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Published in:
Physics Letters B

DOI:
10.1016/0370-2693(88)91840-0

$f_1(1285)$ FORMATION IN PHOTON–PHOTON FUSION REACTIONS

TPC/Two-Gamma Collaboration

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Received 28 April 1988

We have observed formation of the $f_1(1285)$ in the reaction $e^+e^- \to e^+e^-\pi^+\pi^-\eta(\eta\to\gamma\gamma)$. Its $\gamma\gamma^*$ width is determined in several Q^2 bins. The $\gamma\gamma$ coupling parameter for the $f_1(1285)$ is found to be $2.4\pm0.5\pm0.5$ keV. This value is compared to that for the X(1420), another $J=1$ state formed in $\gamma\gamma$ fusion reactions, which may belong to the same meson nonet.

The TPC/Two-Gamma Collaboration has previously reported [1] the first observation of the formation by $\gamma\gamma$ fusion of a spin-one meson. Our observation of that resonance, which we call the X(1420), in the final state $K^\pm K^0_S\pi^\mp$ ($K^0_S\to\pi^+\pi^-$) was subsequently confirmed by the MARK II and JADE Collaborations [2,3]. If the X(1420) is the pure $s\bar{s}$ isoscalar member of an ideally-mixed axial-vector $q\bar{q}$ meson nonet, then the cross section for its formation in $\gamma\gamma$ fusion reactions is expected to be very small relative to that for the formation of the other isoscalar member of the nonet, the $f_1(1285)$. The composition of the $f_1(1285)$ is less controversial than that of the X(1420); it is therefore interesting to measure the cross section for formation of the $f_1(1285)$ by $\gamma\gamma$ fusion not only to measure the coupling of the $f_1(1285)$ to two photons, but also to establish a benchmark against which the X(1420) measurement can be compared.

We describe here our observation of $f_1(1285)$ formation in the reaction $e^+e^- \to e^+e^-\eta\pi^+\pi^-$ ($\eta\to\gamma\gamma$). Our measurements are compared to those recently reported [4] by the MARK II Collaboration. This letter also includes revised results, based on a new model and more data, concerning the formation of the X(1420). We conclude with a comparison of our $f_1(1285)$ and X(1420) results; in particular, we consider the implications of the hypothesis that both states belong to the same $q\bar{q}$ meson nonet.

The reaction discussed here is

$$e^+e^- \to e^+e^-\gamma^*\gamma^* \to e^+e^-A\,, \qquad (1)$$

where A is a spin-one resonance formed by the fusion of the two spacelike virtual photons (γ^*). Yang's theorem states that a spin-one field cannot couple to two real photons [5]. This implies that the cross section for reaction (1) must be small until the Q^2 of at least one of the virtual photons (defined as $-q^2$, where q is its four-momentum) is comparable to a characteristic mass-squared, probably of order M_ρ^2 or M_A^2. This in turn implies that at least one of the final-state leptons will be scattered by a relatively large angle compared to the very small angles characteristic of most $\gamma\gamma$ fusion reactions. When such a lepton is detected, it is called a *tag*. Even in experiments equipped with a forward detector system, the number of tagged events is usually small compared to the number of untagged events. Consequently, the formation of spin-one mesons in $\gamma\gamma$ fusion reactions has only recently been observed. On the other hand, when such a state is observed, the observation of a signal *only* in tagged data can be used to identify a resonance uniquely as a spin-one meson, even with low statistics.

