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Production of the $f_0(975)$ Meson in J/ψ decays*

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ABSTRACT

Preliminary results on the production and decay of the $f_0(975)$ meson in the processes $J/\psi \to \phi\pi^+\pi^-$, $J/\psi \to \phi\pi^0\pi^0$, $J/\psi \to \phi K^+K^-$, and $J/\psi \to \omega\pi^+\pi^-$ are reported on. The data sample, corresponding to 5.8×10^6 produced J/ψ's, were collected with the MARK-III detector at SPEAR. In a coupled-channel fit to the invariant mass distribution of the $\pi^+\pi^-$ system opposite the ϕ, the $f_0(975)$ product branching ratios, resonance parameters and couplings to K^+K^- and $\pi^+\pi^-$ are extracted. An upper limit on $f_0(975)$ production in conjunction with an ω is presented.

I. Introduction

Table I. Two-photon widths of scalar mesons

meson	$\Gamma_{\gamma\gamma}^{measured}$ (KeV)	$\Gamma_{\gamma\gamma}^{q\bar{q}}$ (KeV)
$f_0(975)$	0.27 ± 0.12	4.5
$a_0(980)$	0.23 ± 0.09	1.5

To unambiguously identify a state as a scalar glueball requires a detailed understanding of scalars in quark spectroscopy. However, despite years of study, the spectroscopy of 0^{++} mesons remains unsettled. Due to their narrow observed widths[1] and substantially lower masses, the two well-established 0^{++} states, the $f_0(975)$ and $a_0(980)$, formerly referred to as the S* and δ, respectively, do not seem to fit into the same nonet as the broader and heavier states, the $f_0(1400)$ and $K_0(1430)$. Table I shows the predicted two-photon widths, assuming a $q\bar{q}$ composition for these states. The measured rates[2] are approximately an order of magnitude smaller than the expected rates.[3] As an alternative, it has been suggested that, due to their proximity to $K\bar{K}$ threshold, the $f_0(975)$ and $a_0(980)$ might be weakly-bound $K\bar{K}$ molecules[4,5]. Others have suggested that these objects are four-quark states[6,7]. Au, Morgan and Pennington[8,9] have performed a detailed S-matrix analysis of $\pi\pi$ scattering and conclude that there are several

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poles in the region of the $f_0(975)$ of which one may be a glueball. To study the $f_0(975)$ and other isoscalar mesons in a controlled environment, decays of the J/ψ into two pseudoscalar (PP) final states recoiling against a vector (V) meson are examined. the channels include

$$J/\psi \to \phi\pi^+\pi^- \quad (1)$$
$$\to \phi\pi^0\pi^0 \quad (2)$$
$$\to \phi K^+K^- \quad (3)$$
$$\to \omega\pi^+\pi^- \quad (4)$$

where the ideally mixed ω ($(u\bar{u}+d\bar{d})/\sqrt{2}$) and ϕ ($s\bar{s}$) are expected to project out the respectively, the non-strange and strange quark-based states in the recoil system. In a coupled-channel fit to the invariant mass distributions of the $\pi^+\pi^-$ system opposite the ϕ, the $f_0(975)$ resonance parameters and couplings to $\pi^+\pi^-$ and K^+K^- are extracted.

II. Event Selection

In each of the channels, we require events to have the correct number of charged tracks and at least the required number of neutral tracks. In the all-charged mode, a +- pair is rejected as a ϕ candidate if either track is unambiguously identified as a π or a proton by the time-of-flight system.[10] No time of flight requirements are imposed on the events in the $\omega\pi^+\pi^-$ final state. Four-constraint kinematic fits are performed using the hypotheses listed in Table II.

Table II. Fit Hypotheses

+-+- channel (4-C fits)	+-$\gamma\gamma\gamma\gamma$ channel (6-C fits)
$K^+K^-K^+K^-$	$K^+K^-\pi^0\pi^0$
$K^+K^-\pi^+\pi^-$	$K^+K^-\pi^0\eta$
$\pi^+\pi^-\pi^+\pi^-$	$K^+K^-\eta\eta$
$K^+K^-\pi^+\pi^-(\gamma)$	

Table III.

channel	detection efficiency
$\phi\pi^+\pi^-$	25%
$\phi\pi^0\pi^0$	17%
ϕK^+K^-	15%

