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Signatures for Hybrids

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SIGNATURES FOR HYBRIDS [1]

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Abstract

In this review talk I summarize theoretical expectations for properties of hybrid mesons and baryons, and discuss the prospects for identifying these states experimentally.

1. Introduction: Why hybrids rather than glueballs?

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. There is much indirect evidence of gluonic basis states in mixing effects, for example in the Breit-Fermi one-gluon-exchange Hamiltonian used in potential models and in the η and η' masses. 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 the remaining problematic resonances show no convincing evidence for states with dominant gluonic valence components. Reviews of candidate gluonic states and other unusual hadronic states from the viewpoints of theorists [1] and experimentalists [2] can be found in the proceedings of recent meetings on hadron spectroscopy.

A priori one might expect that a search for gluon constituents in the spectrum should concentrate on dominantly pure states of gluons, since the properties of these might be expected to differ maximally from quark and antiquark states. This naive expectation does not survive detailed investigation. The lightest color-singlet glueball basis states one can form from transverse gluons are $|gg\rangle$, and the quantum numbers allowed for these states are $I=0, J^{PC}= 0^{\pm+}, 2^{\pm+}, 3^{++}, 4^{\pm+}$, and so forth. Since $q\bar{q}$ states can also be made with these quantum numbers, there is a danger of confusion

[1]This is an expanded version of an Invited Contribution to the Conference on Exclusive Reactions at High Momentum Transfers, Marciana Marina, Elba, Italy, 24-26 June 1993.

and one would need to identify all such $q\bar{q}$ states in the mass range anticipated for glueballs. Probably the most reliable glueball mass estimates are derived from lattice gauge theory. These QCD simulations anticipate that the scalar should be the lightest glueball, with a mass of about 1.4 GeV; other glueball states are expected to lie near or above 2 GeV [3]. A 1.4 GeV scalar glueball should be evident in the $I = 0$ $\pi\pi$ S-wave phase shift, which is well-established experimentally to about 2 GeV [4]. This phase shift shows a single narrow state, the $K\bar{K}$-molecule candidate $f_0(975)$ [5], and in addition only a slowly rising phase underneath this state. If there are more scalar resonances coupled to this channel they are evidently very broad (a broad $^3P_0$ $q\bar{q}$ state $f_0(1250)$ is also expected here and has recently been identified in $\gamma\gamma$ [6]). Thus glueball spectroscopy may involve a search for quite broad resonances with conventional $I = 0$ $q\bar{q}$ quantum numbers, which could be a very unproductive or at best ambiguous exercise. Although one can make J^{PC}-exotic states from $|ggg\rangle$ basis states, which would be much more characteristic experimentally, these should appear at rather higher masses. A final problem is that expectations for the preferred decay modes of glueballs are rather obscure theoretically, since glueballs naively have flavor-singlet couplings, but these can be masked by phase space and wavefunction effects. Thus we are led to ask whether gluons might appear elsewhere in the spectrum as constituents, in states which might be more distinct experimentally.

This leads us to the subject of hybrids, which are resonances in which both quarks and gluons are present in the dominant basis state. Since a gluon transforms as a color octet, it may be combined with $q\bar{q}$ and qqq color-octet quark states to make overall color-singlet hybrid basis states. These new basis states will lead to additional resonances beyond those expected by the $q\bar{q}$ and qqq quark model assignments; although physical resonances are linear combinations of conventional and hybrid basis states, even if the mixing is large we will find more levels than the quark model alone expects. Actually it is somewhat misleading to refer to physical resonances as either quark states or hybrid states, since this mixing implies that all physical states have hybrid components. For simplicity we will use a theorist's definition of "hybrid" as states which are purely $|q\bar{q}g\rangle$ or $|qqqg\rangle$ before the QCD quark-gluon and gluon-gluon interactions are introduced, with the understanding that except for exotics there is ordinary-hybrid configuration mixing at some level in physical states.

The detailed predictions for the masses and quantum numbers of hybrid states depend somewhat on the model used to study them. Nonetheless, as we shall see, there is general agreement that these states have characteristic features that make them more attractive experimentally than the broad isosinglet glueballs, so the hybrid sector is where we may first see clear evidence of resonances with large or dominant gluonic components.