The data described here were collected with the TPC/Two Gamma facility [6] at the SLAC storage ring PEP, and resulted from the interaction of 14.5 GeV electrons and positrons. The untagged data represent an $\int \mathscr{L}\mathrm{d}t$ of 140 pb^{-1}; the tagged data, 114 pb^{-1}. The Time Projection Chamber (TPC) was used to measure the momentum (p) and mean $\mathrm{d}E/\mathrm{d}x$ of charged tracks produced at angles more than 340 mrad from the beam. The $\mathrm{d}E/\mathrm{d}x$ and momentum measurements were used to assign a χ^2 value for each particle identification hypothesis (e, μ, π, K, p). Between 25 and 180 mrad from the beam, drift chambers (DC), Čerenkov counters, and muon chambers were used for tracking and particle identification. A tag was identified by its energy deposition in arrays of NaI crystals between 25 and 90 mrad or in lead/scintillator shower counters (SHW) between 100 and 180 mrad from the beam. These detectors gave us good acceptance for tags corresponding to virtual photons with Q^2 between 0.1 and 5 GeV^2. Photons were detected in the NaI and SHW calorimeters, and in two proportional-mode pole-tip calorimeters covering the region 300–600 mrad from the beam, as well as in a hexagonal Geiger-mode calorimeter covering polar angles more than 700 mrad from the beam. Reconstructed e^+e^- conversion pairs in the TPC were also allowed as final-state photons.

To search for $\eta\pi^+\pi^-$ events, we selected events containing exactly two pions, two photons, and at most a single tag. Pion-candidate tracks in the TPC could not belong to a conversion pair, and were required to have $\chi^2_\pi < 10$, $\theta > 420$ mrad (where θ is the angle between the pion momentum and the beam) and $\delta p/p < 30\%$. We also required that the track originate near the interaction point, and that p be greater than a value between 120 and 210 MeV/c, depending on the track's θ and curvature. The photon energies had to exceed minima of 50–500 MeV, depending on the detector. Tags had to deposit at least 4 GeV in the NaI, or 8 GeV in the SHW, and to have matching DC hits.

In addition to these track and photon quality cuts, a number of cuts were made to exclude various backgrounds. Annihilation events were rejected by requiring that the sum of the magnitudes of the pion and photon momenta be less than 10 GeV/c. Exclusive backgrounds arising from ambiguities in particle identification were suppressed by requiring that $\sum\chi^2_\pi + 4 < \mathrm{Min}(\sum\chi^2_e, \sum\chi^2_K, \sum\chi^2_p)$, where the sums are over the pion-candidate TPC tracks. Most remaining exclusive $\pi^+\pi^-$ and $\mu^+\mu^-$ events were removed by requiring in untagged events that the two tracks be separated by less than 170° in azimuth, and in tagged events that the magnitude of the sum of the transverse momenta of the two tracks and the tag be greater than 80 MeV/c. To select exclusive events, we required that the total P_T of the event, defined as the magnitude of the sum of the transverse momenta of the pions, photons, and tag (if any), be less than 300 MeV/c.

Events passing all these cuts were subjected to a two-stage kinematic fit. In the first stage, the measured momenta were fit to the constraint $P_T=0$. Events failing to pass this 2C fit with a χ^2 probability greater than 2% were rejected. We then selected exclusive $\eta\pi^+\pi^-$ candidate events by requiring that the 2C-fitted $\gamma\gamma$ mass be within 150 MeV/c^2 of M_η, and that both fitted photon energies (excepting conversion pairs) be greater than 125 MeV. These events were re-fit with the added constraint $M_{\gamma\gamma}=M_\eta$. Any event failing to pass this 3C fit with a χ^2 probability greater than 3%, or in which either of the 3C-fitted photon energies was less than 125 MeV, was rejected. Finally, all the remaining events were eye-scanned; about 20% were rejected because of evidence that the $\gamma\gamma$ fusion final state was not $\pi^+\pi^-\gamma\gamma$. For example, some events had very low angle TPC tracks that were not reconstructed; others had "photons" that were actually showers produced by backscattered tracks or nuclear interaction products.

The final $\eta\pi^+\pi^-$ sample contains 197 untagged and 129 tagged events. The $\eta\pi^+\pi^-$ invariant-mass spectra are shown in fig. 1. A peak due to formation of the η' is prominent in the mass spectrum of tagged data, but there are only a few η' events in the untagged data. This difference is predicted by a Monte Carlo calculation of our experimental acceptance, which includes the effects of electromagnetic and nuclear interactions, detector response and triggering, and the event selection and fitting procedure described above. A more detailed discussion of this point, and of the $\eta\pi^+\pi^-$ analysis in general, may be found in ref. [7].