In the all-charged mode, only those 4-C fits with the highest chisquared fit probability, $P(\chi^2)$, are retained. The best fit is required to have $P(\chi^2)>5\%$. In the case of the $K^+K^-K^+K^-$ fit, the ϕ is defined to be that +- combination whose fitted invariant mass is closest to the ϕ mass.. Six-constraint fits are then performed for events in the 2-charged, 4-γ mode using all combinations of the 4 to 8 most energetic photons in those 4-C fits with $\chi^2< 50$. Only those 6-C fits with the highest $P(\chi^2)$ are retained for further study provided that $P(\chi^2)>5\%$.To further reduce backgrounds from spurious photons, the angle θ_γ between each photon and the π^0 is required to satisfy $|\cos\theta_\gamma|<0.96$. Events from the two-body decay $J/\psi\to\phi\eta$, $\eta\to\pi^0\pi^0(\pi^0)$, where one of the π^0's is undetected, are removed by requiring the unfitted K^+K^- momentum to be less than 1.28 GeV/c.

The detection efficiencies for the channels containing a ϕ are listed in Table III, where the invariant mass of the K^+K^- pair forming the ϕ is required to satisfy $1.01 < M_{KK} < 1.03$ GeV/c. These efficiencies have been computed by generating ϕPP events according to 3-body phase space. These efficiencies do not include the branching ratio for the decay $\phi \to K^+K^-$. The interactions of the final-state particles with the detector are fully simulated and the resulting Monte Carlo events are reconstructed and passed through the same analysis chain as for real data. The detection efficiencies are nearly independent of the mass of the system produced opposite the ϕ in the region of the $f_0(975)$.

