Quark-structure of the $\delta(980)$ meson

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A nonlocal quark model is used to calculate the width of the decay $\eta' \to \eta\pi\pi$ through an intermediate $\delta(980)$ meson ($\eta' \to \delta\pi \to \pi\pi\eta$) under the two assumptions that the δ meson is a two-quark system and a four-quark system. The decay width calculated in the two-quark case agrees with experimental data, while that found in the four-quark case is about 50 times the experimental value.

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The nonet of scalar mesons $S(J^P = 0^+)$ is the subject of a lively discussion in hadron spectroscopy. It has recently been suggested on the basis of the quark bag model that scalar mesons $S(J^P = 0^+)$ with masses in the 1-MeV region may be four-quark systems.[1] Achasov *et al.*[2] assert that the strong coupling of the $\delta(980)$ meson with the $K\bar{K}$ and $\pi\eta$ channels is evidence of a four-quark structure for this particle, since they believe the total decay width of the δ meson to be $\Gamma_\delta \approx 280$ MeV, rather than $\Gamma_\delta = 52 \pm 8$ MeV (Ref. 3). The question has not been finally resolved. One way to decide between two-quark and four-quark structures for the δ meson is to analyze the decay

$$\eta' \to \eta\pi\pi, \tag{1}$$

since the η' meson can decay through a channel with a δ resonance, i.e., $\eta' \to \eta\delta \to \eta\pi\pi$. The width of decay (1) has been measured more or less accurately[3]:

$$\Gamma_{\text{expt}}(\eta' \to \eta\pi\pi) = (184 \pm 65)\ \text{keV}. \tag{2}$$

It is therefore definitely worthwhile to examine decay (1) to see what we can learn about the two- or four-quark structure of the δ meson.

Let us examine the decay $\eta' \to \eta\pi\pi$ on the basis of the nonlocal quark model (NQM) of Ref. 4, which is a self-consistent relativistic model of a quantum-field bag. This model has proved successful in describing a broad range of hadron decays while using only two parameters to characterize the quark field.[4]

1. Let us examine the assumption that the $\delta(980)$ meson is a two-quark system. Chiral invariance should be considered in an analysis of this decay, since four hadrons participate in the process. In the nonlocal quark model, chiral invariance has been introduced by means of hypothetical σ particles,[5] and on this basis predictions have been generated for the $\pi\pi$ and $K\pi$ scattering lengths and for the slope parameters in the decay $K \to 3\pi$. Figure 1 shows diagrams of the $\eta' \to \eta\pi\pi$ decay in this case.

Because of the chiral invariance,[5] diagrams a and b in Fig. 1 cancel out, so that the invariant amplitude is determined exclusively by diagram c. The amplitude is then written

$$M_{inv}(\eta' \to \eta\pi\pi) = g_{\eta'\pi\delta}\,\frac{1}{m_\delta^2 - (q_0 + q_2)}\,g_{\eta\delta\pi} + (q_2 \leftrightarrow q_1) \tag{3}$$

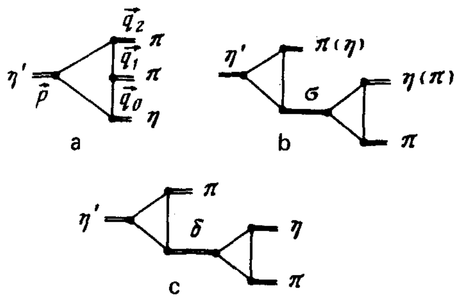

FIG. 1.

Here $g_{\eta'\pi\delta}$ and $g_{\eta\delta\pi}$, the structure factors of the corresponding quark units, are calculated by the standard procedure in the nonlocal quark model and written in the form

$$g_{\eta'\pi\delta} = g_0 \cos(\theta_\Sigma - \theta_\eta),$$

$$g_{\eta\pi\delta} = g_0 \sin(\theta_\Sigma - \theta_\eta),$$

where

$$g_0 = \frac{\sqrt{2}}{3} h_p \sqrt{h_\delta}\, 256 \frac{\pi}{L} V_5(\xi),$$

$\sin\theta_\Sigma = 1/\sqrt{3}$, θ_Σ is the ideal mixing angle, $\theta_\eta = -18°$ is the mixing angle of the η and η' mesons, $h_p = 0.13$ and $h_\delta = 0.12$ are the effective constants of the pseudoscalar and scalar mesons, respectively,[6] and $V_5(\xi)$ is an invariant integral, calculated in the standard manner[5] $[V_5(1.4) = 0.45]$.

