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Observation of spin 1 resonance formation in the final state $KK\pi$ produced in tagged two-photon collisions

JADE Collaboration

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Abstract. Resonance formation has been observed in tagged two photon collisions. Since there is no corresponding signal in the untagged data these resonances have been interpreted as having $J=1$. Assigning the signal at a mass of ~ 1.4 GeV/c^2 to the $f_1(1420)$, the product of the branching fraction and the two-photon width has been determined to be

$$B(f_1(1420)\rightarrow K\bar{K}\pi)\cdot\tilde{\Gamma}_{f_1(1420)}=2.3\,^{+1.0}_{-0.9}\pm 0.8 \text{ keV}.$$

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Introduction

Hadron spectroscopy in the mass region of 1.4 GeV/c^2, while being in a rather confused state, is a rich source of interesting physics [1]. In particular the $\eta(1440)$ has attracted much attention because of its candidature for being a bound gluonic state. The nature of the $f_1(1420)$ has also been the subject of much debate and conflicting experimental evidence. On one hand it has been observed with $J^{PC}=1^{++}$ decaying predominantly into $K^*(892)\,K$ [2], and on the other as $J^{PC}=0^{-+}$ with the decay $a_0(980)\,\pi$ dominating [3]. It has also been suggested that there are in fact two states at this mass [4].

New results on this matter were recently provided by the TPC/2γ collaboration [5, 6] with the observation of a resonance at ~ 1.4 GeV/c^2 produced in tagged two-photon collisions and decaying into $K_s^0\,K^{\pm}\pi^{\mp}$. No corresponding signal was observed in the collision of two approximately real photons, and so, because of the Yang-Landau theorem [7] they concluded that the resonance has spin$\,=1$. This was confirmed by the Mark II [8], JADE [9] and CELLO

[10] collaborations. Similarly in the $\eta\pi\pi$ final state a resonance has been observed at ~ 1.3 GeV/c^2 [6, 10–12]. This has been attributed to the $f_1(1285)$, which is a member of the 1^{++} nonet [13]. In this paper our previously reported preliminary data on the $K_s^0 K^\pm \pi^\mp$ final state are described in detail.

Apparatus

The JADE detector has recorded data over a period of seven years at the PETRA e^+e^- storage ring. Details of the JADE detector can be found elsewhere [14], but those components which are particularly relevant to this analysis deserve mention here. The inner detector or 'jet chamber' is a cylindrical drift chamber with the wires parallel to the beam axis. This is used for charged particle detection and with the magnetic field of 0.48 T provides momentum determination. It also aids in particle identification via dE/dx measurements at up to 48 points along the particle's track. The Time-Of-Flight (TOF) counters consist of 42 sheets of plastic scintillator mounted just outside the inner detector. These also play a major role in the trigger system. The electromagnetic shower calorimeter consists of a system of leadglass blocks positioned just outside the magnet solenoid. The forward detectors are positioned ± 3.0 m from the interaction region along the beam pipe and are used to detect scattered electrons. Several different configurations of forward detectors have been used. For approximately one third of the data considered here they consisted of an array of 32 leadglass counters covering the angular region 43–75 mrad. For the remainder of the data the forward detectors consisted of a lead-scintillator sandwich covering the range 32–75 mrad.

Data reduction

The reaction of interest here is $e^+e^- \to e^+e^- K_s^0 K^\pm \pi^\mp$, where one of the scattered electrons is detected in the forward counters and where the K_s^0 decays into $\pi^+\pi^-$. The main trigger for this topology required an energy deposition (tag) in one of the forward counters together with an energy cluster in the leadglass calorimeter associated with a set TOF counter and a track in the inner detector. The data were recorded over beam energies ranging from 6.0 to 23.39 GeV/c^2 and corresponded to an integrated luminosity of 213 pb^{-1}. For the average beam energy of ~ 18.2 GeV/c^2 the second forward detector configuration correspond to a $|q^2|$ range of 0.3–1.8 (GeV/c)^2.

