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Chiral Symmetry and $\psi' \to \psi\pi\pi$ Decay

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Unbroken chiral symmetry (with a vanishing σ term) relates the $\psi' \to \psi\pi\pi$ decay amplitude to three basic parameters. Two of these parameters put strong angular correlations in the amplitude which, apparently, are not observed. Taking these two parameters to vanish, we obtain an isotropic decay which is strongly peaked in the region where the invariant mass of the $\pi\pi$ system is large.

Although the newly discovered narrow boson resonances[1-4] at $M=3.095$ GeV (ψ or J) and at $M'=3.684$ GeV (ψ') have yet to be fully explored, the data so far[5] indicate that these particles are of a hadronic nature with quantum numbers $J^P=1^-$ and $I^{GC}=0^{--}$. The ψ' has been observed[6] to decay into a ψ with a branching ratio of 0.57 ± 0.08. In these decays, the mode $\psi'\to\psi\pi\pi$ predominates with a charged $\pi^+\pi^-$ pair being produced with a probability[6] of 0.56 ± 0.10. The relative rates for $\psi'\to\psi\pi^+\pi^-$ and $\psi'\to\psi+$neutrals indicate that the $\pi\pi$ system has $I=0$. Thus, including $\pi^0\pi^0$ pairs, the $\psi'\to\psi\pi\pi$ mode should account for some 84% of the $\psi'\to\psi$ decays.

The pions produced in the $\psi'\to\psi\pi\pi$ decay have modest energies, their invariant mass squared lying in the interval $4m_\pi^2 \leq m_{\pi\pi}^2 \leq (M'-M)^2$ (0.08 GeV$^2 \leq m_{\pi\pi}^2 \leq 0.35$ GeV^2). In this energy interval, pion-pion rescattering corrections are small.[7] Moreover, since the ψ' and ψ resonances are very narrow, their interaction with the pions is very small. Thus, the low-energy constraints implied by chiral symmetry, which we assume is obeyed in the decay, should extrapolate into the whole physical momentum region without large corrections. We shall assume that the breaking of chiral symmetry is a small effect and neglect the σ term. We find that the decay amplitude then involves three parameters—coefficients of three different momentum-dependent terms. Two of these terms produce strong angular correlations in the decay. The data[6] suggest that the decay is isotropic and indicate that the two coefficients of these terms are small. Guided by the data, we take these two parameters to vanish and obtain an isotropic decay amplitude which is strongly peaked at large $m_{\pi\pi}$. Thus, chiral symmetry connects the absence of angular correlations with a strong dependence on the invariant mass of the produced $\pi\pi$ pair. We should emphasize that if the terms with the strong angular dependence were present (terms which fully respect the chiral symmetry), then the $m_{\pi\pi}$ mass distribution would no longer be expected to peak at large values of $m_{\pi\pi}$.

We turn now to our calculation. We denote the four-momenta and polarization vectors of ψ' and ψ by P'^{μ} and $\vec{\epsilon}\,'$ and by P^{μ} and $\vec{\epsilon}$, respectively. In the laboratory frame, the produced ψ particle is slowly moving, with a maximum velocity of $0.15c$. Hence, we can treat it as a nonrelativistic particle with a purely spatial polarization vector ϵ_l, and write the decay matrix element as a spatial sum,

$$M=\sum_{l,m=1}^{3}\epsilon_l M_{lm}\epsilon_m'. \tag{1}$$

We denote the pion four-momenta and isospin indices by q_1^{μ} and a and q_2^{ν} and b, with the energy-momentum balance reading $q_1+q_2+P=P'$. Current algebra relates the decay amplitude to the matrix element of axial currents which have their pion poles removed, and an additional matrix element of the symmetry-breaking σ term. We have the exact identity[8]

$$M\delta_{ab}=F_\pi^{-2}q_1^{\mu}q_2^{\nu}\langle\psi,P,\epsilon|i(\overline{A}_{\mu,a}(q_1)\overline{A}_{\nu,b}(q_2))_+|\psi',P',\epsilon'\rangle-F_\pi^{-1}(q_1^2+q_2^2+m_\pi^2)\langle\psi,P,\epsilon|\Sigma_{ab}|\psi',P',\epsilon'\rangle. \tag{2}$$

On the pion mass shell $q_1^2=q_2^2=-m_\pi^2$, the second, σ term above is of the order m_π^2, and we shall assume that it is negligibly small. The structure of the axial-current matrix element measures properties of the ψ'-ψ system. In the limit where this system is nonrelativistic, there are three different terms, giving

$$M=F_\pi^{-2}\{\vec{\epsilon}\cdot\vec{\epsilon}\,'[-q_1^{\mu}q_{2\mu}A+q_1^0q_2^0B]+(\vec{\epsilon}\cdot\vec{q}_1\vec{\epsilon}\,'\cdot\vec{q}_2+\vec{\epsilon}\cdot\vec{q}_2\vec{\epsilon}\,'\cdot\vec{q}_1)C\}. \tag{3}$$