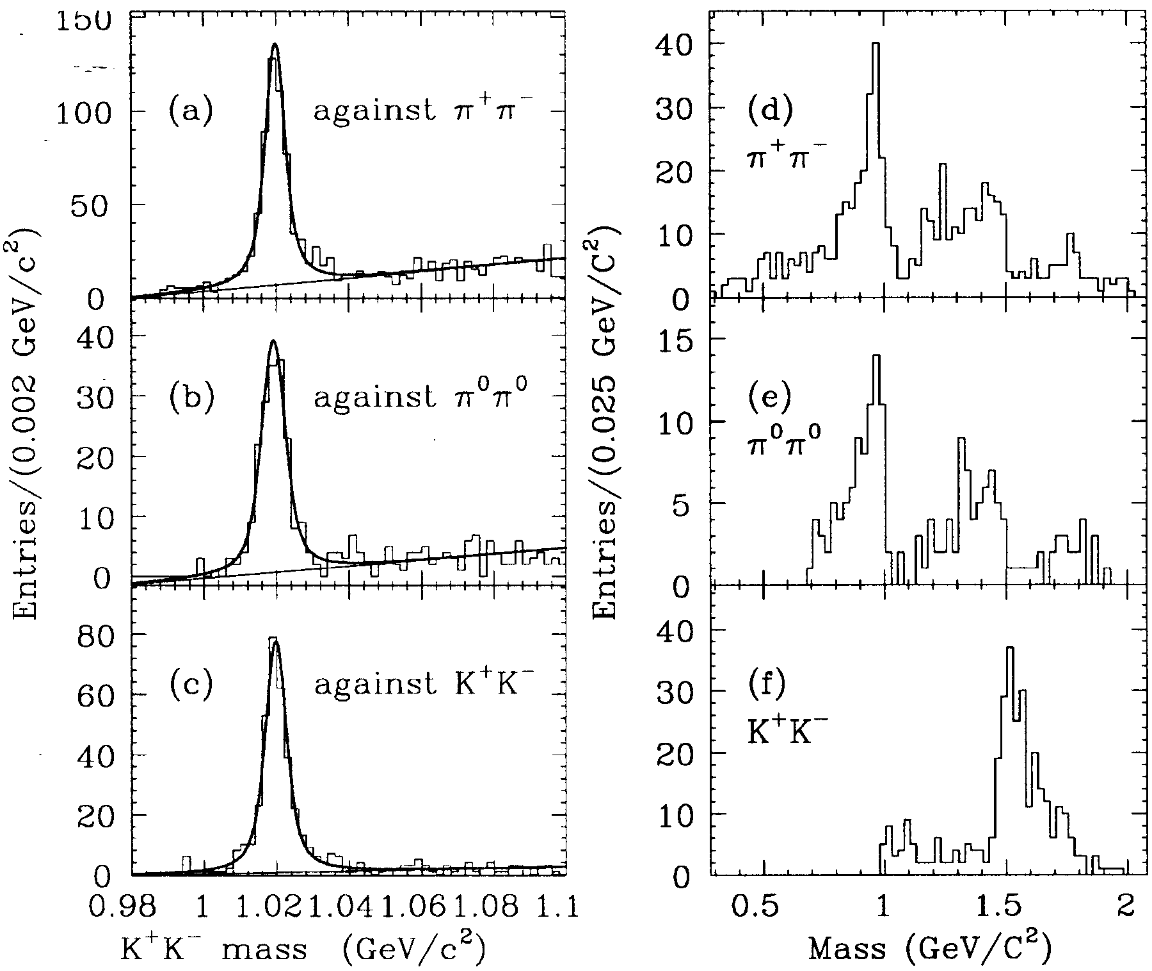

Fig. 1 (a-c): K^+K^- invariant mass distributions from the ϕ; (d-f): invariant mass distributions of the $\pi^+\pi^-$, $\pi^0\pi^0$ and K^+K^- systems opposite the ϕ.

The K^+K^- invariant mass distributions in the $K^+K^-\pi^+\pi^-$, $K^+K^-\pi^0\pi^0$ and $K^+K^-K^+K^-$ channels are shown in Figures 1a, 1b and 1c, respectively. A clean ϕ signal is seen in all three channels over backgrounds of 5-15%.

III. Results

A. $J/\psi \to \phi + X$

The invariant mass distributions of the two-pseudoscalar systems recoiling against the ϕ are shown in Fig. 1(d-f). Below 1 GeV/c^2, the spectra are dominated by the $f_0(975)$. Above 1 GeV/c^2, the $\pi\pi$ spectra exhibit box-like structures in the region between 1.1 and 1.5 GeV/c^2. These effects have been observed by the DM2 collaboration[11] and previously by the MARK-I experiment.[12] Of the decays considered here, the $\phi\pi\pi$ channel is the only one in which the $s\bar{s}$ quarks appearing in the vector are not present in the $\pi\pi$ final state. In the case of the $f_0(975)$, the state itself couples strongly to $s\bar{s}$, but then decays through the only kinematically accessible channel, $\pi\pi$.

A fit to the $\pi^+\pi^-$ invariant mass spectrum using a relativistic S-wave Breit-Wigner distribution over a phase space background is shown in Fig. 2. The fit does not describe the asymmetric distributions of events around the $f_0(975)$ peak. The mass and width from this fit are M=(947.0±0.5) MeV/c^2 and Γ=(86±26) MeV, respectively. These quantities do not agree particularly well with the Particle Data Group (PDG) book values for the $f_0(975)$ mass and width of 976 MeV/c^2 and 34 MeV, respectively.

Correcting for detector efficiency, the ϕ branching ratio to K^+K^-, and the branching ratio of $f_0(975)$ to $\pi^0\pi^0$ yields a product branching ratio of $B(J/\psi \to \phi f_0(975)) \times B(f_0(975) \to \pi\pi) = (3.4 \pm 0.7 \pm 0.3) \times 10^{-4}$, where the first error is statistical and the second error is dominated by the systematic uncertainty on the number of produced J/ψ's.

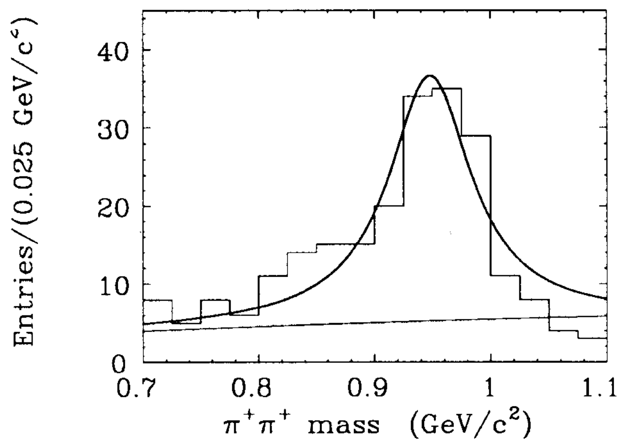

Fig. 2. Relativistic Breit-Wigner fit to $f_0(975)$ signal.