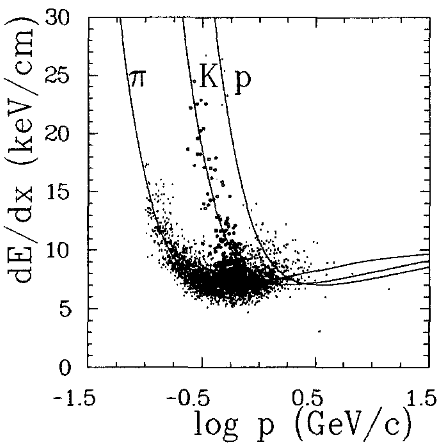

Fig. 1. dE/dx vs. log p. Then open circles are the selected kaons

A fiducial volume was defined around the interaction region by the cylinder with radius (r) perpendicular to the beam axis, and length z along the beam axis. Approximately 37000 events were selected which contained (a) four tracks with a net charge of zero emanating from a volume defined as $r \leqq 40$ mm and $|z| \leqq 200$ mm; and (b) no photons. Of these 1760 were found to contain a tag of $E_{\text{tag}} > 0.6\,E_{\text{beam}}$. After visual inspection to remove events of the wrong topology not identified as such by the pattern recognition programs, 1182 events remained. To ensure good determination of the momentum and the dE/dx it was required that each track had at least 16 hits in the inner detector associated with it, and that the track fit in the $r\phi$ plane to the hits had an associated χ^2/d.o.f<1.5.

Charged kaons were selected as follows. Figure 1 shows the plot of dE/dx against momentum (p) for tracks in the selected events. Kaon candidates were required to have $p < 0.75$ GeV/c and a dE/dx measurement consistent with the kaon hypothesis with a probability of association $(P_{\chi^2}) > 1\%$. The tracks which fulfilled these conditions are indicated by the full circles in Fig. 1. Neutral kaons were then selected by forming two-particle combinations from the remaining three tracks. It was required that the closest approach in the $r\phi$ plane of each track in the pair to the event vertex be >4 mm, and that each had a dE/dx measurement consistent with the π expectation with $P_{\chi^2} > 1\%$. Figure 2 shows the distribution of the invariant mass, $M_{\pi\pi}$, of pairs satisfying these criteria. A clear K_s^0 signal is observed, the width of which is consistent with the mass resolution of JADE. Note that it is possible to have more than one combination per event passing these cuts. In all cases a similar dE/dx restriction is placed on the third pion, i.e. that not belonging to the K_s^0. The mass of the pair was further required to lie in the K_s^0 band defined

