Evidence for a Spin-1 Particle Produced by Two Photons

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Two-photon production of $K_S^0 K^{\pm}\pi^{\mp}$ states has been studied by the TPC/Two-Gamma experiment at the SLAC storage ring PEP. A resonance of mass 1.42 GeV was seen when one of the photons was quite virtual but not when both photons were nearly real. Production of a spin-1 meson, which cannot be made by two real photons, would fit these observations. The Q^2 dependence of the data in the resonance region agrees with this spin assignment and is incompatible with a spin-0 hypothesis. The mass and width of the resonance are similar to those of the E meson, which has been assigned $J^P=0^-$ and $J^P=1^+$ by different experiments.

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The TPC/Two-Gamma experiment at the SLAC storage ring PEP has studied the two-photon process $e^+e^- \to e^+e^- K_S^0 K^{\pm}\pi^{\mp}$, $K_S^0 \to \pi^+\pi^-$, at a center-of-mass energy of 29 GeV. We report here the observation of a resonance in the $K_S^0 K^{\pm}\pi^{\mp}$ invariant-mass spectrum at 1.42 GeV when either the scattered e^+ or e^- was detected (single tag). In a recent publication,[1] we reported finding no resonance in the same final state for the case in which both photons were nearly real and neither the scattered e^+ nor e^- was detected (no tag). These results imply the production of a spin-1 resonance, which cannot be made by two real photons. Two mesons decaying into $K\bar{K}\pi$ final states are known to exist in this mass region. The ι $[\eta(1440)]^2$ has been extensively studied in radiative J/ψ decays[3] from which it is known to have $J^P=0^-$ and $I=0$. The E $[f_1(1420)]^2$ has been seen in several hadronic reactions,[4,5] also with $I=0$. However, the spin and parity assignment of the E is in dispute, with $J^P=1^+$ seen in some experiments[4] and 0^- in others.[5] If the latter assignment is correct, it is important to know whether the E is the same particle as the ι, which would otherwise be a glueball candidate.[6] The meson reported here as spin-1 may be the E seen in some of the hadronic experiments,[4] but could not be the ι.

The time projection chamber (TPC)[7] was used to determine the identity and momentum of the four charged hadrons in the final state, while the forward spectrometers[8] detected the scattered e^+ or e^- "tag." The tag momentum vector was measured with a magnetic spectrometer consisting of a septum magnet and fifteen drift-chamber planes. The tag energy was determined by total absorption in a segmented forward calorimeter with NaI crystals at small angles and a Pb-scintillator shower counter at larger angles. This combination of momentum and energy measurements supplied a value for Q,[2] the negative of the virtual-photon four-momentum squared.

The single-tag data were collected in two running periods, having different characteristics. The older data set, with an integrated luminosity of 50 pb^{-1}, was obtained with a TPC magnetic field of 4 kG and had a typical momentum resolution of particles studied in this analysis of $\sigma/p \approx 6\%$. The 40 pb^{-1} of newer data, taken with a magnetic field of 13 kG and less material inside the TPC, gave an improved momentum resolution of $\sigma/p \approx 1.5\%$. The trigger required a minimum energy deposition in a forward calorimeter and at least one charged track in the central detector.

Off line, events were selected with a tag of energy > 6 GeV in one of the forward calorimeters. Four charged tracks of total charge zero were required in the TPC, projecting back to the e^+e^- vertex within distances sufficient to keep K^0_S candidates. Particle identification was accomplished by use of dE/dx and momentum measurements from the TPC.[1] One track was identified as a charged kaon and was required to have momentum > 310 MeV. The other three tracks had to be consistent with the pion hypothesis and have momenta > 120 MeV. To avoid background from the $K^+K^-\pi^+\pi^-$ process, any pion candidate of charge opposite to that of the identified charged kaon had to be inconsistent with the kaon hypothesis.

To help ensure that the resulting events represented exclusive $K^\pm\pi^\mp\pi^+\pi^-$ production, the requirement was imposed that the magnitude of the sum of the transverse momenta, $|\sum \mathbf{p}_T|$, for the four tracks plus the tag be < 220 MeV, a value suggested by a Monte Carlo study. The resulting 35 events were then scanned to remove those with calorimeter energy depositions not associated with charged tracks, or with extra tracks not detected by the analysis program. The remaining 24 events, coming equally from the two data samples, had a $|\sum \mathbf{p}_T|$ spectrum which was peaked at zero.

$K^0_S \to \pi^+\pi^-$ candidates were next sought in this sample by our calculating the dipion effective mass, using pion four-momenta at the position of closest approach of the π^+ and π^- tracks. The resulting invariant masses are plotted in Fig. 1, where a K^0_S signal is apparent despite the combinatorial background. To select events with a K^0_S, a mass cut of 498 ± 45 MeV was applied, providing a final sample of seventeen events. The rejected events had either tracks which were mistakenly called charged kaons (as a result of measurement errors) or unobserved particles (as indicated by relatively large $|\sum \mathbf{p}_T|$ values).

