

GLUONIC EXCITATIONS IN MESONS*

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We report on some interesting recent theoretical and experimental advances on J^{PC} exotics and hybrid mesons. These are the decay selection rules governing J^{PC} exotic decay, the experimental evidence for a $J^{PC} = 1^{-+}$ exotic in $\eta\pi$ and $\rho\pi$, and the production of charmonium hybrids at forthcoming B -factories.

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1. Introduction

In the last two years states beyond the predictions of the quark model have emerged in several J^{PC} sectors, for example

- A preliminary study by VES confirms that there is evidence for two isovector 0^{-+} states in the mass region 1.4–1.9 GeV [1]. The parameters of the resonances are mass $1790 \pm 6 \pm 12$ MeV and width $225 \pm 9 \pm 15$ MeV for the well known resonance $\pi(1800)$; and mass $1580 \pm 43 \pm 75$ MeV and width $450 \pm 60 \pm 100$ MeV for the new resonance. All known quark models predict only one state in this mass region. Hence there is evidence for degrees of freedom beyond simple $q\bar{q}$.
- Perhaps most striking is the embarrassment of riches for isovector states which are $J^{PC} = 1^{-+}$ exotic, *i.e.* whose J^{PC} quantum numbers cannot be built from a fermion–antifermion operator (with derivatives). E852 reports a resonance with mass $1370 \pm 16^{+50}_{-30}$ MeV and width $385 \pm 40^{+65}_{-105}$ MeV [2]; and Crystal Barrel a resonance with mass $1400 \pm 20 \pm 20$ MeV and a width of $310 \pm 50^{+50}_{-30}$ MeV [3]. Both collaborations observe the resonance in $\eta\pi$. A second, distinct, resonance has appeared in $\rho\pi$.

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E852 reports a mass of 1593 ± 8 MeV with a width of 168 ± 20 MeV [4]. There have also been claims of an enhancement in the high mass region $\gtrsim 1.6$ GeV in $f_1\pi$, $a_0(980)\rho$ and $\eta'\pi$ [5]. Because the quantum numbers are exotic, neither state qualifies as a conventional meson, indicating evidence for the existence of degrees of freedom beyond $q\bar{q}$.

The emergence of degrees of freedom beyond conventional mesons signals the end of the hegemony of the quark model as a comprehensive description of bound states. Indeed, it is the beginning of the emergence of new states which indicate the presence of dynamical glue in QCD, *i.e.* of gluonic excitations in mesons, also called “hybrid mesons”. For the $J^{PC} = 0^{-+}$, 1^{-+} values under consideration, there are J^{PC} exotic and hybrid mesons predicted to exist in lattice QCD [6, 7].

2. Symmetrization selection rules

Hybrid mesons have been shown to be bound states with a total decay width of $\mathcal{O}(\frac{1}{N_c})$ in the large number of colours N_c expansion of QCD [8] — the same behaviour as for conventional mesons. This means that hybrids are expected to be observable states in experiment.

The decay widths of $J^{PC} = 0^{+-}$, 1^{-+} , 2^{+-} , ... exotic hybrid mesons, four-quark states and glueballs have recently been realized to exhibit decay selection rules to final state $J = 0$ mesons, which have considerable generality in QCD [9].

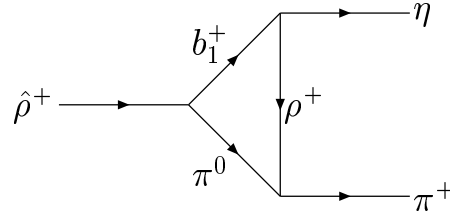


Fig. 1. Decay of 1^{-+} to $\eta\pi$ via final state interactions.