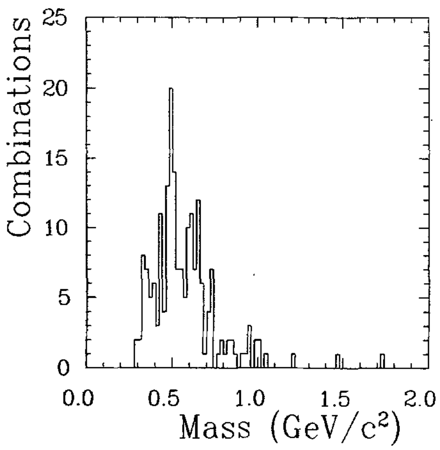

Fig. 2. $M_{\pi\pi}$ for selected combinations

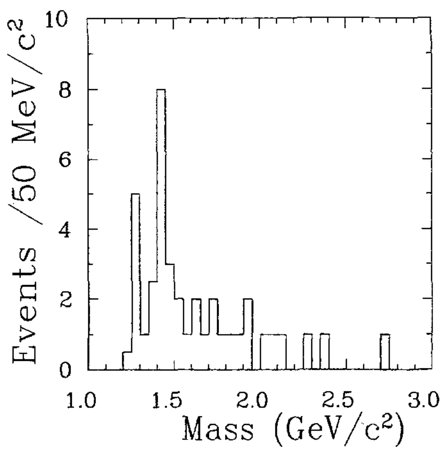

Fig. 4. $K_s^0\, K^{\pm}\pi^{\mp}$ mass distribution for events passing all cuts

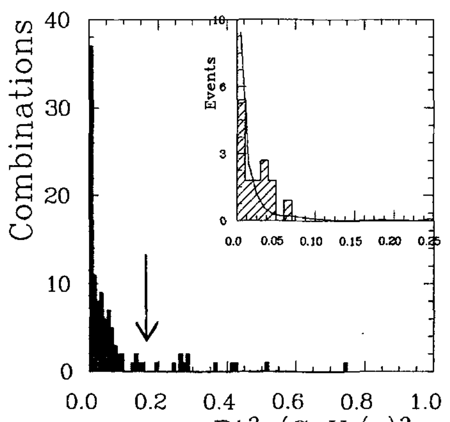

Fig. 3 p_t^2 for selected combinations. The insert shows the p_t^2 distribution for the sixteen events in the $f_1(1420)$ signal region (histogram) compared to the Monte Carlo expectation (curve) for $f_1(1420)$ production

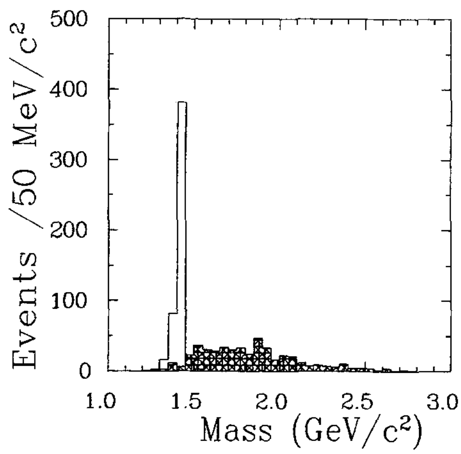

Fig. 5. $M_{K_s^0 K^{\pm}\pi^{\mp}}$ for notag events (shaded) and spin = 0 Monte Carlo expectation (open)

by $0.46 < M_{\pi\pi} < 0.54$ GeV/c^2 and was then constrained to the K_s^0 mass.

In order to reject incompletely reconstructed events it was required that the sum of the transverse momentum of the event, including that of the tag, be $|\Sigma p_t| < 0.4$ GeV/c. Figure 3 shows the $|\Sigma p_t|^2$ distribution for the selected combinations prior to this cut. The position of the cut is indicated. After all cuts forty events remained. The $K_s^0\, K^{\pm}\pi^{\mp}$ invariant mass distribution for combinations in these events is shown in Fig. 4 in which each event has a weight of one.

An enhancement is observed at ~ 1.4 GeV/c^2 and possibly also at ~ 1.3 GeV/c^2 although the significance of the latter is much smaller. Note that the mass resolution of JADE in this region is ~ 50 MeV/c^2 (FWHM). If these were due to the production of $J=0$ or $J=2$ resonances then they would also be observable in the collision of two approximately real photons, i.e. in untagged events. The shaded histogram in Fig. 5 shows the $K_s^0\, K^{\pm}\pi^{\mp}$ mass distribution in the untagged data sample. The selection criteria leading to this sample were identical to those described above save that it was demanded that there was no tag in the forward counters. There is no evidence for a signal at ~ 1.4 GeV/c^2. Also shown is the expected number of events, calculated using Monte Carlo methods, which would be observed in the untagged sample if the sixteen events in the mass range 1.35–1.55 GeV/c^2 were due to a spin 0 resonance. The two are clearly incompatible. Similar conclusions are reached when considering the data at ~ 1.3 GeV/c^2. Thus we observe resonance production in tagged $\gamma\gamma^*$ collisions and no corresponding signal in events in which both photons are approximately

