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Journal
Physical Review Letters, 59(18)

ISSN
0031-9007

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Publication Date
1987-11-02

DOI
10.1103/physrevlett.59.2016

Evidence for a Spin-1 Resonance in the Reaction $\gamma\gamma^* \rightarrow K^0K^{\pm}\pi^{\mp}$

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(Received 29 April 1987; revised manuscript received 18 September 1987)

We confirm the observation of a spin-1 resonance at 1423 MeV in the $K_S^0K^{\pm}\pi^{\mp}$ system produced in single-tagged two-photon interactions. The Dalitz plot indicates that this resonance decays primarily via a K^*K intermediate state. We measure a radiative width times branching ratio $B_{K\bar{K}\pi}(M^2/Q^2)\Gamma_{\gamma\gamma^*} = 3.2 \pm 1.4 \pm 0.6$ keV on the assumption of a ρ-pole form factor.

PACS numbers: 14.40.Cs, 13.40.Hq, 13.65.+i

Two mesons, the $\eta(1440)$ and $f_1(1420)$, appear at nearly the same mass in a wide variety of experiments. Different experiments obtain different spin and parity assignments for mesons in this mass region, although most radiative J/ψ decay experiments obtain $J^P = 0^-$ and a mass near 1450 MeV,[1] while hadrorproduction experiments find $J^P = 1^+$ or 0^- and a mass near 1420 MeV.[2]

The $K^0K^{\pm}\pi^{\mp}$ final state is a major decay mode of the $\eta(1440)$ and $f_1(1420)$ and so can be used to study their production in photon-photon interactions. Although rather stringent limits[3] have been placed on $\Gamma(\eta(1440) \rightarrow \gamma\gamma)$, where the photons are on the mass shell, the TPC/Two-Gamma Collaboration has recently reported[4] evidence for a state near 1420 MeV in the $K^0K^{\pm}\pi^{\mp}$ system produced in tagged $\gamma\gamma^*$ interactions. We report on a similar study with 220 pb^{-1} of data taken with the Mark II detector at the SLAC e^+e^- storage ring PEP and confirm this observation.[5] The production at only larger Q^2, indications of a dominant K^*K decay mode, and our failure to observe it in $\eta\pi^+\pi^-$ lead us to identify this state tentatively with the $J^{PC} = 1^{++}$ $f_1(1420)$.

The major features of the Mark II detector have been well described elsewhere.[6,7] The small-angle tagging system (SAT) and shower counter identify and measure scattered electrons at polar angles between 21 and 83 mrad from the incident e^+ or e^- direction. Events with one SAT track having energy greater than 7 GeV are accepted in this analysis. To study the reaction

$$e^+e^- \rightarrow e^+e^-K^0K^{\pm}\pi^{\mp}, \qquad (1)$$

we further select events with four charged tracks of net charge zero in the central detector. We then require that two of these tracks reconstruct to a K_S^0 which decays at least 2.0 mm from the primary vertex. The projection of these two tracks to the secondary vertex, and cuts that require a positive flight path and $480 < m_{\pi^+\pi^-} < 520$ MeV, define the K_S^0 sample. The distribution in $m_{\pi^+\pi^-}$ before the last cut is shown in Fig. 1 and indicates very little background. To eliminate a possible $f'(1520) \rightarrow K_S^0\bar{K}_S^0$ background, we remove events in which the $\pi^+\pi^-$ pair opposite the identified K_S^0 has an invariant mass between 480 and 520 MeV. Most tracks produced by Reaction (1) have momenta below 1 GeV/c and therefore, whenever possible, time-of-flight information is used to identify the charged K and π tracks. Each candidate event is then examined in detail for such things as untracked $K^{\pm}$ decays, poorly measured tracks,

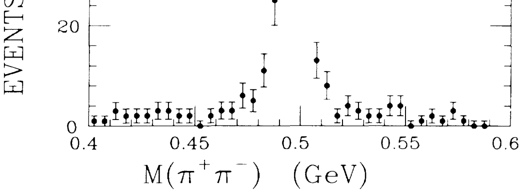

FIG. 1. Invariant mass of $\pi^+\pi^-$ pairs used to define the K_S^0 sample.