Specifically, the decay width for $1^{-+} \rightarrow \eta\pi$ is believed to be tiny. This decay has attracted considerable study and detailed arguments in QCD have been developed to show that the connected part of the quenched Euclidean three point correlation function of the interpolating fields for the three states vanish exactly, if isospin symmetry is assumed [10]. Connecting the three point correlators to decay amplitudes encounters difficulties with the way limits are taken for time $t \rightarrow \infty$ [11] which was not fully appreciated in Ref. [10]. These effects can be grouped under the name “final state interactions”, and such an effect is indicated in Fig. 1. Final state interactions

break the symmetrization selection rules. The contribution from the graph in Fig. 1 has been estimated in a model to give an $\eta\pi$ width to a 1.6 GeV 1^{-+} hybrid of less than 57 ± 14 MeV [12].

3. 1^{-+} exotics

Some brief highlights from the history of the enhancement at 1.4 GeV in $\eta\pi$ is now presented. It was initially claimed that the enhancement is non-resonant and can be fitted with a Breit–Wigner mass of 1413 MeV and a substantial width of 687 MeV [13]. The Crystal Barrel recently claimed that the phase motion in the $\eta\pi$ P-wave is $213^\circ \pm 5^\circ$ and that the enhancement should hence be interpreted as resonant [3]. E852 independently claimed that strong phase motion is observed against the a_2 , indicating the resonant nature of the enhancement.

Lattice QCD mass predictions and the predicted weak coupling of the 1^{-+} to $\eta\pi$ does not appear consistent with the claim that the 1^{-+} at 1.4 GeV is indeed a hybrid meson [14]. We now explore a conservative explanation for the 1.4 GeV enhancement.

The fact that non-trivial phase motion occurs is supported by both Crystal Barrel and E852, in very different production processes. However, it is possible that the phase motion is really due to a resonant 1^{-+} at 1.6 GeV (where the $\rho\pi$ data favours it to be) interfering with a non-resonant background $\eta\pi$ P-wave, which “shifts” the peak from 1.6 GeV to 1.4 GeV. A recent K-matrix analysis has demonstrated that this is indeed a strong possibility [12].

The 1^{-+} at 1.6 GeV shows classic phase motion against the a_2 , a_1 , $\pi(1300)$, $\pi(1800)$ and the $\pi_2(1670)$ [4], so that its resonance nature is not in doubt. It is interesting to consider the various interpretations of a J^{PC} exotic resonance in the general context of the minimally supersymmetric Standard Model. Here we think of building the bound states non-relativistically in terms of their perturbative constituents. Denote the gluon and gluino by g and $\tilde{g}$ respectively; and the quark and squark by q and $\tilde{q}$ respectively. In principle one can imagine the following low-lying bound states with exotic J^{PC} : glueballs (gg), gluinoballs ($\tilde{g}\tilde{g}$) and squarkballs ($\tilde{q}\tilde{q}$). At this stage we do not consider (more massive) bound states with a higher number of constituents. Note that $q\bar{q}$ does not yield exotic J^{PC} and that glueballinos ($g\tilde{g}$) and baryons (qqq) have half-integral spin, and so they should not be considered. Within isospin symmetry, isovector glueballs and gluinoballs are not allowed, since the gluon and gluino have isospin 0. If isospin symmetry is not assumed, the $\eta\pi$ can couple to an isoscalar glueball or gluinoball. However, lattice QCD expects the 1^{-+} in the mass region 3 – 4.1 GeV [14], distant from the mass region we are interested in. Also, gluinoballs cannot be J^{PC} exotic, as we now show.