To construct a more realistic model of the mass distribution, a coupled-channel propagator[13] to account for the opening of the KK channel is incorporated. The width $d\Gamma$ for the sequential decay $J/\psi \to \phi f_0(975) \to K^+K^-\pi^+\pi^-$ in the Lorentz-invariant phase space volume element dLIPS is written as

$$d\Gamma = \frac{1}{2m_\psi}|M|^2 \, dLIPS \tag{4}$$

where

$$|M|^2 \propto \sum_{\lambda_\psi} |A|^2 |P_\phi|^2 |P_{f_0}|^2, \tag{5}$$

$$A = \frac{A_S}{\sqrt{\int |A_S|^2 dLIPS}} + r e^{i\delta} \frac{A_D}{\sqrt{\int |A_D|^2 dLIPS}}, \tag{6}$$

$$A_S = \sum_{\lambda_\phi} (\varepsilon_\psi^\mu \varepsilon_\phi^\mu)(\varepsilon_\phi^\sigma \Delta_K^\sigma) = \varepsilon_\psi^\mu \Delta_K^\mu, \tag{7}$$

$$A_D = \sum_{\lambda_\phi} \frac{(\varepsilon_\psi^\mu q_\phi^\mu)(\varepsilon_\phi^\nu q_\psi^\nu)}{m_\psi^2} (\varepsilon_\phi^\sigma \Delta_K^\sigma) = \frac{(\varepsilon_\psi^\mu q_\phi^\mu)(q_\psi^\nu \Delta_K^\nu)}{m_\psi^2}. \tag{8}$$

The S- and D-wave amplitudes A_S and A_D are constructed from the polarization vectors ε_ψ and ε_ϕ of the J/ψ and ϕ, their 4-momenta q_ψ and q_ϕ, and the difference of the K^+ and K^- 4-momenta, Δ_K, from the ϕ decay. The labels "S" and "D" refer to the angular momentum between the ϕ and $f_0(975)$. The amplitude A depends on the $f_0(975)$-mass and therefore modulates the shape of the $f_0(975)$-propagator, P_{f_0}. The terms λ_ϕ and λ_ψ are the ϕ-and J/ψ-helicities; P_ϕ is the ϕ-propagator. The term r is the modulus of the D-wave coefficient divided by the modulus of the S-wave coefficient and δ is the relative phase. The factors r and δ are determined in a fit to the production- and decay-angular distributions of the ϕ. The fit function includes a background term modelled by 4-body phase space which is added incoherently to $|M|^2$.

The fit results are shown in Table IV for different regions of $\pi\pi$ and KK masses. The factor α is the fraction of observed events labeled as background. These fractions are consistent with the background levels observed under the ϕ in Fig. 1. The S- and D-waves are approximately 180 degrees out of phase and the S-wave amplitude is dominant. The fit results in the different regions are similar, indicating that the KK events produced near threshold opposite the ϕ are due to the $f_0(975)$.

Table IV. Results of fitting the ϕ angular distributions to determine A.

Channel	mass interval (GeV/c^2)	r	$\cos\delta$	α
$\pi^+\pi^-$	0.7-1.1	0.62±0.08	-0.96±0.02	0.14±0.07
$\pi^+\pi^-$	0.3-0.7	0.57±0.08	-0.96±0.03	0.00±0.05
$\pi^0\pi^0$	0.7-1.1	0.59±0.11	-0.97±0.03	0.07±0.10
K^+K^-	0.98-1.4	0.54±0.16	-0.96±0.09	0.11±0.11

Having determined $|A|^2$, a fit to the $f_0(975)$ line shape in the $\phi\pi^+\pi^-$ channel is then performed to extract the $f_0(975)$ pole mass, the square of the $f_0(975)\to\pi\pi$ coupling constant g_π^2, and the ratio of the squares of the KK to $\pi\pi$ couplings g_K^2/g_π^2. The fit results are shown in Table V and Fig. 3(a). The pole mass is in excellent agreement with the PDG value. The ratio of squares of coupling constants indicates that the $f_0(975)$ is mainly strange-quark based. The $\pi\pi$ line shape is distorted due to the opening of the KK channel to which the $f_0(975)$ is strongly coupled., From the g_π^2 coupling constant, an "underlying width" of about 620 MeV is obtained. The observed width, ~80 MeV, is somewhat broader than the 15 MeV width predicted assuming the $f_0(975)$ is a $K\overline{K}$ molecule. The curve in Fig 3(b) is *not* a fit to the data; it is a prediction from the fit results in Fig. 3(a) corrected for the relative efficiencies between the two channels (cf. Table III).

