PHYSICAL REVIEW D VOLUME 52, NUMBER 3 1 AUGUST 1995

BRIEF REPORTS

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Photoproduction of hybrid mesons from CEBAF to DESY HERA

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(Received 12 December 1994)

Decay widths, branching ratios, and production dynamics of some recently discovered $J^{PC} = 1^{-+}$, 0^{-+}, 1^{--}, and 2^{-+} mesons are found to be in remarkable agreement with the predicted properties of hybrid mesons. We propose tests for this new dynamics, emphasize the critical role of πb_1 or πh_1 decay channels in discriminating hybrids from conventional states, and suggest that photoproduction may offer special opportunities for isolation and confirmation of hybrids.

PACS number(s): 12.39.Mk, 13.60.Le

There is a substantial area in the standard model of particles and interactions where we remain fundamentally ignorant: while the gluon degrees of freedom expressed in the Lagrangian of quantum chromodynamics have been established beyond doubt in high momentum data, their dynamics in the strongly interacting limit epitomized by hadron spectroscopy is quite obscure. It is possible that this is about to change [1].

For the first time there is a candidate scalar glueball [2–4] whose mass 1.5–1.6 GeV is consistent with the predictions from lattice studies of QCD [5]. Furthermore, its production and decay properties in a range of experiments fit more naturally with those of a gluonic excitation than of a conventional quark-antiquark ($q\bar{q}$) nonet state. If these are the first hints of gluonic excitation at a mass scale anticipated by theory, then this raises the possibility that in the 1.5–2 GeV mass range there is a rich spectroscopy of "hybrid" states where the gluonic fields or "flux tubes" are excited in the presence of colored quark sources [6–8]. In this Brief Report we present evidence supporting this notion and propose ways of testing the hypothesis in forthcoming experiments.

It is well known that hybrid mesons can have quantum numbers for spin parity and charge conjugation (J^{PC}) in combinations such as 0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, etc., which are unavailable to conventional mesons and as such provide a potentially sharp signature for hybrids. A central theme in this Brief Report will be to note that even when hybrid and conventional mesons have the *same* J^{PC} quantum numbers, they may still be distinguished. The essential reason is that although superficially identical in their overall quantum numbers, the two states have different internal structures which give rise to characteristic selection rules [8,9]. We illustrate this with particular reference to the vector meson $\rho(1460)$ whose decays typify those of 1^{--} hybrid dynamics.

(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 $J^{PC} = 1^{--}$ states 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 [10,11]. The extensive analysis of data in Ref. [12] revealed the clear presence of $\rho(1460)$ [13] with a strong πa_1 mode but no sign of πh_1, in accord with the hybrid situation. Furthermore, Ref. [12] finds evidence for $\omega(1440)$ with no visible decays into πb_1 which again is in significant contrast to the expectations for 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 [8,14]. 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. [12] 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

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0556-2821/95/52(3)/1706(4)/$06.00

or size of the two ($L = 0$) states differs [8,15]. Thus, for example, decays to $\pi + \rho$, $\pi + \omega$, or $K + K^*$ may be significant in some cases [9]. Though still suppressed relative to the dominant pathway, (ii) above, this too is the case for $\rho(1460)$. It is also interesting to note that for a hybrid $\omega(1440)$, the preferred $(L = 0) + (L = 1)$ decay paths are predicted to be kinematically suppressed leaving the $\pi\rho$ and possibly $\eta\omega$ as dominant decays.

(iv) In the case of *production*, where an exchanged π, ρ, or ω is involved, it is possible that the strength could be significant at least to the extent that the exchanged off-mass-shell state may have different structure to the incident on-shell beam particle [16]. 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. As we shall discuss later, this may explain the production of the candidate exotic $J^{PC} = 1^{-+}$ (Ref. [17]) and a variety of anomalous signals in photoproduction.