There is a second peak in the tagged $\eta\pi^+\pi^-$ mass spectrum with no untagged counterpart. If this peak, centered at a mass of 1273 ± 11 MeV/c^2, were due to the formation of a $J=0$ meson, for example, the Monte Carlo simulation implies that we would see a peak of about 50 events in the untagged-data mass spectrum, as shown in fig. 1a. Since that spectrum clearly does not contain a peak near 1273 MeV/c^2,

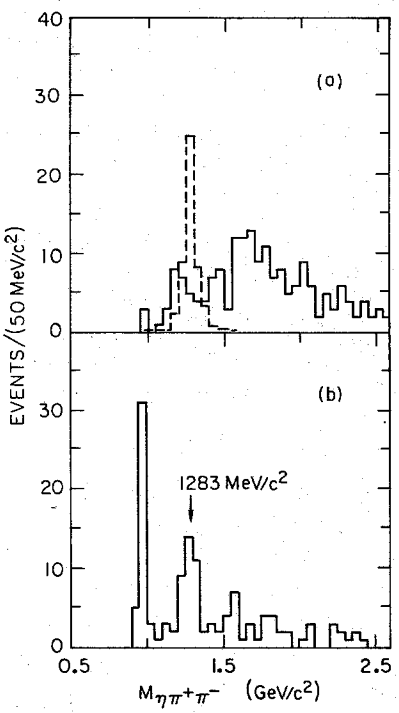

Fig. 1. The 3C-fitted $\eta\pi^+\pi^-$ invariant mass spectra of the final event samples: (a) untagged data; (b) tagged data. The dashed histogram in (a) shows the peak expected there if the peak in (b) were due to formation of a resonance with $J\neq1$.

whereas the spectrum of tagged data does, we conclude that the events in the tagged data are due to the formation of a $J=1$ resonance [5]. The mass and width of the peak are consistent with those expected for the $f_1(1285)$, which is known to decay in this channel [8].

Before discussing our $f_1(1285)$ results, we briefly discuss the formalism we use to describe $\gamma\gamma$ fusion reactions. We will define virtual $\gamma\gamma$ widths $\Gamma^{ij}_{\gamma^*\gamma^*}$ for a resonance R coupling to two virtual photons whose polarizations are given by i and j (which may be either T for transverse or L for longitudinal). If the resonance has mass M, spin J, and width Γ, the $\Gamma^{ij}_{\gamma^*\gamma^*}$ are given in terms of the cross sections for $\gamma^*\gamma^*\to$R defined in ref. [9] by

$$\sigma_{ij}=\frac{32\pi(2J+1)}{N_iN_j}\frac{W^2}{2\sqrt{X}}\frac{\Gamma}{(W^2-M^2)^2)+\Gamma^2M^2}\times\Gamma^{ij}_{\gamma^*\gamma^*}(Q_1^2,Q_2^2,W^2)\,. \qquad (2)$$

Here, N_i is the number of polarization states (1 for $i=\mathrm{L}$, 2 for $i=\mathrm{T}$), W is the invariant mass of the final state R, and $X=k^2W^2$, where k is the magnitude of the virtual photon momenta in the $\gamma^*\gamma^*$ center of mass. For singly-tagged events, we define $\Gamma^{ij}_{\gamma^*\gamma^*}(Q^2)$ as $\Gamma^{ij}_{\gamma^*\gamma^*}(Q^2, 0, M^2)$ if the e^+ is tagged, or $\Gamma^{ji}_{\gamma^*\gamma^*}(0, Q^2, M^2)$ if the e^- is tagged.

