begin{cases} 0^{-+}, 1^{-+}, 2^{-+} & (S_{q\bar{q}} = 1), \\ 1^{--} & (S_{q\bar{q}} = 0) \end{cases} . \quad (9)$$

The flux tube model extends this bag model list by adding a degenerate set with reversed $\{P, C\}$ to the lowest hybrid multiplet. Constituent gluon models differ in that their lowest hybrid multiplet has P-wave $q\bar{q}$ quantum numbers [17] and so is nonexotic, although exotics appear in excited hybrid multiplets. An investigation of $q\bar{q}g$ interpolating fields [18] shows that hybrids can have *any* J^{PC}.

B. Hybrid masses.

Hybrids have been studied using a wide range of models and techniques. These are the MIT bag model [19], constituent gluon models [17,20,21], the flux tube model [22–31], an adiabatic heavy-quark bag model [32], heavy-quark lattice gauge theory [33] and QCD sum rules [34–38]. There have been no published Monte Carlo lattice gauge theory studies of hybrid masses; a study of exotic hybrid masses would be an interesting application of this technique. In all the theoretical approaches employed to date the lightest hybrids (H_q, involving u, d flavors) are predicted to have masses in the $\approx 1\frac{1}{2}$-2 GeV region. A summary of hybrid mass predictions for the especially interesting 1^{-+} exotic is given in the table below, taken from [28]. A more detailed discussion of these predictions and the literature on hybrids is given by Barnes, Close and Swanson [28]; for other recent reviews of hybrids see [39].

Much of the recent interest in hybrids has derived from the flux tube model, which gives rather precise predictions for masses and decay modes of hybrids. The original flux tube references [23–25] cited masses of ≈ 1.9 GeV for the lightest (u, d) hybrid multiplet, ≈ 4.3 GeV for $c\bar{c}$ hybrids and ≈ 10.8 GeV for $b\bar{b}$ hybrids. There is an overall variation of about 0.2-0.3 GeV in these predictions, as indicated in Table I. Multiplet splittings are usually neglected in the flux tube model. This approximation may not be justified; a large inverted spin-orbit term was found for hybrids by Merlin and Paton [25].

TABLE I. Predicted 1^{-+} Hybrid Masses.

state	mass (GeV)	model	Ref.
$H_{u,d}$	1.3-1.8	bag model	[19]
	1.8-2.0	flux tube model	[22-25,28]
	2.1-2.5	QCD sum rules (most after 1984)	[35-37]
	2.1	constituent gluon model	[21]
H_c	≈ 3.9	adiabatic bag model	[32]
	4.1-4.5	flux tube model	[23-25,28]
	4.1-5.3	QCD sum rules (most after 1984)	[35-37]
	4.19(3) ± sys.	HQLGT	[33]
H_b	10.49(20)	adiabatic bag model	[32]
	10.8-11.1	flux tube model	[23-25]
	10.6-11.2	QCD sum rules (most after 1984)	[35-37]
	10.81(3) ± sys.	HQLGT	[33]

A recent Hamiltonian Monte Carlo study [28] of the flux tube model determined hybrid masses without using the questionable approximations of the earlier flux tube model studies, such as an adiabatic separation of quark and flux-tube motion and a small oscillation approximation for the flux tube. This Monte Carlo study generally confirmed the accuracy of the earlier flux-tube model mass estimates, both for $q\bar{q}$ and $c\bar{c}$ mesons (compared to experiment) and for hybrids (compared to the earlier approximate analytical calculations). These flux tube predictions are shown in Fig.1 below for light quarks and in Fig.2 in the discussion of charmonium hybrids.

