$\varphi\pi$ Production by Photons as a Signature for Four-Quark States

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$\varphi\pi$ production in e^+e^- annihilation and diffractive photoproduction are suggested as a signature for the production and decay of a vector $QQ\overline{Q}\overline{Q}$ state. Rates are estimated and photoproduction in particular appears to give a reasonable signal.

If the underlying dynamics of hadron spectroscopy is the clustering of colored Q and $\overline{Q}$ into color singlet systems, then $Q^2\overline{Q}^2$ states should necessarily exist. Jaffe[1] has suggested that the low-lying 0^+ nonet associated with the ϵ, δ, and S^* mesons might be an example of a $Q^2\overline{Q}^2$ system bound by magnetic color-exchange forces. Other states of this type have also been pointed out but there is no convincing evidence so far supporting the existence of magnetic exotics.

The most striking feature of the $Q^2\overline{Q}^2$ system is the presence of states with exotic isospin and hypercharge quantum numbers not found in the $Q\overline{Q}$ system. However, such states are not easily produced and detected: Jaffe has shown that the lowest-lying states are "cryptoexotic" and do not have exotic quantum numbers (the 0^+ nonet above), while states with exotic quantum numbers are higher and wider since they have more phase space for decay by breakup into two $Q\overline{Q}$ mesons. Furthermore, states with exotic quantum numbers are not produced from a single photon in e^+e^- annihilation or in photoproduction, nor in diffractive excitations or as s-channel resonances in nucleon-antinucleon annihilation. There is therefore interest in producing and identifying the cryptoexotic states of the $Q^2\overline{Q}^2$ system.

Since the cryptoexotic states have the same quantum numbers as the conventional $Q\overline{Q}$ mesons, their identification as true $Q^2\overline{Q}^2$ objects is difficult. Certain qualitative features of the scalar nonet support Jaffe's assignment, in particular the near degeneracy of the isovector δ with the isoscalar S^* which is dominantly coupled to kaons, rather than with the isoscalar which is dominantly coupled to pions as in the conventional quark-antiquark meson states; e.g., the ρ-ω and A_2-f degeneracies. However, this is still not very convincing.

One possible approach is to find an unambiguous signature in the decays, using modes forbidden for $Q\overline{Q}$ decays and allowed for $Q^2\overline{Q}^2$. One suggested candidate[2] is the $\varphi\pi$ decay mode forbidden by the Okubo-Zweig-Iizuka (OZI) rule for any $Q\overline{Q}$ decay. The discovery of a $\varphi\pi$ resonance would immediately indicate a new kind of hadron and suggest a $Q^2\overline{Q}^2$ state. This is also true for the $f'\pi$, $\psi\pi$, or any charmonium-pion resonance.

One feature of the color-spin magnetic interaction introduced by Jaffe is that the most strongly bound systems do not have quark pairs of the same flavor. This excludes the states with exotic quantum numbers and also requires that any low-lying isovector state contain a pair of strange quarks: e.g., $u\overline{d}s\overline{s}$. Such an isovector state will decay by breakup into two mesons containing a pair of strange quarks between them. If the state has even G parity, the $\varphi\pi$ mode is allowed, while the $\omega\pi$ mode is forbidden, in marked contrast to isovector mesons in the $Q\overline{Q}$ configuration with even G, such as the B meson which decays dominantly into $\omega\pi$ and not into $\varphi\pi$. Thus a promising candidate for an easily recognized $Q^2\overline{Q}^2$ state is an isovector, even-G meson detected by the $\varphi\pi$ decay mode.

The lowest isovector, even-G meson in the $Q^2\overline{Q}^2$ system is an axial-vector meson with the quantum numbers of the B meson but with $\varphi\pi$ allowed and $\omega\pi$ suppressed. However, such a state does not have a simple production mechanism and the allowed decay would be of s-wave character, giving a rather large width. It could be produced by K^* exchange in reactions like $K^-p \to \varphi\pi\Sigma$, but would be subject to the same ambiguities which hamper unambiguous identification of A_1 production: An incident kaon can produce a $\varphi\pi\Sigma$ final state by the kaon dissociating into φK followed by a rescattering of the kaon on the nucleon. Note that this state is not easily produced in weak interactions (in contrast to the A_1, which seems to show up in τ decays) because it has the opposite G parity and would be produced only by a second-class current.

There are no additional isovector, even-G mesons in the s-wave $Q^2\overline{Q}^2$ configuration. More promising candidates are found among the vector mesons in the p-wave excited $Q^2\overline{Q}^2$ configuration. These states could be produced by a photon, either in e^+e^- annihilation or in photoproduction. Here the $\varphi\pi$ signature would be unambiguous in annihilation, where there are no additional hadrons, and hopefully also in photoproduction where kinematics should enable choosing a $\varphi\pi$ system from the photon fragmentation region. Note that the standard Deck diagram which confuses diffractive production of the A_1 is not relevant here, as it would require $\varphi\pi$ production from the photon and subsequent rescattering of the pion on the nucleon. The original dissociation of the photon into $\varphi\pi$ is OZI forbidden and should be strongly suppressed.

