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IS THE $\delta(980)$ A BROAD $q\bar{q}q\bar{q}$ STATE ?

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ABSTRACT

The conventional ($q\bar{q}$) or unconventional ($q\bar{q}q\bar{q}$) interpretation of the scalar $\delta(980)$ meson is reconsidered by analyzing a series of processes ($\eta' \rightarrow \eta\pi\pi$ decay, $D, E \rightarrow \delta\pi$ decays and δ^0 -tadpole contributions to e.m. mass-mixings) which are sensitive to these alternative interpretations. A conventional ($q\bar{q}$) nature for the $\delta(980)$ turns out to be preferred in all the cases.

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The existence and identification of unconventional hadronic states (i.e., non- $q\bar{q}$ mesons or non- qqq baryons) is usually recognized¹⁾ as a crucial point in present day, QCD-inspired theories. Besides glueballs, popular candidates for such states are the $q\bar{q}q\bar{q}$ colour-singlet systems with $J^{PC} = 0^{++}$ which, according to the original proposal by Jaffe²⁾, should be identified with the lowest lying scalar mesons with masses around 1 GeV. Among these, one has the well-established isovector resonance $\delta(980)$, with mass and (apparent) width³⁾

$$m_\delta = 981 \pm 3 \text{ MeV}, \quad \Gamma_\delta = 52 \pm 8 \text{ MeV} \quad (1)$$

and two isoscalar states, the well-defined $S^*(980)$ and the ambiguous $\pi\pi$ resonance $\epsilon(\sim 700)$. The purpose of the present paper is to discuss the nature of the $\delta(980)$ resonance or, more precisely, to discriminate whether it is a conventional $q\bar{q}$ state ($\delta^0 \sim (u\bar{u} - d\bar{d})/\sqrt{2}$) or an unconventional $q\bar{q}q\bar{q}$ system ($\delta^0 \sim (u\bar{u} - d\bar{d})s\bar{s}/\sqrt{2}$). The main differences between these alternative interpretations originate in the different decay mechanisms which in the last case reduce to a simple dissociation of a $q\bar{q}q\bar{q}$ system into two $q\bar{q}$ mesons. This requires²⁾ a decay width much larger than that quoted in Eq. (1) (but compatible with some observations; see below) and coupling ratios which are very different from those of a conventional $q\bar{q}$ -state.

Several attempts⁴⁾⁻⁹⁾ to understand the quark content and width of the δ meson deserve attention. Törnqvist⁴⁾, on the basis of a unitarized quark model, finds a broad δ which is a unitarized, remnant $q\bar{q}$ -state. In a potential model approach^{*}), Weinstein and Isgur⁵⁾ have solved the four-particle Schrödinger equation with a simplified Hamiltonian and concluded that if any such multiquark systems exist, they are likely to be weakly bound $K\bar{K}$ -states. On the other hand, in a coupled channel ($\delta \rightarrow \pi\eta, K\bar{K}$) analysis performed by Flatté⁶⁾, the data¹¹⁾ on $Kp \rightarrow \Sigma\delta$ transitions were found to be compatible with a rather narrow ($\Gamma_\delta \sim 80 \text{ MeV}$), conventional δ but also with a broad ($\Gamma_\delta \sim 300 \text{ MeV}$), $q\bar{q}q\bar{q}$ state. This unconventional interpretation was subsequently criticized by Martin et al.⁷⁾ who noticed that it led to a poor description of the $K\bar{K}$ mass-spectrum away from threshold, and by Irving⁸⁾ who repeated the coupled channel analysis (taking the production mechanisms into account) and obtained a narrow width ($\Gamma_\delta \sim 51 \text{ MeV}$) and couplings consistent only with a $q\bar{q}$ interpretation. On the contrary, Achasov et al.⁹⁾ have reanalyzed the same set of data (coupling also

^{*}) In this framework, it has been shown¹⁰⁾ that $QQ\bar{Q}'\bar{Q}'$ states made of four heavy quarks are in general not stable, except perhaps when $m_Q/m_{Q'} \gtrsim 300$.

the $\pi\eta'$ channel) and concluded that a good description can also be achieved in terms of a negligible background and a broad ($\Gamma_\delta \sim 280$ MeV) δ resonance which couples to the different channels consistently only with a $q\bar{q}q\bar{q}$ interpretation.

