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Are Glueballs and Hybrids Found?

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ARE GLUEBALLS AND HYBRIDS FOUND?

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The lightest scalar glueball and ground state hybrids may have been found. I compare signals reported at this conference with theoretical expectations and highlight the questions that need to be addressed in forthcoming experiments.

There has been a sudden and dramatic change of emphasis in the search for glueballs and hybrids. In the past a case has been made on behalf of some signal or other, believed in strongly by a handful of theorists or experimentalists and an uphill battle has been fought (and usually lost) to convince other than the true believers that the holy grail has been found. At this conference there is a general belief that glueballs, in particular $f_0(1500)$ [1] and possibly $\xi(2230)$ [2] have at last been sighted, and that hybrid states, notably the $\pi(1800)$ [3] and exotic $1^{-+}(1900)$ [4] also have been found. I shall attempt to weigh the pros and cons.

A Scalar Glueball?

In advance of these data, theoretical arguments suggested that gluonic activity be manifested in the 1.5 GeV region. Lattice QCD predicted the lightest "primitive" (i.e. quenched approximation) glueball to be 0^{++} with mass 1.55 $\pm$ 0.05 GeV [5]. Recent lattice computations place the mass slightly higher at 1.74 $\pm$ 0.07 GeV [6] with an optimised value for phenomenology proposed by Teper [7] of 1.57 $\pm$ 0.09 GeV. That lattice QCD computations are now concerned with such fine details represents considerable progress. Whatever the final concensus may be, these results suggest that scalar mesons in the 1.5 GeV region merit special attention. If indeed a scalar glueball exists at such accessible mass, then surely we ought to be able to find it. Conversely, if a spectroscopy of glueballs were to be confirmed as predicted by the lattice, this would have potentially profound implications for the future of theoretical physics and the numerical simulation of analytically intractable problems.

Complementing this is the growing evidence that there is now an overabundance of 0^{++} mesons in the $I = 0$ channels. The fact that the $J^{PC} = 0^{++}Q\bar{Q}$ nonet, and the predicted scalar glueball, are in the same 1.5 GeV region suggests that there will be mixing between the glueball and the "conventional" states; naive expectations about the flavour content of glueball decays should therefore be reexamined. I shall argue that this may be a pivotal matter in the emerging phenomenology[8].

The $f_0(1500)$ certainly satisfies much of the glueball folklore[9]. Not only is its mass right but it is seen in production mechanisms that are traditionally believed to favour glueballs, namely

1. Radiative J/ψ decay[10]
2. Central region away from quark beams and targets: $pp \to p_f(G)ps$[11]
3. $p\bar{p}$ annihilation at low energy where destruction of quarks creates opportunity for gluons to be manifested[1].

At this meeting we have a further tantalising hint in the sighting[3] of $f_0(1500)$ in decays of the hybrid meson candidate[12,13] $\pi(1800) \to \pi f_0(1500) \to \pi\eta\eta$.

The qualitative observation, number 1 above, receives some quantitative support from ref. [14,15]. By combining the known B.R. $(\psi \to \gamma R)$ for any resonance R with perturbative QCD calculation of $\psi \to \gamma(gg)_R$ where the two gluons are projected onto the J^{PC} of R, Cakir and Farrar estimate the gluon branching ratio $B(R \to gg)$. They suggest that

$$\begin{aligned} B(R[Q\bar{Q}] \to gg) &= 0(\alpha_s^2) \simeq 0.1 \\ B(R[G] \to gg) &= \tfrac{1}{2} \text{ to } 1 \end{aligned} \qquad (1)$$

and illustrate this for known $Q\bar{Q}$ resonances (such as $f_2(1270)$).

The inferred $B(R \to gg)$ tends to be larger if any of the following occur

- $B(\psi \to \gamma R)$ is large
- $\Gamma(R \to \text{all})$ is small
- $R = 0^{++}$ versus 2^{++}

(2)

The analysis of ref. [10] suggests $B(\psi \to \gamma f_0(1500) \simeq 10^{-3})$. As a rough guide, we find[15] if a scalar state around 1500 MeV is produced at 1ppm, then $B(S \to gg) \simeq 90/\Gamma_T$ (MeV). Thus a very broad $Q\bar{Q}$ state (width $\gtrsim$ 500 MeV) could be present at this level, but for $f_0(1500)$ with Γ_T = 100-150 MeV, one infers $B(f_0 \to gg) = 0.6$ to 0.9 which is far from $q\bar{q}$. Such arguments need more careful study but do add to the interest in the $f_0(1500)$.