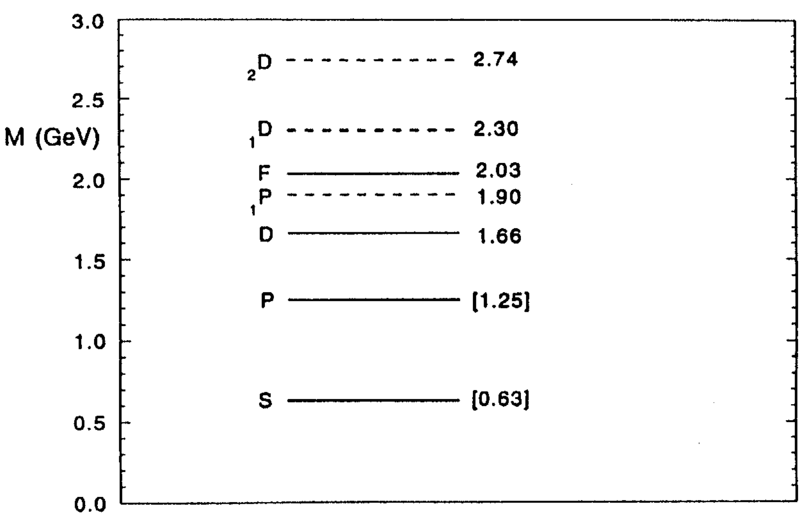

Fig.1. The light qqbar (q=u,d) and hybrid spectrum in the flux tube model [28].

By varying the model parameters over a plausible range, this study concluded that the lightest hybrid masses in the flux tube model were

$$M(H_{u,d}) = 1.8 - 1.9 \text{ GeV} \tag{10}$$

for light quark hybrids and

$$M(H_c) = 4.1 - 4.2 \text{ GeV} \tag{11}$$

for charmonium hybrids. Excited hybrids were also considered, and the first hybrid orbital excitation ($_\Lambda L = {}_1D$) was found at about 2.3 GeV, 400 MeV above the lightest (${}_1P$) hybrids. The same numerical result was found earlier by Merlin [26] using the adiabatic approximation. This ${}_1D$ multiplet contains the J^{PC} states $(1,2,3)^{\pm\mp}$ and $2^{\pm\pm}$, which includes the exotics $1^{-+}, 2^{+-}$ and 3^{-+}. One way to test the experimental candidates for ground-state hybrids near 1.8 GeV [40] and 1.6-2.2 GeV [41] would be to search for members of this excited ${}_1D$ hybrid multiplet about 0.4 GeV higher in mass.

C. Light hybrid decay modes.

Theoretical models predict rather characteristic two-body decay modes for hybrids. Both constituent gluon [20] and flux tube [27] models find that the lightest hybrids decay preferentially to pairs of one $L_{q\bar{q}}$=0 and one $L_{q\bar{q}}$=1 meson "S+P", for example πf_1 and πb_1. These unusual modes previously received little experimental attention because they involve complicated final states, which may explain why hybrids were not discovered previously. The flux-tube decay predictions of Isgur, Kokoski and Paton [27] are quite interesting because they suggest that many hybrids are so broad that they will be effectively invisible, whereas a few hybrids should be narrow enough to be easily observable in certain channels. The $I = 1$ $J^{PC} = 1^{-+}$ exotic had already been cited as an attractive experimental candidate, and this work suggested that this state should be relatively narrow, $\Gamma_{tot} \approx 200$ MeV, and that the S+P modes πb_1 and πf_1 should be the dominant final states. These studies have motivated several experimental investigations of πb_1 and πf_1, which show possible indications of resonant amplitudes in 1^{-+}.

These original flux tube decay calculations were for the three exotic J^{PC} quantum numbers in the lowest flux-tube multiplet. Since this multiplet contains a total of eight J^{PC} assignments, $1^{\pm\pm}$ (for $S_{q\bar{q}} = 0$) and $2^{\pm\mp}$; $1^{\pm\mp}$; $0^{\pm\mp}$ (for $S_{q\bar{q}} = 1$), one might wonder whether any of the *nonexotic* hybrids are narrow enough to be observed. The decay amplitudes of these nonexotic hybrids were recently calculated by Close and Page [29], who also checked the exotic decay amplitudes and found reasonable numerical agreement with Isgur, Kokoski and Paton.

Close and Page predict that many of these nonexotic hybrids are also so broad as to be effectively unobservable. There are two striking exceptions. One is a 1^{--} ω-hybrid with a total width of only ≈ 100 MeV, which decays to $K_1(1270)K$ and $K_1(1400)K$; this should be searched for in K_1K final states, perhaps in photoproduction. A second interesting nonexotic hybrid is a π_2, with $\Gamma_{tot} \approx 170$ MeV. This may be the high-mass state which has been reported in several photoproduction experiments a mass near 1775 MeV [40]. Other notable conclusions are that 1) several other hybrids, including exotics, have total widths near 300 MeV and so should be observable, and 2) the $I = 0$ 0^{+-}

exotic found by Isgur *et al.* to have $\Gamma_{b_1\pi} = 250$ MeV actually has very large K_1K modes and so should be unobservable.