Because the gluinos are Majorana fermions, their parity is the imaginary number i . Hence the intrinsic parity of $\tilde{g}\tilde{g}$ is $i^2 = -1$. Adding this to the angular momentum L between the gluinos, we obtain the parity $P = (-1)^{L+1}$. Because the gluinos are their own antiparticles, the charge conjugation $C = 1$. Since the gluinos are fermions, we require that the gluinos must be antisymmetric under exchange. Since the gluinos are both in colour octet and combine to form a colour singlet via a delta-function, which is symmetric under exchange, we require the remainder of the wave function to be antisymmetric under exchange. Exchange of the gluinos just gives $(-1)^{L+S+1}$, where S is the non-relativistic spin of the gluinoball. Hence, $L + S$ must be even. Using the relations

$$P = (-1)^{L+1} \quad C = 1 \quad L + S = \text{even} \quad \vec{J} = \vec{L} + \vec{S} \quad (1)$$

it is easy to demonstrate that no J^{PC} exotics (*i.e.* 0^{--} , 0^{+-} , 1^{-+} , 2^{+-} , 3^{-+} , ...) can be built.

Squarkballs cannot be J^{PC} exotics either, as we now demonstrate. Since the intrinsic parity of the squark and antisquark are the same, $P = (-1)^L$. Because charge conjugation takes the particle into the antiparticle, and the squarks are spinless, $C = (-1)^L$. Using these relations, and $\vec{J} = \vec{L}$, one can show that no J^{PC} exotics are allowed.

Experimental evidence for isovector J^{PC} exotic states in the 1 – 2 GeV mass region hence indicates that they are not conventional mesons, squarkballs, glueballs or glueballinos. The most conservative explanation is that they are hybrid mesons ($q\bar{q}g$), or four-quark states ($qq\bar{q}\bar{q}$) or linear combinations. The 1.6 GeV 1^{-+} appears to be consistent with expectations for a hybrid meson [14].

If the hybrid lies at 1.6 GeV, an interesting observation can be made. The heavy quark expansion of QCD in Coulomb gauge [15] demonstrates that spin-orbit splittings of low-lying hybrids should be as follows: $0^{-+} < 1^{-+} < 2^{-+}$ and $0^{+-} < 1^{+-} < 2^{+-}$. The ordering from 0 to 2 with 1 in between is required by the lowest order in the heavy quark expansion, and must be the same for both sets [15]. Either 0 or 2 is low-lying. The stated ordering follows from the fact that $0^{+-} < 2^{+-}$ is the ordering found in lattice QCD [6]. If spin-orbit splittings for heavy quark hybrids are a guide for light quark hybrids, as is the case for conventional mesons, we expect the $0^{-+} < 1^{-+}$ at 1593 ± 8 MeV [4]. The new 0^{-+} at $1580 \pm 43 \pm 75$ MeV found by VES [1] may or may not satisfy this bound. $\pi(1800)$ does not satisfy the bound. Since lattice QCD also supports that $1^{-+} < 0^{+-}$ [6, 14], we can deduce the ordering $0^{-+} < 1^{-+} < 0^{+-} < 1^{+-} < 2^{+-}$ in the heavy quark expansion. It may in fact not be coincidental that non- $Q\bar{Q}$ degrees of freedom are appearing in the two low-lying J^{PC} combinations in this list.

Whether the heavy quark limit is successful or not for light hybrids will indicate whether there can be a successful “quark model” for hybrids.

4. Production of charmonium hybrids at B -factories

The weak reaction $b \rightarrow c\bar{c}s$ where the $c\bar{c}$ is in a colour octet is enhanced by colour factors above colour singlet $c\bar{c}$ production [16]. In the weak decay vertex the $c\bar{c}$ in the hybrid will be in a colour octet at small interquark separations, as in the adiabatic bag model, which is very successful when compared with lattice QCD [17]. We hence expect B mesons to decay significantly to $c\bar{c}$ hybrids (ψ_g). Estimates in NRQCD indicate that $\mathcal{B}(B \rightarrow 0^{+-} X) \lesssim \frac{1}{2}0.1\%$ [18], so that the branching ratio to all hybrids can be $\mathcal{O}(1\%)$. Given that CLEO has already detected the χ_{c2} with a tiny branching ratio of $\mathcal{B}(B \rightarrow \chi_{c2} X) = 0.25 \pm 0.10\%$, there appears to be no reason why a search for charmonium hybrids should not be feasible at B -factories.

