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**Exotica For Elsa:
Baryonia, Dibaryons,
Glueballs and Hybrids**

T Barnes

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EXOTICA FOR ELSA:
BARYONIA, DIBARYONS, GLUEBALLS AND HYBRIDS

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I. INTRODUCTION.

This paper is a review of three types of unusual states which have attracted the interest of workers in QCD in recent years, specifically multiquark states (baryonia and dibaryons), glueballs and hybrid mesons and baryons. As we shall see, ELSA should be able to contribute to the clarification of the status of these various states through measurement of their electromagnetic couplings.

I shall begin by showing you my most important transparency, which gives a measure of the popularity of each of these unusual states as a function of time. This "SLAC index" is obtained by summing all dated preprints or publications in the SLAC preprint file which contain given title keywords in a specified year. The obvious biases inherent in this procedure will hopefully not invalidate the general observations I shall make.

First, we see that baryonia, although very popular in the late 1970's have declined in interest to a rather low level. This probably reflects the current belief that fall-apart decays make $q^2\bar{q}^2$ states so broad as to be undetectable, if they exist at all. Although theoretical interest has not ended [1-3], it seldom leads to the use of the word baryonium in preprint titles.

Dibaryons also developed in the late 1970s. These states suffer fall-apart decays as well, and may also elude experimental observation. The steady-state interest in this subject may be due to the repeated observation of resonance in dibaryon channels. The problem for the future here is to distinguish a true q^6 hadron from, for example, an

excited nucleon plus a spectator.

Glueballs have shown a spectacular increase in interest since about 1980. This is a result of both experimental and theoretical developments. In the former, the detection of the iota and theta mesons presented us with two candidate glueballs. Theoretical calculations of the spectrum of glueballs in various models have recently been carried out using the MIT bag model, lattice QCD, QCD sum rules and a flux tube model. Approximate agreement between these models has stimulated experimental interest in other glueball and glue-rich channels.

Figure 1. Relative popularity of baryonia, dibaryons, glueballs and hybrids: the SLAC index.

Hybrids, product states of quarks and gluons, are a rather recent invention and have not attracted the same attention as glueballs. They may prove experimentally more accessible than most glueballs, with their somewhat lower masses and characteristic exotic quantum numbers. With this in mind, one of the principal objectives of this talk will be to motivate ELSA experimentalists to consider a search for these hybrid states.

II. MULTIQUARK STATES; BARYONIA AND DIBARYONS.

In this section I will briefly review the theoretical and experimental status of $q^2\bar{q}^2$ (baryonia) and q^6 (dibaryon) states. I will be especially brief about dibaryons, which are reviewed in these proceedings by Seth [4].

IIa). A QUICK INTRODUCTION TO THE MIT BAG MODEL.

As many of the predictions for both quark and gluon states we shall discuss arise from the MIT bag model, it is appropriate to briefly review this model here, as well as to sound a cautionary note regarding the many systematic uncertainties encountered in bag model calculations.

In today's bag model practice, one begins by assuming that a hadron is a spherical region of radius a , which contains to zeroth-order in α_s a specified number of non-interacting quarks, antiquarks and gluons in given modes (figure 2).

Figure 2. A hadron in the MIT bag model.

The energies of the various quark and gluon eigenmodes are fixed by linear boundary conditions on ψ and A , which require that no colored flux leaves the bag. The two lowest and most often encountered modes are the $1S_{\frac{1}{2}}$ quark and the $1^+ TE$ gluon.

$$\psi_{\uparrow}(1S_{\frac{1}{2}}) = \alpha_{\uparrow} \begin{bmatrix} j_0(kr) \begin{bmatrix} 1 \\ 0 \end{bmatrix} \\ 1 \otimes j_1(kr) \begin{bmatrix} \cos \theta \\ \sin \theta e^{i\phi} \end{bmatrix} \end{bmatrix} \Theta(a-r) \quad (2.1)$$

$$\omega_q = 2.042791 \dots a^{-1} \text{ for } m_q=0 \quad (2.2)$$

$$\vec{A}(TE) = \alpha_g j_1(k_g r) \vec{Y}_{1lm} \quad (2.3)$$

$$k_g = 2.744 \dots a^{-1} \quad (2.4)$$

The radius of the bag was traditionally determined by solving a pressure balance equation, which balanced the internal zitterbewegung pressure of the constituents against an external bag pressure or energy density B_0 . This leads to a slightly different radius for every hadron, making calculation of overlap integrals a complicated task in which the workmanship is clearly surpassing the material. More frequently one now chooses a fixed radius a , of approximately one fermi, for all the basis states used in a given problem. Whereas the 1975 MIT bag model [5] included a bag volume term in the mass of a hadron, this term is now sometimes included and sometimes not. The choice reflects the feeling of many theorists that the bag is not a physical object, but is instead merely a way of generating conveniently truncated quark and gluon wavefunctions.