In addition Close and Page investigate the "forbidden" decay modes such as $\hat{\rho}(1900) \rightarrow \rho\pi$, and find that, due to differences in the ρ and π spatial wavefunctions, these S+S modes are present with partial widths of typically ~ 10 MeV. An important $\rho\pi$ coupling was found earlier by deViron and Govaerts [38] using QCD sum rules. Thus it is interesting to search relatively straightforward modes such as $\rho\pi$ for hybrids, in addition to the favored but more difficult S+P modes such as $b_1\pi$, πf_1 and K_1K.

D. Prospects for charmonium hybrids at a TCF.

The predictions of the recent flux tube model calculations ([28], shown below) and heavy-quark LGT [33] that hybrid charmonium states should appear beginning at 4.1-4.2 GeV are especially relevant for the physics program of a Tau-Charm Factory.

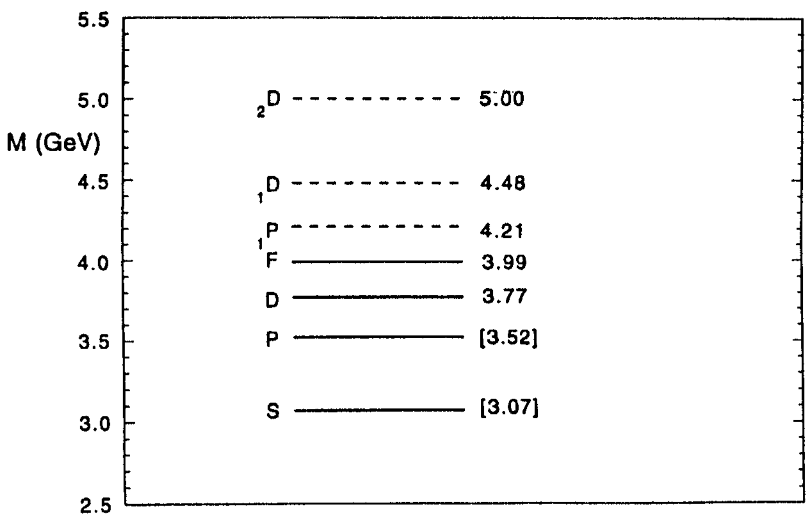

Fig.2. Charmonium and ccbar-hybrid masses in the flux tube model [28].

Charmonium spectroscopy is rather well understood up to about 3.8 GeV, so searches for unusual states should be straightforward near this mass. Since only a few open charm channels occur below 4.3 GeV, for a considerable range of masses one might anticipate rather narrow hybrid resonances. This possibility is supported by the theoretical preference of hybrids for S+P decay modes, which have thresholds of about 4.3 GeV for $c\bar{c}$ and 11.0 GeV for $b\bar{b}$. Calculations of the decay widths of charmonium hybrids have been carried out in the flux tube model by Close and Page [31], assuming masses of ≈ 4.1-4.2 GeV. The partial widths (to D^*D) are found to be quite small, typically only $\sim 1 - 10$ MeV. Thus if there are relatively unmixed charmonium hybrids, the 1^{--} vector hybrids should appear as narrow spikes in R in this mass range. For this reason a detailed scan of R starting near the open charm threshold would be a first priority at a Tau-Charm Factory.

Close and Page subsequently speculate about a more complicated possibility, which is that the $\psi(4040)$ and $\psi(4160)$ may be equal-weight linear combinations of $3S\ |c\bar{c}\rangle$ and 1^{--} $c\bar{c}$-hybrid basis states. (The usual assignment is that the $\psi(4040)$ is a $3S$ $c\bar{c}$ and the $\psi(4160)$ is a $2D$ $c\bar{c}$ [43].) The Close-Page linear combinations would explain why the e^+e^- widths are approximately equal and relatively large for both states, which is surprising if one is a D wave $c\bar{c}$. The assignments for the ψ states above open-charm thresholds can be tested by measurements of their branching fractions to $D\bar{D}$, $D^*\bar{D}$, ..., $D_s^*\bar{D}_s$. The branching fractions predicted by these models are very sensitive to the initial state assignments [42]; unfortunately they have not yet been measured accurately. Determination of these branching fractions would be another high priority at a TCF.