2. Hybrid mesons; masses and quantum numbers

Both meson and baryon hybrids are anticipated theoretically, since we can form color-singlet basis states from $q\bar{q}g$ and $qqqg$. Although these hybrid basis states mix with ordinary quark-model basis states such as $|q\bar{q}\rangle$ and $|qqq\rangle$ to form physical hadrons, we anticipate more physical states than the quark model alone predicts, and if the mixing is not large, the dominantly hybrid states may have unusual properties.

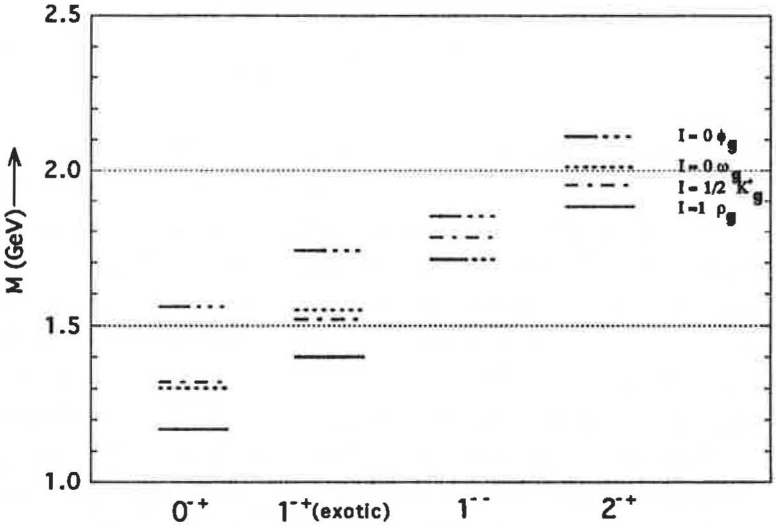

Figure 1: Light hybrid mesons in the bag model [9].

We first consider hybrid mesons because they have a very attractive feature: some $|q\bar{q}g\rangle$ hybrid basis states have exotic-J^{PC} quantum numbers forbidden to ordinary $q\bar{q}$ states, and for these exotics the mixing and possibility of confusion with $|q\bar{q}\rangle$ does not arise. Identification of dominantly hybrid states or other unusual hadrons which have quantum numbers accessible to conventional quark model states will remain an ambiguous exercise until the quark states in the relevant mass region are well established. Identifying all the relevant $q\bar{q}$ states in the $\approx 1.5 - 2.5$ GeV mass region of interest for hybrids will require considerable experimental effort. In contrast, identification of a state with exotic J^{PC} quantum numbers would at least indicate that we have found a state beyond the conventional quark model. One could then determine decay modes and search for other members of a multiplet, to see whether the new state agrees with expectations for a hybrid or glueball or perhaps a molecular multiquark state. Hadronic molecules such as the $K\bar{K}$ candidates $f_0(975)$ and $a_0(980)$ [5] and other possibilities such as vector-vector states [7] will complicate the identification of hybrids somewhat by contributing non-$q\bar{q}$ resonances to the meson spectrum, and these molecules can also have exotic quantum numbers. Fortunately, molecules should have rather characteristic features [8] such as S-wave meson-meson quantum numbers and masses not far below the associated two-meson threshold, so it should be easy to distinguish them from hybrids.

The masses of light hybrid mesons ($q = u, d$ and s) have been estimated using the MIT bag model [9, 10], QCD sum rules [11], the flux tube model [12] and heavy-quark lattice gauge theory [13]. The flavor quantum numbers of $q\bar{q}g$ are those of the $q\bar{q}$ pair, so light hybrids span conventional flavor nonets. In the bag model the lightest gluon mode is TE, with $J^P = 1^+$; combining this with the $J^P = 0^-$ and 1^- of $q\bar{q}$ in their lowest bag modes gives

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

Consideration of other multiplets shows that all J^{PC} can be made from $q\bar{q}g$ basis states. The $J^{PC} = 1^{-+}$ is of special interest because this is the lightest J^{PC}-exotic predicted by the bag model. The exact mass depends on the details of the bag parameters chosen, but is typically estimated to be about $M(1^{-+}) \approx 1.5$ GeV. The spectrum of physical hybrids ($q\bar{q}g$ states mixed perturbatively with $q\bar{q}$, gg and $q\bar{q}gg$ components) found by Barnes, Close and deViron [9] in this multiplet is shown in Fig.1. Similar results for the bag model hybrid spectrum were reported by Barnes and Close, Chanowitz and Sharpe, and Flensberg, Peterson and Sköld [10].