Spin-spin splittings in the bag model such as $[\rho\pi]$ and $[\Delta P]$ are usually attributed to one gluon exchange, so they are proportional to the strong coupling constant α_s . In the 1975 bag model this was taken to be $\alpha_s=2.2$, which gives a good fit to light meson and baryon masses if the unperturbed bag model wavefunctions are used. There is now considerable evidence that this gives an overestimate of α_s [6], which may be as small as ~ 0.7 at the mass scale of light hadrons. The uncertainty in the size of spin-spin splittings of unusual states such as dibaryons or hybrids in the bag model may thus be quite large, as much as a factor of three.

Another uncertainty in the bag model is the mean mass of a given multiplet. The source of this uncertainty is the presence of many spin-independent contributions to the energy, for example the Casimir energy, quark and gluon self-energies and center-of-mass effects. As

there is no general consensus regarding the correct treatment of these terms and their numerical values, an overall uncertainty of $\sim \pm 200$ Mev can easily arise in bag model calculations. Apparent close agreement, say to < 50 Mev, of two bag model mass calculations may only indicate that the same procedure was followed by both groups, and certainly does not imply an accuracy of the same order.

As a final warning regarding the bag model and its reliability in predicting marginally stable states such as the $S=2$ "H" dibaryon [7,8], we note that the zeroth-order bag model [9] with constant bag pressure B_0 predicts the mass of a $3n$ multiquark hadron to be

$$E_{3nq} = n^{\frac{3}{2}} E_{3q} \quad (2.5)$$

If true, this result would mean that deuterons would collapse into multiquark hadrons, with a binding energy of ~ 150 Mev/nucleon. Improved bag model results, which are perturbations on this zeroth-order bag model, should evidently be interpreted with a degree of caution.

IIb). BARYONIA ($q^2\bar{q}^2$).

The possible existence and detection of these four-quark mesons was first discussed in detail by Jaffe [10] in 1977, in the context of the MIT bag model. One assembles a $q^2\bar{q}^2$ configuration in the lowest mode in the bag,

$$|q^2\bar{q}^2\rangle = |(1S_{\frac{1}{2}})^2 (\bar{1}S_{\frac{1}{2}})^2\rangle \quad (2.6)$$

and calculates the spectrum using the original 1975 bag model parameters [7,8]. These modes with u, d and s quarks populate a literal forest of 0^+ , 1^+ and 2^+ levels, some of which are shown in figure 3. These include flavor-exotic levels such as $I=3/2$ and 2. Why have such states not been seen?

The answer was given by Jaffe in his original paper: "The great width of most $q^2\bar{q}^2$ mesons will account for their experimental elusiveness" [10]. The problem is that all these states are predicted to lie above two meson thresholds, so they suffer extremely fast "fall-apart" decays.

Figure 3. All 0^+ and the lightest 1^+ and 2^+ $1S_{\frac{1}{2}}$ $1\bar{S}_{\frac{1}{2}}$ $q^2\bar{q}^2$ states.

Figure 4. Fall-apart decay of a $q^2\bar{q}^2$ state.

Only a very few $q^2\bar{q}^2$ states, which we shall discuss, were expected to be stable enough to detect experimentally.

Despite Jaffe's large-width warning, a belief has arisen among some theorists, perhaps without sufficient motivation, that four-quark states could be very narrow! This has led to searches for narrow peaks in $P\bar{P}$ annihilation in particular, which might easily

couple to baryonia.

Figure 5 Production of baryonium in $P\bar{P}$ annihilation.

We are all familiar with the ensuing archtypal baryonium cycle;

- (1) discovery of a 3σ bump in $\sigma_{\text{tot}}(P\bar{P})$ or elsewhere,
- (2) theoretical claims regarding the assignment of the recently discovered baryonium state, and
- (3) retraction of the discovery on the accumulation of better statistics.

The decline of interest in baryonia evidenced in figure 1 is presumably due to increasing acceptance of their very large widths, as well as to the demoralizing effect of repeated discoveries and retractions of 3σ narrow bumps.

The three remaining, relatively broad "classic" candidate four-quark states are summarized below.

State	$I^G J^{PC}$	Width	Decays
$\epsilon(\sim 1300)$	$0^+ 0^{++}$	200-600 Mev	$\pi\pi/K\bar{K} \sim 10$
$S(975)$	$0^+ 0^{++}$	$33 \pm 6 \text{ Mev}$	$\pi\pi/K\bar{K} \sim 3$
$\delta(980)$	$1^- 0^{+(+)}$	$54 \pm 7 \text{ Mev}$	$\eta\pi, K\bar{K}$ seen

Table 1. Classic $q^2\bar{q}^2$ candidates.