The width of $f_0(1500)$ is also anomalous for a $^3P_0(Q\bar{Q})$. For a 0^{++} nonet one expects that

$$\Gamma(f_0^{n\bar{n}}) >> \Gamma(a_0) \gtrsim \Gamma(K^*)$$

Using data on 2^{++} mesons as input one expects the quasi-two body contributions to be of order 400, 280 and 250 MeV respectively. The latter are in accord with the Crystal Barrel $\Gamma(a_0) \simeq 270 \pm 40$ and the K^* width of 287 ± 23 (essentially all $K\pi$). The broad $f_0(1370)$ could be the $n\bar{n}$ state; the $f_0(1500)$

width of 116 ± 16 MeV is far too small and if $4\pi(\sigma\sigma)$ is a considerable fraction of this, the intrinsic $\pi\pi, KK, \eta\eta$ will be only tens of MeV. A detailed discussion is in ref[8].

Thus the $f_0(1500)$ has the right mass and is produced in the right places to be a glueball. Its total width is out of line with expectations for a $Q\bar{Q}$. Its branching ratios are interesting and may also signify a glueball that is mixed in with the neighbouring $Q\bar{Q}$ nonet. Whereas gluons decay in a flavour blind manner perturbatively, this property will tend to be hidden in strong QCD. If the flux tube model[16] is a guide to strong QCD, the decays of glueballs will be either into pairs of glueballs (or strongly coupled glue states such as η) or by mixing into nearby $Q\bar{Q}$ states of the same quantum number. This latter may be expected to be important for 0^{++} glueball in the 1.5 GeV region.

We give a pedagogical example that is more general than the particular example of interest here.

In first order perturbation the mixing of the primitive glueball G_0 and $Q\bar{Q}$ leads to

$$|G\rangle = |G_0\rangle + \xi \left\{ \frac{|u\bar{u} + d\bar{d}\rangle}{E(G_0) - E(d\bar{d})} + \frac{|s\bar{s}\rangle}{E(G_0) - E(s\bar{s})} \right\} \tag{3}$$

where ξ is the mixing amplitude, $E(G_0)$ and $E(Q\bar{Q})$ being the masses of the relevant states. In a world where flavour symmetry were exact in the sense that $E(s\bar{s}) \equiv E(d\bar{d})$ then the glueball mixes with $|u\bar{u} + d\bar{d} + s\bar{s}\rangle$ and hence its decays will preserve flavour symmetry. Thus we see that in the real world where $E(s\bar{s}) \neq E(d\bar{d})$ dramatic effects may result, especially if the primitive glueball is in the midst of the $q\bar{q}$ nonet such that

$$E(d\bar{d}) < E(G_0) < E(s\bar{s})$$

For example, if the glueball lies midway between these, then the $Q\bar{Q}$ mixture in eqn. 3 is $|u\bar{u} + d\bar{d} - s\bar{s}\rangle$ and the subsequent decays into meson pairs will violate flavour symmetry radically. In particular there will be destructive interference in the $K\bar{K}$ channels arising from the $(u\bar{u} + d\bar{d})$ and the $|s\bar{s}\rangle$ components. In ref. [8] we have discussed this is some detail and suggested that the suppression of $K\bar{K}$ observed for $f_0(1500)$ is a consequence.

It is important to note that such a mixing for a pure $Q\bar{Q}$ state would also kill $\eta\eta$ along with $K\bar{K}$. However, the $|G_0\rangle$ component can decay into glueball pairs, or into $\eta\eta$ and $\eta\eta'$, restoring these channels in accord with data. Indeed, the presence of $f_0(1500) \rightarrow \eta\eta$ and absence or suppression of $K\bar{K}$ is itself supportive of the glueball picture in that for a simple $Q\bar{Q}$ decay, the $K\bar{K}$ and $\eta\eta$ tend to be highly correlated, independent of the $Q\bar{Q}$ 1-8 mixing angle.

The experimental agenda now will be to
- establish $f_0(1450)$ and $K^*(1430)$
- quantify the KK branching ratio of $f_0(1500)$
- find the predicted [8] $s\bar{s}$ member of the multiplet
- clarify status of $f_J(1720)$.

It is important to confirm the status of these states in central production and in $\psi \to \gamma X$. If $f_0(1500)$ is the first glueball then the 2^{++} and 0^{-+} predicted by the lattice should also be sought. If the $\xi(2230)$ reported at this conference $\psi \to \gamma X$, is a real 2^{++} state in then the beginnings of a glueball spectroscopy may be at hand. The production rate may also be quantitatively in accord with that for a tensor glueball [15]. Establishing the 2^{++} and measuring its $\eta\eta$ branching ratio is a high priority.

Quarkballs, Glueloops and Hybrids

The origins of the masses of gluonic excitations on the lattice are known only to the computer. Those in the flux tube have some heuristic underpinning. The $Q\bar{Q}$ are connected by a colour flux with tension 1 GeV/fm which leads to a linear potential in accord with the conventional spectroscopy.