It follows from the preceding discussion that a definite conclusion concerning the quark content and the decay width of the δ is hard to achieve at least on the basis of simplified models or detailed coupled channel analyses of the $Kp \rightarrow \Sigma\delta$ data (where the production mechanism of the δ on baryons could play an important role). For these reasons we turn our attention to a series of processes which are free from the above uncertainties and where the quark content of the δ is expected to play an essential role. These processes are

- i) the $\eta' \rightarrow \eta\pi\pi$ decay,
- ii) the $D, E \rightarrow \eta\pi\pi$ decays, and
- iii) the tadpole contributions to e.m. mass differences and mixings.

The $\eta' \rightarrow \eta(p)\pi(q_1)\pi(q_2)$ decay and the dominance¹²⁾ of the $\eta' \rightarrow \delta\pi \rightarrow \eta\pi\pi$ decay chain (from which relevant information on the $\delta\pi\eta$ and $\delta\pi\eta'$ couplings can be extracted) have already been discussed in a previous work¹³⁾. The δ -dominated amplitude is given by^{*)}

$$A_\delta(\eta' \rightarrow \eta\pi\pi) = g_{\delta\eta'\pi} g_{\delta\eta\pi} \left\{ [(p+q_1)^2 - m_\delta^2 - i m_\delta \Gamma_\delta]^{-1} + [q_1 \rightleftharpoons q_2] \right\} \quad (2)$$

where the total width Γ_δ can be reasonably approximated³⁾ by $\Gamma_\delta \approx \Gamma(\delta \rightarrow \eta\pi) = g_{\delta\eta\pi}^2 |\vec{q}| / 8\pi m_\delta^2$. From Eq. (2) and the experimental value³⁾

$$\Gamma(\eta' \rightarrow \eta\pi\pi)_{\text{exp}} = 187 \pm 40 \text{ keV} \quad (3)$$

one can easily deduce a value for $g_{\delta\eta\pi}^2$ or, equivalently, for $\Gamma(\delta \rightarrow \eta\pi)$ provided one knows the ratio $g_{\delta\eta'\pi}^2 / g_{\delta\eta\pi}^2$. If the δ meson is a conventional $q\bar{q}$ state, one has

$$g_{\delta\eta'\pi}^2 / g_{\delta\eta\pi}^2 \equiv K_0 = 0.55 \pm 0.06 \quad (4)$$

where K_0 is the relative content of non-strange quarks in the η' and η wave functions whose numerical value (4) is known from several independent analyses¹⁴⁾. In this case one obtains

*) The δ meson propagator in Eq. (2) induces $\pi\pi$ and $\pi\eta$ mass distributions which, essentially, coincide with those obtained from a constant amplitude and are therefore in good agreement with data.

$$\Gamma(\delta \rightarrow \eta\pi)_{\delta(q\bar{q})} = 32 \pm 8 \text{ MeV} \quad (5)$$

On the other hand, if the δ is a four-quark state one has $g_{\delta\eta\pi}^2/g_{\delta\eta'\pi}^2 = K_0$ and, consequently,

$$\Gamma(\delta \rightarrow \eta\pi)_{\delta(q\bar{q}q\bar{q})} = 17 \pm 4 \text{ MeV} \quad (6)$$

When these alternative results (5) and (6) are compared with the experimental value (1) quoted for the total δ -width, one has to conclude that a $q\bar{q}$ interpretation for the δ meson is favoured.