The very broad width of the ϵ makes it a reasonable $q^2\bar{q}^2$ candidate, although the conventional $^3P_0 q\bar{q}$ mesons are also expected to be very broad states [11]. As the scalar glueball, with ϵ quantum numbers, is also expected at about the 1984 Particle Data Group ϵ mass [12], this "state" may well be due to the effect of independent $q\bar{q}$, $q^2\bar{q}^2$ and gg states.

The S and δ mesons are not ideal $q^2\bar{q}^2$ meson candidates because of

their moderate widths of ~ 50 Mev. These widths are surprisingly narrow if the fall-apart decays $\delta \rightarrow \eta\pi$ and $S \rightarrow \pi\pi$ are allowed. One way out is the hidden- $s\bar{s}$ solution of Jaffe [10], which assigns the S and δ to $\frac{1}{\sqrt{2}}(u\bar{u}+d\bar{d})s\bar{s}$ states. Because of the difficulty of eliminating their $s\bar{s}$ quarks, these states might be relatively stable. Note that the bag model couplings of those states found by Jaffe contain phenomenologically important numerical errors [1-3]. An alternate possibility is the Isgur-Weinstein [13] suggestion that the S and δ might be $K\bar{K}$ nuclei; this nicely accounts for their masses as $2m_K$ minus nuclear binding energy.

Ideally we could distinguish these different assignments by calculating strong decay widths. Unfortunately, the strong decay width of an unusual state such as gg or $q^2\bar{q}^2$ is not reliably calculable by theorists at present, even as an order of magnitude estimate. What can be calculated reliably ($\pm 30\%$) are electromagnetic couplings of $q\bar{q}$ states in the quark model, and we shall suggest these as a test of $q\bar{q}/gg/q\bar{q}g/q^2\bar{q}^2/\dots$ assignments in our final section. It is here that ELSA can hopefully make an important contribution to our understanding of meson spectroscopy.

IIc). DIBARYONS (q^6).

Here I shall be very brief, referring the reader instead to the comprehensive review given by Seth in these proceedings.

Interest in dibaryons, like baryonia, was greatly stimulated by a bag model calculation of dibaryon masses by Jaffe in 1977 [7]. Jaffe noted that the 1975 MIT bag model parameters predicted a strongly stable $J^P=0^+ S=2$ dihyperon at 2150 Mev, about 80 Mev below the $\Lambda\Lambda$ threshold! This result was confirmed, using the same bag model parameters, by the careful work of Aerts, Mulders and de Swart [8].

Why is it so important to predict a dibaryon below its lowest two-baryon threshold? Just as in the baryonium case, barring exceptional circumstances a dibaryon will have fall-apart decays.

Figure 6. Fall-apart decay of a dibaryon.

Jaffe gave a list of predicted q^6 dibaryon levels in the bag model, but he included a very interesting cautionary comment: "Most of the "states" listed in the table probably do not correspond to particles or resonances."

The reason a q^6 state above a BB' threshold may not even appear as a resonance is that it may be continuously deformable through configurations of decreasing classical energy to a separated pair of $B+B'$ baryons. Like a mass at the top of a potential $V(x)$, such a "state" would have no quantum mechanical analogue.

Figure 7. A world without dibaryons.

In such a scenario, the possibility of fall-apart of a dibaryon or baryonium means that these multiquark hadrons do not even exist as resonances. They instead simply give rise to short-range repulsive forces in BB' scattering, as it is energetically unfavorable for the B and B' to be superimposed.

Despite these theoretical concerns, dibaryon channels experimentally persevere in displaying resonance, for example in $NN \rightarrow NN$ and $\pi d \rightarrow NN$. There are two obvious explanations for resonance in these channels; either a q^6 dibaryon actually is being produced (figure 8a) or a single nucleon is being excited, say to a delta (figure 8b).

Figure 8a.

Figure 8b.

As the three two-star dibaryon resonances quoted by the 1984 Particle Data Group [12] have masses and widths consistent with $\Delta+N_{\text{spec}}$ and $\Sigma+N_{\text{spec}}$, I would suppose that only figure 8b has been seen in these "dibaryon resonances". A measurement of $NN \rightarrow NN\pi$ which can separate $\Delta+N_{\text{spec}}$ from q^6 is planned at Los Alamos in 1985 by D. Bugg and collaborators [14]; this should be of great interest to anyone with a definite preference for 8a or 8b.

III. GLUEBALLS.

One of the most striking predictions of QCD is the existence of glueballs, which are bound states of two or more gluons in an overall color singlet state. Although physical glueballs are expected to be strongly mixed linear combinations of gg , $q\bar{q}g$, $q\bar{q}$ and so forth, we nonetheless expect the glueball basis states to produce extra states in the $I=0$ meson spectrum beyond those expected in the $q\bar{q}$ quark model.

