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IS THE $\epsilon(700)$ A FOUR QUARK BAG?

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ABSTRACT

Following the proposal of Jaffe and Johnson that the lowest mass O^{++} nonet should be composed of $qq\bar{q}\bar{q}$ states, we use the results of recent analyses of high statistics data to show that the $\epsilon(700)$ does indeed have couplings to mesons and baryons in keeping with it being a predominantly $\bar{u}udd$ state.

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More complicated quark configurations than the expected $q\bar{q}$ of mesons (M_2) and qqq of baryons (B) have been shown to bind in several dynamical schemes incorporating colour¹⁾⁻⁵⁾. The simplest of these multiquark states are mesons composed of four quarks ($qq\bar{q}\bar{q}$, M_4): these naturally arise in the MIT bag model, for example⁶⁾. While some of these states have a very strong coupling to $\bar{B}B$ channels and deserve the name baryonium⁷⁾, others have no such special relationship to baryon channels and can decay just as well to multimeson modes. Indeed, if the relative orbital angular momentum of each pair of constituent quarks is small, these states will readily dissociate into two $q\bar{q}$ (M_2) mesons. The bag just falls apart.

This M_4 decay needs no $q\bar{q}$ pair to be produced, in contrast to the decay of an M_2 meson. Thus the M_4 decay may be regarded as superallowed: for, in a QCD framework, one argues that the couplings of these mesons, g , satisfy the approximate relation

$$g(M_4 \rightarrow M_2 M_2) : g(M_2 \rightarrow M_2 M_2) = 1 : \alpha_s/\pi \quad (1)$$

with one factor of α_s -- the running coupling constant of quark-gluon interactions -- for each $q\bar{q}$ pair produced. As is common practice in such a superficial discussion, we ignore (for the moment at least) the question of what is the exact momentum at which α_s is to be evaluated. For a low mass state especially, this could, of course, be so low that $\alpha_s/\pi \sim 1$ (see later). However, if, in the M_2 decay, α_s/π is really less than one, the M_4 decay will be superallowed, resulting in the ratio of Eq. (1) being larger than one. If this is the case, we may similarly expect the coupling of an M_4 meson to $\bar{B}B$ to be larger than that of an M_2 meson too (with the same caveats as before), since

$$g(M_4 \rightarrow \bar{B}B) : g(M_2 \rightarrow \bar{B}B) = \left(\frac{\alpha_s}{\pi}\right) : \left(\frac{\alpha_s}{\pi}\right)^2 \quad (2)$$

The on-shell coupling to $\bar{B}B$ is, of course, not accessible if the meson states we compare are much below 2 GeV. Nonetheless, the relation of Eq. (2) should still hold if the baryons are off-shell, in which case this can be explored in backward production.

Now the lowest multiplet of M_4 states contains no "exotic" members and is just a normal SU_3 nonet^{8),1)}. Jaffe and Johnson⁶⁾ have shown, in the MIT bag model, that this lowest 0^{++} nonet has mass below 1 GeV and propose that this is lower in mass than $q\bar{q}$ p-states, which form a conventional 0^{++} nonet. Counter

to the description of Morgan⁹⁾, they identify the broad $\epsilon(700)$ as an isoscalar $q\bar{q}q\bar{q}$ state. The $\epsilon'(1250)$ -- if such a state is really needed in addition to an ϵ and S^* to describe the $\pi\pi$ phase shift, δ_0^0 ^{9),10)} -- would then be the corresponding number of the $q\bar{q}$ nonet. Leaving aside the vexing question of where are all the states in the higher mass conventional nonet¹¹⁾, we set about asking in this note, whether the $\epsilon(700)$ really has the properties we expect of a four quark meson, viz. Eqs. (1) and (2).

I) As, of course, noted by Jaffe and Johnson⁶⁾ clear indications that the $\epsilon(700)$ may be a $q\bar{q}q\bar{q}$ state are provided by the fact that $\Gamma_\epsilon \gg \Gamma_\rho$, suggesting α_s/π is small despite the low mass of the states. However, before we can proceed to check Eq. (2) too, which is the main point of this paper, we must be able to quantify the relationship of Eq. (1). This is not quite straightforward, despite the fact that both ϵ and ρ are elastic $\pi\pi$ resonances. The difficulty is that the ϵ is a very broad structure not easily described by a simple Breit-Wigner form over its entire width with straightforwardly interpretable couplings. For a narrow elastic resonance, the coupling is simply related to the width, which in turn can be defined in several equivalent ways, two examples being (i) from the imaginary part of the pole position on the second sheet or (ii) from the residue of this pole. For a broad structure like the ϵ , such definitions are highly ambiguous. Fits to the $I = 0$ s-wave $\pi\pi$ phase shift with a pole form give the imaginary part of its position to be anywhere from 320 MeV to infinity¹²⁾. Moreover, its residue bears little relationship to the strength of the physical coupling, the pole being so distant¹²⁾.