A similar conclusion has been reached independently by Intemann and Greenhut¹⁵⁾ from a more detailed analysis of the $\eta' \rightarrow \eta\pi\pi$ Dalitz plot and the related $\eta' \rightarrow 3\pi$ e.m. decay. However, the real meaning of our preceding discussion is that a reasonable δ -dominance description^{12),13),15)} of the $\eta' \rightarrow \eta\pi\pi$ decay rate (3) is in sharp disagreement with the broad δ -meson traditionally associated with its $q\bar{q}q\bar{q}$ interpretation. For example, the recent proposal by Achasov et al.⁹⁾ of a broad, $\Gamma(\delta \rightarrow \eta\pi) \approx 280 \text{ MeV}$, $q\bar{q}q\bar{q}$ δ -meson leads to $g_{\delta\eta\pi}^2 = K_0 g_{\delta\eta'\pi}^2 = 21.4 \text{ GeV}^2$ and finally to $\Gamma(\eta' \rightarrow \eta\pi\pi) \approx 12 \text{ MeV}$, which is two orders of magnitude larger than the experimental value (3). This striking discrepancy is due to the large width attributed to the δ and cannot be substantially diminished by invoking either a (non- δ) background (which is absent in the analysis by Achasov et al.⁹⁾ or a $K\bar{K}$ threshold effect (which is essentially inoperative for the values of the invariant masses of the $\pi\eta$ system involved in the $\eta' \rightarrow \eta\pi\pi$ decay).

We now turn to a similar discussion concerning the decay chains

$$D \rightarrow \delta\pi \rightarrow \eta\pi\pi, \quad E \rightarrow \delta\pi \rightarrow \eta\pi\pi \quad (7)$$

of the axial-vector mesons $D(1285)$ and $E(1420)$. As before, we are dealing with $\eta\pi\pi$ final states but the δ resonances are now produced on-mass-shell and thus one can simply consider the two-body decays $D \rightarrow \delta\pi$ and $E \rightarrow \delta\pi$. We are directly interested in the ratio

$$R \equiv \Gamma(E \rightarrow \delta\pi) / \Gamma(D \rightarrow \delta\pi) \quad (8)$$

which depends on the quark content of the D and E mesons, the relative phase space factor and the $q\bar{q}$ or $q\bar{q}q\bar{q}$ nature of the final δ . Concerning the first point, one can safely conclude that the $s\bar{s}$ component of the D meson is smaller than that of its partner E. This is supported by the following experimental observations: i) one has³⁾ $m_E - m_D = 134 \pm 14$ MeV (moreover, the ideal mass mixing relations $m_{A_1} \approx m_D$ and $m_{A_1} + m_D \approx 2m_{Q_A}$ are approximately fulfilled), ii) D mesons are produced (roughly five times) more copiously than E mesons in πp scattering and $p\bar{p}$ annihilation in flight, and iii) one has³⁾ $\Gamma(D \rightarrow 4\pi)/\Gamma(D \rightarrow K\bar{K}\pi) = 4.1 \pm 1.5$ and $\Gamma(E \rightarrow 4\pi)/\Gamma(E \rightarrow K^*\bar{K} + c.c.) < 0.90$. Independently, the phase space for the $E \rightarrow \delta\pi$ decay turns out to be 2.6 times larger than that of the $D \rightarrow \delta\pi$ decay. Consequently, if the δ is a $q\bar{q}q\bar{q}$ system coupled through its $s\bar{s}$ piece to the D and E, one necessarily has

$$R_{\delta(q\bar{q}q\bar{q})} = \Gamma(E \rightarrow \delta\pi)/\Gamma(D \rightarrow \delta\pi) \gg 1$$

which is hard to reconcile with the experimental observation of a small $E \rightarrow \delta\pi$ branching ratio³⁾ which leads to $R_{\text{EXP}} \lesssim 1$.

A more quantitative analysis of the ratio R, Eq. (8), can be made in terms of the D-E mixing angle, θ_1 . Fits of the data on masses and decay widths of the $J^{PC} = 1^{++}$ mesons give¹⁶⁾ $\theta_1 \approx 67^\circ$. Imposing the SU(3) mass formula as an additional constraint leads to $\theta_1 \approx 44^\circ$. A more accurate analysis of Törnqvist¹⁷⁾, in terms of a unitary (energy-dependent) mixing scheme, leads to $\theta_1(s=m_D^2) \approx 49^\circ$ and $\theta_1(s=m_E^2) \approx 60^\circ$. Assuming the extreme values of these analyses^{16),17)}, correcting by the above-mentioned phase space factor, and introducing the experimental width³⁾ $\Gamma(D \rightarrow \delta\pi) = 9.7 \pm 4.1$ MeV allows us to find

$$\Gamma(E \rightarrow \delta\pi)_{\delta(q\bar{q})} \simeq 9.2 \pm 3.9 \text{ MeV} \quad (9)$$

