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E/ι decays to $K\bar{K}\pi$ in $\bar{p}p$ annihilation at rest

OBELIX Collaboration

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Abstract

The results of the analysis of 3940 $(K\bar{K}\pi)\pi\pi$ events from a sample of 18 millions $\bar{p}p$ annihilations in the liquid hydrogen target of the OBELIX spectrometer at LEAR (CERN) are presented. The presence of two pseudoscalar states at 1.416 ± 0.002 GeV$/c^2$, with width 0.050 ± 0.004 GeV$/c^2$, and at 1.46 ± 0.01 GeV$/c^2$, with width 0.105 ± 0.015 GeV$/c^2$, is

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established. The lighter mass resonance decays mainly to $K\bar{K}\pi$, possibly with final state interactions and a small contribution coming from $a_0\pi$. The higher mass 0^{-+} state, which is seen for the first time in $\bar{p}p$ annihilation at rest, decays only to $K^*\bar{K}$. Masses, widths and decay modes are in agreement with the analysis of J/ψ radiative decay performed by the Mark III Collaboration. From the fit the G-parity was determined to be +1. The dominant three-body decay mode of the lighter pseudoscalar is observed for the first time in this measurement.

A striking expectation of Quantum ChromoDynamics (QCD), the non-Abelian field theory of strong interaction, is the existence of new kind of mesons, made by valence gluons, the glueballs (gg or ggg), or by admixtures of quarks, antiquarks and gluons ($q\bar{q}g$), called hybrids. Another example of non-$q\bar{q}$ mesons are multiquark states, $q\bar{q}q\bar{q}$.

An experimental confirmation of the existence of these states would be an important test of the theory and would give fundamental information on the behaviour of QCD in the confinement region.

The search for non-$q\bar{q}$ mesons has indeed represented the main motivation of light meson spectroscopy over the last years. The difficulty of this search is mostly due to the complexity of the hadron spectrum, where $q\bar{q}$ states overlap, in the same mass region, with the radial excitations. Moreover, many meson nonets occupy a similar mass region. Thus, assigning states to nonets can be a complicated task, and how to recognize a meson as $q\bar{q}$ or non-$q\bar{q}$ is a basic problem. Obviously, an assignment of quantum numbers which are not allowed to a $q\bar{q}$ state (0^{+-}, etc.) would represent the best signature for an exotic state. Nature is more complicated and up to now no exotic candidate displays unambiguously forbidden quantum numbers.

Despite all this, the nonet structure is the best tool we possess for recognizing non-$q\bar{q}$ mesons, together with an indication of the masses, which are not known a priori, but can be found from approaches such as QCD-inspired potential models. Among these, the model built by Godfrey and Isgur [1] is often used in order to test whether a new discovered resonance does or does not belong to one of the $q\bar{q}$ nonets. Studies of lattice QCD [2–4] appear to be coming to a consensus that the ground state glueball lies around 1.5 GeV/c^2, with an uncertainty of a few 0.1 GeV/c^2.

Among the non-$q\bar{q}$ candidates, the case of the E/ι meson occupies, undoubtedly, a special role. The E-meson was discovered in 1963 in $\bar{p}p$ annihilations at rest [5], in the ($K\bar{K}\pi$) decay mode, at a mass of 1.425 GeV/c^2 and with spin-parity J^{PC} 0^{-+}. For nearly 30 years several experiments looked at the 1.4 GeV/c^2 mass region in a variety of different reactions: from $\bar{p}p$ at rest and in flight to π or K peripheral induced reactions; from pp and πp central production to $\gamma\gamma$ collisions in e^+e^- annihilation; from J/ψ radiative decay to J/ψ hadronic decay. A puzzling scenario turned out, in which appeared that the quantum numbers associated with the states observed in the mass spectrum [$\iota(0^{-+})$ or $E(1^{++})$] were different for different production mechanisms, and the J^{PC} were not unique, even within the same type of reaction. This led to an intense debate, still not concluded, known as the "*E/ι puzzle*", on the mere existence of the new states and on the possibility that one or more of them might be a non-$q\bar{q}$ meson, like a glueball, a hybrid, or a multiquark state [6–13].

The ASTERIX Collaboration at LEAR observed [14], in $\bar{p}p$ annihilation at rest in gaseous target, a structure at 1.413 GeV/c^2 in the channel $K^{\pm}K^0_{\text{miss}}\pi^{\mp}\pi^+\pi^-$. A 0^{-+} assignment was deduced, although a spin-parity analysis could not be performed due to the limited statistics.

New light on the puzzle was shed by a partial wave analysis of the E/ι region performed by the Mark III Collaboration on the $K\bar{K}\pi$ final state from J/ψ radiative decay [15]. From a data sample of roughly 700 events from 6 millions collected data, Mark III interpreted the E/ι signal as due to the presence of three overlapping resonances seen, for the first time, all at a time:

i) $\eta(1420)$ with $J^{PC} = 0^{-+}$ and decay via $a_0(980)\pi$

ii) $\eta(1490)$ with $J^{PC} = 0^{-+}$ and decay via $K^*\bar{K}$

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iii) $f_1(1420)$ with $J^{PC} = 1^{++}$ and decay via $K^*\bar{K}$.