Here the momentum components q_1^{μ} and q_2^{ν} are measured in the laboratory frame. Except possibly for S-wave pion-pion rescattering corrections,[7] the momentum-dependent variation of the amplitudes A, B, and C should be small, and we shall assume that these amplitudes may be taken to be (real) constant parameters. Relativistic corrections increase the number of independent amplitudes (for example, they add a term involving $q_1^{\mu}q_{2\mu}\vec{\epsilon}\cdot\vec{P}\vec{\epsilon}\,'\cdot\vec{P}$), but these should also be small corrections.

The polarization of the ψ particle produced in the decay is analyzed by the leptonic decays $\psi\to\mu^+\mu^-$, $\psi\to e^+e^-$. Since these leptons are extremely relativistic, the leptonic-decay modes involve the replacement $\sum_{\rm pol}\epsilon_l\epsilon_m^*\to\delta_{lm}-\hat{k}_l\hat{k}_m$, where $\hat{k}$ is a unit vector in the direction of the relative lepton momentum $\vec{k}$ measured in the ψ rest frame, a frame which is well approximated by the laboratory frame. Similarly, the original ψ' particle is produced by relativistic e^+e^- annihilation, and it is produced with an alignment $\langle\epsilon_l'\epsilon_m'^*\rangle=\frac{1}{2}(\delta_{lm}-\hat{z}_l\hat{z}_m)$, where $\hat{z}$ is a unit vector along the beam direction. Working out the three-body phase space, we find that the distribution for the sequential decay $\psi'\to\psi\pi^+\pi^-$, $\psi\to\mu^+\mu^-$, e^+e^- is given by

$$\frac{d\Gamma}{dm_{\pi\pi}d\Omega_{q_{\pi\pi}}d\Omega_P d\Omega_k}=\frac{3}{2}B_l\frac{q_{\pi\pi}P}{(4\pi)^6M'^2}M_{l'm'}^*M_{lm}(\delta_{l'l}-\hat{k}_{l'}\hat{k}_{l'})(\delta_{m'm}-\hat{z}_{m'}\hat{z}_m). \tag{4}$$

Here $m_{\pi\pi}^2=-(q_1+q_2)^2$ is the invariant mass squared of the pion-pion system, $q_{\pi\pi}=|\vec{q}_{\pi\pi}|=\frac{1}{2}(m_{\pi\pi}^2-4m_\pi^2)^{1/2}$ is the magnitude of the relative momentum of this system in its center of mass, and $P=(2M')^{-1}[(M'^2-M^2)^2-2(M'^2+M^2)m_{\pi\pi}^2+m_{\pi\pi}^4]^{1/2}$ is the momentum of the ψ in the laboratory frame. The solid-angle element $d\Omega_{q_{\pi\pi}}$ is that of the relative momentum $\vec{q}_{\pi\pi}$ measured in the $\pi\pi$ rest frame; $d\Omega_P$ and $d\Omega_k$ are the solid-angle elements of the ψ momentum and relative lepton momentum measured in the laboratory frame. The branching ratio into the lepton pair is denoted by B_l and the matrix elements M_{lm} follow from comparing Eqs. (1) and (3). The total rate, without regard for the decay mode of the ψ particle, is obtained from Eq. (4) by deleting the factor B_l and by integrating over the solid angle Ω_k.

If we write the laboratory momentum components q_1^{μ} and q_2^{ν} in terms of $q_{\pi\pi}$, P, Lorentz boost factors, and appropriate angular factors, we find that the terms associated with the parameters B and C involve strong angular correlations.[9] The data presently available[6] appear not to support much angular variation, and we shall tentatively assume that $B=C=0$. Clearly, the actual values of these parameters need to be measured experimentally. With $B=C=0$, the decay distribution (4) is independent of the directions of $\vec{q}_{\pi\pi}$ and $\vec{P}$ so that we may as well integrate over their solid angles to obtain

$$\frac{d\Gamma}{dm_{\pi\pi}d\Omega_k}=\frac{3}{2}B_l\frac{q_{\pi\pi}P}{(4\pi)^4M'^2}\frac{1}{4}(m_{\pi\pi}^2-2m_\pi^2)^2\left(\frac{A}{F_\pi^2}\right)^2(1+\cos^2\theta_k), \tag{5}$$

where θ_k is the angle between the relative lepton momentum $\vec{k}$ and the beam direction $\hat{z}$. The total dif-