The $K^0_S K^\pm \pi^\mp$ invariant-mass spectrum of this sample is shown in Fig. 2. There is a clear peak of thirteen events in the mass region from 1.3 to 1.6 GeV. The significance of the peak depends on the background, which we can estimate by using the "sideband" with masses above 1.6 GeV. If we assume that the background is constant in mass, the peak region should then contain about 1.6 background events. A check on this was obtained from the no-tag $K^0_S K^\pm \pi^\mp$ data,[1] which is nearly flat over the whole mass region, and thus represents continuum $K^0_S K^\pm \pi^\mp$ production. A Monte Carlo extrapolation of this continuum to the single-tag spectrum

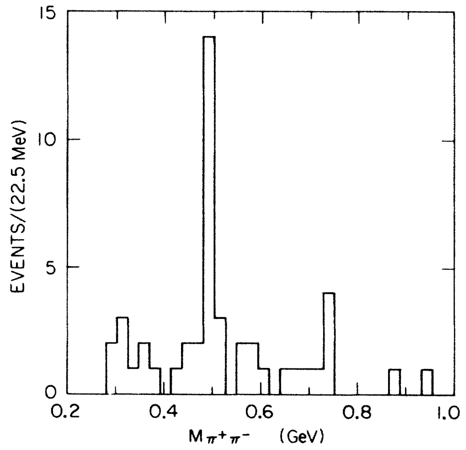

FIG. 1. Invariant $\pi^+\pi^-$ masses from $K^\pm\pi^\mp\pi^+\pi^-$ events with two entries per event.

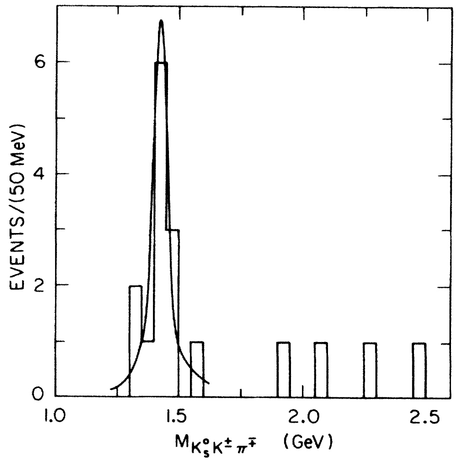

FIG. 2. Histogram of the invariant $K^0_S K^\pm \pi^\mp$ mass spectrum. The solid line is a Monte Carlo calculation for the expected shape of an E meson with phase space decay.

predicted about 1.4 background events in the peak region. A further check on the background is obtained from our observed ratio of about 5 for the no-tag to single-tag continuum in the production of $K^+K^-\pi^+\pi^-$ and $2\pi^+2\pi^-$ final states. This is consistent with the ratio seen in the high-mass part of the $K\bar{K}\pi$ sample and would imply a background under the single-tag peak of about one event. Considering statistical and systematic errors on these estimates, we take the background under the peak to be 2 ± 2 events. The probability that even a background of four events could fluctuate up to the observed thirteen events is 3×10^{-4}, so that the peak is significant.

A Breit-Wigner fit was applied to the mass region below 1.6 GeV, with the assumption of a constant background and inclusion of the detector mass resolution. The resulting mass of 1.417 ± 0.013 GeV and width of $0.035^{+0.047}_{-0.020}$ GeV are similar to those of the E meson. A Monte Carlo calculation with the E parameters ($M=1.42$ GeV, $\Gamma=0.05$ GeV) and a $K\bar{K}\pi$ phase-space decay mode gave the solid curve in Fig. 2, which fits the spectrum well. Those hadronic experiments which assigned $J^P=1^+$ to the E observed the K^*K decay mode predominantly, and about two-thirds of our events are consistent with such a decay. However, the limited statistics in our data preclude a definite determination of the decay mode.

The peak seen in the single-tag data, if it represented the production of a spin-0 meson with Q^2 dependence similar to that of other observed two-photon resonances, should have appeared with about thirty events in the no-tag data. Instead the no-tag data showed a flat mass spectrum with only five events in the mass region below 1.6 GeV.[1] The obvious explanation of this effect is that the single-tag resonance has spin 1. According to the Yang-Landau theorem,[9] two real photons cannot produce a spin-1 particle, and the two photons in the no-tag reaction are nearly real. However, in the single-tag case, spin-1 production is allowed with a rate proportional to Q^2 (for small Q^2).