Unfortunately for the experimentalist, quantum numbers of the lighter "gg" glueballs are matched by nonexotic $q\bar{q}$ quantum numbers.

$$J^{PC}(gg) = 0^{++}, 2^{++}, 3^{++}, 4^{++}, 5^{++}, \dots \quad I=0 \quad (3.1)$$

These states may be hard to tell from the $q\bar{q}$ states, especially if mixing is important. The >3 gluon sector includes exotic (non- $q\bar{q}$) quantum numbers such as $I=0$, $J^{PC}=1^{-+}$, but bag model estimates [15] place such three gluon states very high in mass, $> 2\frac{1}{2}$ GeV.

There were some theoretical claims that glueballs might have very narrow widths, < 1 MeV [16]. As no such states have been observed and width calculations tend to be on very shaky ground theoretically, it is probably more realistic to note that glueballs do not suffer the fall-apart decays which appear to give multiquark hadrons extremely large strong decay widths. At present there is no theoretical consensus regarding expected glueball widths.

Why have glueballs become so interesting of late, as demonstrated by the SLAC index of figure 1? The interest is probably due to concurrent favorable developments both theoretical (1) and experimental (2):

- (1) Approximate agreement has emerged between spectrum predictions for light gg glueballs in the bag model, lattice calculations and QCD sum rules, and
- (2) the ψ radiative decay experiments have produced two "classic" glueball candidates, the $\iota(1440)$ and $\theta(1690)$ mesons.

ψ radiative decays may be a good source of glueball resonances because they proceed partially through a two gluon intermediate state;

Figure 9. Two-gluon intermediate states in $\psi \rightarrow X\gamma$.

A theoretical analysis of the $\psi \rightarrow \gamma gg$ Feynman diagram [17] leads one to expect the production of $J^P=2^{++}$ tensor mesons as well as 0^{++} and 0^{-+} scalars and pseudoscalars. One generally scans specific final states X in $\psi \rightarrow X\gamma$ for prominent resonances in $M(X)$ which do not correspond to known $q\bar{q}$ states. States thus far identified have all been $J^{PC}=2^{++}$ or 0^{-+} ; their measured branching fractions in $\psi \rightarrow X\gamma$ are shown in figure 10.

Figure 10. Identified resonances in psi radiative decays.

The two surprises are the large signals from the iota and theta, which had not been clearly identified before. In summary, their properties are

<u>J^{PC}</u>	<u>Mass(Mev)</u>	<u>Width (Mev)</u>	<u>Final States and Comments</u>
$i(0^{-+})$	1440 ± 10	76 ± 10	$K\bar{K}\pi$ May be $(q\bar{q})_R$, $\eta\pi\pi(?)$ $q\bar{q}g$ or gg . $\gamma\rho(?)$
$\theta(2^{++})$	1690 ± 30	180 ± 50	$\eta\eta$ $K\bar{K}$ $\pi\pi \ll \eta\eta, K\bar{K}$, so is not $f_R(q\bar{q})$.

Table 2: The iota and theta.

The bag model [18-20] can account for the masses of the iota and theta if they are "gg" glueballs, although a revised value of $\alpha_s \sim 1$ is required. One may alternatively keep $\alpha_s \sim 2$ and add various self-energy effects in order to accommodate $i, \theta = gg$. Even more encouraging was the agreement of lattice QCD calculations with the bag model glueball mass estimates; in 1983 a consistent picture appeared, with three bag model calculations and two lattice ones in approximate agreement on the gg spectrum;

J^{PC} (gg)	Mass (lattices, 1983)	Mass (bag models, 1983)	Mass (lattices, 1984)
0^{++}	$\sim 800 \text{ Mev} \pm 200 \text{ Mev}$	$\sim 800 \text{ Mev}$	$\sim 1200 \text{ Mev}$
0^{-+}	$\sim 1400 \text{ Mev}$ (one lattice result $\sim 1900 \text{ Mev}$)	$\sim 1400 \text{ Mev}$	$\sim 1.5 \times (\text{lattices},$ 1983)
2^{++}	$\sim 1700 \text{ Mev}$	$\sim 1600 \text{ Mev}$	same as above
2^{-+}	$\sim 2100 \text{ Mev}$	$\sim 2200 \text{ Mev}$	

Table 3. Glueball mass estimates.

Alas, this consensus has been shattered by more accurate measurements of the lattice string tension, using $K=0.9 \text{ GeV/fm}$ (taken from charmonium potential models or Regge theory) as input. Early theoretical measurements of this quantity in lattice units [21] have recently increased by a factor of about 1.5-2 [22], carrying the overall glueball mass scale with them. The lightest (scalar) glueball mass is currently estimated to be $\sim 1300 \text{ Mev}$ by Parisi et al [23] and $\sim 1200 \text{ Mev}$ by Berg and Billoire [24]. If these lattice results are correct, we expect the 0^{-+} glueball at $\sim 2300\text{-}3000 \text{ Mev}$ and the 2^{++} at 2800 Mev . Such heavy states are obviously not the $i(1440)$ and $\theta(1690)$.

