Exclusive Production of $K^+K^-\pi^+\pi^-$ in Photon-Photon Collisions

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We report a measurement of the reaction $\gamma\gamma \rightarrow K^+K^-\pi^+\pi^-$ in both tagged and untagged events at PEP. The cross section rises with invariant $\gamma\gamma$ mass to about 15 nb at 2 GeV and falls slowly at higher masses. We find clear evidence for the processes $\gamma\gamma \rightarrow \phi\pi^+\pi^-$ and $\gamma\gamma \rightarrow K^{*0}(892)K\pi$. Upper limits (95% C.L.) of 1.5 and 5.7 nb in the mass range from 1.7 to 3.7 GeV are obtained for $\phi\rho^0$ and $K^{*0}\bar{K}^{*0}$ production, respectively.

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Vector-meson pair production is expected to be a general feature of $\gamma\gamma$ collisions because of the hadronic character of the photon.[1] At the present time, only $\rho^0\rho^0$ production has been established; a cross section in excess of 100 nb near threshold for the process $\gamma\gamma \rightarrow \pi^+\pi^-\pi^+\pi^-$, with major $\rho^0\rho^0$ and $\rho^0\pi^+\pi^-$ components, was observed by several experiments.[2] A measurement of $\gamma\gamma \rightarrow \pi^+\pi^-\pi^0\pi^0$ yielded a much lower cross section and only upper limits for $\rho^+\rho^-$ production,[3] thus ruling out a single $\rho\rho$ resonance of well-defined isospin. These observations can be understood in terms of interfering $I=0$ and 2 four-quark states[4,5] predicted by the MIT bag model,[6] or as a consequence of meson (Regge pole) exchanges.[7] Cross sections peaked near threshold are predicted for production of other vector-meson pairs: 3–60 nb for $\rho^0\omega$,[4,5] and 6–400 nb for $\omega\omega$.[5,7] Efforts to observe these final states have so far been unsuccessful; the preliminary upper limits on their production in five- and six-pion channels do not exclude these models.[8] The four-quark models further predict peak cross sections of 10–70 nb for $\phi\rho^0$ (Refs. 4 and 5) and 0.1–1.5 nb for $K^{*0}(892)\bar{K}^{*0}(892)$.[4,5]

The particle identification properties of the time projection chamber (TPC) at the e^+e^- colliding-beam facility PEP at SLAC are used here to make the first investigation of $K^+K^-\pi^+\pi^-$ production in the reaction $e^+e^- \rightarrow e^+e^-K^+K^-\pi^+\pi^-$ and to search for the final states $\phi\rho^0$ and $K^{*0}\bar{K}^{*0}$. We place bounds on $\gamma\gamma$ excitation of these double–vector-meson states and find evidence for $\phi\pi^+\pi^-$, $K^{*0}K\pi$, and nonresonant $K^+K^-\pi^+\pi^-$ production.

The TPC/Two-Gamma detector system has been described earlier[9,10]; we summarize briefly the features relevant for the present investigation. The TPC was operated in a 0.4-T solenoidal magnetic field and a momentum resolution of $(\delta p/p)^2 = (0.06)^2 + [(0.035\ \mathrm{GeV}^{-1})p]^2$ was achieved for particles within the fiducial volume. Identification of charged particles was provided by measurement of ionization loss (dE/dx) over the same volume with a resolution of 3.7% for tracks with more than 80 ionization samples. Charged particles in the forward spectrometers were tracked by 15 drift chamber planes through a septum magnet. Detection of tagging electrons or positrons was accomplished by NaI arrays between 22 and 90 mrad, by lead/scintillator shower counters between 100 and 180 mrad, and by lead/proportional-chamber pole-tip calorimeters between 280 and 620 mrad. Photon detection above 620 mrad was provided by lead/Geiger-mode chamber calorimeters outside the magnet coil.

Data were taken at 29-GeV e^+e^- center-of-mass energy with two independent triggers: an untagged trigger requiring at least two TPC tracks, and a tagged trigger which required a coincidence of an energy deposition in one of the forward calorimeters (a tag) and a charged track in the trigger drift chambers at the inner and outer radii of the TPC. For the untagged trigger, the TPC tracks had to be in different 60° azimuthal sectors and at polar angles greater than 30°, and had to project back to the vertex to within 20 cm along the beam line. The untagged and tagged event samples correspond to integrated luminosities of 73 and 50 pb^{-1}, respectively.

