Is the resonance in the $\varphi\pi^0$ system near 1.5 GeV a four-quark signal?

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The observation of a narrow resonance in the $\omega\eta$ system near 1.5 GeV would furnish a positive answer to the question posed in the title and would signify the discovery of two four-quark states.

Resonance structure was recently discovered[1] in the $\varphi\pi^0$ system in the reaction $\pi^- p \to \varphi\pi^0 n$ on the Lepton-*F* apparatus at the Institute of High-Energy Physics. This structure is called the "*C* state." The existence of this structure is also confirmed by the results of a study of the $\varphi\pi^-$ channel in the inclusive reaction.[2] Recent studies yield the following for the *C* state[3] at $q_L = 32.5$ GeV/c:

$$M(C) = 1490 \pm 25 \text{ MeV}, \quad \Gamma(C) = 165 \pm 30 \text{ MeV},$$

$$\sigma(\pi^- p \to Cn) BR(C \to \varphi\pi^0) = 35 \pm 15 \text{ nb}. \tag{1}$$

The decay $C \to \varphi\pi^0$ does not go by a mechanism suppressed by the Okubo-Zweig-Izuki rule: i.e., The *C* resonance is strongly coupled with the $\varphi\pi^0$ channel.[3] The isospin $I = 1$ and the strong coupling with the $\varphi\pi^0$ channel make the *C* resonance a possible candidate for a four-quark ($q^2\bar{q}^2$) state[3] with the symbolic structure

$$C \sim s\bar{s}(u\bar{u} - d\bar{d})/\sqrt{2}. \qquad (2)$$

In the present letter we wish to propose an experiment which would resolve the question of the $q^2\bar{q}^2$ nature of the C state. The basic idea here is that no matter what $q^2\bar{q}^2$ multiplet the C resonance is in, there should be a mass-degenerate partner $\tilde{C}$ with the opposite G parity ($I = 0$) and with the symbolic quark structure

$$\tilde{C} \sim s\bar{s}(u\bar{u} + d\bar{d})/\sqrt{2}, \qquad (3)$$

which should be manifested as a narrow resonance in the mass spectrum of the $\omega\eta$ system.

In the $q^2\bar{q}^2$ scheme, the C state could belong to the following flavor multiplets: a 9-plet, a 36-plet, or a linear combination of an 18-plet and its conjugate 18*-plet with a definite G parity.

In a sense, four-quark mesons "consist" of pairs of "white" and "colored" two-quark $q\bar{q}$ mesons. If the C state belongs to a 9-plet or 36-plet, the flavor structure of its wave function would have the following forms, respectively:

$$C \sim \alpha\,\{\varphi\pi^0 + \rho^0\eta_s \mp 1/\sqrt{2}(\bar{K}\tau_3 K^* + \bar{K}^*\tau_3 K)\} + \ldots \qquad (4)$$

$$K = \begin{pmatrix} K^+ \\ K^0 \end{pmatrix}, \quad K^* = \begin{pmatrix} K^{*+} \\ K^{*0} \end{pmatrix}, \quad \tau_3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}.$$

In (4) and below, we are writing out only the pairs of white $q\bar{q}$ mesons, since they determine the Zweig-superallowed decay channels. By virtue of the most general symmetry properties of the flavor wave function, the C state in a $q^2\bar{q}^2$ system should be accompanied by an isoscalar state with a negative G parity in a 9-plet and a 36-plet, respectively:

$$\tilde{C} \sim \alpha\{\pm(\omega\eta_s + \varphi\eta_0) + 1/\sqrt{2}(\bar{K}K^* + \bar{K}^*K)\} + \ldots . \qquad (5)$$

Here

$$\eta_s = s\bar{s} = \eta' \cos(\theta_p + \theta_q) - \eta \sin(\theta_p + \theta_q), \qquad (6)$$

$$\eta_0 = (u\bar{u} + d\bar{d})/\sqrt{2} = \eta \cos(\theta_q + \theta_p) + \eta' \sin(\theta_q + \theta_p),$$

θ_p is the angle of the mixing of the eighth component of the $\mathrm{SU}(3)_f$ octet and the $\mathrm{SU}(3)_f$ singlet of pseudoscalar mesons: $\theta_p = 54.7^0$.