Finally, we note that the non-vector hybrids can also be produced at a TCF through a "continuum cascade", as suggested by D.Bugg, and discussed in references [43,44]. In this approach one produces a high-mass $c\bar{c}$ system in the continuum, for example at 5 GeV; this may then decay hadronically to hybrid charmonium levels of various J^{PC} accompanied by a light hadron or hadrons. The $c\bar{c}$-hybrid in turn decays hadronically to a characteristic state such as the ψ. Thus one can search for example for the decay chain

$$e^+e^- \rightarrow c\bar{c} \rightarrow H_c\,\eta;\quad H_c \rightarrow \eta\psi;\quad \psi \rightarrow e^+e^-$$

in the final state $\eta\eta e^+e^-$, triggering on a lepton pair at the ψ mass and $\gamma\gamma$ pairs from the two ηs. The $\eta\psi$ invariant mass distribution can then be studied for evidence of hybrids or $c\bar{c}$ states. Other quantum numbers can be investigated by replacing η by other hadrons, for example $(\pi\pi)_S$, in the hadronic cascades.

E. Hybrid Experimental Candidates

There are several experimental candidates for hybrids, but just as for glueballs there are no generally accepted states at present.

In the exotic channels (which would provide the most convincing evidence for hybrids), previous claims by GAMS that a resonant signal had been detected in the 1^{-+} wave of $\pi\eta$ [45] have now been withdrawn. A KEK experiment [46] finds evidence for a resonant 1^{-+} $\pi\eta$ wave, but with the mass and width of the $a_2(1320)$; this surprising result obviously must be checked carefully for "feedthrough" of the a_2 amplitude. VES [47] has studied $\pi\eta$ and $\pi\eta'$ and report a broad, higher-mass effect in $\pi\eta$ and especially in $\pi\eta'$, near 1.6 GeV. The phase motion of the 1^{-+} component has not yet been determined. Studies of the πf_1 final state suggested by the flux tube model are underway [41,47], and preliminary evidence for a possible 1^{-+} signal has been reported by E818 at BNL [41].

There have been several observations of a photoproduced $I = 1$ state in $\rho\pi$ and πf_2 at about 1775 MeV [40], which is too heavy to be the $\pi_2(1670)$ without complicated interference effects. Although the quantum numbers of this state have not been determined definitively, 1^{-+} is preferred over 2^{-+}. A possible narrow 1^{-+} state has been reported by GAMS in $\eta\eta'$ at a mass of 1910 MeV [48]; here there are rather few events, so it will be important to improve the statistics. Several experiments plan future studies of these channels, including E818 (to study $\pi^- f_1$) [49] and E852 (to study πf_1 and $\pi\eta$) [50] at BNL.

In addition to exotic hybrids there are several nonexotic candidates; recall for example the Close-Page result that a hybrid with π_2 quantum numbers is expected to be relatively narrow, and should be visible in πf_2. One way to *distinguish hybrids from $q\bar{q}$ spin-singlet states is through their strong decay* amplitudes; for example, in the π_2 sector the relative F/P and D/S amplitude ratios in $\pi_2(q\bar{q}) \to \rho\pi$ and πf_2 are reasonably well constrained in the $^3P_0$ and flux tube decay models [51]. These decay models provide an interesting selection rule for $q\bar{q}$ decays; they forbid the decay of a spin-singlet $q\bar{q}$ state to two final spin-singlet quarkonia,

$$(q\bar{q})_{S=0} \not\to (q\bar{q})_{S=0} + (q\bar{q})_{S=0} \ .$$

In the π_2 channel this selection rule forbids the decay of a $^1D_2$ $q\bar{q}$ π_2 to a $^1S_0$ π plus a $^1P_1$ b_1,

$$\pi_2(q\bar{q}) \not\to \pi b_1$$

but allows it for a hybrid π_2 which does not have the $q\bar{q}$ pair in an $S = 0$ configuration. Close and Page find the πb_1 mode of a π_2 hybrid should be rather large, so it is especially important to search the πb_1 channel for evidence of a 2^{-+} signal.

Other nonexotic hybrid candidates which have been suggested recently are a $\pi(1800)$ reported by VES [52] and the nonstrange 1^{--} states near 1.4-1.7 GeV [53]. The $\pi(1800)$ is cited as a possible hybrid because it has unusual branching fractions, including a significant coupling to $\pi\eta\eta$, apparently through the glueball candidate $f_0(1500) \to \eta\eta$. This $\pi(1800)$ is also reported by VES in $\omega\rho$, $\eta a_0(980)$, $\pi f_0(980)$ and $\pi f_0(1300)$. The decay mode $\pi(1800) \to \rho\pi$ is notably absent, and πf_2 is also weak or absent.