In the off-line selection for the untagged sample, we require exactly four particles originating from the vertex to be detected in the TPC. To reject annihilation events, the total measured energy is required to be less than 8 GeV. For the tagged sample, one of the four particles can be in the forward spectrometer, in addition to the tag. The tag energy thresholds are 4 GeV in the NaI arrays and 10 GeV in the shower counters. These thresholds and the detector boundaries determine the range of Q^2, the magnitude of the four-momentum transfer squared of the photon. For the untagged sample, the average Q^2 is less than 0.03 GeV^2; for the tagged sample, Q^2 ranges from 0.2 to 7.0 GeV^2, with an average of 1.3 GeV^2. To avoid uncertainties from forward drift chamber inefficiencies, we do not require a momentum measurement for the tag.

The TPC particle identification uses up to 183 ionization samples per track. Only tracks which have at least 30 samples are used in the analysis, and a truncated mean dE/dx is calculated from the lowest 65% of the samples. A χ^2 fit is made of this truncated mean and the measured momentum of the track to a theoretical curve of dE/dx versus momentum for each particle species; χ_i^2 is then the value for species i. A kaon is identified unambiguously if χ_K^2+4 is less than the χ^2 for the e, π, and p hypotheses. A particle is compatible with the kaon hypothesis if $\chi_K^2<8$. Analogous definitions hold for pions. Unambiguous π-K separation is obtained for momenta below 900 MeV. A particle detected in the forward spectrometer is assumed to be a pion. To obtain a uniquely identified $K^+K^-\pi^+\pi^-$ final state, we require two particles to be compatible with the kaon hypothesis and the remaining two to be compatible with the pion hypothesis. In addition, at least one kaon and one pion must be unambiguously identified. The final state is then required to be consistent with $K^+K^-\pi^+\pi^-$ in only one permutation of particle species and charge assignments.

To ensure a clean sample of exclusive $\gamma\gamma\to K^+K^-\pi^+\pi^-$ events, we require that the transverse momentum of the tracks be balanced as follows. For the untagged sample we require $|\sum \mathbf{p}_\perp|<0.4$ GeV. For the tagged sample we include the tag in the calculation of $|\sum \mathbf{p}_\perp|$, and require $|\sum \mathbf{p}_\perp|<0.4$ GeV perpendicular to the plane defined by the beam and the tag; in this plane the cut on $|\sum \mathbf{p}_\perp|$ is variable, according to the resolution and the angular range of the tagging device. These cuts result in a final selection of 292 untagged and 29 tagged events. An eye scan of the sample has verified that the events have four tracks and that fewer than 20% of the events contain additional energy depositions in the calorimeters. We estimate the background from e^+e^- annihilation into $q\bar{q}$ or $\tau\bar{\tau}$ to be less than 2 events.

Mass spectra of the kaon pairs for the untagged and tagged samples are shown in Figs. 1(a) and 1(b). A clear ϕ signal is observed in both spectra. The untagged sample contains twenty $\phi\pi^+\pi^-$ events, the tagged sample eight, of which one is doubly tagged.[11] None of these contain additional photon candidates. Here, a ϕ is defined by $M(K^+K^-)<1.04$ GeV, where $M(K^+K^-)$ denotes the invariant K^+K^- pair mass. In Fig. 1(c), the mass spectra of the pion pairs from events with and without ϕ's are plotted. In neither spectrum is there evidence for a ρ^0 signal.

Next, events containing ϕ mesons are removed from the $K^+K^-\pi^+\pi^-$ sample and the particle pairing $K^\pm K\pi^\mp$ is investigated to see if a $K^{*0}\bar{K}^{*0}$ enhancement is discernible. There is a clear indication of K^{*0} production in Fig. 2(a), which shows $M(K^+\pi^-)$ vs $M(K^-\pi^+)$, and in the distribution of the unlike-sign mass combinations in Fig. 2(b). The shaded histogram of Fig. 2(b) represents the like-sign distribution. Angular distributions of the K^{*0} in the $\gamma\gamma$ center-of-mass frame and of the kaon in the K^{*0} rest frame are consistent with isotropy.

The acceptances for various processes were calculated as functions of $W_{\gamma\gamma}$, the center-of-mass energy of the $\gamma\gamma$ system, by a Monte Carlo simulation of the detector. Events were generated for untagged $K^+K^-\pi^+\pi^-$, $K^{*0}K\pi$, $K^{*0}\bar{K}^{*0}$, and $\phi\pi^+\pi^-$ production, and for tagged $K^+K^-\pi^+\pi^-$ and $\phi\pi^+\pi^-$ production. All distributions were generated isotropically and according to phase space. The detector simulation included multiple scattering, nuclear interactions and energy loss in the detector material, decay of the final-state particles, and detector resolution. The