$$\Gamma(E \rightarrow \delta\pi)_{\delta(q\bar{q}q\bar{q})} \simeq 68 \pm 28 \text{ MeV} \quad (10)$$

when $\theta_1 \approx 67^\circ$. The case $\theta_1 \approx 44^\circ$ leads to

$$\Gamma(E \rightarrow \delta\pi)_{\delta(q\bar{q})} \simeq 0.8 \pm 0.3 \text{ MeV} \quad (11)$$

$$\Gamma(E \rightarrow \delta\pi)_{\delta(q\bar{q}q\bar{q})} \simeq 800 \pm 300 \text{ MeV} \quad (12)$$

For both mixing angles one reaches the same conclusion, namely that while a $q\bar{q}$ δ -meson implies the values of $\Gamma(E \rightarrow \delta\pi)$ quoted in Eqs. (9) and (11), which are not a large fraction of the known E total width³⁾ $\Gamma_E = 50 \pm 10$ MeV (as experimentally required³⁾), the alternative assumption of a $q\bar{q}q\bar{q}$ δ -meson leads to the large values (10) and (12) for $\Gamma(E \rightarrow \delta\pi)$, in sharp disagreement with the data.

Obviously, the situation becomes more dramatic and the preceding conclusion reinforced when the mixing angle θ_1 approaches the ideal value $\theta_{id} \approx 35^\circ$, for which one has $D = (u\bar{u} + d\bar{d})/\sqrt{2}$ and $E = s\bar{s}$. That this could be the case in nature is suggested by some recent results. Experimental evidence¹⁸⁾ for a new pseudoscalar object, $i(1440)$, nearly degenerate with the $E(1420)$ meson, has led to phenomenological analyses^{19),20)} on the spectroscopy of the E and i states. Ishikawa and Chanowitz¹⁹⁾ have interpreted the $i(1440)$ as a glueball, whereas Lipkin et al.²⁰⁾ have given the status of $q\bar{q}$ radial excitation to this state. Remarkably enough, both lines of analyses^{19),20)} suggest that the E and D mesons are likely to be almost ideally mixed ($\theta_1 \approx 35^\circ$). Therefore, both interpretations of the $i(1440)$ exclude an exotic nature for the $\delta(980)$.

Let us finally turn to the discussion of the e.m. mass differences and e.m. mixings inside the vector-meson and pseudoscalar-meson nonets for which the contribution of tadpole²¹⁾ diagrams is known to be unambiguously required. The tadpole is a neutral isovector object with $J^{PC} = 0^{++}$ and therefore its identification with the physical $\delta^0(980)$ meson is suggestive and has been widely accepted²¹⁾. To proceed with our investigation into the nature of the δ meson we have to adhere to this traditional identification, although we recognize that other realizations of the old tadpole mechanism (such as those proposed^{22),23)} in terms of quark mass differences) could be more attractive.

The experimental information^{3),24)} concerning the $\rho - \omega$ and $\rho - \phi$ e.m. mixings is rather satisfactory and has been recently reviewed^{22),25)}. In terms of the mass matrix elements, this information is given by the values (in 10^{-3} GeV^2)

$$\begin{aligned} | \text{Im } m_{\rho\omega}^2 | &\ll \text{Re } m_{\rho\omega}^2 = -3.5 \pm 0.2, \\ \text{Im } m_{\rho\phi}^2 &= 0.53 \pm 0.18, \quad \text{Re } m_{\rho\phi}^2 = -0.58 \pm 0.18 \end{aligned} \quad (13)$$

The contributions of the intermediate states allowing for these transitions can easily account^{22),25),26)} for the data on $m_{\rho\phi}^2$ and $\text{Im } m_{\rho\omega}^2$ but not for $\text{Re } m_{\rho\omega}^2$, which is predicted to be $+0.7 \times 10^{-3} \text{ GeV}^2$. Such a discrepancy constitutes an

excellent example of the necessity of tadpole contributions which, on the other hand, have to preserve the satisfactory agreement obtained for the $\rho - \phi$ transition. This is perfectly achieved with a tadpole having the properties of a $q\bar{q} \delta^0$ -meson which, due to the Zweig rule, has a coupling to $\rho\phi$ strongly suppressed with respect to $\rho\omega$. By contrast, a tadpole $\delta^0 = (u\bar{u} - d\bar{d})s\bar{s}/\sqrt{2}$ leads to the opposite effect and there is no hope of accounting for the experimental values (13).