Although the weakness of the $\rho\pi$ S+S mode is indeed suggestive of a hybrid, a $\pi(1800)$ second radial excitation is expected in quark potential models (Godfrey and Isgur [54] predict 1.88 GeV), so one should consider this assignment as well. Radial quarkonia can have unusual branching fractions due to nodes in their decay amplitudes, and in the $^3P_0$ decay model with SHO wavefunctions the amplitude for $\pi(3S) \to \rho\pi$ has a node at $M = 1.88$ GeV for $\beta = 0.35$ GeV. The weakness of the $\rho\pi$ mode is therefore understandable for a 3S state. The same model however predicts a weak $\pi f_0(1300)$ mode, which disagrees with experiment. The decay amplitude for $\pi(3S) \to \pi\rho(2S)$ is predicted to be quite large [55], so a search for a $\pi\rho(1450)$ final state would be useful.

The unusual properties of the nonstrange $I = 0$ and $I = 1$ vectors near 1.5 GeV have led to suggestions that hybrid vector states may be present near this mass [53,56]. In $I = 1$, for example, the two states $\rho(1450)$ and $\rho(1700)$ are usually assigned to 2^3S_1 and $^3D_1$ respectively, but the very large $\rho(1450) \to 2(\pi^+\pi^-)$ mode [56] is in conflict with quark model expectations for a 2^3S_1 state [56-58]. A better understanding of these vector states may require a detailed isobar analysis of their quasi two-body strong decay modes.

These comparisons of strong decay modes illustrate the importance of having an accurate understanding of the decays of radially excited $q\bar{q}$ states. Careful studies of the strong decays of radially excited $q\bar{q}$ candidates such as the $\pi(1300)$, $\rho(1450)$, $\phi(1680)$, $\pi(1800)$ and so forth will be required if we are to distinguish $q\bar{q}$ from non-$q\bar{q}$ states with identical quantum numbers.

IV. MULTIQUARK SYSTEMS AND MOLECULES

A. Introduction

Multiquark systems have had a complicated history, and current theoretical expectations for these states now differ radically from the earliest suggestions. In the pre-QCD quark model era it was thought that multiquark hadrons should exist as resonances in the hadron spectrum. After the discovery of QCD and confinement it was still widely expected that multiquark hadrons should exist (in color singlet sectors), and models typically predicted a very rich spectrum of states. In the light $q^2\bar{q}^2$ sector these "baryonium" resonances were expected to appear beginning at about 1 GeV. It was clear however that there were problems with these predictions, because in the relatively uncomplicated flavor-exotic channels such as $I = 2$ $J^{PC} = 0^{++}$ no $q^2\bar{q}^2$ resonances were observed [59] whereas they were predicted to be relatively light (≈ 1.2 GeV in the MIT bag model). Similarly, the evidence for dilambda hypernuclei [60] makes the existence of an H six-quark resonance well below $\Lambda\Lambda$ threshold (another bag model prediction) appear very unlikely.

The problem with these predictions of multiquark resonances such as $q^2\bar{q}^2$ was that they were above $(q\bar{q})(q\bar{q})$ thresholds, and could spontaneously dissociate "fall-apart" into two mesons [61]. Thus the mass predictions in models which assumed *a priori* that the $q^2\bar{q}^2$ system existed as a single hadron were spurious, because the physical eigenstates were usually a continuum of scattering states [62]. Whether single multiquark clusters exist as resonances under any conditions is a detailed dynamical question, which should be investigated using models that allow the system itself freedom to choose between a single cluster or separate color singlets. At present it appears that single $q^2\bar{q}^2$ hadronic clusters may only exist as resonances in heavy-light systems such as $c^2\bar{q}^2$ [63].