Schierholz [25] suggests that the familiar value of the string tension $K=(420 \text{ MeV})^2=0.9 \text{ GeV/fm}$ may be overestimated by a factor of ~ 3 , so that the glueball masses may return in 1985 to their low 1983 values. It is doubtful that charmonium potential models can accommodate as small a value of K as this idea requires, but this can be tested. One might consider using another physical number such as m_ρ to calibrate the lattice mass scale. This procedure will probably resolve the glueball mass scale problem; unfortunately, at present the two most popular formulations of lattice fermions (Wilson and Susskind) give results for m_ρ which differ by a factor of two as well [26].

Finally, we note that a rather more complete review of theoretical predictions for glueballs has recently been compiled by Sharpe [27], and a review of experimental glueball candidates in ψ radiative decays and other channels has been given by Chung [28]. A summary of Chung's list in the ELSA region, with some additions, is given below.

<u>State</u>	<u>J^{PC}</u>	<u>Mass(Mev)</u>	<u>Width(Mev)</u>	<u>Final States</u>
$\epsilon(1300)$	0^{++}	~ 1300	$200-600$	$\pi\pi$ $K\bar{K}$ $\eta\eta?$
$g_s(1240)$	0^{++}	1240 ± 10	140 ± 10	$K_s K_s$
$G(1590)$	0^{++}	1592 ± 25	210 ± 40	$\eta\eta$
$\eta(1275)$	0^{-+}	~ 1275	~ 70	$\eta\pi\pi$
$f(1440)$	0^{-+}	1440 ± 10	76 ± 10	$K \bar{K} \pi$ $\eta\pi\pi?$ $\gamma\rho?$
$f_T(1440)$	2^{++}	~ 1440	~ 100	$K^+ K^-$
$\theta(1690)$	2^{++}	1690 ± 30	180 ± 50	$\eta\eta$ $K\bar{K}$ $\pi\pi?$

Table 4. Glueball candidates below 1.7 Gev.

IV. HYBRIDS.

As we have seen, glueballs may be difficult objects to find experimentally. The only glueball likely to be below 2 Gev is the 0^{++} gg scalar at ~ 1200 Mev, according to the majority of recent lattice estimates. The quantum numbers $I^G J^{PC} = 0^+ 0^{++}$ are experimentally very unattractive, due to low multiplicity, large backgrounds and the possibility of confusion with the $q\bar{q} 0^{++}$ and perhaps even four-quark states if the latter exist.

Fortunately, we also may look for glue in product states of quarks and gluons. These hybrid [29,30] states, also called hermaphrodites [31] or meiktons [32], have primarily been studied in the light quark sector using the MIT bag model [31-35] and QCD sum rules [36,37]. It is these light-quark hybrids which are of relevance to ELSA. The combinations of greatest interest are the lightest hybrid mesons ($q\bar{q}g + \dots$) and hybrid baryons ($qqqg + \dots$).

IVa). HYBRID MESONS($q\bar{q}g$).

First consider the $q\bar{q}g$ mesons in the MIT bag model. The lowest multiplet is made from a color octet $q\bar{q}$ pair and the lightest (TE) gluon model.

	$q\bar{q}(q=u,d,s)$	$\odot$	8	$=$	$q\bar{q}g$
color	8	$\odot$	8	$\subset$	1
J^{PC}	$0^{-+}, 1^{--}$	$\odot$	$1^{+-} (TE)$	$=$	$\left\{ \begin{array}{l} 2^{-+} \\ 1^{-+} \\ 0^{-+} \end{array} \quad 1^{--} \right\}$
					$S_{q\bar{q}}^{-+}=1 \quad S_{q\bar{q}}^{--}=0$
I	$0, \frac{1}{2}, 1$	$\odot$	0	$=$	$0, \frac{1}{2}, 1$

Note the presence of the characteristic J^{PC} exotic state (non- $q\bar{q}$ quantum numbers) in this $q\bar{q}g$ ground state multiplet. This is an obvious target for experimentalists who wish to search for unambiguous evidence of gluonic states in the spectrum.

What spectrum of $q\bar{q}g$ states do we expect? Three groups [33-35] have completed calculations of the spectrum of states in the bag model once gluon exchange effects are included, and their results are in good agreement numerically. The spectrum found in reference [34] is reproduced below.

Figure 11. Hybrid meson spectrum in the MIT bag model.