UKQCD’s quenched lattice QCD calculation with infinitely heavy quarks predicts the low-lying hybrids, including the 1^{-+} and 0^{-+} , to be at 4.04 ± 0.03 GeV (with unquenching estimated to raise the mass by 0.15 GeV), well below the $D^{**}D$ threshold of 4.27 GeV [16]. We highlight two J^{PC} exotic hybrids of specific interest.

1^{-+} :

A quenched lattice QCD calculation by MILC predicts a mass of $4390 \pm 80 \pm 200$ MeV [7]. If the state lies below the $D^{**}D$ threshold, it will decay to $D^*\bar{D}$, $D\bar{D}^*$ which is estimated in models at 3–4 MeV and $D^*\bar{D}^*$ which vanishes in the same model [19].

The prominent decays will be either by cascade $\psi_g \rightarrow gg + c\bar{c}$ or by annihilation $\psi_g(C = +) \rightarrow gg \rightarrow \text{light hadrons}$. These are at the same order in α_s . The decay $\psi_g \rightarrow \text{light hadrons}$ is expected to be favoured at least for $C = +$ states for the following reason. A measure of the relative importance of the cascade width compared to the annihilation width may be provided by $\Gamma(\psi' \rightarrow \psi \text{ light hadrons}) = \mathcal{O}(0.16 \text{ MeV})$ versus $\Gamma(\eta'_c \rightarrow \text{light hadrons}) \simeq \Gamma(\eta_c \rightarrow \text{light hadrons}) \times \Gamma^{ee}(\psi')/\Gamma^{ee}(\psi) = \mathcal{O}(5 \text{ MeV})$. The $\psi' \rightarrow \psi$ light hadrons gives information about $\psi' \rightarrow \psi gg$, while $\eta'_c \rightarrow \text{light hadrons}$ informs about $\eta'_c \rightarrow gg$. Both processes are $\mathcal{O}(\alpha_s^2)$ in rate. Those rates suggest what to expect for cascade and annihilation decays of charmed hybrids. The rates of $\psi_g \rightarrow (c\bar{c}) + \text{light hadrons}$ and $\psi_g(C = +) \rightarrow \text{light hadrons}$ are both down by one power in α_s . Ignoring differences in wave function overlaps we roughly estimate $\Gamma(\psi_g \rightarrow (c\bar{c}) + \text{light hadrons}) = \mathcal{O}(0.5 \text{ MeV})$ and $\Gamma(\psi_g(C = +) \rightarrow \text{light hadrons}) = \mathcal{O}(20 \text{ MeV})$ [16].

0^{+-} :

The decay 0^{+-} to $D\bar{D}$, $D^*\bar{D}$, $D\bar{D}^*$, $D^*\bar{D}^*$ is forbidden by quantum numbers. MILC predicts a mass of $4610 \pm 110 \pm 200$ MeV [7]. If the state lies below the $D^{**}D$ threshold, its prominent decays will hence be by cascade or annihilation.

The light hadron production rate from ψ_g decays with $C = -$ is expected to be suppressed by one power of α_s with regards to $\psi_g(C = +)$ decays. Note that the production rate of conventional charmonia from either $\psi_g(C = +)$ or $\psi_g(C = -)$ decays is expected to be of the same order in α_s and thus similar. We estimate that $\Gamma(\psi_g \rightarrow c\bar{c} + \text{light hadrons}) = \mathcal{O}(0.5 \text{ MeV})$ and $\Gamma(\psi_g(C = +) \rightarrow \text{light hadrons}) = \mathcal{O}(5 \text{ MeV})$.

A detailed list of search channels can be found in Ref. [16].

In conclusion, even though experimental evidence for gluonic excitations in mesons is already emerging, forthcoming B -factories have tantalizing prospects for exciting dynamical glue.

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