In contradistinction to the situation when the resonance formed has $J=0$, for which only σ_{TT} can be non-zero, both σ_{LT} and σ_{TT} can contribute to the cross section for the formation of a $J=1$ meson A in singly-tagged events. In the singly-tagged case, the cross section for reaction (1) is proportional to

$$\Gamma_{\gamma\gamma^*}(Q^2)\equiv[1+\epsilon^{-1}\mathscr{R}(Q^2, M_{\mathrm{A}}^2)]\Gamma^{\mathrm{LT}}_{\gamma\gamma^*}(Q^2)\,. \qquad (3)$$

Here $\mathscr{R}(Q^2, W^2)\equiv\sigma_{\mathrm{TT}}/\sigma_{\mathrm{LT}}$, and ϵ^{-1} is the average value, for the given Q^2 and W^2, of $\mathscr{L}_{\mathrm{TT}}/\mathscr{L}_{\mathrm{LT}}$, where the $\mathscr{L}_{ij}$ are the $\gamma^*\gamma^*$ effective luminosities defined in ref. [9]; in our experiment $\epsilon\approx 1$. Bose symmetry and gauge invariance together imply that as $Q^2\to 0$, $\mathscr{R}\to 0$ and $\Gamma_{\gamma\gamma^*}(Q^2)\propto Q^2$. Hence $\Gamma_{\gamma\gamma^*}(Q^2)$ cannot be written as $\Gamma_{\gamma\gamma^*}(0)$ times a normalized function of Q^2, as is done for resonances with $J=0$. Instead, we define the $\gamma\gamma$–A coupling parameter $\tilde{\Gamma}_{\gamma\gamma}(\mathrm{A})$ by

$$\tilde{\Gamma}_{\gamma\gamma}(\mathrm{A})\equiv\lim_{Q^2\to 0}\frac{M_{\mathrm{A}}^2}{Q^2}\Gamma^{\mathrm{LT}}_{\gamma\gamma^*}(Q^2)\,. \qquad (4)$$

If $\tilde{\Gamma}_{\gamma\gamma}(\mathrm{A})\neq 0$, we then define the effective $\gamma\gamma^*$ form factor $\tilde{F}$ for the meson A by

$$\Gamma_{\gamma\gamma^*}(Q^2)=\frac{4X}{M_{\mathrm{A}}^4}\tilde{F}^2(Q^2)\tilde{\Gamma}_{\gamma\gamma}(\mathrm{A})\,. \qquad (5)$$

As $Q^2\to 0$, $\tilde{F}(Q^2)\to 0$ and $M_{\mathrm{A}}^2\tilde{F}^2(Q^2)/Q^2\to 1$.

Cahn has derived a model for the formation by $\gamma\gamma$ fusion of $J^{PC}=1^{++}$ mesons [10] [#1]. His model predicts $\mathscr{R}=Q^2/2W^2$, so that

$$\tilde{F}^2(Q^2)\approx(1+Q^2/2M_{\mathrm{A}}^2)\frac{Q^2}{M_{\mathrm{A}}^2}F^2(Q^2)\,, \qquad (6)$$

where F is a form factor (as yet unspecified) satisfying the normalization condition $F(0)=1$. The vector meson dominance model suggests that F may be similar to the rho form factor, $F_\rho(Q^2)=(1+Q^2/M_\rho^2)^{-1}$.

The parity of a $J=1$ state decaying to three particles influences the distribution of θ^*, the angle between the $\gamma\gamma$ axis and the normal to the decay plane. An analysis of our observed θ^* distribution, described elsewhere [7], indicates that positive parity is favored for the $J=1$ resonance we observe in the $\eta\pi^+\pi^-$ final state, although negative parity cannot be excluded. We will assume that this resonance is the $f_1(1285)$, and will proceed to use the Cahn model, with the assumption $F=F_\rho$, to determine $\tilde{\Gamma}_{\gamma\gamma}(f_1(1285))$. Our experimental acceptance was determined using a Monte Carlo simulation similar to that described above, now incorporating the Cahn model and the decay $f_1(1285)\to a_0(980)\pi\to\eta\pi\pi$. Our acceptance, however, is not sensitive to the details of the Monte Carlo model [7]. We assumed a background of 8 ± 3 events in the mass region 1200 MeV/$c^2<W<1350$ MeV/c^2, corresponding to a net signal of 26 events. Fig. 2 shows the values of $\tilde{F}^2(Q^2)\times\tilde{\Gamma}_{\gamma\gamma}(f_1(1285))$ we find in three bins of Q^2, as well as the values the MARK II results imply for this quantity [#2]. The Cahn model with $F=F_\rho$ best fits our data for