According to the flux-tube model, the J^{PC} quantum numbers of the *lowest lying*[1] hybrid mesons may be divided into two classes: (a) 0^{-+}, 1^{+-}, 1^{--}, 1^{++}, 2^{-+} (deemed "conventional" in that they can also be shared by standard $q\bar{q}$ states) and (b) 0^{+-}, 1^{-+}, 2^{+-} (deemed "exotic").

In the hybrid 1^{--} and 1^{++} the $q\bar{q}$ are coupled to a spin singlet; all other J^{PC} are spin triplets.

If the $\rho(1460)$ has signposted the existence of the vector hybrid nonet, then we need to establish which of the other seven multiplets should also be visible. States whose couplings are predicted to be strong, with highly visible decay channels and moderate widths relative to the ρ candidate, *must* be seen if hybrids are to be established. Conversely, channels where no signals are seen should be those whose signals are predicted in Refs. [8,9] to be weak. We shall make the case that these criteria do appear to be realized in the data.

Exotic J^{PC}

The most obvious signature for a hybrid meson is the appearance of a flavored state with an exotic combination for J^{PC}. It was noted in Ref. [14] and confirmed in Ref. [9] that the 0^{+-} width is predicted to be over 1500 MeV thereby rendering the state effectively invisible. The 2^{+-} is also predicted to be very broad and hard to see if its mass is ≥ 1.9 GeV. 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

$$\pi b_1 : \pi f_1 : \pi\rho \;=\; 170\text{ MeV} : 60\text{ MeV} : 10\text{ MeV}\ . \tag{1}$$

The narrow $f_1(1285)$ provides a useful tag for the $1^{-+} \to \pi f_1$ and Ref. [17] 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 though they admit that more data are required for a firm conclusion.

The partial widths for πb_1 and πf_1 in Eq. (1) are similar to those predicted in Ref. [14] but we note also the possibility that the $\pi\rho$ channel is not negligible relative to the signal channel πf_1. In view of property (iv) above, it is plausible that ρ exchange couples strongly to the incident π^-, thereby resolving the puzzle of the production mechanism that was commented upon in Ref. [17]. We shall comment on the possible photoproduction of this state later.

Conventional J^{PC}

Previous discussions of the dynamics of hybrids in flux-tube models have been limited to exotic J^{PC} [14]; the first calculation of the widths and branching ratios of hybrid mesons with conventional quantum numbers is in Ref. [9]. This predicts that for hybrids at ~ 2 GeV made from u, d flavored quarks the 1^{+-}, 1^{++} states are over 500 MeV wide in both $I = 0,1$ states; by contrast the 0^{-+}, 2^{-+}, and the 1^{--} are predicted to be potentially accessible. Hence we predict that the most visible J^{PC} states are those that coincide with the lowest lying hybrids of the bag model, namely 1^{--}; $(0,1,2)^{-+}$ [6,7]. Moreover, the $q\bar{q}$ spin content is identical in the two models. 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^{--} which motivated this analysis. Turning to the 0^{-+} wave, we note that the VES Collaboration at Protvino sees an enigmatic and clear 0^{-+} signal in diffractive production with 37 GeV incident pions on beryllium [18]. They study the channels $\pi^- N \to \pi^-\pi^+\pi^- N$; $\pi^- K^+ K^- N$ and see a resonant signal $M \approx 1790$ 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 $\pi + \rho$; $K + K^*$:

$$\frac{0^{-+} \to \pi^-\rho^0}{0^{-+} \to \pi^- f_0(1300)} < 0.3\ (95\%\ \text{C.L.})\ , \tag{2}$$

$$\frac{0^{-+} \to K^- K^*}{0^{-+} \to (K^- K^+ \pi)_S} < 0.1\ (95\%\ \text{C.L.})\ . \tag{3}$$

The width and large couplings to kaons are both surprising if this were the second radial excitation of the pion (the first radial excitation is seen as a broad enhancement in accord with expectations). Furthermore, the preference for decay into $(L = 0) + (L = 1)$ mesons at the expense of $L = 0$ pairs is in accord with expectations for hybrids.