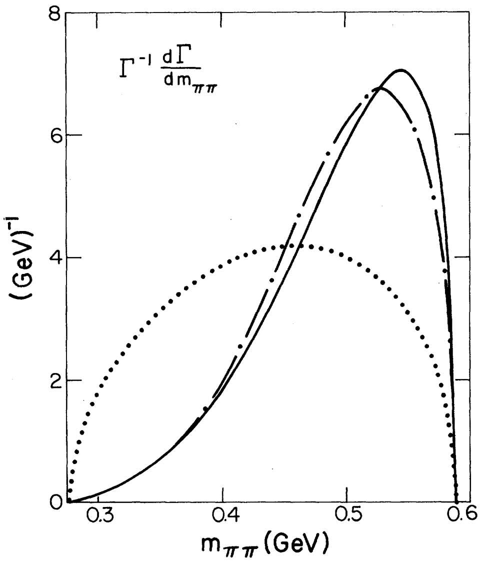

FIG. 1. The decay spectrum $\Gamma^{-1}\, d\Gamma/dm_{\pi\pi}$ as a function of $m_{\pi\pi}$ given by Eq. (6) (solid line); given by simple phase space (dotted line); and given by Eq. (6) modified by pion-pion rescattering (dot-dashed line).

ferential spectrum is given by

$$\frac{d\Gamma}{dm_{\pi\pi}} = \frac{1}{2}\frac{q_{\pi\pi}P}{(4\pi)^3 M'^2}(m_{\pi\pi}^2 - 2m_\pi^2)^2\left(\frac{A}{F_\pi^2}\right)^2. \qquad (6)$$

This function is displayed in Fig. 1 together with the simple phase-space curve (the factor $q_{\pi\pi}P$ normalized to the same area) and the modification brought about by the rescattering of the pions which are in a relative S state. We see that the factor $(m_{\pi\pi}^2 - 2m_\pi^2)^2$, introduced by the chiral symmetry coupled with the assumed vanishing of the parameters B and C, modifies the simple phase-space curve substantially, giving a peak at large $m_{\pi\pi}$. The chiral-symmetry-breaking corrections which we have neglected give a constant term relative to the factor $m_{\pi\pi}^2 - 2m_\pi^2$ in the amplitude. They may alter somewhat the small $m_{\pi\pi}$ behavior of the decay spectrum (6).

Integrating (6) over the invariant $\pi\pi$ mass range gives a width

$$\Gamma(\psi' \to \psi\pi^+\pi^-) = 1.4A^2/4\pi \text{ MeV}. \qquad (7)$$

Using[5,6] $\Gamma(\psi' \to \psi\pi^+\pi^-) = 0.32\Gamma(\psi' \text{ total}) \simeq 150$ keV, we find that the dimensionless parameter $A^2/4\pi$ approximately equals $\frac{1}{10}$.

We emphasize again that chiral symmetry does not determine uniquely the parameters of the decay $\psi' \to \psi\pi\pi$. It does predict a depletion of events with low $\pi\pi$ invariant mass if terms which give anisotropic distributions are small. Should this turn out to be an accurate description, there would still remain two important theoretical questions: Why are the anisotropic terms small and what is the precise role of chiral symmetry breaking (the σ term)?

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Note Added.—The essential aspects of the special case of the isotropic decay amplitude are, of course, reproduced by the chiral σ model in the tree approximation.[10] This alternative approach illustrates something of the nature of our result. Here one couples the ψ'-ψ system to σ-π fields with a chirally invariant interaction $A\psi'^{\mu}\psi_\mu(\pi^2 + \sigma^2)$. An estimate of the symmetry-breaking contribution [the σ term of Eq. (2)] is provided by directly coupling the σ field to the vacuum so that the pion field has a finite mass m_π. In this σ model, the factor $-2q_1{}^{\mu}q_{2\mu} = m_{\pi\pi}^2 - 2m_\pi^2$ appearing in the decay amplitude Eq. (3) is replaced by $(m_{\pi\pi}^2 - m_\pi^2)(m_\sigma^2 - m_{\pi\pi}^2)^{-1}F_\pi^2$. The σ-field propagator factor $(m_\sigma^2 - m_{\pi\pi}^2)^{-1}$ will be replaced, when rescattering corrections are included, by essentially the denominator factor D^{-1} which we have taken into account.[7] We see that, in this model, the effect of the chiral symmetry breaking is to shift the position of the zero at $m_{\pi\pi}^2 = 2m_\pi^2$ to a new zero position at $m_{\pi\pi}^2 = m_\pi^2$. This would slightly broaden the decay spectrum displayed in Fig. 1.

[1]J. J. Aubert *et al.*, Phys. Rev. Lett. 33, 1404 (1974).

[2]J.-E. Augustin *et al.*, Phys. Rev. Lett. 33, 1406 (1974).

[3]C. Bacci *et al.*, Phys. Rev. Lett. 33, 1408, 1649(E) (1974).

[4]G. S. Abrams *et al.*, Phys. Rev. Lett. 33, 1453 (1974).