A detailed analysis of the Q^2 dependence of the data is required to make the spin assignment more quantitative. The e^+e^- cross section for the two-photon production of a resonance with mass M, spin J, and total width Γ can be written

$$\frac{E_1E_2d^6\sigma}{d^3\mathbf{p}_1d^3\mathbf{p}_2}=\mathcal{L}\left(\frac{32\pi(2J+1)}{N_1N_2}\right)\left(\frac{W^2}{2\sqrt{X}}\right)\left(\frac{\Gamma}{(W^2-M^2)^2+\Gamma^2M^2}\right)\Gamma_{\gamma\gamma^*},$$

where p_i (E_i) are the laboratory momenta (energies) of the scattered leptons, W is the center-of-mass energy, and $X=(q_1\cdot q_2)^2-q_1^2q_2^2$, with q_i the photon four-momenta. The number of helicity states N_i is 1 for a longitudinal (L) photon and 2 for a transverse (T) photon. $\mathcal{L}$ is the two-photon luminosity as calculated from QED,[10] with use of the photon polarization combinations expected to dominate for small Q^2 (TT for spin 0 and TL or LT for spin 1). The Q^2 dependence of the two-photon width $\Gamma_{\gamma\gamma^*}$ is expected to be X for spin 0[11] and Q^2/M^2 for spin 1,[12] multiplied in each case by a vector-dominance-model (VDM) form factor squared $[1+Q^2/M_V^2]^{-2}$, with M_V the mass of some vector meson. These assumptions regarding the luminosity and the Q^2 dependence become less reliable as Q^2 gets large.

A comparison of these spin-0 and spin-1 models with the data requires a different treatment of the no-tag and single-tag samples. For the no-tag data ($Q^2<0.1$ GeV^2), where no resonance was seen, an upper limit on the number of events was determined by comparison with a Monte Carlo simulation using an E-like resonant mass shape. Of the thirteen single-tag events, only eleven satisfied fiducial cuts designed to ensure accurate Q^2 values. These were divided into three Q^2 bins, and a Q^2-independent background totaling two events was subtracted. Figure 3(a) shows both no-tag and single-tag data, corrected for acceptance with a Monte Carlo calculation using the spin-0 model. Plotted is $B\Gamma_{\gamma\gamma^*}$, where B is the branching ratio to $K\bar{K}\pi$, with a correction made for the unseen decay modes on the assumption that the resonance has $I=0$. The curve is the best fit to the data of the expected spin-0 Q^2 dependence, under the assumption of a ρ-pole form factor ($M_V=M_\rho$), which has provided a good description for other two-photon resonances. Clearly the no-tag upper limit (95% C.L.) falls far below expectations for a spin-0 resonance, and this would hold for any VDM form factor chosen. Thus the data are inconsistent with the spin-0 hypothesis.[13] The acceptance-corrected data with use of the spin-1 model are shown in Fig. 3(b). Both the single-tag data and the no-tag upper limit (67% C.L.) are quite consistent with the solid curve, which is a fit of the expected spin-1 Q^2 dependence to the single-tag points, assuming again a ρ-pole form factor. Uncertainty in the models at high Q^2 and the large errors prevent an accurate determination of the VDM form-factor dependence. While the experiment has acceptance for larger Q^2 than shown in the plot (up to 7 GeV^2), the curve would correspond to less than one event in that region, and none is observed.

Extrapolating the spin-1 model curve to $Q^2=0$, we derive a value for $BM^2\Gamma_{\gamma\gamma^*}/Q^2$ of 6 ± 2(stat.)± 2(syst.) keV. Renard[14] has applied the quarkonium formalism to estimate $M^2\Gamma_{\gamma\gamma^*}/Q^2$ for several states with resulting values of 2.5 keV for a $u\bar{u}$, $d\bar{d}$ meson, 0.2 keV for an $s\bar{s}$ meson, and 0.2 keV for a $q\bar{q}g$ hybrid. If we assume that the $K\bar{K}\pi$ decay mode of our observed resonance is dominant, the value obtained from the data is consistent with