From (4), (5), and (6), we find

$$r = \frac{\Gamma(\tilde{C} \to \omega\eta) + \Gamma(\tilde{C} \to \bar{K}^*K) + \Gamma(\tilde{C} \to KK^*)}{\Gamma(C \to \varphi\pi) + \Gamma(C \to \rho\eta) + \Gamma(C \to \bar{K}^*K) + \Gamma(C \to \bar{K}K^*)} \lesssim 0.65. \qquad (7)$$

The quantity r is essentially independent of whether we have $\theta_p = -18^0$ or -10^0. The maximum value of r is reached in a case in which the s wave is predominant in the decay products; when the p wave is predominant, we have $r = 0.5$.

If the C state is a linear combination of an 18-plet and its conjugate 18*-plet with a positive G parity, we would have

$$C \sim \alpha_1(\varphi\pi^0 - \rho^0\eta_s) + \alpha_2\bar{K}^*\tau_3 K^* + \dots . \tag{8}$$

The second term in (8) does not contribute to the decay of the C resonance, since this resonance lies below the threshold for the $K^*\bar{K}^*$ channel. The partner of the C resonance, the $\tilde{C}$ state with a negative G parity, has the following flavor structure:

$$\tilde{C} \sim \alpha_1(\varphi\eta_0 - \omega\eta_s) + \alpha_2\bar{K}^*K^* + \dots . \tag{9}$$

From (8), (9), and (6) we find

$$r' = \frac{\Gamma(\tilde{C}\to\omega\eta)}{\Gamma(C\to\varphi\pi)} \lesssim \begin{cases} 0{,}24\,(\theta_p = -18^0), \\ \\ 0{,}3\,(\theta_p = -10^0). \end{cases} \tag{10}$$

If the $C(1500)$ resonance is a $q^2\bar{q}^2$ state with the symbolic quark structure in (2), then the $\omega\eta$ system should contain a narrow resonance $[\Gamma(\tilde{C}) \lesssim 100$ MeV; see (7) and (10)] with a mass of about 1.5 GeV, due to the $\tilde{C}$ four-quark state with the symbolic structure in (3). The observation of this resonance would be unambiguous evidence of the $q^2\bar{q}^2$ nature of the C state and would signify the discovery of yet another $q^2\bar{q}^2$ resonance, $\tilde{C}$. Unfortunately, it is difficult to say what the cross section for the production of the $\tilde{C}$ resonance should be. On the basis of the most general (and possibly not very profound) considerations, it would seem natural to find the cross section for the production of the $\tilde{C}$ resonance in the reaction $\pi^- p \to \omega\eta n$ to be comparable in magnitude to the cross section for the production of the C resonance in the reaction $\pi^- p \to \varphi\pi^0 n$, i.e., on the order of 10 nb at $q_L = 32.5$ GeV/c [see (1)].

What can we say about the other terms of the $q^2\bar{q}^2$ multiplet (9, 36, 18, and 18*)? The answer to this question depends entirely on the specific model: on the mass splitting in the multiplet, on the spin-parity J^P, etc. It may be that other states are very wide and are manifested not as peaks in the mass spectra but as poles in the P matrix.[4]

In principle, Zweig-superallowed decays may be suppressed by dynamic factors of some sort ($\alpha^2 \ll 1$ or $\alpha_1^2 \ll 1$). In such a case, the decays $C \to \varphi\pi^0, \rho\eta\,(K^*\bar{K}, K\bar{K}^*)$ and $\tilde{C} \to \omega\eta\,(\bar{K}K^*, \bar{K}^*K)$ arise from the bleaching of pairs of colored $q\bar{q}$ mesons in the wave functions. As before, relation (7) or (10) holds. However, there is not much hope that the widths of the C and $\tilde{C}$ resonances will be determined exclusively by these quasi-two-particle decays. In this case we would expect $\Gamma(\tilde{C}) \approx \Gamma(C)$.

We might also note that the $\omega\eta$ channel is very convenient for identification on the Lepton-F apparatus.

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