$$\tilde{\Gamma}_{\gamma\gamma}(f_1(1285))=2.4\pm 0.5\pm 0.5\ \mathrm{keV}\,. \qquad (7)$$

The second error is systematic, and includes contri-

[#1] Cahn's definition of $\Gamma^{ij}_{\gamma^*\gamma^*}(Q_1^2, Q_2^2, W^2)$ for $J=1$ leads, for a given cross section, to $\Gamma^{ij}_{\gamma^*\gamma^*}$ and $\Gamma^{ij}_{\gamma\gamma^*}$ functions greater by a factor $4\sqrt{X}/W^2$ than those defined by eq. (2); in the case of $\Gamma^{ij}_{\gamma\gamma^*}(Q^2)$, this factor is equal to $2(1+Q^2/M_{\mathrm{A}}^2)$. This results in his $\tilde{\Gamma}_{\gamma\gamma}$ values being greater than ours by a factor of 2. The differences between the two conventions are discussed in more detail in ref. [7], and are also summarized in ref. [11].

[#2] For footnote see next page.

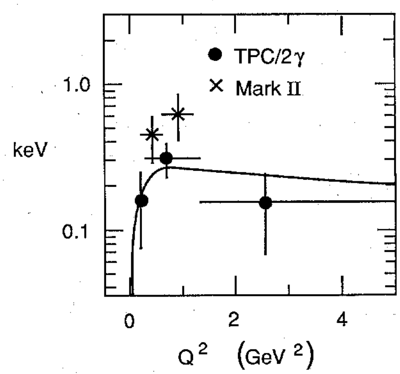

Fig. 2. $\tilde{F}^2(Q^2)\tilde{\Gamma}_{\gamma\gamma}(f_1(1285))$. Errors shown are statistical only. The curve is the prediction of the Cahn model with $F=F_\rho$ and $\tilde{\Gamma}_{\gamma\gamma}(f_1(1285))=2.4$ keV. The MARK II results derived (see footnote 2) from ref. [4] are also shown.

butions from uncertainties in luminosity (5%), detector response and triggering (5%), the efficiency of the event selection and fitting procedure (15%), and the branching fraction for $f_1(1285) \to \eta\pi\pi$ (12%) [8]. The MARK II group, whose assumption regarding the overall Q^2 dependence of the cross section for reaction (1) was the same as ours, found a somewhat larger value: $\tilde{\Gamma}_{\gamma\gamma}(f_1(1285)) = 4.7 \pm 1.3 \pm 0.9$ keV [#3].

As previously reported [1], we have observed another $J=1$ state, the X(1420), in the $K^\pm K^0_S \pi^\mp$ ($K^0_S \to \pi^+\pi^-$) channel. Once again, positive parity is preferred, but negative parity cannot be excluded [7]; the observed mass, width, and decays of the X(1420) are consistent with the properties of the $f_1(1420)$, a state seen in hadronic interactions [12]. The nature of the X(1420) is uncertain: while it may be a $q\bar{q}$ meson belonging to the same nonet as the $f_1(1285)$, more exotic possibilities, including $q^2\bar{q}^2$ [13] and $q\bar{q}g$ [14], have also been suggested.