We therefore choose instead to specify the coupling of each resonance to $\pi\pi$ in a pragmatic way by its effect on the real $M_{\pi\pi}$ axis, where experiments are performed. This can be done by defining

$$\frac{2}{\pi} \int_{M_1}^{M_2} dM |f_\ell(M^2)|^2 = g_\ell^2 \quad (3)$$

which corresponds to integrating over the experimentally determined partial wave intensities for $\pi\pi$ scattering, where M_1, M_2 specify the appropriate resonance region. This choice of definition is motivated by its straightforward relation to data and by the fact that for a narrow resonance (one narrower than the ρ) $g_\ell^2 \rightarrow \Gamma_\ell$ ^{*}). In practice, we take $M_1 = 2\mu$, while $M_2 = 1 \text{ GeV}$ for the ϵ , so

*) Of course, multiplying the integrand of Eq. (3) by any function with the value of one at the resonance mass would have this same limit. We comment on this ambiguity below.

as to avoid the S^* region, and $M_2 = 1.2$ GeV for the ρ . We can then quantify the superallowed nature of the $\epsilon \rightarrow \pi\pi$ decay by

$$\frac{g_{\epsilon\pi\pi}^2}{g_{\rho\pi\pi}^2} = 2.1 \pm 0.1 \quad (4)$$

using the results of the phase shift analyses of the CERN-Munich data^{13)*)}.

As already remarked, Eq. (3) is not a unique definition of the effective coupling for real M^2 , though it is a most intuitive one physically. However, we could, for example, equally well take $1/\pi \int_{M_1}^{M_2} dM^2 |f_\ell(M^2)|^2 = \gamma_\ell^2$, which in the narrow resonance limit becomes $m_\ell \Gamma_\ell$. Numerically, $\gamma_{\epsilon\pi\pi}^2 / \gamma_{\rho\pi\pi}^2 = 1.95 \pm 0.1$. Since this is so close to the result of Eq. (4), we do not consider the ambiguity in the quantification of "superallowedness" any further.

From the ratio of Eq. (4) we learn then that, in the present context, a typical phenomenological value for $(\alpha_s/\pi)^2$ is $\frac{1}{2}$.

II) With the scale thus set, the purpose of this note is to test whether the ϵ also has a larger coupling than the ρ to $N\bar{N}$, as consistency with a $qq\bar{q}\bar{q}$ nature would require, Eq. (2). Since these light mesons can obviously only couple to off-shell baryons, we can explore their couplings in this situation by considering their production in backward scattering. Such a process is expected to be controlled by baryon exchange at sufficiently high energies. However, the higher the energy the smaller the cross-section, making a clean separation of s and p wave dipion production unfeasible. We therefore propose to study the process $K^- p \rightarrow \Lambda(\pi^+\pi^-)$ at 4.25 GeV/c¹⁴⁾. While this may be thought a rather low momentum, nucleon exchange is clearly indicated by the dip seen at $u \approx -0.15$ GeV²¹⁴⁾, which is characteristic of this $I_u = \frac{1}{2}$ exchange. Moreover, these data have more than sufficient statistics to allow a clear s and p wave separation.

The lowest order mechanisms for producing four and two quark mesons in this process are shown in Figs. 1a,c. For later reference, we also illustrate a higher order contribution to M_4 production (Fig. 1b), which by the QCD rules should be suppressed by factors of α_s from that of Fig. 1a -- this we discuss later.

) If M_2 should be larger for the ϵ , e.g., 1.5 GeV¹⁰⁾, so that, after removing the S^ effect, there is no need for an $\epsilon'(1250)$ too, then the coupling for this wider ϵ , and hence the ratio of Eq. (4), would increase by some 30%. Here our definition of the $\epsilon(700)$ is the isospin zero $\pi\pi$ s-wave from threshold to 1 GeV, and no other.