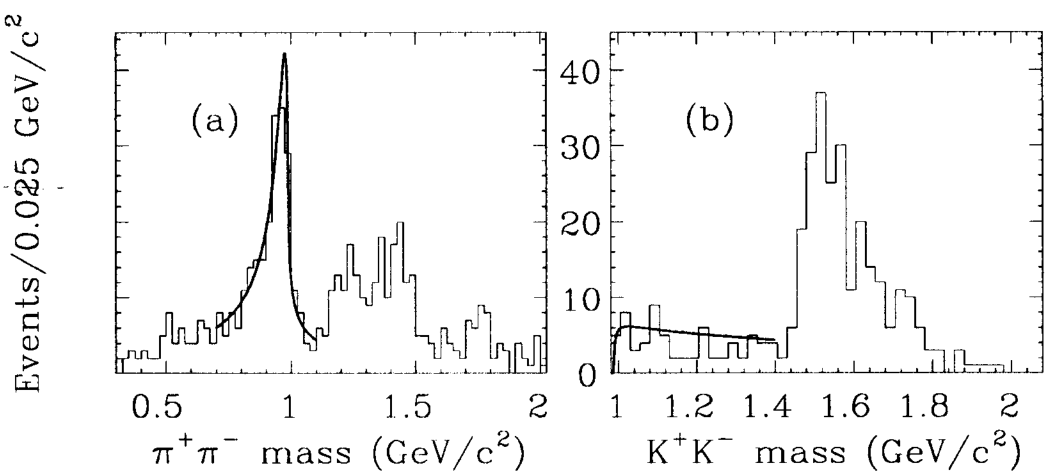

Fig. 3. (a) Coupled channel Breit-Wigner fit to the $f_0(975)\to\pi^+\pi^-$ line shape. (b) $K\bar{K}$ prediction from the fit in (a).

The $f_0(975)$ product branching ratios for the two $\pi\pi$ modes are shown in Table VI. Both values include the appropriate isospin correction factors for the decay of an isoscalar into two pions. The systematic errors include uncertainties due to the J/ψ flux (8%), non-ϕ background subtraction (8%), efficiency function model dependence (10%), and in the $\pi^0\pi^0$ channel, an additional 15% uncertainty due to the $|\cos\theta_\gamma|$ requirement. Within the errors, the corrected product branching ratios from the two modes are in agreement.

Table V. $f_0(975)\to\pi^+\pi^-$ coupled channel fit results.

Mass	(976±6) MeV/c^2
g_π^2	(650±440) MeV
g_K^2/g_π^2	4.6±1.0

Table VI. Product Branching ratios.

Channel	$B(J/\psi\to\phi f_0(975))\times B(f_0(975)\to\pi\pi)$
$\pi^+\pi^-$	$(4.2\pm0.3\pm0.6)\times10^{-4}$
$\pi^0\pi^0$	$(5.0\pm0.5\pm1.0)\times10^{-4}$

B. $J/\psi\to\omega\pi^+\pi^-$[14]

Fig. 4(a) displays the Dalitz plot of $M^2_{\omega\pi^+}$ vs. $M^2_{\omega\pi^-}$, in which prominent bands due to the decays $b_1(1235)\to\omega\pi$ and $f_2(1270)\to\pi^+\pi^-$ are visible. In addition, there is an enhancement at low $\pi^+\pi^-$ mass which does not correspond to any known state. The

$f_0(975)$ signal is not easily visible in this plot due to interference with the other amplitudes.

In Fig. 4(b), the invariant mass of the $\pi^+\pi^-$ system recoiling against the ω is shown. In addition to the prominent $f_2(1270)$ signal and low-mass structure, a small enhancement near the $f_0(975)$ mass is evident. Similar features been observed by the DM2 collaboration. They fit the 900-1400 MeV/c^2 range to an incoherent sum of two Breit-Wigner functions over a polynomial background, fixing the $f_0(975)$-width to 35 MeV/c^2 and obtain[15]

$$M(f_0(975))=(959.4\pm6.5)\ \mathrm{MeV}/c^2 \quad (9)$$

$$B(J/\psi\to\omega f_0(975)) \times B(f_0(975)\to\pi\pi)=(1.10\pm0.21\pm0.16)\times 10^{-4} \quad (10)$$