In ref. [1] we reported a value of $6 \pm 2 \pm 2$ keV for $B_{K\bar{K}\pi}\tilde{\Gamma}_{\gamma\gamma}(X(1420))$, where $B_{K\bar{K}\pi}$ is the branching fraction for $X(1420) \to K\bar{K}\pi$. But that result was based on a model with $\mathscr{R}=0$, and without the factor $4X/M_A^4$ in eq. (5). Had we used the Cahn model with $F=F_\rho$, as described above, our result would have been $2.1 \pm 0.7 \pm 0.7$ keV. Since our original report, we have completed the analysis of about 25% more data; we have also narrowed the W region used to measure $\Gamma_{\gamma\gamma^*}$ and excluded some events because of the probable presence of low-energy photons. In addition, we have considered the possibility that the X(1420) is a mostly $s\bar{s}$ state for which the assumption $F=F_\phi \equiv (1+Q^2/M_\phi^2)^{-1}$ might be more appropriate than $F=F_\rho$. Our new results, using the Cahn model, are

$$\begin{aligned} B_{K\bar{K}\pi}\tilde{\Gamma}_{\gamma\gamma}(X(1420)) & \\ = 1.3 \pm 0.5 \pm 0.3\ \text{keV}, & \quad \text{if } F=F_\rho, \\ = 0.63 \pm 0.24 \pm 0.15\ \text{keV}, & \quad \text{if } F=F_\phi . \end{aligned} \tag{8}$$

Assuming $F=F_\rho$, the MARK II Collaboration found $B_{K\bar{K}\pi}\tilde{\Gamma}_{\gamma\gamma}(X(1420)) = 1.65 \pm 0.7 \pm 0.3$ keV [#3]. Fig. 3 shows the values we find for $B_{K\bar{K}\pi}\tilde{F}^2(Q^2) \times \tilde{\Gamma}_{\gamma\gamma}(X(1420))$ in three bins of Q^2, as well as the Cahn model predictions for both $F=F_\rho$ and $F=F_\phi$, normalized by the values given in eq. (8). If suggestions that the X(1420) is an exotic $q\bar{q}g$ or $q^2\bar{q}^2$ state are correct, then the true value of $\tilde{\Gamma}_{\gamma\gamma}(X(1420))$ may well differ significantly from those given in eq. (8), since the Cahn model was derived specifically for $q\bar{q}$ mesons. Note that the experimental results shown in figs. 2 and 3 are almost independent of the form assumed for $\tilde{F}^2(Q^2)$ (e.g., the Cahn model with $F=F_\rho$ or $F=F_\phi$), as is explained in ref. [7]. It is only the extrapolation of these results to $Q^2=0$ in order to determine $\tilde{\Gamma}_{\gamma\gamma}$ which is highly model-dependent.

If the state we see at 1273 MeV/c^2 is the $f_1(1285)$, and if the X(1420) is the other isoscalar member of the axial-vector $q\bar{q}$ meson nonet, then their $\tilde{\Gamma}_{\gamma\gamma}$ values are related [15]:

$$\frac{\tilde{\Gamma}_{\gamma\gamma}(f_1(1285))}{\tilde{\Gamma}_{\gamma\gamma}(X(1420))} = \frac{M_{1285}}{M_{1420}} \cot^2(\theta_A - \theta_0) , \tag{9}$$

where θ_A is the singlet–octet mixing angle of the nonet, and $\theta_0 = \arcsin(1/3) \approx 19.5°$. Assuming $B_{K\bar{K}\pi} \approx 1$, we find $\theta_A = 54.4 \pm 7.5°$ if $F=F_\rho$ for the X(1420), in

[#2] Ref. [4] presents values for $\tilde{\Gamma}_{\gamma\gamma}(f_1(1285))$ derived from data in two Q^2 bins. In order to convert these results to the quantity shown in fig. 2b, and to our conventions, we have multiplied each value given in ref. [4] by $\tilde{F}^2_\rho(Q^2_{\rm bin})/2$. In this expression, $\tilde{F}_\rho(Q^2)$ is the spin-one effective form factor predicted by the Cahn model with $F=F_\rho$, and $Q^2_{\rm bin}$ is the location of the point in question, as shown in ref. [4].