2. London *et al.*[7] have constructed a Dalitz diagram for the decay $\eta' \to \eta\pi\pi$ in terms of the variables

$$\kappa = \frac{T_+ - T_-}{Q}\left(\frac{m_{\eta'} + 2m_\pi}{m_\eta}\right)^{1/2}, \qquad \phi = \frac{T_\eta}{Q}\,\frac{m_\eta + 2m_\pi}{m_\pi} - 1,$$

The experimental data do not suggest any resonance state. In our case, the invariant matrix element is determined by (3), and the Dalitz distribution is

$$\frac{\partial\Gamma(\eta' \to \eta\pi\pi)}{\partial\kappa\,\partial\phi} = \text{const}\left[\frac{1 - 0.053\phi}{(1 - 0.053\phi)^2 - 0.06\kappa^2}\right]^2$$

It is easy to see that the deviation from a uniform distribution is negligible in the parameter ranges $0 \leqslant \kappa \leqslant 1$ and $-1 \leqslant \phi \leqslant 1$.

3. Figure 2 is a diagram for the decay $\eta' \to \eta\pi\pi$ for the case in which the $\delta(980)$ meson is a four-quark system. The corresponding structure factors $g_{\eta'\pi\delta}$ and $g_{\eta\delta\pi}$ have

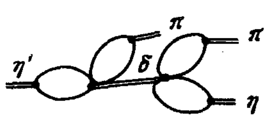

FIG. 2.

TABLE I.

	NQM		Achasov[2]	Bramon[8]	expt.[3]
	$(q\bar{q})$	$(q^2\bar{q}^2)$			
$g g^2_{\eta'\pi\delta}$ (GeV^2)	2,19	12,9	11,14	2,14 ± 0.33	–
$g^2_{\eta\pi\delta}$ (GeV^2)	3,84	22,6	22,28	3,9 ± 0,6	0,184 ± 0,065
Γ (MeV)	0,628	22	18,6	0.628 ± 0,15	

been calculated elsewhere.[6] Their numerical values are listed in Table I.

The width of the $\eta' \to \eta\pi\pi$ decay is calculated from[1)]

$$\Gamma(\eta' \to \eta\pi\pi) = g^2_{\delta\eta'\pi}\, g^2_{\eta\pi\delta}\ (7.5\times 10^{-5}\ \text{GeV}^{-3})\,. \tag{4}$$

The results are also shown in Table I.

4. Table I also shows the results of Ref. 8, where $g_{\delta\eta'\pi}$ and $g_{\delta\eta\pi}$, the structure constants, were determined by a phenomenological method. In Ref. 2, which furnished evidence for a four-quark structure of the δ meson, the structure constants were defined as $g_{\delta\pi\eta'} = g_{\delta KK}/\sqrt{3}$ and

$$g_{\delta\pi\eta} = -\sqrt{\frac{2}{3}}\, g_{\delta KK}\,, \quad \text{where} \quad \frac{g^2_{\delta KK}}{4\pi} = 2.66\ \text{GeV}^2\,.$$

The widths of the decay $\eta' \to \eta\pi\pi$ with these values of the constants are also shown in Table I, in the fourth column. We see from the table that if the experimental data on the $\eta' \to \eta\pi\pi$ decay width are correct, then the δ(980) meson is apparently a two-quark system.

Achasov *et al.*[2] commented that the matrix element in (3) could be reduced by a factor of about 1.5-2 by incorporating a mass operator in the propagator of the δ meson. Correspondingly, the width $\Gamma(\eta' \to \eta\pi\pi)$ would decrease by a factor of about three or four. In this case, the decay width $\Gamma(\eta' \to \eta\pi\pi)$ obtained by us for the two-quark case would be in extremely close agreement with the experimental value of 0.184 ± 0.065 MeV. This is evidence of a two-quark structure of the δ meson.

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[1)]In Eq. (5), in Ref. 8, there is an error in a calculation of the phase volume.

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