The simplest glue loop is based on four lattice points that are the corners of a square. As lattice spacing tends to zero one has a circle, the diameter is $\simeq 0.5$ fm, the circle of flux length is then $\simeq 1.5$ fm and, at 1 GeV/fm, the ballpark 1.5 GeV mass emerges. In the limit of lattice spacing vanishing, its 3-D realisation is a sphere, and hence it is natural that this is 0^{++}.

The next simplest configuration is based on an oblong, one link across and two links long. The total length of flux is $\simeq \frac{3}{2}$ larger than the square and the ensuing mass $\simeq \frac{3}{2}\times 1.5$ GeV $\simeq 2.2$ GeV. In the 3-D continuum limit this rotates into a rugby ball shape rather than a sphere. A decomposition in spherical harmonics contains $L \gtrsim 0$, in particular 2^{++}. This is by no means rigorous (!) but may help to give a feeling for the origin of the glueball systematics in this picture, inspired by the lattice.

Finally one has the prediction that there exist states where the gluonic degrees of freedom are excited in the presence of $Q\bar{Q}$. With the 1 GeV/fm setting the scale, one finds [16] that the lightest of these "hybrid" states have masses of order 1 GeV above their conventional $q\bar{q}$ counterparts. Thus hybrid charmonium may exist at around 4 GeV, just above the $D\bar{D}$ pair production threshold. More immediately accessible are light quark hybrids that are expected in the 1.5 to 2 GeV range after spin dependent mass splittings are allowed for.

At this conference we have tantalising sightings of an emerging spectroscopy as I shall now review.

The Hybrid Candidates

It is well known that hybrid mesons can have J^{PC} quantum numbers in combinations such as $0^{--}, 0^{+-}, 1^{-+}, 2^{+-}$ etc. which are unavailable to conventional mesons and as such provide a potentially sharp signature.

It was noted in ref.[17] and confirmed in ref.[12] that the best opportunity for isolating exotic hybrids appears to be in the 1^{-+} wave where, for the I=1 state with mass around 2 GeV, partial widths are typically

$$\pi b_1 : \pi f_1 : \pi\rho \;=\; 170\,MeV : 60\,MeV : 10\,MeV \tag{4}$$

The narrow $f_1(1285)$ provides a useful tag for the $1^{-+} \to \pi f_1$ and ref.[18] has recently reported a signal in $\pi^- p \to (\pi f_1)p$ at around 2.0 GeV that appears to have a resonant phase.

Note the prediction that the $\pi\rho$ channel is not negligible relative to the signal channel πf_1 thereby resolving the puzzle of the production mechanism that was commented upon in ref. [18]. This state may also have been sighted in photoproduction this month[19] with $M = 1750$ and may be the $X(1775)$ of the Data Tables, ref.[22].

A recent development is the realisation that even when hybrid and conventional mesons have the **same** J^{PC} quantum numbers, they may still be distinguished [12,13] due to their different internal structures which give rise to characteristic selection rules[23,16,12]. As an example consider the $\rho(1460)$.

(i) If $q\bar{q}$ in either hybrid or conventional mesons are in a net spin singlet configuration then the dynamics of the flux-tube forbids decay into final states consisting only of spin singlet mesons.

For $J^{PC} = 1^{--}$ this selection rule distinguishes between conventional vector mesons which are $^3S_1$ or $^3D_1$ states and hybrid vector mesons where the $Q\bar{Q}$ are coupled to a spin singlet. This implies that in the decays of hybrid ρ, the channel πh_1 is forbidden whereas πa_1 is allowed and that πb_1 is analogously suppressed for hybrid ω decays; this is quite opposite to the case of $^3L_1$ conventional mesons where the πa_1 channel is relatively suppressed and πh_1 or πb_1 are allowed[24,20]. The extensive analysis of data in ref.[21] revealed the clear presence of $\rho(1460)$[22] with a strong πa_1 mode but no sign of πh_1, in accord with the hybrid situation. Furthermore, ref.[21] finds evidence for $\omega(1440)$ with no visible decays into πb_1 which again contrasts with conventional $q\bar{q}$ ($^3S_1$ or $^3D_1$) initial states and in accord with the hybrid configuration.

(ii) The dynamics of the excited flux-tube in the **hybrid** state suppresses the decay to mesons where the $q\bar{q}$ are $^3S_1$ or $^1S_0$ "$L = 0$" states. The preferred decay channels are to $(L = 0) + (L = 1)$ pairs[16,17]. Thus in the decays of hybrid $\rho \to 4\pi$ the πa_1 content is predicted to be dominant and the $\rho\rho$ to be absent. The analysis of ref.[21] finds such a pattern for $\rho(1460)$.