The resonance also appears to couple strongly to the enigmatic $f_0(980)$:

$$\frac{0^{-+} \to \pi^- f_0(980)}{0^{-+} \to \pi^- f_0(1300)} = 0.9 \pm 0.1\ , \tag{4}$$

which was commented upon with some surprise in Ref. [18]. 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 [18]) and hence the

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[1] The exotic 0^{--} and its (conventional) 0^{++} J^{PC} partner are predicted to be higher excited states, at least in the flux-tube model, and are not considered further here.

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. [18]. Important tests are now that there should be a measurable decay to the $\pi\rho$ channel with only a small πf_2 or KK^* branching ratio. 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. Historically the ACCMOR Collaboration [19] noted a 2^{-+} structure around 1.8 GeV, coupled to πf_2, and too near to the $\pi_2(1670)$ for these to be the $1\,^1D_2$ and $2\,^1D_2$ (radial excitation) of conventional quarkonium. Chanowitz and Sharpe [7] suggested that the 1.8 GeV state might set the mass scale for hybrid excitations. This structure is tantalizingly similar to sightings of a possible 2^{-+} (or even 1^{-+}, see below) at 1.77 GeV, width 100–200 MeV in photoproduction via π exchange [20] and coupled to $\pi\rho$ and πf_2. An earlier low energy photoproduction experiment [21] also shows a clear structure at 1.7 – 1.9 GeV though its quantum numbers are not identified; we note that hybrid 2^{-+}, 1^{-+} are both favorably photoproduced according to the Tables 7 and 8 in Ref. [9] *via* π exchange or ω exchange. There are also some indications of a doubling of states in the $I = 0$ $\eta\pi^0\pi^0$ channel where the Crystal Barrel at LEAR [22] finds both $\eta_2(1650)$ [which is probably the partner of $\pi_2(1670)$] and also a candidate $\eta_2(1850)$ decaying into $f_2\eta$ (unlikely to be $s\bar{s}$).

If these various experiments are heralding activity in the 2^{-+} wave, a search for the πb_1 decay channel becomes pivotal. This follows once again from the selection rule forbidding the decay of a spin singlet meson into pairs of spin singlets: this prevents the decay of $^1D_2(\pi_2) \to b_1\pi$ whereas this channel is allowed and potentially significant for π_2^{hybrid} [9].

In this context, the results of Ref. [23] are interesting. They studied $\gamma p \to (b_1\pi)p$ at 25–50 GeV incident energy with the specific intention of seeking hybrids. At that time the only calculations of hybrid branching ratios in the literature were for the *exotic* J^{PC} states and Ref. [23] assumed them to be a guide to the nonexotic cases also. Our calculations [9] show that this assumption is not generally true. In particular, as noted above, the selection rule forbids the $b_1\pi$ decay modes for the case of hybrid ω and conventional $^1D_2$ (π_2) quarkonium while allowing it for conventional ($^3S_1$ or $^3D_1$) ω or hybrid π_2, respectively. As the $b_1\pi$ is the trigger channel in Ref. [23], several of the conclusions of that experiment merit reexamination. In particular, if one insists on diffractive production then any signals are *not* hybrid 1^{--}; conversely, if one allows also ω exchange (which is not negligible at 25–50 GeV), then either (or both) hybrid 2^{-+}, 1^{-+} production can feed the $b_1\pi$ signal but conventional $^1D_2$ quarkonium is forbidden in this mode. ω exchange also can feed 1^{++}: a $2^3P_1 \to b_1\pi$ is allowed whereas a hybrid 1^{++} is forbidden in this channel.

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 reexamine these channels. As several of these candidates appear in photoproduction, it may be worthwhile to consider the possibility that the $(L = 0) + (L = 0)$ suppression (into $\rho\omega$ or $\rho\pi$) may be overruled when the "ρ" is a γ. With this in mind we identify from Tables 7–9 of Ref. [9] the potentially significant photon couplings (where "photon" is equated with ρ *via* vector meson dominance and the exchanged particle is ω or π in this analysis).