The predictions of the flux tube model for hybrids are especially interesting because this model gives good results for both the spectrum and decays of conventional quark states. The lightest hybrid flux-tube multiplet is quite rich, and contains the quantum numbers $J^{PC} = 1^{\pm\pm}, 2^{\pm\mp}, 1^{\pm\mp}$ and $0^{\pm\mp}$, all approximately degenerate. Note the presence of the 1^{-+} exotic, as in the bag model, and the additional exotics 0^{+-} and 2^{+-}. The mass of this multiplet (with $q = u, d$) is somewhat higher than bag model expectations, and has varied between ≈ 1.7 GeV and 2.0 GeV in the flux tube literature [12].

QCD sum rules can be used to estimate the masses of the exotic hybrids, since these are expected to be the lightest resonances in these J^{PC}-exotic channels. There have apparently been several algebraic errors in the sum rule literature in the past, which are discussed by Latorre, Narison, Pascual and Tarrach [14]. The most recent work of Latorre *et al.* [15] finds $q = u, d$ exotic hybrid masses of $M(1^{-+}) \approx 2.1$ GeV and $M(0^{--}) \approx 3.8$ GeV.

Finally, Wilson loop techniques have been applied to the study of hybrids in the heavy-quark limit by the Liverpool group [13]. Their result for the lightest "E_u" hybrid multiplet, which has a 1^{-+} member and other exotics, is $M(hybrid) \approx m_{Q\bar{Q}} +$ 1 GeV. If applicable to light quarks, this result is broadly consistent with the estimates found using other models, except perhaps the higher QCD sum rule estimate.

Of course, one may also attempt to identify non-exotic hybrids in the meson spectrum, and there are many suggestions for possible hybrid states in the literature (see for example [16], the reviews [1, 2] and the other phenomenological references in the bibliography). These attempts will probably remain controversial due to confusion with $q\bar{q}$ states until true exotic hybrids are identified, following which the identification of non-exotic partners in hybrid multiplets should be more straightforward.

There has recently been considerable interest in searches for heavy-quark hybrids. The advantage of these systems is that they should be relatively pure in Hilbert space, because the mixing between $|q\bar{q}g\rangle$ and other basis states is driven by $\vec{j}^a \cdot \vec{A}^a$, which is reduced due to the lower velocities of heavy quarks. Since the spectrum of heavy quarkonium is less complicated than in light hadronic systems, experimental identification of heavy hybrids might be more straightforward.

There are several model calculations of heavy-quark hybrid masses in the literature. The mass estimated for the lowest $c\bar{c}$-hybrid multiplet has varied over the range $\approx 4.2 - 4.5$ GeV in flux tube references [12]. Perantonis and Michael [13] find 4.04 GeV for the lightest $c\bar{c}$-hybrids in quenched heavy-quark lattice gauge theory, and estimate 4.19 GeV as a full QCD result. They also note that the effective $Q\bar{Q}$ potential for hybrids is rather shallow, so radially and orbitally excited hybrids should lie not far above the hybrid ground state. Finally, Narison [11] quotes a QCD sum rule result of 4.1 GeV for the 1^{-+} exotic $c\bar{c}$-hybrid, consistent with lattice gauge theory and the 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. Typical mass estimates for $b\bar{b}$-hybrids are 10.5 GeV (Narison, sum rules [11]) and up to 11.1 GeV (Merlin and Paton, flux tube model [12]).

In summary, although there is considerable variation in detail, all these approaches predict that the lightest exotic hybrid mesons have masses of $\approx 1.5 - 2.0$ GeV, and in heavy-quark systems (from the flux-tube model and lattice gauge theory) lie near the lightest $Q\bar{Q}$ mass plus $\approx 1 - 1\frac{1}{2}$ GeV. The exotic quantum numbers $J^{PC} = 1^{-+}$ are often suggested for experimental searches in light-quark systems, because all techniques find a hybrid with these quantum numbers, and the flux tube model predicts in particular that the 1^{-+} state with isospin 1 should be relatively narrow.

3. Signatures for hybrid mesons: decays and couplings

In addition to general searches for extra or J^{PC}-exotic resonances, one can use theoretical expectations for hybrid decay modes to motivate experimental searches in particular strong final states or in electromagnetic processes.