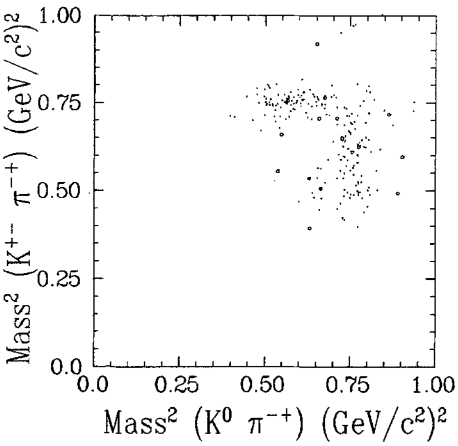

Fig. 6. $M^2_{K^0_S\pi^\mp}$ vs $M^2_{K^\pm\pi^\mp}$ for $f_1(1420)$ candidates (open circles) and Monte Carlo expectation (points)

photons [7], the most probable explanation for this is that the observed resonances have $J=1$. Possible candidates are the $J^{PC}=1^{++}$ $f_1(1420)$ and $f_1(1285)$. The $f_1(1420)$ decays mainly via $K^*(892)\,K$. Figure 6 shows the correlation plot between $M^2_{K^0_S\pi}$ and $M^2_{K^\pm\pi^\mp}$ for the 16 events around 1.4 GeV/c^2, compared to the Monte Carlo expectation for the K^*K decay. Given the small statistics no firm conclusion can be made. The insert in Fig. 3 shows the p_t^2 distribution for these sixteen events (shaded histogram) and the Monte Carlo prediction for $f_1(1420)$ production. Good agreement is seen. These sixteen events span the $|q^2|$ range 0.2–1.6 (GeV/c)^2 with an average value of ~ 1.0 (GeV/c)^2.

Two-photon width determination

Assuming that this resonance is the $f_1(1420)$ we may determine its two-photon partial width. The cross-section for the production of a resonance R through the reaction $e^+e^-\to e^+e^-R$ is obtained by the integration of [15]

$$\frac{E'_1\,E'_2\,d^6\sigma}{d^3p'_1\,d^3p'_2}=\sum_{ij}\mathscr{L}_{ij}\,\sigma_{ij} \qquad (1)$$

where the p's and E's are the momenta and energies of the scattered electrons, the $\mathscr{L}_{ij}$ are the luminosity functions which have been calculated [15], and the sum ij is over longitudinal (L) and transverse (T) polarisation states. The cross-section for a particular polarisation state may be written [16]

$$\sigma_{ij}=\frac{32\pi(2J+1)}{N_i\,N_j}\,\frac{W^2}{2\sqrt{X}}\,\frac{\Gamma}{(W^2-M^2)^2+M^2\Gamma^2}\,\Gamma^{ij}_{\gamma\gamma^*}$$

where N is the number of polarisation states ($N_L=1$, $N_T=2$), W the cm energy of the $\gamma\gamma^*$ system, Γ, M and J are the total width, mass and spin of the resonance and $X=(q_1\,q_2)^2-q_1^2\,q_2^2$, q_i being the photon four-momentum, and $\Gamma^{ij}_{\gamma\gamma^*}$ is the width for a particular polarisation combination. In the single tag case when one of the photons has $q^2\sim 0$, only two terms in the above summation are non-zero: TT and LT (or TL by interchanging the photons). Therefore the above reduces to the following:

$$\frac{E'_1\,E'_2\,d^6\sigma}{d^3p'_1\,d^3p'_2}=32\pi(2J+1)\,\frac{W^2}{2\sqrt{X}}\cdot\frac{\Gamma}{(W^2-M^2)^2+M^2\Gamma^2}\left(\frac{\mathscr{L}_{LT}}{N_L\,N_T}\,\Gamma^{LT}_{\gamma\gamma^*}+\frac{\mathscr{L}_{TT}}{N_T\,N_T}\,\Gamma^{TT}_{\gamma\gamma^*}\right).$$