[#3] We have divided the $\tilde{\Gamma}_{\gamma\gamma}$ values reported in refs. [2,4] by 2, in order to convert them to the convention defined by eqs. (2) and (4); see also ref. [10].

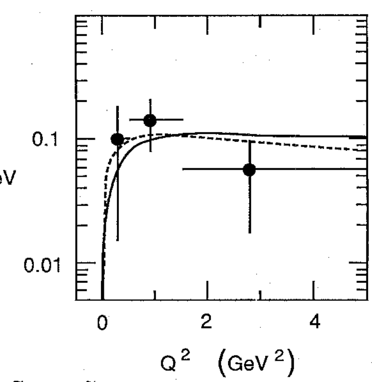

Fig. 3. $B_{K\bar{K}\pi}\tilde{F}^2(Q^2)\tilde{\Gamma}_{\gamma\gamma}(X(1420))$. Errors shown are statistical only. the curves shown are the predictions of the Cahn model with different form factors: the solid curve is its prediction if $F=F_\phi$ and $B_{K\bar{K}\pi}\tilde{\Gamma}_{\gamma\gamma}(X(1420)) = 0.63$ keV; the dashed curve is its prediction if $F=F_\rho$ and $B_{K\bar{K}\pi}\tilde{\Gamma}_{\gamma\gamma}(X(1420)) = 1.3$ keV.

agreement with the MARK II group's results [#4]. If instead $F=F_\phi$, we find $\theta_A=45.4\pm6.2°$. As the difference between these results illustrates, the mixing angle implied by these data is rather model-dependent. If $\theta_A=45.4°$, the X(1420) would be a mostly $s\bar{s}$ state, and the $f_1(1285)$ mostly $(u\bar{u}+d\bar{d})/\sqrt{2}$, but each would contain an admixture of about 3% of the other's dominant $q\bar{q}$ component; if $\theta_A=54.4°$, this increases to about 11%.

In summary, we have observed formation of the axial-vector meson $f_1(1285)$ in $\gamma\gamma$ fusion reactions. Using the Cahn model for the formation of such mesons, and assuming $F=F_\rho$, we found $\tilde{\Gamma}_{\gamma\gamma}(f_1(1285))=2.4\pm0.5\pm0.5$ keV. If the $J^{PC}=1^{++}$ nonet containing the $f_1(1285)$ were ideally mixed, its other isoscalar member would be a pure $s\bar{s}$ state and its singlet–octet mixing angle, θ_A, would have the value $\arcsin(1/\sqrt{3})\approx35.3°$. If the isoscalar partner of the $f_1(1285)$ is the X(1420), another $J=1$ state seen in $\gamma\gamma$ fusion reactions, then θ_A can be extracted from the ratio of $\tilde{\Gamma}_{\gamma\gamma}(f_1(1285))$ to $\tilde{\Gamma}_{\gamma\gamma}(X(1420))$. Using two different assumptions for the X(1420) form factor, we found $\theta_A=54.4\pm7.5°$ and $\theta_A=45.4\pm6.2°$. These results are consistent with the 42.2° mixing angle implied by the Gell–Mann–Okubo quadratic mass formula. However, we have no evidence contrary to hypotheses that the X(1420) is an exotic $q\bar{q}g$ or $q^2\bar{q}^2$ state.

We thank the PEP staff for their dedication and productive running of the machine, and our engineers and technicians for their efforts in the construction and maintenance of the detectors. This work was supported in part by the United States Department of Energy, the National Science Foundation, the Joint Japan–United States Collaboration in High-Energy Physics, and the Foundation for Fundamental Research on Matter in the Netherlands.

[#4] The MARK II Collaboration's measured ratio $\tilde{\Gamma}_{\gamma\gamma}(f_1(1285))/\tilde{\Gamma}_{\gamma\gamma}(X(1420))$, given in ref. [4], is 3.0 ± 1.8. If used in eq. (9), this value, which assumes $F=F_\rho$ for both states, would imply $\theta_A=48.2^{+12.2}_{-5.3}$.

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