Theoretical models predict rather characteristic two-body decay modes for hybrids. Both flux tube [12] and constituent gluon [17] 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, for example πf_1 and πb_1. These unusual modes have received little experimental attention because they involve complicated final states, which may explain why hybrids were not been discovered previously. There is already some data on these final states; an $I = 1$, $J^{PC} = 1^{-+}$ exotic is reported at 1.775 GeV by a SLAC photoproduction experiment [18], and will be studied by E687 at Fermilab. The Crystal Barrel collaboration has results for πb_1 but sees no evidence for unusual states [19]. Several experiments plan future studies of these channels, including E818 (to study $\pi^- f_1$) [20] and E852 (to study πf_1 and $\pi\eta$) [21], both at BNL. Finally, E781 at Fermilab plans a sensitive search for hybrids using the Primakov effect [22].

Much of the experimental work on possible hybrids has concentrated on the $\pi\eta$ system, since this is easy to analyze (all odd-L $\pi\eta$ waves are exotic) and an important P-wave contribution in the angular distribution near and above 1.3 GeV has long been known [23]. Of course the important question is whether this P-wave amplitude is resonant, and the analysis is complicated by the interference of the P-wave with the resonant D-wave $a_2(1320)$ amplitude. There are recent experimental studies of this final state by GAMS [24] and E179 at KEK [25] which suggest that the exotic P-wave amplitude is indeed resonant. The VES group has reported results from phase shift analyses of $\pi^-\eta$ and $\pi^-\eta'$, and see evidence for a broad enhancement at 1.6 GeV which appears more strongly in $\pi\eta'$ [26]. They suggest that this may be due to a $q\bar{q}g$ exotic state (perhaps not resonant) because this behavior was predicted by Close and Lipkin [27]. The Crystal Barrel collaboration reports a nonresonant or at least very broad P-wave [19]. Several other experiments have reported results for $\pi\eta$ and related channels such as $\pi\eta'$; see for example the HADRON93 proceedings for summaries of recent work. In view of the disagreements between experiments and complications in the analyses the nature of this P-wave amplitude should probably be considered an open question until the phase motion of the P-wave has been accurately understood.

Heavy-quark hybrids, in particular charmonium hybrids, may be accessible at high-luminosity e^+e^- machines. One may search for the "extra" 1^{--} hybrid states directly through a high-statistics scan of R; the hybrids are expected to appear relatively weakly since they must couple to the photon through their $c\bar{c}$ components, but if the hybrids lie below their preferred S+P open-charm decay threshold at ≈ 4.3 GeV they may appear as relatively narrow peaks. It should be possible to produce charm hybrids with other quantum numbers than 1^{--} through cascade decays, in which an initial high-mass 1^{--} $c\bar{c}$ pair cascades to a charm hybrid plus a light hadronic system such as η or $\pi\pi$. Flux tube arguments suggest that the charm hybrid and light hadronic system should be produced in a relative P-wave, which may assist in the identification of hybrid states with specified quantum numbers. The prospects for detecting heavy-quark hybrids using these techniques have recently been discussed by Barnes and Close [28].

4. Hybrid baryons

One may also form color-singlet quark-and-gluon basis states from $qqqg$, and these are expected to lead to hybrid baryon resonances not predicted by the naive qqq quark model. There are no hybrid baryon exotics since all J^P can be made from qqq quark model states, so one must identify hybrid baryons as additional states with conventional baryon quantum numbers in a well established qqq background.

To date detailed calculations of the masses of hybrid baryons have been reported only in the bag model. In the bag model the color-octet qqq components of the lowest unmixed $|qqqg\rangle$ hybrid baryon basis states span a **70** under SU(6), which has the spin-flavor decomposition (in $^{2j+1}D(SU(3)_f)$ notation) $\mathbf{70} = {}^2\mathbf{10} \oplus {}^4\mathbf{8} \oplus {}^2\mathbf{8} \oplus {}^2\mathbf{1}$. Since a transverse gluon contributes only $^3\mathbf{1}$ states, the final $|qqqg\rangle$ hybrid basis states do not span the complete sets of spin-flavor quantum numbers we associate with irreducible SU(6) multiplets. The spin-flavor SU(2)⊗SU(3) decomposition of the lightest multiplet of $|qqqg\rangle$ basis states for $q = u, d, s$ combined with a spin-1 gluon is