Using the non-relativistic quark model calculations performed by Renard [17] and Cahn [18] for spin 1 resonance production, these partial widths can be written (for intermediate values of q^2)

$$\Gamma^{LT}_{\gamma\gamma^*}=\frac{4X}{W^2}\,\frac{q^2}{W^2}\,F^2(q^2)\,\tilde{\Gamma}$$

$$\Gamma^{TT}_{\gamma\gamma^*}=\frac{4X}{W^2}\left(\frac{q^2}{W^2}\right)^2\,F^2(q^2)\,\tilde{\Gamma}$$

where q^2 is the four-momentum of the off-shell photon, F is a form factor and $\tilde{\Gamma}$ is a constant representing the strength of the coupling of the photons to the resonance. Note that these partial widths are zero as $q^2\to 0$. Because of our limited statistics we will assume a VMD form factor of the type

$$F(q^2)=\frac{1}{1-\dfrac{q^2}{M_V^2}} \qquad (2)$$

where M_V is a vector meson mass which will be taken as the ρ mass unless otherwise stated.

The above was incorporated into a Monte Carlo calculation and then related to the observed data via

$$\sigma=32\pi(2J+1)\,I\tilde{\Gamma}=\frac{N_{\rm obs}}{\varepsilon B\mathscr{L}}$$

where I is the result of the integration of (1) with the constant terms removed, $N_{\rm obs}$ is the observed number of events, ε is the detection efficiency, B is the branching ratio into the observed final state and $\mathscr{L}$ is the experimental integrated luminosity.

We consider first the case of the $f_1(1420)$. Events of the kind $f_1(1420)\to K^*K$ were generated [19] using the above model assuming that the $f_1(1420)$ were produced in a helicity $=1$ state. The produced events were then passed through a simulation program of the JADE detector and were subjected to the same selection criteria as the data. Consideration was given to the changing geometry of JADE (e.g. different tagging systems), and the efficiencies for the various configurations were weighted according to the integrated luminosities. This weighted efficiency was then corrected for particular effects which were not included in the simulation, i.e.:

(i) the response of the leadglass system to low energy pions,

(ii) dE/dx cuts,

(iii) small adjustments to the TOF coverage and efficiency,

(iv) inefficiencies in the tagging system.

The efficiency was defined by the fraction of simulated events which passed all selection criteria and lay in the mass range 1.35–1.55 GeV/c^2. Of the sixteen events in this mass range in Fig. 4 we estimate that four are due to background. Various sources of systematic error have been investigated. These are

(a) uncertainties in the selection procedure ($\pm 20\%$), (this is mainly due to the sensitivity of the data to the cut on the momentum of the charged kaon),

(b) uncertainties in the trigger efficiency ($\pm 20\%$),

(c) uncertainties in the background estimation ($\pm 10\%$),

(d) determination of the integrated luminosity ($\pm 2.5\%$)

(e) uncertainties in the TOF corrections ($\pm 0.4\%$).

Combining these in quadrature gives an overall systematic error of 31%. Using the signal of twelve events we then determine

$$B(f_1(1420)\to K\bar{K}\pi)\,\tilde{\Gamma}_{f_1(1420)}=2.3\,^{+1.0}_{-0.9}\pm 0.8\ \text{keV}$$

where the first error is determined from poissonian statistics and the second is due to systematic effects. This is in agreement with measurements made by TPC/2γ [6] ($1.3\pm 0.5\pm 0.3$ keV) and Mark II [8] ($1.6\pm 0.7\pm 0.3$ keV).*

It has been suggested that the 1^{++} nonet is almost ideally mixed in which case the $f_1(1420)$ would consist of almost pure $s\bar{s}$. It may then be more reasonable to use a ϕ pole in the above form factor (2). This has a large effect on the integration of (1) and the subsequent efficiency determination. The value of $\tilde{\Gamma}$ becomes

$$B(f_1(1420)\to K\bar{K}\pi)\,\tilde{\Gamma}_{f_1(1420)}$$
$$=1.5\,^{+0.6}_{-0.5}\pm 0.5\ \text{keV} \qquad \text{(using a } \phi \text{ pole).}$$