The pseudoscalar nonet can be similarly treated. Now, the relevant experimental data^{*)} are^{3),22),27)} (in 10^{-3} GeV^2)

$$(m_{\pi^+}^2 - m_{\pi^0}^2)^{\text{exp}} = 1.27, (m_{K^+}^2 - m_{K^0}^2)^{\text{exp}} = -4.0, (m_{\eta\pi}^2)^{\text{exp}} \simeq -3.6 \quad (14)$$

which, from a theoretical point of view^{21),28)}, require two types of contributions. The first one is the conventional photonic contribution²⁸⁾ which leads to the following estimates^{28),29)} (in 10^{-3} GeV^2)

$$(m_{\pi^+}^2 - m_{\pi^0}^2)^{\text{e.m.}} = 1.2, (m_{K^+}^2 - m_{K^0}^2)^{\text{e.m.}} = +2.5, (m_{\eta\pi}^2)^{\text{e.m.}} = +0.41 \quad (15)$$

where the quark content of the physical η has been taken^{**) in agreement¹⁴⁾ with the second equality of Eq. (4). Comparing Eqs. (14) and (15) one clearly observes the necessity of a second type of contribution usually associated with a δ tadpole²¹⁾ (which preserves the achieved agreement in the π sector). In order to reach the experimental result for $(m_{K^+}^2 - m_{K^0}^2)$ the strength of that contribution must be $(m_{K^+}^2 - m_{K^0}^2)^{\text{tad}} = -6.5 \times 10^{-3} \text{ GeV}^2$. This implies (in 10^{-3} GeV^2)}

$$(m_{\eta\pi}^2)_{\delta(q\bar{q})} = (m_{\eta\pi}^2)^{\text{e.m.}} + \frac{\sqrt{2}}{\sqrt{3}} (m_{K^+}^2 - m_{K^0}^2)^{\text{tad}} = -3.9 \quad (16)$$

^{*)} The quoted value of the $\eta\pi$ e.m. mixing is an average of several results (ranging from -3.1×10^{-3} to $-4.7 \times 10^{-3} \text{ GeV}^2$) coming from different analyses^{22),27)} on the $\eta \rightarrow 3\pi$ decays, the differences in binding energies for light hypernuclei and the e.m. mass splitting of hadrons.

^{**) We take $K_0 = 1/2$ for numerical calculations. Using a different $\eta - \eta'$ mixing angle (in the usually accepted range) does not modify the main conclusions of this δ -tadpole study.}

$$(m_{\eta\pi}^2)_{\delta(q\bar{q}q\bar{q})} = (m_{\eta\pi}^2)^{e.m.} - \frac{1}{\sqrt{6}} (m_{K^+}^2 - m_{K^0}^2)^{tad.} = + 3.1 \quad (16)$$

for the full contribution to the $\pi\eta$ e.m. mixing. Again, a $q\bar{q}$ interpretation for the δ^0 turns out to be in reasonable agreement with the data (14) whereas the alternative $q\bar{q}q\bar{q}$ interpretation has to be discarded.

In conclusion, a (rather exhaustive) series of processes, whose dynamics has been found to be sensitive to the quark content of the $\delta(980)$ meson, has been discussed. These processes include the $\eta' \rightarrow \eta\pi\pi$ decay, the D and $E \rightarrow \delta\pi$ decays and the δ -tadpole contribution to e.m. mass differences and mass mixing phenomena for pseudoscalar and vector mesons. In the first case, the description of the $\eta' \rightarrow \eta\pi\pi$ decay width in terms of a δ -dominated amplitude requires a rather narrow δ -width and in all the cases the $q\bar{q}$ interpretation for the $\delta(980)$ turns out to be favoured. Even if the evidence furnished by each separate process is not compelling, it seems reasonable to conclude from the over-all picture that a $q\bar{q}q\bar{q}$ nature of the $\delta(980)$ can safely be excluded.

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