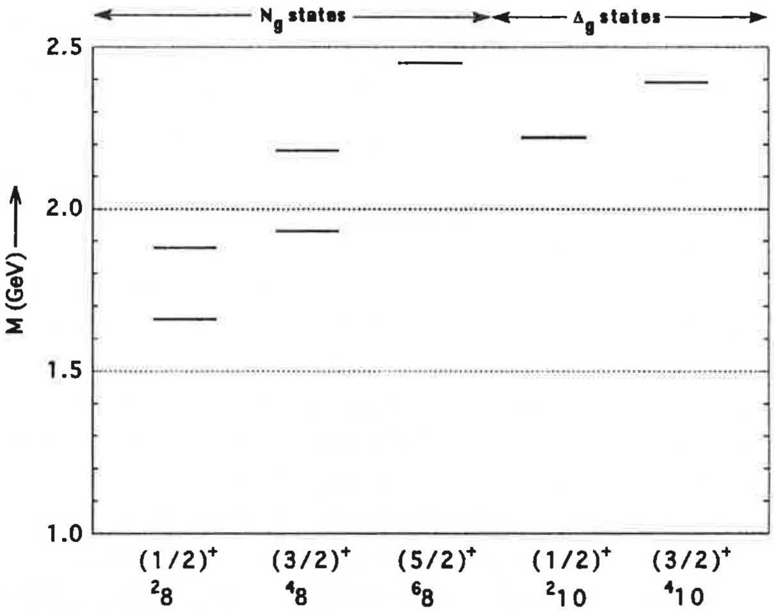

Figure 2: Bag model spectrum of light nonstrange hybrid baryons [29].

$$qqqg = \; {}^4\mathbf{10} \oplus {}^2\mathbf{10} \oplus {}^6\mathbf{8} \oplus ({}^4\mathbf{8})^2 \oplus ({}^2\mathbf{8})^2 \oplus {}^4\mathbf{1} \oplus {}^2\mathbf{1} \; , \tag{2}$$

so we expect this set of light hybrid baryon states in addition to the complete qqq SU(6) multiplets. The lightest gluon mode has $J^P = 1^+$ in the bag model, which therefore predicts that all these lightest hybrid baryons have (+)-parity.

The spectrum of light, physical (mixed with qqq and $qqqgg$) hybrid levels with $q = u, d$ found by Barnes and Close [29] is shown in Fig.2. A very similar pattern of multiplet splittings was found by Golowich, Haqq and Karl [30], albeit with an overall mass scale about 200 MeV lower, due to their choice of more conventional bag model parameters. This work was extended to $q = u, d, s$ by Carlson and Hansson [31].

Since the nonstrange baryon spectrum is reasonably well established to about 2 GeV, one might expect to confirm or refute the bag model description of the hybrid baryon spectrum easily. Remarkably this has not been possible, because there are qqq experimental candidates already known near each of the light hybrid levels predicted. This may imply hidden hybrid levels near the dominantly qqq levels, or perhaps some resonances usually assigned to qqq are actually hybrids. The Roper is often cited as a possible misidentified hybrid [32, 33], because the lightest hybrid baryon in the bag model has Roper quantum numbers, and Golowich, Haqq and Karl [30] predicted a mass for this hybrid of about 1400-1450 MeV, consistent with the Roper mass. Note that the expectation of a hybrid baryon near the Roper mass is closely linked to the bag prediction of a 1^{-+} exotic hybrid meson near $1\frac{1}{2}$ GeV, since these predictions use similar bag model parameters. The flux tube model probably supports a radial-qqq assignment for the Roper because flux tube hybrid baryons are expected to occur at much higher masses [34], although detailed spectrum calculations in this model have not yet been carried out.

Although we cannot distinguish between dominantly qqq and $qqqg$ baryons by their quantum numbers, one might identify a dominantly-$qqqg$ (or excited flux tube) hybrid baryon by anomalous couplings relative to conventional qqq baryons; possibilities include both strong and electromagnetic couplings. There are indications that some familiar predictions for light baryon properties in the qqq quark model are rather insensitive to admixtures of $qqqg$ basis states [35], and this mixing may be large. If these results apply throughout the spectrum and the mixing angles are indeed large, the distinction between ordinary and hybrid baryons will be lost, and the only evidence for hybrids would be an overpopulation of levels relative to the qqq quark model. Fortunately the success of the unmixed qqq quark model in describing the properties of experimental baryon resonances makes this complicated strong-mixing scenario seem unlikely.