More realistic models of multiquark systems were subsequently developed which gave the $q^2\bar{q}^2$ system freedom to choose dynamically between a bound system and a two-meson scattering state. The variational calculations of Weinstein and Isgur [64] are the best known of these studies; in this work it was found that most 0^+ sectors of the light $q^2\bar{q}^2$ system had two free mesons as the ground state, but that the $I = 0$ and $I = 1$ $qs\bar{q}\bar{s}$ sectors actually had a weakly bound, deuteronlike $K\bar{K}$ pair as the ground state. These states were obvious assignments for the problematical $f_0(980)$ and $a_0(980)$ resonances, which were difficult to explain as $^3P_0$ $q\bar{q}$ states but could easily be understood as $K\bar{K}$ systems with nuclear binding energies of 10s of MeV. These states have been the "prototypes" for hadron molecules, although they remain somewhat controversial. We note in passing that molecule states as a general category are not at all controversial, since the $> 10^4$ known nuclear levels are all examples of hadronic molecules. Here we will discuss meson molecules; candidates also exist in baryon sectors, for example the $\Lambda(1405)$, which may be a $\bar{K}N$ bound system [65].

Signatures for the *a priori* most likely molecular states [66] can be abstracted from our experience with short-ranged hadronic forces and the Weinstein-Isgur results:

1) *J^{PC} and flavor quantum numbers of an L=0 hadron pair.*

2) *A binding energy of at most about* $50 - 100$ *MeV.*

3) *Strong couplings to constituent channels.*

4) *Anomalous EM couplings relative to expectations for conventional quark model states.*

B. Experimental molecule candidates

1) $f_0(975)$ and $a_0(980)$: The "$K\bar{K}$-molecules".

Weinstein and Isgur [64] found an exception to the fall-apart phenomenon in the scalar sector, with parameters corresponding to the $qs\bar{q}\bar{s}$ system. Here weakly-bound deuteronlike states of kaon and antikaon were found to be the ground states of the four-quark system; Weinstein and Isgur refer to these as "K$\bar{\text{K}}$ molecules". The scalars $f_0(975)$ and $a_0(980)$ were obvious candidates for these states, having masses just below $K\bar{K}$ threshold and strong couplings to strange final states. Subsequently the $\gamma\gamma$ couplings of the $f_0(975)$ and $a_0(980)$ were found to be anomalously small relative to expectations for light $^3P_0$ $q\bar{q}$ states ($q = u, d$), as discussed in references [67,68]. The status of the $K\bar{K}$ molecule assignment and the many points of evidence in its favor have been discussed recently by Weinstein and Isgur [69,70].

Morgan and Pennington have argued against a molecule interpretation of the $f_0(975)$ [71]. Their criticism however applies to a $K\bar{K}$ potential model in which the $f_0(975)$ is a single pole in the scattering amplitude. The more recent work of Weinstein and Isgur [69,70] incorporates couplings to meson-meson channels and heavier $^3P_0$ $q\bar{q}$ states, so the physical resonances are not only $|K\bar{K}\rangle$. Since there has been much criticism of the idea of a pure $K\bar{K}$ bound state, a direct quote from Weinstein and Isgur [69] (regarding the $I = 0$ state) is appropriate:

> *"Despite its name and location, the "$K\bar{K}$ molecule" is not a simple $K\bar{K}$ bound state. Its stability is dependent on its couplings to the other $I = 0$ channels and at $E = M_S$, the coupled-channel wavefunction has substantial components of the other states."*

Although the f_0 and a_0 states remain dominantly $K\bar{K}$, these modifications may answer the objections of Morgan and Pennington. Pennington suggests that the term "deuteronlike" may be a misnomer, if couplings to other states than $K\bar{K}$ play an important rôle in these states [67]. Thus it appears that the important question regarding the f_0 and a_0 may be one of detail, specifically how large the subdominant non-$K\bar{K}$ components are in these states and how they can be observed experimentally.

The experimental measurements which would be most useful for studies of these states at a TCF are 1) their $\gamma\gamma$ widths, which are as yet rather poorly known, and 2) their cross sections in ψ hadronic decays, in $\psi \to \omega f_0$ and ϕf_0. (The latter are flavor-tagging and in studies at BES have shown that the $f_0(980)$ does appear to be a mixed flavor state.) Other interesting measurements at low energies are the radiative transitions $\phi \to \gamma f_0$ and γa_0.

which depend strongly on the scalar assignment [72] and may be measured at DAPHNE [73] and CEBAF [74].