[5]See F. J. Gilman, invited talk presented at the Orbis Scientiae II, University of Miami, Coral Gables, Florida, 19–24 January 1975 (to be published) (SLAC Report No. SLAC-Pub-1537).

[6]G. S. Abrams *et al.*, Phys. Rev. Lett. 34, 1181 (1975).

[7]Pion-pion rescattering corrections are negligible for (even) angular momentum states higher than S waves. We can estimate the effect for S waves by the conventional $|D|^{-2}$ factor which accounts for the variation brought about by the elastic cut in the $\pi\pi$ scattering amplitude. A reasonable model of D appears in Eq. (7) of R. L. Goble and J. L. Rosner, Phys. Rev. D 5, 2345 (1972), which is based on the earlier work of L. S. Brown and R. L. Goble, Phys. Rev. Lett. 20, 346 (1968), and Phys. Rev. D 4, 723 (1971). Here we use the value $M_0 = 1$ GeV in this model, as is suggested by recent data on $\pi\pi$ scattering, and find that $|D|^{-2}$ has a very broad

peak in the center of the $m_{\pi\pi}$ range with the peak some 36% above the values of $|D|^{-2}$ at the endpoints of the $m_{\pi\pi}$ range. This variation is insignificant in comparison with the large variation which we find is implied by chiral symmetry as displayed in Fig. 1.

[8]This identity is completely analogous to that for pion-nucleon scattering except that here there is no vector-current, equal-time-commutator contribution. See, for example, the discussion leading to Eq. (63) of L. S. Brown, W. J. Pardee, and R. D. Peccei, Phys. Rev. D 4, 2801 (1971).

[9]A full analysis of the decay correlations will be presented elsewhere.

[10]M. Gell-Mann and M. Levy, Nuovo Cimento 16, 705 (1960). For a recent discussion see B. W. Lee, *Chiral Dynamics* (Gordon and Breach, New York, 1972).

New Resonances in e^+e^- Annihilations as the Daughters of $\phi(1019)$

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The experimental consequences of a scheme to identify the newly discovered resonances in e^+e^- annihilation as the daughters of the $\varphi(1019)$ meson are discussed. The two narrow-width resonances with masses at 3105 and 3695 MeV are proposed to be described by closely located zero-pole systems instead of simple poles.

The newly discovered resonances observed in e^+e^- annihilation[1,2] and in a hadronic interaction,[3] i.e., the two narrow-width resonances at masses 3105 and 3695 MeV, and a resonance around 4300 MeV with a width of several hundred MeV, are frequently considered[4] to indicate the existence of new quantum numbers like charm and color. The decisive test of such new-quantum-number schemes, if in the charmed-quark scheme, is to observe the charmed particle-antiparticle ($D\bar{D}$) pair-production threshold between 3695 and 4300 MeV in order to explain the large width of the 4300-MeV mass resonance, or to observe the spin-zero meson composed of charm-anticharm quarks from the decay of these three resonances. Also in the charmed-quark scheme the K/π ratio is expected to rise above the $D\bar{D}$ production threshold. In case of the absence of such observations to support the existence of new quantum numbers, we should be aware of the possibility that these new resonances might just be ordinary hadrons, and most possibly the daughters of the $\phi(1019)$ meson. The purpose of this Letter is to discuss the experimental indications of such an ordinary-hadron scheme. Since some consequences of this ordinary-hadron scheme will contradict the expectations from the new-quantum-number ideas, the verification or the denial of this scheme by experiments will shed important light on the nature of these newly discovered resonances, especially when the decisive experimental evidences to support the existence of new quantum numbers are absent.

An immediate question from such an ordinary-hadron scheme is why the widths of the 3105- and 3695-MeV resonances are so narrow. The possibility of a strong-coupling but narrow-width resonance was discussed earlier[5] as the result for a closely located zero-pole system to saturate unitarity. In a more familar language the dynamical zero near the resonance can be either in the Green's function of the resonance, or in the vertex functions between the resonance and the individual hadron channels. In order to demonstrate the effect of a dynamical zero explicitly, a multichannel N/D model is taken with a dynamical zero put into the N functions by hand. The strengths of the input potentials are adjusted to move the position of the output resonance pole. As the pole moves close to the zero the expected strong width-narrowing effect is observed. In this kind of simple model the mass of the zero must be smaller than the mass of the resonance; otherwise the resonance becomes a ghost. Such a dynamical zero in this model becomes a Castillejo-Dalitz-Dyson pole in a one-channel N/D calculation.

The partial-wave amplitudes of dual-resonance models contain alternately zeros and poles. I suppose that the underlying dynamics of the strong interaction, e.g., a complete unitarization of the dual-resonance model by including all the significant channels, moves the positions of the zeros and I let the closely located zero-pole systems