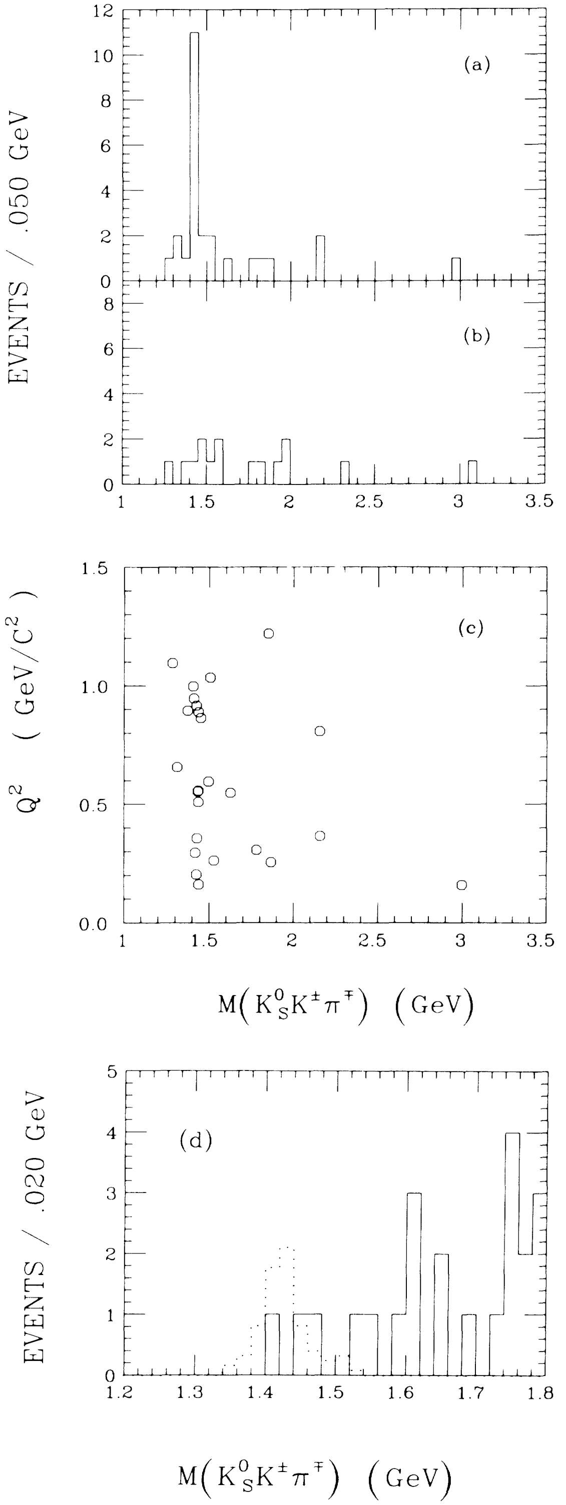

FIG. 2. $K_S^0K^\pm\pi^\mp$ invariant mass for (a) the accepted-event sample and (b) the events with extra γ's. Scatter plot of this invariant mass vs Q^2 for the accepted events. (d) The relevant region of $K_S^0K^\pm\pi^\mp$ invariant mass for untagged events.

and especially extra γ's detected in the liquid-argon barrel calorimeters or the proportional-chamber end caps, that are not associated with charged tracks. The events with extra gammas are primarily "feed-down" from higher-multiplicity $\gamma\gamma^*$ interactions and form a sample that can be used to study potential backgrounds to Reaction (1).