A characteristic feature of the $J^{PC}=0^{-+}$ and 2^{-+} non-exotic states as well as the exotic 1^{-+} is the non-degenerate $I=0$ and 1 states; $m(\omega_g)=m(\rho_g) + \sim 100$ Mev. This effect reflects the ease of internal annihilation of the $q\bar{q}$ pair, which are already in a color octet. This feature may allow one to distinguish hybrids with non-exotic quantum numbers from conventional $q\bar{q}$ mesons.

Three of the hybrid levels predicted by the bag model in figure 11 may have already been seen experimentally. The evidence for these is as follows.

- (1) The $I=0, 0^{-+}$ $q\bar{q}g$ state may be the $\iota(1440)$ [38,39]. We shall discuss implications of this at the end of the paper.
- (2) A front-back asymmetry in the $\eta\pi$ system which first appears at ~ 1.4 Gev has been seen in $\pi^- p \rightarrow \pi^0 \eta N$ by Apel et al [40]. This is probably due to the exotic channel ($I=1, J^{PC}=1^{-+}$) interfering with the $A_2(1320)$ meson, and may indicate the presence of the exotic $1^{-+} \rho_g$ hybrid meson expected at this mass. Alternative explanations are favored, as the 1^{-+} signal does not show resonant phase behavior [40].
- (3) The $f\pi$ channel in $\pi^- p \rightarrow \pi^- \pi^+ \pi^- p$ as analysed by the ACCMOR group [41] shows an apparent resonance bump in the non-exotic $J^{PC}=2^{-+}$ channel at $M(f\pi)=1850$ Mev, too light to be a radial excitation of the $2^{-+} q\bar{q}$ state $A_3(1670)$, but consistent with bag model estimates of the $2^{-+} q\bar{q}g$ hybrid mass. This signal alternatively may be interpreted as an interference between the A_3 and an $A'_3(\sim 2100)$ [41].

An experimental search for hybrid states should probably concentrate on the $J^{PC}=1^{-+}$ exotic channel. Particularly interesting final states include $\pi\eta$, $\pi\eta'$, $\pi\rho$, πB and πD for the $I=1 \rho_g$ hybrid and $\pi\pi^*$, $\eta\eta'$ and πA_1 , for the $I=0 \omega_g$ hybrid [33,34,42]. The $\eta\pi$ combination in particular is being studied in $P\bar{P} \rightarrow \eta\pi\pi$ by the ASTERIX group at LEAR, since possible evidence for an exotic signal in $\eta\pi$ already exists [40]. A problem with $\eta\pi$ is a generalized G-parity $SU(3)$ selection rule [43,44] which should suppress $h(1^{-+}) \rightarrow \eta\pi$; the $\rho\pi$ channel does not violate this selection rule and may show any 1^{-+} exotic more clearly. The preference for the decay mode $\rho_g \rightarrow \rho\pi$ over $\rho_g \rightarrow \eta\pi$ was also found in a QCD sum rule calculation of hybrid decays [37].

If the bag model was the only source of theoretical expectations of an exotic $1^{-+} q\bar{q}g$ hybrid meson at ~ 1.5 Gev, we might well be concerned about the model-dependence of this state. Fortunately, there are calculations of the mass of this and other exotic $q\bar{q}g$ states

using QCD sum rules, modified Wilson loops and a flux tube model. The QCD sum rules find the 1^{-+} to be the lightest $q\bar{q}g$ exotic, with an estimated mass of $m \sim 1.3$ GeV [36]. The Wilson loop technique, although strictly applicable only to heavy quarks, gives an estimated light-quark hybrid mass of $\sim 1 \text{ GeV} + m(q\bar{q})$ when extrapolated to small quark mass [45]. The flux tube model finds a somewhat larger mean hybrid mass of ~ 1.9 GeV [42]. Thus, four independent theoretical models agree that the light ($q=u,d$) exotic $J^{PC}=1^{-+}$ $q\bar{q}g$ hybrid mesons should exist at $m(q\bar{q}g) \sim 1\frac{1}{2}-2$ GeV.

At present, given theoretical uncertainties in the strong couplings of gluonic states, there are few suggestions regarding preferred hadronic final states for glueball or hybrid decays. One possibility is that strange final states will be preferred in gluon decays [46]. An interesting result arises in the flux tube model of Isgur, Kokoski and Paton [42], which finds that hybrid mesons largely decouple from S-wave meson final states, instead going into unusual modes such as πB and πD .

IVb). HYBRID BARYONS ($qqqg$).