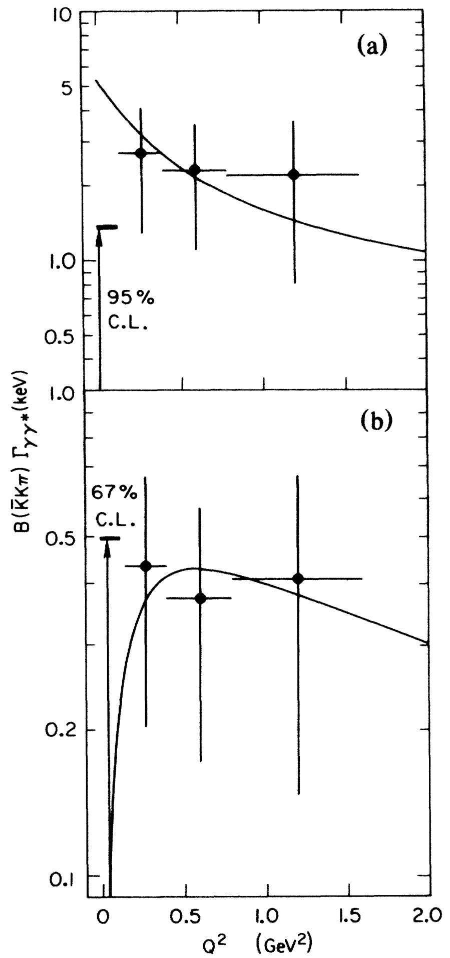

FIG. 3. $B(K\bar{K}\pi)\Gamma_{\gamma\gamma^*}$, where the data are acceptance-corrected with (a) the spin-0 Monte Carlo model and (b) spin-1 Monte Carlo model, as described in the text. The upper limits near $Q^2=0$ come from no-tag data, where no resonance was seen. The curves are the best fits to the single-tag points of the expected (a) spin-0 and (b) spin-1 Q^2 dependence.

the $u\bar{u},d\bar{d}$ estimate, given the uncertainties in both data and theory.

Since no spin-1 resonance has been observed in two-photon interactions before, it would be desirable to know the production rate for an established spin-1 meson such as the D [$f_1(1285)$].[2] However, given the D branching ratio to $K\bar{K}\pi$ of 11%, Renard's estimate for a $u\bar{u},d\bar{d}$ state would predict about 0.6 event in our single-tag data at the D mass. This is consistent with the observed spectrum but not distinguishable from the larger signal at 1.42 GeV.

In conclusion, a resonance has been seen in single-tag, but not in no-tag two-photon interactions, providing evidence that the spin of the resonance is 1. This result is borne out by a quantitative analysis of the Q^2 dependence of the data, which is incompatible with a spin-0 hypothesis and consistent with spin 1. The charge conjugation must be $C=+1$, since the state is produced by two photons. The parameters of the resonance are similar to those of the $J^P=1^+$ E meson seen in some, but not all, hadronic experiments.

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[1] H. Aihara *et al.*, Phys. Rev. Lett. **57**, 51 (1986).

[2] M. Aguilar-Benitez *et al.*, Particle Data Group, Phys. Lett. **170B**, 1 (1986).

[3] D. L. Scharre *et al.*, Phys. Lett. **97B**, 329 (1980); C. Edwards *et al.*, Phys. Rev. Lett. **49**, 259 (1982); J. D. Richman, *QCD and Beyond: Proceedings of the 20th Recontre de Moriond,* edited by J. Tran Thanh Van (Editions Frontières, Gif-sur-Yvette, 1985), p. 471; J. E. Augustin, *ibid.*, p. 479.

[4] C. Dionisi *et al.*, Nucl. Phys. **B169**, 1 (1980); T. A. Armstrong *et al.*, Phys. Lett. **146B**, 273 (1984).

[5] P. Baillon *et al.*, Nuovo Cimento **50A**, 393 (1967); S. U. Chung *et al.*, Phys. Rev. Lett. **55**, 779 (1985); A. Ando *et al.*, KEK Report No. 86-8, 1986 (to be published); D. F. Reeves *et al.*, Phys. Rev. D **34**, 1960 (1986).

[6] K. Ishikawa, Phys. Rev. Lett. **46**, 978 (1981); M. Chanowitz, Phys. Rev. Lett. **46**, 981 (1981); C. E. Carlson *et al.*, Phys. Lett. **99B**, 353 (1981); J. Donoghue *et al.*, Phys. Lett. **99B**, 416 (1981).

[7] H. Aihara *et al.*, IEEE Trans. Nucl. Sci. **N530**, 63, 67, 76, 117, 153, and 162 (1983).

[8] M. P. Cain *et al.*, Phys. Lett. **147B**, 232 (1984).

[9] C. N. Yang, Phys. Rev. **77**, 242 (1950); L. F. Landau, Dokl. Akad. Nauk. SSSR **60**, 207 (1948).

[10] V. M. Budnev *et al.*, Phys. Rep. **15C**, 181 (1975).

[11] G. Köpp *et al.*, Nucl. Phys. **B70**, 461 (1974).

[12] M. Poppe, DESY Report No. 86-014, 1986 (to be published).

[13] While a spin-2 meson at this mass is unlikely, it would have a Q^2 dependence which rises as Q^2 decreases, unlike the data shown in Fig. 3(a).

[14] F. M. Renard, Nuovo Cimento **80A**, 1 (1984); in a private communication, Renard informed us of an error in his paper which, when corrected, would raise his estimates for $q\bar{q}$ states by a factor of $\frac{15}{4}$. In addition, there is a difference in our definitions for $M^2\Gamma_{\gamma\gamma^*}/Q^2$ which would lower his estimates by a factor of 2 for comparison with our data, giving the values we ascribe to Renard in the text.