The net transverse momentum with respect to the e^+e^- axis, $\sum \mathbf{p}_T$, including the measured outgoing beam electron or positron, is required to be less than 150 MeV/c. There remain 27 events attributed to Reaction (1). All but one of these have only one combination of tracks consistent with the $K^0K^\pm\pi^\mp$ hypothesis, and we plot their invariant masses in Fig. 2(a). Note the dominant peak between 1400 and 1500 MeV. A fit in 20-MeV bins by a Gaussian distribution gives $M = 1423 \pm 4$ MeV and $\sigma = 14 \pm 2$ MeV, consistent with the detector resolution determined with Monte Carlo simulations. The invariant mass of the background events with extra γ's is shown in Fig. 2(b). These events show no peaking. Figure 2(c) shows the scatter plot of the invariant four-momentum transfer Q^2 vs $M(K^0K^\pm\pi^\mp)$. The peak events are clearly produced at relatively large Q^2 confirming the observations of Ref. 4. Monte Carlo studies (described below) show that the detector acceptance also increases from 1% to 5% as Q^2 increases from threshold to 1.0 $(\mathrm{GeV}/c)^2$.

In Fig. 3(a) we show the Dalitz plot for the thirteen events with masses between 1.4 and 1.5 GeV. Although the statistics are limited, the events appear to be grouped in the $K^*(890)$ bands. The Dalitz plot for the sidebands ($1.3 < M < 1.4$ and $1.5 < M < 1.6$ GeV) together with the corresponding ($1.3 < M < 1.6$ GeV) background "extra photon" events is shown in Fig. 3(b) and shows no clustering in the K^* bands. Alternatively, a decay via the $a_0(980)\pi$ intermediate state would have resulted in a clear signal in the $\eta^0\pi^+\pi^-$ final state, since the $a_0(980)$ decays predominantly into $\eta\pi$. No such signal was seen.[7]

To measure the detection efficiency, we generate Monte Carlo events for a 1425-MeV spin-1 resonance, R, with helicity 1, and with an equal mixture of $K^{*0}K^0$ and $K^{*-}K^+$ decays. The same careful scanning procedure is applied to these Monte Carlo events to obtain the final detection efficiently. The eleven events above background in Fig. 2(a) then correspond to a cross section $\sigma(e^+e^- \to e^+e^-R) = 10.3 \pm 4.0 \pm 1.5$ pb over the Q^2 interval 0.2–1.1 $(\mathrm{GeV}/c)^2$. For a spin-0 resonance, with a Q^2 dependence dominated by a ρ-pole form factor, this would correspond[7] to an expected

$$\Gamma(R \to \gamma\gamma)B(R \to K\bar{K}\pi) = 2.2 \pm 0.8 \pm 0.3 \text{ keV}.$$

The absence of such a resonance in $\gamma\gamma$ interactions at $Q^2 \simeq 0$ has already been noted.[3] To derive such a limit for this experiment we select events as above, but with no SAT energy and with a $\sum \mathbf{p}_T$ less than 100 MeV/c. Figure 2(d) shows the relevant region of invariant mass for these untagged events. The dotted histogram represents the Monte Carlo expectation for 7.5 events of a spin-0 resonance at a mass of 1425 MeV with a Γ of 20 MeV, leading to the limit $\Gamma(R \to \gamma\gamma)B(R \to K\bar{K}\pi) < 0.5$ keV [95% confidence level (C.L.)], well below the above expectation. Since real photon-photon collisions cannot produce a spin-1 particle,[8] while a spin-0 particle would be produced even more copiously than observed, we assume the observed peak to be spin 1.

Following Cahn,[9] we parametrize the observed tagged cross section as

$$\sigma(e^+e^- \to e^+e^-R) = 2\left(\frac{\alpha^2}{\pi^2}\right)\left(\frac{24\pi^2}{M^3}\right)\tilde{\Gamma}_{R\gamma\gamma^*}\int\frac{dQ^2}{M^2}F^2(Q^2)\left\{\ln\left(\frac{Q^2_{\rm cut}}{m_e^2}\right)\left(\ln\frac{1}{\tau'}-\frac{7}{4}\right)+\left(\ln\frac{1}{\tau'}\right)^2-3\ln\frac{1}{\tau'}-\frac{\pi^2}{6}+\frac{23}{8}\right.$$
$$\left.+\frac{1}{2}\frac{Q^2}{M^2}\left[\left(\ln\frac{Q^2_{\rm cut}}{m_e^2}\right)\left(\ln\frac{1}{\tau'}-\frac{3}{2}\right)+\left(\ln\frac{1}{\tau'}\right)^2-\frac{5}{2}\ln\frac{1}{\tau'}-\frac{\pi^2}{6}+\frac{19}{8}\right]\right\}, \qquad (2)$$