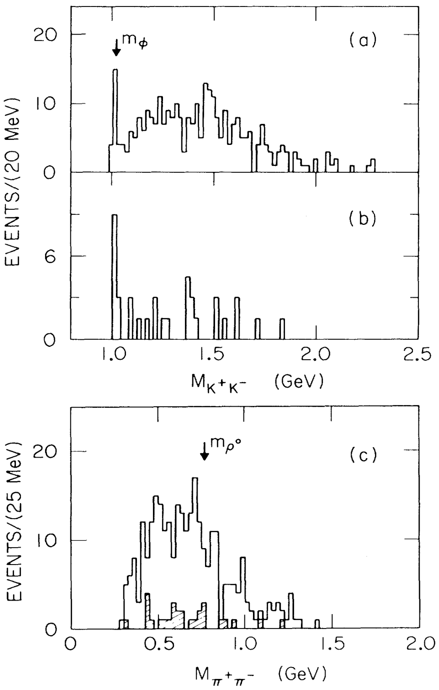

FIG. 1. K^+K^- mass distribution for (a) untagged and (b) tagged $\gamma\gamma \rightarrow K^+K^-\pi^+\pi^-$ events. (c) $\pi^+\pi^-$ masses for events without ϕ mesons, i.e., $M(K^+K^-) > 1.04$ GeV, and (shaded) events with ϕ mesons, i.e., $M(K^+K^-) < 1.04$ GeV; both tagged and untagged events included.

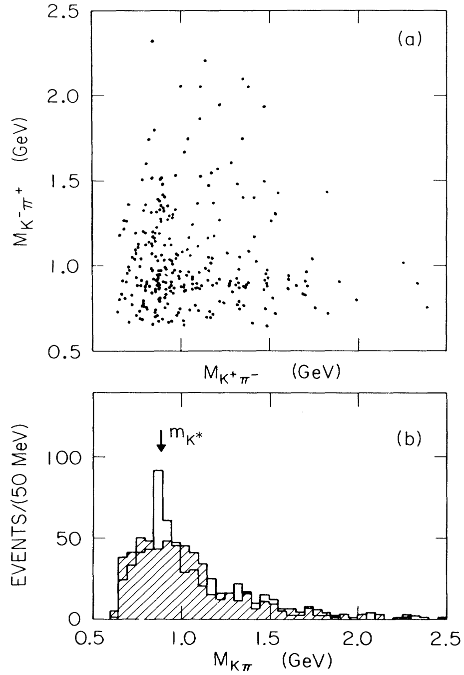

FIG. 2. (a) Correlation plot of $M(K^+\pi^-)$ vs $M(K^-\pi^+)$ for untagged $\gamma\gamma \rightarrow K^+K^-\pi^+\pi^-$ after $\phi\pi^+\pi^-$ events have been removed. (b) $K\pi$ pair mass distributions for the same sample. Unshaded histogram is $M(K^{\pm}\pi^{\mp})$; shaded is $M(K^{\pm}\pi^{\pm})$.

trigger efficiency was determined experimentally, from independently triggered data.

To avoid regions of the detector where the acceptance cannot be well determined, we have imposed on data and generated events the additional requirements that tracks in the TPC have polar angles greater than 350 mrad, with $p_\perp > 120$ MeV, and that at least two tracks have $p_\perp > 200$ MeV. To reduce uncertainties from corrections for energy loss in the detector material, we required the kaon momentum to be larger than 300 MeV. The acceptances for $K^+K^-\pi^+\pi^-$, $K^{*0}K\pi$, and $K^{*0}\bar{K}^{*0}$ are found not to differ significantly. The data were corrected for a background from higher-multiplicity events. This correction was mass dependent with a maximum of 20%. In the calculation of the $\phi\pi^+\pi^-$ cross section, 30% of the events in the ϕ mass range are judged to be background from other $K^+K^-\pi^+\pi^-$ final states, and are subtracted from the sample. The sources of systematic uncertainties included are the effect of the kinematic cuts on the acceptance of the events, the loss of particles through nuclear interactions in the inner detector region, the dE/dx particle identification, the calculation of the trigger efficiency, the background subtraction, and the e^+e^- luminosity. We calculated the $\gamma\gamma$ flux factors using the standard formalism.[12]

The average $\phi\pi^+\pi^-$ cross section in the $W_{\gamma\gamma}$ region from 1.7 to 3.7 GeV is 1.2 ± 0.4 (statistical) ± 0.5 (systematic) nb for the untagged sample. For the tagged sample, the corresponding cross section is $1.8 \pm 1.2 \pm 0.6$ nb. We set an upper limit of 1.5 nb (95% C.L.) for untagged $\phi\rho^0$ production in the mass range from 1.7 to 3.7 GeV. For the mass range from 2 to 2.6 GeV, where predicted contributions from four-quark resonances[4,5] can be estimated to be between 2 and 16 nb, we find an upper limit of 2.7 nb (95% C.L.).