The 1^- $Q^2\overline{Q}^2$ states need one unit of orbital angular momentum to make the odd parity. Since there are three independent relative coordinates in a four-body system, the one unit of orbital angular momentum can be in any of these three degrees of freedom. Several 1^- states can be constructed by using the three possible orbital excitations and the different ways of coupling the quark spins to $S=0$, 1, or 2, any of which can be coupled with $L=1$ to make $J=1$. The detailed predictions for this configuration are strongly model dependent and are not attempted here. It is sufficient to point out that some states in this configuration should have an appreciable overlap with the $\varphi\pi$ state in a relative s wave and therefore should have an appreciable branching ratio for a decay by breakup into this channel. This state would be produced from a photon by the creation of an isovector nonstrange pair with the quantum numbers of the ρ and subsequent creation of a strange pair from the vacuum by strong interactions (gluon exchange).

It seems unlikely that recently observed narrow states in e^+e^- annihilation[3] are related either to these states or to baryonium. Decays by breakup into $\varphi\pi$ are not suppressed and should have typical hadronic widths of the order of several hundred MeV. Baryonium states prefer to decay into baryon-antibaryon channels rather than into two mesons because they consist of separated diquark-antidiquark pairs with a high relative orbital angular momentum. The centrifugal barrier prevents individual quark-antiquark pairs from coming together and forming two mesons; thus the $B\overline{B}$ decay with an additional $Q\overline{Q}$ pair creation is favored. But such states of high L are not likely to be produced from a photon which makes only 1^- states and has a point coupling which produces a pair at the same point and low L. Thus even if a 1^- baryonium state exists with $L=3$ and $S=2$, it is not likely to be produced via a single photon.

We now attempt to estimate the masses and production cross sections for the isovector, even-G $Q^2\overline{Q}^2$ vector meson. We use Jaffe's notation and denote this state by $C_\rho{}^s$ indicating a cryptoexotic state with the quantum numbers of the ρ and an additional $s\overline{s}$ pair. From Jaffe's assignment of the ϵ, δ, and S^* as the lowest s-wave $Q^2\overline{Q}^2$ states at 1000 MeV, and 500 MeV added for p-wave excitation, we obtain 1500 MeV for the mass of the $C_\rho{}^s$. This is well above the $\varphi\pi$ threshold with the $K\overline{K}$ and $K^*\overline{K}$ channels also open. Since all these hadronic decays are allowed by their p-wave character there is no reason to expect the $C_\rho{}^s$ to be particularly narrow. Its decay momentum for the $K\overline{K}$ mode is larger than that of the ρ which has a p-wave decay width of 100 MeV and similar to that of the f' which has a d-wave decay width of 40 MeV. Thus a width of several hundreds of MeV can be expected for the $C_\rho{}^s$. For our estimates of cross sections, we use a value of 500 MeV, which we consider to be on the pessimistic side. If the actual width is narrower, production rates will be larger than our estimates.

The coupling of $C_\rho{}^s$ to the photon is most conveniently expressed by using the ratio $R(X)$ of the production of any state X by a photon to muon pair production. We then assume that $R(C_\rho{}^s)$ is the product of $R(\rho)$, taken as a measure of the production of the isovector $q\overline{q}$ pair, and a suppression factor $G(s\overline{s})$ for producing an additional $s\overline{s}$ pair:

$$R(C_\rho{}^s)=R(\rho)G(s\overline{s}). \tag{1}$$

If we take $\frac{1}{10}$ for $G(s\overline{s})$ and 6.5 keV for the leptonic width of the ρ, we obtain

$$\Gamma^{ee}(C_\rho{}^s)\approx 0.5\text{ keV}. \tag{2}$$

With the values $M=1500$ MeV, $\Gamma^{\text{tot}}=500$ MeV, and $\Gamma^{ee}=0.5$ keV, we obtain the following estimates for the production of the $C_\rho{}^s$.