where $\tilde{\Gamma}_{R\gamma\gamma^*}=(M^2/Q^2)\Gamma_{R\gamma\gamma^*}$ in the low-Q^2 limit, $\tau' \equiv (M^2+Q^2)/s$, $Q^2_{\rm cut}=0.1$ is the antitagging cutoff, and the residual Q^2 dependence is contained in the form factor, for which we assume the form $F(Q^2)=(1+Q^2/m_\rho^2)^{-1}$. From Eq. (2) evaluated at $\sqrt{s}=29$ GeV, $M=1.425$ GeV, and $m_\rho=0.76$ GeV we obtain from our cross-section measurement, over the Q^2 interval 0.2–1.1 (GeV/c)^2, $B(R \to K\bar{K}\pi)\tilde{\Gamma}_{R\gamma\gamma^*}=3.2 \pm 1.4 \pm 0.6$ keV, lower than the Ref. 4 value of $12 \pm 4 \pm 4$ keV. It is important to note that this result is sensitive to the assumed Q^2 dependence. For example, an $F(Q^2)=(1+Q^2/m_\phi^2)^{-1}$, which might be more appropriate for a resonance with quark composition $s\bar{s}$, would yield

$$B(R \to K\bar{K}\pi)\tilde{\Gamma}(R \to \gamma\gamma^*)=2.1 \pm 1.0 \pm 0.4 \text{ keV}.$$

The axial-vector nonet is usually taken to consist of the $a_1(1270)$, $K_{1A}(1340)$, $f_1(1285)$, and $f_1(1420)$ with ideal mixing, i.e., with quark composition $f_1(1285) \simeq (u\bar{u}+d\bar{d})/\sqrt{2}$ and $f_1(1420) \simeq s\bar{s}$. A nonrelativisitc quark model with these assumptions predicts[10,11] that

$$\tilde{\Gamma}(f_1(1420) \to \gamma\gamma^*) = \tfrac{2}{15}\,(M_{f_1}/M_{f_2})\Gamma(f_2(1270) \to \gamma\gamma) \cong 0.4 \text{ keV},$$

almost an order of magnitude smaller than our measurement with the assumption that $B(R \to K\bar{K}\pi)=1$. The

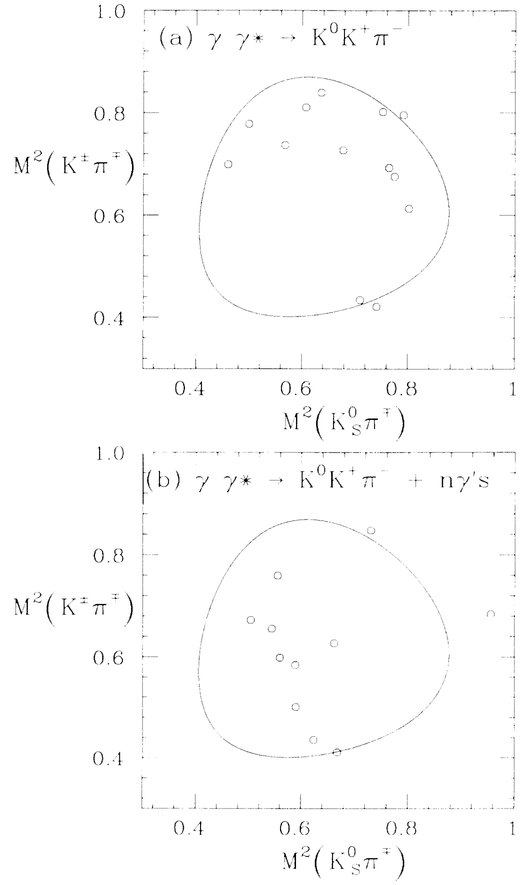

FIG. 3. Dalitz plot for (a) accepted events and (b) background sample.