In analogy with Eq. (3) we concern ourselves only with the couplings for real values of $M_{\pi\pi}$ and not off in the complex plane. We define the square of the effective couplings of the ϵ and ρ to $N\bar{N}$ (where the antinucleon is reggeized with mass squared equal to u) as the average coupling squared to each spin amplitude to which the resonance contributes -- whether helicity or transversity amplitude. We perform a maximum likelihood fit, as described in Ref. 14), event by event and determine the cross-sections for producing the $\pi^+\pi^-$ pair in an s and p wave state in each fixed u bin, for $0.6 \leq M_{\pi\pi} \leq 0.92$ GeV. We correct for the unseen $\epsilon \rightarrow \pi^0\pi^0$ mode and for the fact that the distribution of $\pi^+\pi^-$'s is only measured for part (though the dominant part) of the resonance range of Eq. (3)*).

Thus integrating over $\pi\pi$ mass in each effective resonance region, we obtain the ratio $g_{\epsilon N\bar{N}}^2(u)/g_{\rho N\bar{N}}^2(u)$. The result is shown in Fig. 2. It is seen that this ratio is certainly larger than one: indeed, it is larger than the corresponding ratio for $\pi\pi$ couplings. Fitting this for $0 \leq -u' \leq 1.6$ GeV² gives

$$\frac{g_{\epsilon N\bar{N}}^2(u)}{g_{\rho N\bar{N}}^2(u)} = 3.3 \pm 0.7 \quad \text{with a constant form}$$

$$= 4.5 + 1.3u \quad \text{with a linear form} \quad (5)$$

as shown in Fig. 2. Thus, the ϵ really has a much larger coupling than the ρ to $N\bar{N}$ in keeping with it having a $qq\bar{q}\bar{q}$ nature, as Jaffe has suggested.

We have only considered the coupling of the ϵ and ρ to $N\bar{N}$, where this is physical, i.e., where one baryon is on-shell and the other has a mass squared of $u \leq 0$. However, the ϵ and ρ also make important contributions to the amplitude for $\pi\pi \rightarrow N\bar{N}$ but in the unphysical region. Here, fixed t and u dispersion relations can, in principle, be evaluated using data on $\pi N \rightarrow \pi N$ and $N\bar{N} \rightarrow \pi\pi$ scattering, in order to determine these same ϵ and ρ couplings, but where now both nucleons are off-shell. Such an analysis is rather sensitive to

*) This latter correction is made by scaling the coupling for each wave by

$$\int_{M_1}^{M_2} dM |f_\ell|^2 / \int_{0.6 \text{ GeV}}^{0.92 \text{ GeV}} dM |f_\ell|^2$$

With the choice of resonance range of Eq. (3), more than 80% of each resonance is included in the $\pi\pi$ mass range we fit.

the form of the ϵ pole used, with all the ambiguities discussed above. Nonetheless, the analyses of Ref. 15), quoted in Ref. 16), are in keeping with our results that the ratio of Eq. (5) is greater than one. This consistency occurs despite the different kinematic regions -- the couplings we measure being physical.

As already mentioned, there exists a second simple mechanism for ϵ production (Fig. 1b, cf 1a,1c). This, according to the QCD rules, should be suppressed compared to the graph of Fig. 1a if the appropriate $\alpha_s/\pi < 1$. We now set about testing if this suppression really occurs.

Let us consider the analogues of graphs (a,b,c) of Fig. 1 for forward dipion production. These are shown in Fig. 3 -- (a,b) for M_4 production, (c) for M_2 . We assume the dominant mechanism for $0^{++} M_4$ production is unnatural parity $q\bar{q}$ exchange^{*)}: for the process $\pi^- p \rightarrow \pi^- \pi^+ n$, there is ample evidence for π exchange predominating. It is data on this reaction at 17.2 GeV/c¹³⁾ that provide the $\pi\pi$ phase shifts we have used above, from which we have deduced the ratio of Eq. (4). Naively counting powers of α_s/π , we would believe it is the mechanism (a) rather than (b) that is responsible for this result. Now consider $\pi^- \pi^+$ production in $K^- p \rightarrow (\pi^- \pi^+) \Lambda$. If the ϵ is mainly a $u\bar{u}d\bar{d}$ state with very little admixture of $(\bar{u}u + \bar{d}d)\bar{s}s$ (which describes the orthogonal S^* state) then $K^- p \rightarrow \epsilon \Lambda$ cannot occur by mechanism (a) but only (b) of Fig. 3. Superficially this looks very similar to the corresponding ρ production diagram (Fig. 3c), with which we compare its size. This we can do by considering once again results from the high statistics $K^- p$ experiment¹⁴⁾, but now for forward $\pi\pi$ production.