The unsuppressed widths are, for $I = 1$ hybrid states (in keV),

$$\begin{aligned} 2^{-+} &\to \pi^+\gamma = 70, \ \omega\gamma = 250 \ , \\ 1^{-+} &\to \pi^+\gamma = 70, \ \omega\gamma = 180 \ , \\ 0^{-+} &\to \pi^+\gamma = 275, \ \omega\gamma = 0 \ , \\ 1^{++} &\to \pi^+\gamma = 145, \ \omega\gamma = 455 \ , \end{aligned} \tag{5}$$

and for the $I = 0$ hybrid sector important widths include

$$\begin{aligned} 2^{-+} &\to \rho\gamma = 127 \ , \\ 1^{-+} &\to \rho\gamma = 90 \ , \\ 1^{++} &\to \rho\gamma = 220 \ , \\ 1^{--} &\to \pi\gamma = 120 \ . \end{aligned} \tag{6}$$

The 1^{++} channel has the strongest photon couplings but is predicted to be broad and hard to isolate (unless its mass is unexpectedly low, as for the enigmatic $f_1(1430)$ in the isoscalar sector). Both 1^{-+}, 2^{-+} have similar photoproduction rates and healthy $b_1\pi$ branching ratios and hence are candidates for the signal in Ref. [23]. The 0^{-+} may be prominent in low-energy photoproduction where π exchange is important but its $\omega\gamma$ coupling is suppressed by a selection rule for hybrids which will disfavor the 0^{-+} photoproduction at higher energies.

The above are all upper limits on the electromagnetic couplings and may be used to estimate upper limits for the photoproduction rates. In the case of π exchange, at least, there is reason to expect that the actual strengths will be $\geq 20\%$ of these [9]. This is especially favorable to *low-energy* photoproduction and as such offers a rich opportunity for the program at an upgraded CEBAF or possibly even at the DESY *ep* collider HERA. If the results of Ref. [23] 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.

We also note that in $\pi^- p \to (f_1\pi^-)p$, Ref. [17] sees a broad 1^{++} signal that is more prominent than their exotic 1^{-+} candidate. They interpret this 1^{++} as a radial excitation; however, we note that if the production mechanism involves ρ exchange, then the hybrid couplings predicted in Ref. [9] imply that hybrid 1^{++} should be produced in this same experiment with a greater strength than the 1^{-+}. Experimentally it may be possible to distinguish between the radial $^3P_1$ axial meson and the hybrid (spin singlet) configuration by studying πN or $\gamma N \to (b_1\pi)N$; a hybrid 1^{++} decouples from this channel.

Thus to summarize, we suggest that data are consistent with the existence of low lying multiplets of hybrid mesons based on the mass spectroscopic predictions of Ref. [8] and the production and decay dynamics of Ref. [9]. Specifically the data include

$$\begin{aligned}
0^{-+}(1790\ \mathrm{MeV};\Gamma = 200\ \mathrm{MeV}) &\to \pi f_0; K\bar{K}\pi\ , \\
1^{-+}\ (\sim 2\ \mathrm{GeV};\Gamma \sim 300\ \mathrm{MeV}) &\to \pi f_1; \pi b_1(?)\ , \\
2^{-+}(\sim 1.8\ \mathrm{GeV};\Gamma \sim 200\ \mathrm{MeV}) &\to \pi b_1; \pi f_2\ , \\
1^{--}(1460\ \mathrm{MeV};\Gamma \sim 300\ \mathrm{MeV}) &\to \pi a_1\ . \qquad (7)
\end{aligned}$$

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.

We thank T. Barnes, A. Donnachie, and several experimental colleagues at the Rutherford Appleton Laboratory for helpful discussions.

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