Electron-position annihilation.—The contribution to R at the resonance peak is given approximately by

$$R^{\mathrm{pk}} \approx B[170\Gamma^{e\bar{e}}(\mathrm{keV})/\Gamma^{\mathrm{tot}}(\mathrm{MeV})] \approx B\Gamma^{e\bar{e}}(\mathrm{keV})/3, \qquad (3)$$

where B is the branching ratio of the decay mode. The cross section is obtained by multiplying R by $\sigma_{\mu\mu}$ at the appropriate mass. For $m^2 = 2.25$,

$$\sigma^{\mathrm{pk}}(Q^2 = 2.25) = R^{\mathrm{pk}}\sigma_{\mu\mu} = (88R^{\mathrm{pk}}/2.25)\ \mathrm{nb} = 14B\Gamma^{e\bar{e}}(\mathrm{keV})\ \mathrm{nb}. \qquad (4)$$

Thus

$$\sigma(e^+e^- \to C_\rho{}^s \to \varphi\pi)_{Q^2 = 2.25\,\mathrm{GeV}^2} = 7B(C_\rho{}^s \to \varphi\pi)\ \mathrm{nb}. \qquad (5)$$

If the branching ratio of the $C_\rho{}^s$ is roughly 50% to each of the $\pi\varphi$ and $K\bar{K}$ modes this gives a value of 3–4 nb for the $\varphi\pi$ cross section. To get an idea of whether this is measurable, we examine the size of $\sigma(e^+e^- \to \pi^+\pi^-)$ at this energy,

$$\sigma(e^+e^- \to \pi^+\pi^-) = (\pi\alpha^2/3Q^2)[F_\pi(Q^2)]^2 = 8\ \mathrm{nb}. \qquad (6)$$

Thus the $\varphi\pi$ cross section is of the order of half the $\pi\pi$ cross section and should be measurable.

A small background can be produced by the OZI-forbidden process

$$e^+e^- \to \gamma \to (Q\bar{Q})_{I=1} \to \varphi\pi. \qquad (7)$$

This background can be estimated in any experiment by using the $\omega\pi$ and $\rho\pi$ signal measured in the same experiment and the known OZI-forbidden $\varphi\rho\pi$ coupling,[4]

$$\begin{aligned} R(\gamma \to Q\bar{Q} \to \varphi\pi) &= (g_{\varphi\rho\pi}/g_{\omega\rho\pi})^2 R(\gamma \to \omega\pi) \\ &= 9(g_{\varphi\rho\pi}/g_{\omega\rho\pi})^2 R(\gamma \to \rho\pi) \\ &= 0.02R(\gamma \to \rho\pi). \qquad (8) \end{aligned}$$

Note that this OZI-forbidden background (7) is an interesting effect in itself and worthy of investigation even if no $C_\rho{}^s$ signal is found.

The existence of $Q^2\bar{Q}^2$ states containing heavy quarks has also been suggested, and one might consider looking for a vector meson $C_\rho{}^c$ which has a $c\bar{c}$ pair and decays into $\psi\pi$. However, the suppression factor $G(c\bar{c})$ can be expected to be much smaller than $G(s\bar{s})$ because of the higher mass of the charmed quark, and the $\psi\pi$ signal in e^+e^- annihilation is therefore probably very small.

Photoproduction.—The direct production of $C_\rho{}^s$ in e^+e^- annihilation is suppressed by the large value of Γ^{tot} because it is a resonance cross section at the unitarity limit. This suppression is not present in photoproduction which is far from the unitarity limit. We can estimate the photoproduction cross section for $C_\rho{}^s$ by comparing it with ω photoproduction, which is well known and has a similar signature ($\pi^+\pi^-\pi^0$ as compared with $K^+K^-\pi^0$):

$$\frac{[d\sigma(\gamma A \to C_\rho{}^s A)/dt]_{t_0}}{[d\sigma(\gamma A \to \omega A)/dt]_{t_0}} = \frac{\Gamma^{e\bar{e}}(C_\rho{}^s)}{\Gamma^{e\bar{e}}(\omega)}\,\frac{m_\omega}{m_{C_\rho{}^s}}\left(\frac{\sigma(C_\rho{}^s N)}{\sigma(\omega N)}\right). \qquad (9)$$

If we use quark additivity to estimate $\sigma(C_\rho{}^s N)$, it is equal to $\sigma(\rho N) + \sigma(\varphi N) \approx \frac{3}{2}\sigma(\rho N)$. With $m_{C_\rho{}^s} = 2m_\rho$ and $\Gamma^{e\bar{e}}(\omega) = \frac{1}{9}\Gamma^{e\bar{e}}(\rho)$,

$$\left.\frac{d\sigma(\gamma A \to C_\rho{}^s A)}{dt}\right|_{t_0} \approx 9\left.\frac{d\sigma(\gamma A \to \omega A)}{dt}\right|_{t_0} \frac{\Gamma^{e\bar{e}}(C_\rho{}^s)}{\Gamma^{e\bar{e}}(\omega)}. \qquad (10)$$

Thus even in the unlikely event $\Gamma^{e\bar{e}}(C_\rho{}^s) = (1/100) \times \Gamma^{e\bar{e}}(\rho)$, the cross section should be comparable to the well-measured Compton scattering. This suggests that $\gamma A \to \varphi\pi A$ is readily measurable experimentally.

Thus both direct production and photoproduction are promising for the search for the $C_\rho{}^s$, with the photoproduction providing greater sensitivity in the event that our estimates are too high, or the total width of the $C_\rho{}^s$ is even larger than 500 MeV.

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