The cross section for the untagged $K^+K^-\pi^+\pi^-$ events, excluding $\phi\pi^+\pi^-$ events, is shown in Fig. 3(a) as a function of $W_{\gamma\gamma}$. The calculated acceptance is given in Fig. 3(b). We observe a rise to about 15 nb at 2 GeV and a gradual falloff for $W_{\gamma\gamma}$ larger than 2 GeV. Fractions of $K^+K^-\pi^+\pi^-$, $K^{*0}K\pi$, and $K^{*0}\bar{K}^{*0}$ production are evaluated by comparison of density distributions in the scatter plot of Fig. 2(a) with comparable Monte Carlo generated plots. The fractions and the cross sections for the untagged and tagged samples are summarized in Table I. After correcting for K^{*0} decay branching ratios, we derive an upper limit of 5.7 nb (95% C.L.) for untagged $K^{*0}\bar{K}^{*0}$ production.

The measured upper limits on $\phi\rho^0$ production are compatible with the lower predictions of four-quark models,[5] while those for $K^{*0}\bar{K}^{*0}$ are consistent with both predictions.[4,5] However, the significant produc-

TABLE I. Observed fractions of $\gamma\gamma \to K^+K^-\pi^+\pi^-$ contributed by various production processes, for $W_{\gamma\gamma}$ from 1.7 to 3.7 GeV; and cross sections for those processes times the ϕ and K^{*0} branching ratios into the observed states. The first error shown is statistical; the second is systematic.

Produced state	Fraction untagged	σR (nb) untagged	σR (nb) tagged $\langle Q^2 \rangle = 1.3$ GeV^2
$K^+K^-\pi^+\pi^-$	$0.44 \pm 0.14 \pm 0.05$	$3.7 \pm 1.2 \pm 1.0$	
$K^{*0}K\pi$	$0.42 \pm 0.13 \pm 0.05$	$3.5 \pm 1.1 \pm 1.0$	$4.5 \pm 1.2 \pm 1.1$
$K^{*0}\bar{K}^{*0}$	$0.09 \pm 0.06 \pm 0.04$	$0.8 \pm 0.5 \pm 0.4$	
$\phi\pi^+\pi^-$	$0.05 \pm 0.01 \pm 0.01$	$0.6 \pm 0.2 \pm 0.2$	$0.9 \pm 0.6 \pm 0.3$

tion of the three-body final states $\phi\pi^+\pi^-$ and $K^{*0}K\pi$ has not been explicitly predicted.

The ratio of untagged to tagged cross sections for combined production of $K^+K^-\pi^+\pi^-$ and $\phi\pi^+\pi^-$ can be inferred from Table I to be $1.6 \pm 0.5 \pm 0.4$. The Q^2 dependence is less pronounced than the one observed in the process $\gamma\gamma \to \eta'$.[13] In this process the reduction in cross section with Q^2 follows the ρ form factor squared for Q^2 less than 1 GeV^2, which amounts to a factor of 5.9 averaged over the Q^2 range of the tagged data presented here. In a measurement of the total cross section,[14] with W between 2 and 20 GeV, the Q^2 dependence in the range from 0.1 to 1.6 GeV^2 agrees with a generalized vector meson dominance model; the reduction in this model would be a factor of 3.2.

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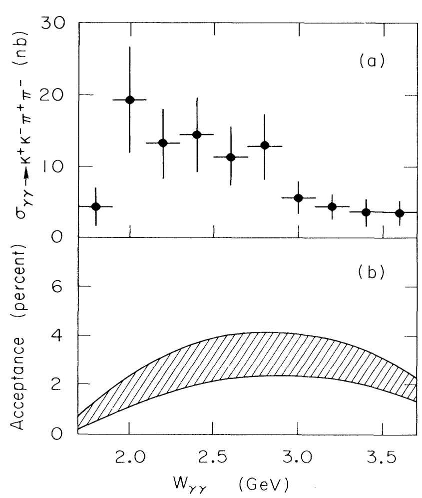

FIG. 3. (a) Cross section vs $W_{\gamma\gamma}$ of $\gamma\gamma \to K^+K^-\pi^+\pi^-$ for the untagged sample, excluding the $\phi\pi^+\pi^-$ events. The error bars reflect the statistical and systematic errors, added in quadrature. (b) The calculated acceptance for this reaction. The width of the band reflects the uncertainty. A mass-independent error of 10% due to the uncertainty in the e^+e^- luminosity has to be added in quadrature to obtain the systematic error used in (a).

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