* The Mark II values of $\tilde{\Gamma}$ have been divided by a factor of two because of different normalisation conventions [6, 20, 21]

A similar analysis was applied to the data in the mass range 1.25–1.30 GeV/c^2 in Fig. 4 which are tentatively interpreted as being due to the $f_1(1285)$. Because of the limited number of events a statistically significant measurement is not possible. The value obtained for $\tilde{\Gamma}_{f_1}(1285)$, which is not quoted here, is in agreement with the results obtained using the $\eta\pi\pi$ decay mode [6, 10–12] where the statistics are larger. The current world average is calculated to be $\tilde{\Gamma}_{f_1(1285)}=2.2\pm 0.2$ keV.

If the $f_1(1420)$ and $f_1(1285)$ are both members of the 1^{++} nonet then making further assumptions of $SU(3)$ and nonet symmetry we can write [18]

$$\frac{\tilde{\Gamma}_{f_1(1285)}}{\tilde{\Gamma}_{f_1(1420)}}=\frac{M_{f_1(1285)}}{M_{f_1(1420)}}\left(\frac{\sin\theta+\sqrt{8}\cos\theta}{\sqrt{8}\sin\theta-\cos\theta}\right)^2$$

where θ is the mixing angle between the singlet and octet states of the nonet. Using the result presented here and the above world mean for $\tilde{\Gamma}_{f_1(1285)}$, assuming that $B(f_1(1420)\to K\bar{K}\pi)=1$, the mixing angle is determined to be

$$\theta=64\,^{+5°}_{-8}.$$

This can be compared to the values given by ideal mixing (35.26°), the quadratic mass formula (42.2°), the Mark II measurements, $\left(49\,^{+5°}_{-8}\right)$ [20] and the TPC/2γ measurements, ($45\pm 6°$) [6]. This implies that the $f_1(1420)$ does have a significant light quark content. However it is emphasised that many assumptions have been made in determining this value. It should be noted here that the LASS collaboration [22] do not observe the $f_1(1420)$ in the interaction $K^-p^+\to K_s^0K^\pm\pi^\mp\Lambda$ and they thus conclude that it is not the $s\bar{s}$ member of the 1^{++} nonet.

It has been suggested by Chanowitz [23] that the $f_1(1420)$ is not, in fact, a member of the 1^{++} nonet but rather is a 1^{-+} exotic state. One way of testing this is to study the distribution of the angle between the $\gamma\gamma^*$ axis and the normal to the decay plane of the $KK\pi$ in the $\gamma\gamma^*$ cm system [18]. This has the form $1\pm\cos^2\alpha$ for $J^{PC}=1^{\pm+}$. Because of limited statistics our data are compatible with both forms of the distribution and so no firm conclusion can be drawn.

It should be mentioned that Monte Carlo studies of $f_1(1420)$ production using the above model indicate that in a significant number of events the scattered electron does not enter the forward counters and the events have a high resultant $|\Sigma p_t|$. A signal of about ten events is seen in our untagged data sample in an analysis identical to that presented here save the transverse momentum cut was reversed such that $|\Sigma p_t|^2 > 0.05$ GeV/c^2. The rate is consistent with that determined from the tagged data sample but background estimation problems prevent a more detailed consideration here.

Conclusions

Evidence for resonance formation has been observed in $\gamma\gamma^*$ collisions with no corresponding signal when both photons are approximately real. The most probable explanation for this is that the resonances have $J=1$, and possible candidates are the $f_1(1420)$ and $f_1(1285)$. Using the model of Renard and Cahn the product of the branching ratio and the two-photon width for the $f_1(1420)$ has been determined to be

$$B(f_1(1420) \to K\bar{K}\pi)\,\tilde{\Gamma}_{f_1(1420)} = 2.3^{+1.0}_{-0.9} \pm 0.8 \text{ keV}$$

and the mixing angle in the 1^{++} nonet was then measured to be

$$\theta = 64^{+5°}_{-8}.$$

These results are in agreement with measurements made by other experiments.

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