2) $f_1(1420)$

Since the $f_1(1420)$ is above the K^*K threshold of 1390 MeV it is a candidate for a nonresonant threshold enhancement ($K^*\bar{K}+h.c.$) rather than a molecular bound state. This possibility was suggested by Caldwell [75], and satisfies the criteria of lying just above the K^*K threshold (antiparticle labels are implicit) and having quantum numbers allowed for that pair in S-wave. The apparent width of the enhancement should not be narrower than the intrinsic width of the K^*, and indeed the PDG values are similar, $\Gamma(f_1(1420)) = 56 \pm 3$ MeV and $\Gamma(K^*) = 50$ MeV. Longacre [76] found that a model with an S-wave nonresonant ($K^*\bar{K} + h.c.$) enhancement gives a good description of this state, and Isgur, Swanson and Weinstein [77] also favor this possibility. The (off-shell) $\gamma\gamma^*$ couplings of the $f_1(1420)$ relative to expectations for a 1^{++} $s\bar{s}$ state may provide a test of the hadron-pair model.

Another test of this K^*K-assignment is in radiative transitions; the dominant radiative mode of a K^*K system will arise from the radiative transition of the K^* constituent, $K^* \to K\gamma$, implying a partial width of

$$\Gamma(f_1(K^*K) \to \gamma K\bar{K}) \approx 80 \text{ KeV} , \qquad (12)$$

and a characteristic pattern of preference for $K^o\bar{K}^o$ over K^+K^- by about a factor of two. An $s\bar{s}$ state would give a similar radiative partial width, $\Gamma(f_1(1420)(s\bar{s}) \to \gamma\phi) \approx 50$ KeV if we scale from the $\Gamma(f_2' \to \gamma\phi) = 96$ KeV of Godfrey and Isgur [54]. Although the radiative rates are similar, there is a crucial difference in the two assignments: The $s\bar{s}$ decay is to $\gamma\phi$, so the final $K\bar{K}$ pair will clearly originate from a $\phi(1019)$ peak. The $K\bar{K}$ events from a K^*K system should instead have a broad distribution in invariant mass. Thus, the two $f_1(1420)$ assignments can easily be distinguished through the $K\bar{K}$ invariant mass distribution observed in $f_1(1420) \to \gamma K\bar{K}$.

3) Other possible molecules.

There are many other possible molecular states, which can only be mentioned briefly here. In the meson sector these include the $f_0(1710)$, which could be a vector-vector molecule involving $K^*\bar{K}^*$ [78–80]. This can be tested at a TCF by searches for a large $K\bar{K}\pi\pi$ mode. Similarly, the $f_0(1500)$ glueball candidate might be a nonstrange vector-vector system [78,81], which would explain the weakness of the $K\bar{K}$ mode. The $f_0(1365)$ should also be considered a possible vector-vector molecule, in view of its very large coupling to $\rho\rho$ despite the near absence of phase space. The 2^{++} state reported by VES [52] in $\rho^o\rho^o$ is another possible vector-vector molecule, although its appearance in the $\rho\rho$

D-wave may be a problem. The $\psi(4040)$, which shows a strong preference for $D\bar{D}$ over $D^*\bar{D}^*$ (opposite to expectations from phase space) was one of the earliest molecule candidates [82]. As the $c\bar{c}$ assignment for this state is a 3S radial excitation, this anomalous branching fraction may be due to a node in the decay amplitude near the $D^*\bar{D}^*$ momentum [42]. Finally, there are several molecule candidates in baryon sectors, such as the $\Lambda(1405)$ [65] (which as a possible $\bar{K}N$ is the earliest molecule candidate excluding nuclei), KN-flavor "Z^*" exotics (discussed in [83,84]) and dibaryons [85].

Since molecular bound states are a special aspect of $2 \to 2$ hadron scattering amplitudes, one might anticipate that an understanding of these scattering amplitudes will lead to reliable predictions of molecules. Theoretical work along these lines is in progress; at present there are different predictions for molecules depending on the scattering mechanism assumed. In one pion exchange models [78,80] many bound states are predicted which should be experimentally observable. In scattering calculations assuming quark-gluon forces (see [79,83,86–89] and references cited therein) few channels are found to have sufficiently strong attractions to form bound states; the vector-vector system [79,87] is one of the few. One of the principal limitations of hadron hadron scattering calculations at the quark-gluon level is the absence of $q\bar{q}$ annihilation in most studies. Annihilation is known to be an important effect when allowed, for example in the $K\bar{K}$ molecules [69,70]. An extension of this work to include $q\bar{q}$ annihilation is in progress [90].

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