Just as one can form ($q\bar{q}g+\dots$) hybrid mesons which do not occur in the quark model, so one can also form ($qqqg+\dots$) hybrid baryons. As the light nonstrange baryon spectrum is rather well established, we might expect that a prediction of "extra" nonstrange baryons with anomalous properties should be easy to test experimentally. This is of special relevance to ELSA, which is particularly suited to the study of nonstrange baryon spectroscopy below $2\frac{1}{2}$ GeV. The spectrum of nonstrange hybrid baryons in the MIT bag model has been calculated by two independent groups [47,48]. The zeroth-order q^3g basis states are constructed from the lowest quark and gluon modes, which gives the following states;

$$qqq(q=u,d) \otimes g = q^3g$$

$$\text{color} \quad 8 \quad \otimes \quad 8 \quad \subset \quad 1$$

$$J^P = \frac{1}{2}^+(N), \frac{3}{2}^+(\Delta) \otimes 1^+ = P_R \left(\frac{1}{2}^+ \right)_2; \left(\frac{3}{2}^+ \right)_2; \left(\frac{5}{2}^+ \right) \\ P_{11}; P_{13} \quad F_{15} \\ \Delta_g \left(\frac{1}{2}^+ \right); \left(\frac{3}{2}^+ \right) \\ P_{31}; P_{33}$$

This lowest multiplet is part of a 70 of $SU(6)$. The spectrum of states after inclusion of gluon exchange effects as found by reference [47] is shown in figure 12; the experimental nonstrange baryon spectrum and their particle data group star rating are shown for comparison. Given the uncertainties of bag model mass predictions (~ 200 Mev?), it is clear that predicted q^3g states are not in conflict with experiment. Instead, the possibility arises that some established baryon resonances which are normally assumed to be $(q^3)^*$ may actually consist of $(q^3)^*$ and q^3g resonances which are nearly degenerate.

In particular this may apply to the Roper $P_{11}(1440)$ resonance, the $P_{11}(1710)$ and the $P_{13}(1720)$. How can we hope to distinguish a mostly- $(q^3)^*$ baryon resonance from a mostly- q^3g one?

One possibility is through their photoproduction amplitudes, as these are very sensitive to the quark spin orientation in the produced resonance. These vary markedly between $(q^3)^*$ and q^3g assignments for a given state. For example, the lightest "Roper" $P_{11} q^3g$ hybrid dominantly has quark spin $S_{qqq} = \frac{3}{2}$.

The current experimental numbers for photoproduction of ten nonstrange baryons off protons are displayed in figure 13, together with the predictions of the very successful Koniuk-Isgur quark model [49]. A misidentified hybrid baryon level would be expected to show disagreement between experimental and the theoretical amplitudes for a $(q^3)^*$ state. Serious disagreement is evident for the four levels $S_{11}(1535)$, $P_{11}(1440)$, $P_{11}(1710)$ and $P_{13}(1720)$. The latter three levels are predicted to have nearby hybrid baryons, which may explain their anomalous photoproduction amplitudes. Alternatively, it may be that the Koniuk-Isgur model requires some refinement, or that the experimental amplitudes are incorrect. An interesting task for ELSA would be a measurement of $P_{13}(1720)$ photoproduction, to see if this apparent failure of the Koniuk-Isgur model survives improved statistics.

Parenthetically, we note that a calculation of photoproduction of these hybrid baryons in the MIT bag model [50] reveals a characteristic pattern of amplitudes which is not consistent with the observed P_{11} and P_{13} results. Evidently, more theoretical work will be called for if these deviations from the Koniuk-Isgur model are confirmed.

Figure 12. Experimental nonstrange baryon spectrum with predicted hybrid states.

V. HOW TO DISTINGUISH $q\bar{q}/gg/q\bar{q}g/q^2\bar{q}^2$.

As we have seen, various models predict a large number of mesons in the 1-2 GeV region. In addition to the $q\bar{q}$ quark model states we also expect the scalar gg glueball (and perhaps the 0^{-+} and 2^{++}) and a number of $q\bar{q}g$ hybrid mesons. There may also be $q^2\bar{q}^2$ baryonia, if they are not too unstable to detect. How can we distinguish between these different possible assignments for a given experimental resonance? Three approaches have been suggested, of which two appear viable at present. These three approaches are as follows:

- 1) All $q\bar{q}$ properties in the 1-2 GeV region are of interest.

The measurement of properties of the ordinary $q\bar{q}$ mesons, in particular the first radial nonet, is vitally important if we are to identify non- $q\bar{q}$ states. These $q\bar{q}$ mesons are very poorly known at

Figure 13. Baryon photoproduction amplitudes.

present, and they are the background which must be identified and removed before any non- $q\bar{q}$ states can be plausibly claimed.

States of particular interest as possible $q\bar{q}$ -radials are the $\eta(1275)$, $\pi(1300)$, $\iota(1440)$, $\rho(1250)$ and $\rho(1600)$. All except the ι and $\rho(1600)$ are so poorly known that even an observation of their existence in any channel would be very interesting.

The importance of establishing the $q\bar{q}$ spectrum is best illustrated by the $\theta(1690)$ 2^{++} meson, which has been singled out as non- $q\bar{q}$ only because the f and f' 2^{++} $q\bar{q}$ states are so well understood.