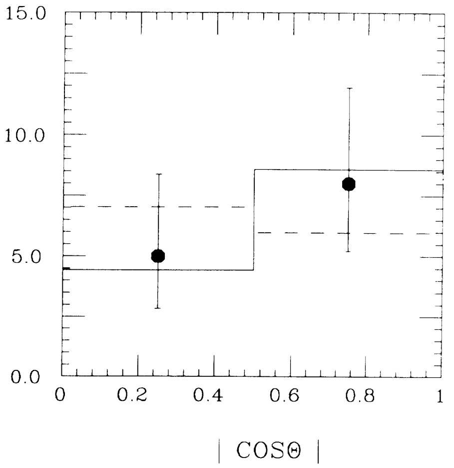

FIG. 4. Measured distribution in $|\cos\theta|$ for the events with $1.4 < M(K^0_S K^\pm \pi^\mp) < 1.5$ GeV. The solid (dashed) histogram is the result of Monte Carlo simulation of the distribution expected for $J^{PC}=1^{++}$ ($J^{PC}=1^{-+}$).

model also predicts that

$$\tilde{\Gamma}(f_1(1285)\to\gamma\gamma^*)/\tilde{\Gamma}(f_1(1420)\to\gamma\gamma^*) \cong \tfrac{25}{2}\, M_{f_1(1285)}/M_{f_1(1420)},$$

larger than our measured ratio[7] of 2.9 ± 1.5. A small deviation from ideal mixing can, however, accommodate these measurements.[7]

Although the $f_1(1285)$ can also decay into $K\bar{K}\pi$, no significant signal is seen at this mass in Fig. 2(a). From the three events below 1.35 GeV, we can calculate a limit

$$B(f_1(1285)\to K\bar{K}\pi)\tilde{\Gamma}(f_1(1285)\to\gamma\gamma^*) < 1.12\ \mathrm{keV}$$

(95% C.L.). Our measurement[7] of $\tilde{\Gamma}(f_1(1285)\to\gamma\gamma^*) = 9.4 \pm 2.5 \pm 1.7$ keV and a branching ratio[12] to $K\bar{K}\pi$ of 0.11 ± 0.03 are consistent with this limit.

On the basis of the relatively large $f_1(1420)$ radiative width and recent observations in hadronic J/ψ decays, Chanowitz[11] has suggested that the observed state is a candidate for an exotic $J^{PC}=1^{-+}$ hybrid $q\bar{q}g$ state (or meikton). A direct test of the spin and parity is obtained from the folded distribution in the cosine of the angle θ between the normal to the decay plane and the incident photon, in the rest frame of the $f_1(1420)$. Cahn[9] has pointed out that at small Q^2 the distribution is $1+\cos^2\theta$ for a $J^{PC}=1^{++}$ particle and $1-\cos^2\theta$ for a $J^{PC}=1^{-+}$ particle. Figure 4 shows the resultant measured folded distribution, normalized to the Monte Carlo simulation, for the thirteen events between 1.4 and 1.5 GeV, together with the expectations[13] from those predictions. No definite conclusion is possible for so few events.

In summary, we have observed a peak near 1425 MeV in $\gamma\gamma^*\to K^0K^{\pm}\pi^{\mp}$ with a Q^2 distribution characteristic of a spin-1 resonance. We tentatively identify it with the $J^{PC}=1^{++}$ $f_1(1420)$, although a departure from ideal mixing is required to accommodate the measured $f_1(1285)$ and $f_1(1420)$ radiative widths in the naive quark model. A more definitive identification awaits a higher-statistics spin and parity determination.

We gratefully acknowledge the significant collaboration of R. N. Cahn and helpful discussions with A. Eisner and M. Chanowitz. This work was supported in part by the U. S. Department of Energy under Contracts. No. DE-AC03-76SF00098, No. DE-AC03-76SF00515, and No. DE-AC02-76ER03064.

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