While 0^{++} production occurs solely by unnatural parity K, K_A, K_B exchange, 1^{--} states can be produced by natural parity K^*, K^{**} exchange also. However, by performing a helicity decomposition of the final pion states, we can, using the same maximum likelihood analysis¹⁴⁾, not only distinguish s and p wave dipion production but also separate unnatural from natural parity exchanges. In order to compare analogous couplings for the ϵ, ρ , we note that in ρ production only the helicity zero contribution is dominantly K exchange. By separating this term, we can deduce the effective spin-averaged ϵ and ρ couplings to $K\bar{K}$, where the antikaon is off-shell with a mass squared of t . By comparing these couplings, we determine what price (if any) we pay for a $u\bar{u}d\bar{d}$ resonance to annihilate internally one of its quark pairs before coupling to $K\bar{K}$ (see left half of Fig. 3b). The ratio of these couplings squared is shown in Fig. 4 in fixed t' bins: the result is close to one. Indeed a fit for $0 \leq -t' \leq 0.8 \text{ GeV}^2$ gives

*) This exchange is presumably higher lying and hence more important than the leading unnatural parity $q\bar{q}q\bar{q}$ exchange.

$$\frac{g_{\epsilon K\bar{K}}^2(t)}{g_{\rho K\bar{K}}^2(t)} = 0.90 \pm 0.09 \quad (6)$$

as seen in Fig. 4 as the hatched band.

As expected, if the ϵ contains no strange quarks, this ratio is much less than the corresponding ratio of $\pi\pi$ couplings, Eq. (4). Moreover, the fact that the ratio of couplings to $K\bar{K}$ for ϵ and ρ is close to unity implies that for an $I = 0$ 0^{++} $q\bar{q}$ system with mass below 1 GeV to produce a $q\bar{q}$ internally to form the $qq\bar{q}\bar{q}$ ϵ (Fig. 3b) is uninhibited -- with the mediating gluon carrying only a small momentum so that $\alpha_s/\pi \sim 1$. This means that the diagram of Fig. 1b is suppressed by just one factor of $\alpha_s/\pi < 1$ compared to Fig. 1a and not two as would naïvely appear to be the case.

By the use of high statistics data (120 events/ μb) on K^-p scattering, we have seen that s wave dipion production has a much larger coupling to $N\bar{N}$ than the p wave, even larger than the corresponding ratio to $\pi\pi$. This is what we would expect if the $\epsilon(700)$ were an M_4 meson and the ρ an M_2 resonance. Moreover, in keeping with the assignment of $u\bar{u}d\bar{d}$ for the ϵ "quark molecule", we find its coupling to $K\bar{K}$ to be no larger than that of the ρ . We conclude that the $\epsilon(700)$ does appear to behave, in its coupling to mesons and baryons, as a $u\bar{u}d\bar{d}$ bag, thereby shedding light on a new chapter of meson spectroscopy.

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Figure captions

- Fig. 1 : Quark diagrams for the backward production of the ϵ as a $qq\bar{q}\bar{q}$ state (in a,b) and of the ρ , a $q\bar{q}$ state (in c), and their subsequent decay to $\pi\pi$ in $K^-p \rightarrow \Lambda(\pi\pi)$.
- Fig. 2 : Results for the ratio of the square of the couplings to $\bar{N}N$ for ϵ and ρ in fixed u' bins: $u' = u - u_{\min}$ with $0.05 \geq u_{\min} \geq -0.01 \text{ GeV}^2$ for $0.62 \leq M_{\pi\pi} \leq 0.9 \text{ GeV}$. The lines are fits to this ratio; solid: a constant fit, dashed: a linear function of u' .
- Fig. 3 : Quark diagrams for the forward production of the ϵ as a $qq\bar{q}\bar{q}$ state (in a,b) and of the ρ , a $q\bar{q}$ state (in c), and their subsequent decay to $\pi\pi$ in $MN \rightarrow (\pi\pi)B$.
- Fig. 4 : Results for the ratio of the square of the coupling to $K\bar{K}$ for ϵ and ρ in fixed t' bins: $t' = t - t_{\min}$ with $-0.01 \geq t_{\min} \geq -0.04 \text{ GeV}^2$ for $0.62 \leq M_{\pi\pi} \leq 0.9 \text{ GeV}$. The hatched band is the result of a constant fit to this ratio.

Fig. 1

Fig. 2

Fig. 4