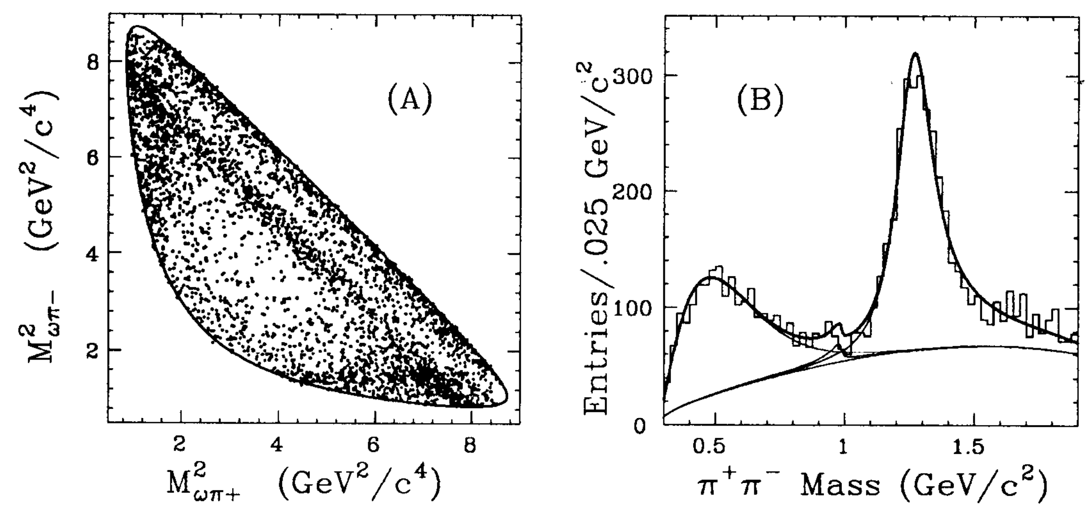

Fig. 4 (a): Dalitz plot of the decay $J/\psi\to\omega\pi^+\pi^-$. (b) Invariant mass of the $\pi^+\pi^-$ system opposite the ω. The solid curves represent the fit described in the text. The curve representing the $f_0(975)$ corresponds to the 90% confidence level upper limit on the product branching ratio.

Due to the weakness of the $f_0(975)$-signal and the uncertainties associated with parameterizing the tails from the low-mass enhancement and the shape of the underlying background in the $f_0(975)$ region, we choose to quote an upper limit on the product branching ratio, using the coupled-channel parameterization of the $f_0(975)$ obtained in the $\phi\pi^+\pi^-$ channel. Fig. 4(b) shows the results of fitting the invariant mass distribution of the $\pi^+\pi^-$ system opposite the ω to the $f_0(975)$ coupled-channel distribution together with a relativistic D-wave Breit-Wigner function to describe the $f_2(1270)$ and a smooth polynomial to model the low-mass enhancement. These functions have been added to a phase space background. The upper limit on the product branching ratio is

$$B(J/\psi\to\omega f_0(975)) \times B(f_0(975)\to\pi\pi)<1.6\times 10^{-4} \qquad (11)$$

at the 90% confidence level. This result is preliminary; a full wave analysis to extract the putative $f_0(975)$ signal is currently being carried out.

IV. Conclusions

A coupled-channel fit to the $f_0(975)$ line shape in the decay $J/\psi\to\phi f_0(975)\to\phi\pi^+\pi^-$ has yielded the following values for the coupling constants:

$$g_\pi^2 = (650 \pm 440)\ \mathrm{MeV}$$

$$g_K^2 / g_\pi^2 = (4.6 \pm 1.0)$$

For recoil masses near 1 GeV/c^2, the production and decay angular distributions of the ϕ in reactions (1)-(3) are similar, indicating that the sharp rise in the KK rate just above threshold is due to the $f_0(975)$. The KK rate predicted from the $\pi\pi$ coupled-channel fit is compatible with the observed spectrum. Little evidence for the production of the $f_0(975)$ opposite the ω is seen; an upper limit on the product branching ratio $B(J/\psi\to\omega f_0(975)) \times B(f_0(975)\to\pi\pi)<1.6\times 10^{-4}$ at the 90% confidence level is obtained. This result is approximately a factor of 3 smaller than the measured product branching ratio in the $\phi\pi^+\pi^-$ channel. These results indicate that the $f_0(975)$ is not the o-like member of an ideally mixed $q\bar{q}$ nonet, as suggested by the mass degeneracy of the $f_0(975)$ and its isovector partner, the $a_0(980)$. One possible explanation of the observed rates and the $f_0(975)/a_0(980)$ mass degeneracy is that these objects are $K\bar{K}$ molecules. However, the observed width of the $f_0(975)$ in the $\phi\pi^+\pi^-$ channel is in mild conflict with the predictions of the molecule model.

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