First consider hybrid baryon strong decays. The two-body decay modes of hybrid baryons in the flux tube model should satisfy a selection rule similar to that for hybrid mesons. In the baryon case the hybrid flux tube basis state has a spatially-odd wavefunction for reflection of the flux tube through the qqq plane, at least in the heavy-quark limit. When a $q\bar{q}$ pair is formed through flux tube breaking, with qqq and $q\bar{q}$ final states, the initial odd spatial symmetry will lead to a small matrix element unless the final meson or baryon has an internal orbital excitation. Since P-wave $q\bar{q}$ mesons have masses of $M \geq 1.2$ GeV, the preferred hybrid baryon decay modes will probably be a P-wave baryon plus a pion, for example N(1520)π. Since these modes are closed to the N(1440) Roper, it is surprising that the Roper is so broad if it is indeed a hybrid.

One may also use electromagnetic couplings to search for hybrid baryons and to test quark model predictions for conventional qqq assignments. This approach will be especially attractive in the future because photoproduction and electroproduction amplitudes will be measured with greatly improved accuracy at CEBAF. Barnes and Close [36] studied the photoproduction amplitudes of the light hybrid multiplet in Fig.2, and found a very characteristic selection rule; the photoproduction amplitudes of some of the light hybrids, those with $^4\mathbf{8}$ qqq substates in their $qqqg$ component, vanish from proton but not neutron targets. This is a generalization of an excited-qqq selection rule previously found by Moorhouse [37], and applies to the lightest hybrid baryon, which is the candidate Roper state. Since the Roper does not satisfy this selection rule experimentally, the bag model hybrid baryon does not appear to be a good description of the Roper. Alternatively it has been suggested that the Roper may be a different combination of hybrid basis states than these simple bag model calculations find [32]. To distinguish between hybrid and excited-qqq assignments for states such as the Roper it will be useful to have accurate quark model predictions for photoproduction and electroproduction amplitudes, since the qqq quark model wavefunctions are reasonably well established. At moderate Q^2, early results by Close and Li [33] suggested that the radial-qqq assignment disagreed with existing Roper electroproduction data [38], but quark model calculations by Warns, Pfeil and Rollnik [39] and Capstick [40] found that more accurate wavefunctions alter these results, and lead to smaller radial-qqq electroproduction amplitudes. More recently, Capstick and Keister [41] have found that relativistic effects are quite important in radial-qqq electroproduction, so previous nonrelativistic calculations may be inaccurate. Evidently careful theoretical studies of electroproduction amplitudes are required for comparison with the accurate experimental data expected from CEBAF. In the higher-Q^2 regime, where we expect to see increasingly important contributions from perturbative QCD processes, it may also be possible to distinguish between dominantly qqq and $qqqg$ baryons. Carleson and Mukhopadhyay [42] note that the transverse electroproduction form factor should distinguish between these cases, and expect a leading power of $G_+(Q^2) \propto 1/Q^3$ for a qqq state but $G_+(Q^2) \propto 1/Q^5$ for electroproduction of a $qqqg$ state. To test these various predictions it will be important to measure resonance electroproduction functions over a wide range of Q^2.

5. Summary and Conclusions

In this review we have discussed theoretical expectations for the properties of hybrid mesons and baryons. Hybrids are hypothetical resonances in which the dominant basis states incorporate both quark and gluonic excitations. Although mixing between pure quark basis states and excited-glue basis states is anticipated and may be large, the additional gluonic basis states will nonetheless lead to more resonances than the quark model alone anticipates. Complications due to mixing with quark states can be avoided in the meson sector, since one can form J^{PC}-exotic combinations such as 1^{-+} from $q\bar{q}g$ basis states. Experimental searches for hybrids with these or other exotic quantum numbers offer the best prospects for identifying hybrids, since these cannot be confused with conventional $q\bar{q}$ states. We also discussed predictions for the spectrum of hybrid mesons and their expected strong decay modes; the favored pair-production decay mode for light hybrids is one L=0 and one L=1 $q\bar{q}$ meson, and this unusual final state may explain why hybrids have not yet been reported. Heavy-quark hybrid mesons may be observable at e^+e^- machines as small peaks in R if they lie below this S+P threshold, or in hadronic cascade decays from initial $Q\bar{Q}$ states. Finally we discussed light-quark hybrid baryons and the prospects for detecting these experimentally, through studies of the spectrum and decays of nonstrange baryons and their photoproduction and electroproduction amplitudes.

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