(iii) The selection rule forbidding $(L = 0) + (L = 0)$ final states no longer operates if the internal structure or size of the two $(L = 0)$ states differ[16,23]. Thus, for example, decays to $\pi + \rho$, $\pi + \omega$ or $K + K^*$ may be significant in some cases[12,13], and it is possible that the **production** strength could be significant where an exchanged π, ρ or ω is involved, as the exchanged off mass-shell state may have different structure to the incident on-shell beam particle. This may be particularly pronounced in the case of **photoproduction** where couplings to $\rho\omega$ or $\rho\pi$ could be considerable when the ρ is effectively replaced by a photon and the ω or π is exchanged. This may explain the production of the candidate exotic $J^{PC} = 1^{-+}$ (ref.[18]) and a variety of anomalous signals in photoproduction.

The first calculation of the widths and branching ratios of hybrid mesons with conventional quantum numbers is in ref.[12]: the $0^{-+}, 2^{-+}$ and the 1^{--} are predicted to be potentially accessible. It is therefore interesting that each of these J^{PC} combinations shows rather clear signals with features characteristic of hybrid dynamics and which do not fit naturally into a tidy $Q\bar{Q}$ conventional classification.

We have already mentioned the 1^{--}. Turning to the 0^{-+} wave, at this conference that the VES Collaboration at Protvino confirm their enigmatic and clear 0^{-+} signal in diffractive production with 37 GeV incident pions on beryllium[3]. Its mass and decays typify those expected for a hybrid: $M \approx 1790$ MeV, $\Gamma \approx 200$ MeV in the $(L = 0) + (L = 1)$ $\bar{q}q$ channels $\pi^- + f_0$; $K^- + K_0^*$, $K(K\pi)_S$ with no corresponding strong signal in the kinematically allowed $L = 0$ two body channels $\pi + \rho$; $K + K^*$.

The resonance also appears to couple as strongly to the enigmatic $f_0(980)$ as it does to $f_0(1300)$, which was commented upon with some surprise in ref. [3]. This may be natural for a hybrid at this mass due to the predicted dominant KK_0^* channel which will feed the $(KK\pi)_S$ (as observed[3]) and hence the channel $\pi f_0(980)$ through the strong affinity of $K\bar{K} \to f_0(980)$. Thus the overall expectations for hybrid 0^{-+} are in line with the data of ref.[3]. Important tests are now that there should be a measureable decay to the $\pi\rho$ channel with only a small πf_2 or KK^* branching ratio. At this conference we learn that in the $\pi\eta\eta$ final state the glueball candidate is seen: $\pi(1.8) \to \pi f_0(1500) \to \pi\eta\eta$. Seeing a glueball in the decays of an excited glue hybrid is suggestive though it would be nice to see a Dalitz plot to be sure that this is indeed scalar resonance production and not a kinematic reflection in the $\pi\eta\eta$ system.

This leaves us with the 2^{-+}. There are clear signals of unexplained activity in the 2^{-+} wave in several experiments for which a hybrid interpretation may offer advantages. These are discussed in ref.[12].

These various signals in the desired channels provide a potentially consistent picture. The challenge now is to test it. Dedicated high statistics experiments with the power of modern detection and analysis should re- examine these channels. Ref.[13] suggests that the hybrid couplings are especially favourable in *low-energy* photoproduction and as such offer a rich opportunity for the programme at an upgraded CEBAF or possibly even at HERA. If the results of ref.[25] are a guide, then photoproduction may be an important gateway at a range of energies and the channel $\gamma + N \to (b_1\pi) + N$ can discriminate hybrid 1^{--} and 2^{-+} from their conventional counterparts.

Thus to summarise, we suggest that data are consistent with the existence of low lying multiplets of hybrid mesons based on the mass spectroscopic predictions of ref.[16] and the production and decay dynamics of ref. [12]. Specifically the data include

$$\begin{array}{llll} 0^{-+} & (1790\,MeV; \Gamma = 200\,MeV) & \to & \pi f_0; K\bar{K}\pi \\ 1^{-+} & (\sim 2\,GeV; \Gamma \sim 300\,MeV) & \to & \pi f_1; \pi b_1(?) \\ 2^{-+} & (\sim 1.8\,GeV; \Gamma \sim 200\,MeV) & \to & \pi b_1; \pi f_2 \\ 1^{--} & (1460\,MeV; \Gamma \sim 300\,MeV) & \to & \pi a_1 \end{array} \tag{5}$$

Detailed studies of these and other relevant channels are called for together with analogous searches for their hybrid charmonium analogues, especially in photoproduction or e^+e^- annihilation.

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