2) Flavor blindness of gluonic couplings.

An early and obvious suggestion of a characteristic experimental glueball signature is that the equality of gluon couplings to all quark flavors should lead to decays to all possible flavor final states, e.g. $G \rightarrow \pi\pi \sim G \rightarrow K\bar{K}$. This idea is now not widely accepted for several reasons. The actual strength of the $q\bar{q}g$ coupling shows important quark mass dependence in the bag model, through wave function effects. This may lead to a preference for strange final states in gluon decays [27]. In any case, the difference in phase space for decays to strange versus nonstrange final states as well as kinematic dependence of amplitudes may lead to branching fractions which would not appear to indicate flavor-independent underlying couplings. A detailed understanding of phase space and recoil effects and matrix elements would be needed to establish the flavor-independence of the decay coupling constants, and this will probably require a much better understanding of glueball wavefunctions than we have at present.

3) Electromagnetic couplings.

The electromagnetic couplings of glueballs, hybrids and $q\bar{q}$ -radial mesons show characteristic features which may allow one to distinguish them. As an example, the theoretical folklore as of 1984 gives the following ranking to the decay $\iota(1440) \rightarrow \rho\gamma$, assuming successively that $\iota(1440) = (q\bar{q})_R$, gg or $q\bar{q}g$;

Figure 14. Expected relative rates of M1 radiative transitions.

Specific numbers calculated in various models for $\iota \rightarrow p\gamma$ are as follows.

<u>$\iota(1440)$ assignment</u>	<u>$\Gamma(\iota \rightarrow p\gamma)$</u>	<u>reference and comments</u>
$(q\bar{q})_R$	0.4 Mev	Godfrey-Isgur [11] relativistic potential model; assumes $\Xi_\eta(1275)$. (may be sensitively dependent on parameters).
gg	<0.2 Mev	Donoghue [51], bag model.
	0.4 Mev	Carlson and Hansson [52], MIT bag model. Corrected from erroneous 16 Kev due to phase space, as authors suggest [53].
	0.4 α_s^2 Mev	Donoghue [51], MIT bag model, assuming Ξ hybrids. We suggest $\alpha_s \sim 1$. <u>Note $\iota=gg$ gives $(\gamma\phi)(1440)$ mode.</u>
$q\bar{q}g$	1.5 α_s Mev	Barnes and Close [54], MIT bag model. Again $\alpha_s \sim 1$.

Table 5. $\iota \rightarrow p\gamma$ for various models of the iota.

Why should the charged-constituent $(q\bar{q})_R$ assignment lead to a smaller rate than $q\bar{q}g$, comparable instead to the neutral gg decay rate? This surprising result is due to the node in the $2S(q\bar{q})$ wavefunction, which leads to a small overlap integral $\langle 2S | \vec{\mu} | 1S \rangle$. In contrast, the $q\bar{q}g$ state need only absorb a gluon to produce a $1S q\bar{q}$ state with a non-suppressed coupling to $q\bar{q}\gamma$.

Channels with particularly favorable Clebsch-Gordon coefficients such as $\Delta I=1$ and $0^{-+}(q\bar{q}g) \rightarrow 1^{--}(q\bar{q})\gamma$ can have very large M1 decay rates. This explains the surprisingly large $q\bar{q}g$ rate quoted above. Experimentally we are very close to distinguishing between these numbers. The recent Mark III measurement of $\phi \rightarrow \gamma\gamma p$ [55] shows an enhancement in the (γp) mass distribution with a mass and width consistent with the $\iota(1440)$. If this (γp) signal indeed comes from the iota, it implies a partial decay rate of

$$\Gamma(\iota \rightarrow p\gamma) = 1.4 \pm 0.6 \text{ Mev} \cdot \text{BR}(\iota \rightarrow K\bar{K}\pi) \quad (5.1)$$

At present it appears that $BR(1 \rightarrow K\bar{K}\pi)$ is near unity. If future measurements with better statistics lower the error in (5.1) by a factor of perhaps three and the theoretical expectations do not significantly change, we shall be in a position to distinguish between various assignments for the ι .

The message for ELSA is that other interesting states such as the $\Theta(1690)$ may have anomalous electromagnetic couplings relative to $q\bar{q}$ states, and measurement of these decay rates will provide theorists with valuable clues regarding the internal structure of these states. A nice example is the very small $\delta \rightarrow \gamma\gamma$ rate noted by Diekmann in these proceedings [56], which is a factor of ~ 50 below expectations for a $\delta = q\bar{q}$ assignment [57], whereas the four-quark or $K\bar{K}$ -molecule pictures may still be allowed. Just as this makes $\delta = q\bar{q}$ appear extremely untenable, so other electromagnetic couplings will hopefully shed light on the other unusual states in the hadronic spectrum.

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