Also the DM2 Collaboration found three structures in the channel $J/\psi \rightarrow \gamma K\bar{K}\pi$ [16], however they were not found to be consistent, as far as decay modes are concerned, with those of Mark III.

Recently, a structure in the E/ι region, studying the decays to $\eta\pi\pi$, was observed in $p\bar{p}$ annihilation at rest in liquid hydrogen by the Crystal Barrel Collaboration [17].

In this paper we report the first observation of two pseudoscalars in the E/ι region, seen in $p\bar{p}$ annihilation at rest, in the channel $K^\pm K^0_{miss}\pi^\mp\pi^+\pi^-$. A spin-parity analysis was performed, according to which the lighter resonance has a dominant three-body decay to $K\bar{K}\pi$, with small contributions coming from $a_0\pi$ and $K^*\bar{K}$. The higher mass resonance decays only to $K^*\bar{K}$.

The experiment was performed at the Low Energy Antiproton Ring (LEAR) at CERN, using the OBELIX spectrometer (whose detailed description can be found in Ref. [18]). The whole apparatus is immersed in a magnetic field, whose intensity reaches its maximum value of 0.5 T along its axis. Antiprotons with a momentum of 200 MeV/c were stopped in a liquid hydrogen target surrounded by a first layer of 30 thin (1 cm) plastic scintillators, arranged in a barrel and providing the annihilation times to the OBELIX time-of-flight system (TOF).

The outer *jet drift chamber* (JDC) is devoted to the tracking of charged particles. It allows the measurements of the particle momentum and of their dE/dx and contributes to the determination of the annihilation vertex and of the topology of the event. The momentum threshold on charged kaons is 200 MeV/c.

About 18 million events were collected in 12 days. A special trigger to select a final state with at least one charged kaon [19] was employed in order to investigate the channel $\bar{p}p \rightarrow K^\pm K^0_{miss}\pi^\mp\pi^+\pi^-$. The sample consisted of 4-prong events with zero total charge, all pointing to the annihilation vertex.

The K^0 was not detected but reconstructed by $1C$ kinematical fit. The selection criteria were based mainly on the identification of the charged kaon by dE/dx. Firstly, the selection algorithm was tuned so to achieve an agreement >90% with time-of-flight identification, a rejection on pion >99.9%, and flat efficiency of about 80% as a function of momentum. Particle identification was applied to all particles detected in the final state, by requiring one kaon and three pions to be recognized. Channels like $\pi^+\pi^-\pi^+\pi^-n\pi^0$ $(n = 0, 1)$ and $K^\pm K^0_s\pi^\mp n\pi^0$ $(n = 0, 1)$ were rejected by kinematical fit and did not contribute to the K^0 missing mass region. A cut on $\pi^+\pi^-$ invariant mass was also applied, in order to reject the $K^\pm K^0_s\pi^\mp n\pi^0$ $(n > 1)$ channels. All these cuts featured a high (>90%) and smooth efficiency for the selected channel and allowed to obtain a consistent background reduction.

The squared missing mass of the $K^\pm\pi^\mp\pi^+\pi^-$ selected events is plotted in Fig. 1a. A clear K^0 signal is present; the hatched area shows the events selected by kinematical fit with C.L. > 90% for the $K^\pm K^0\pi^\mp\pi^+\pi^-$ channel in the mass interval $0.21 < M^2 < 0.31$ GeV$^2/c^4$.

This way, 3940 events, with a contamination upper limit of 20%, were selected. This residual contamination comes mostly from the channels $\pi^+\pi^-\pi^+\pi^-n\pi^0$ $(n > 1)$ with one pion misidentified as a kaon, or $K^+K^-\pi^+\pi^-\pi^0$ with one kaon decaying close to the vertex region. The channel with all pions gives a smooth contribution, decreasing in the mass region of interest. The contribution of $K^+K^-\pi^+\pi^-\pi^0$ simulated events in the $K^\pm\pi^\mp\pi^+\pi^-$ missing mass spectrum, is shown in Fig. 1a. A close agreement with background shape obtained by the fit on real data is apparent.

The $K^\pm K^0_{miss}\pi^\mp$ invariant mass distribution is shown in Fig. 1b. A prominent signal in the mass region around 1.4 GeV/c^2 is evident. There are two entries per event, due to the presence of two identical charged pions in the final state. One can assume that the double charged $K^\pm K^0\pi^\pm$ combination (shaded area of Fig. 1c) reproduces the shape of the non resonant $K^\pm K^0\pi^\mp$ combination. Fig. 1d shows, for illustrative purposes, the result of the subtraction of the combinatorial background from the overall distribution, with one entry per event; the acceptance correction has also been introduced.

The peak evidence is striking and very similar to the old bubble chamber result [5], but with almost one order of magnitude more statistics.

The resonance decay Dalitz plot is shown in Fig. 2a for the events in the mass interval ≥ 1.38 GeV/c^2 of Fig. 1b. Only one arm of the K^* is present, as evident also from the $K^\pm\pi^\mp$ and $K^0\pi^\pm$ invariant mass projections (Figs. 2b and c). This feature is a combined effect of kinematics and apparatus threshold on

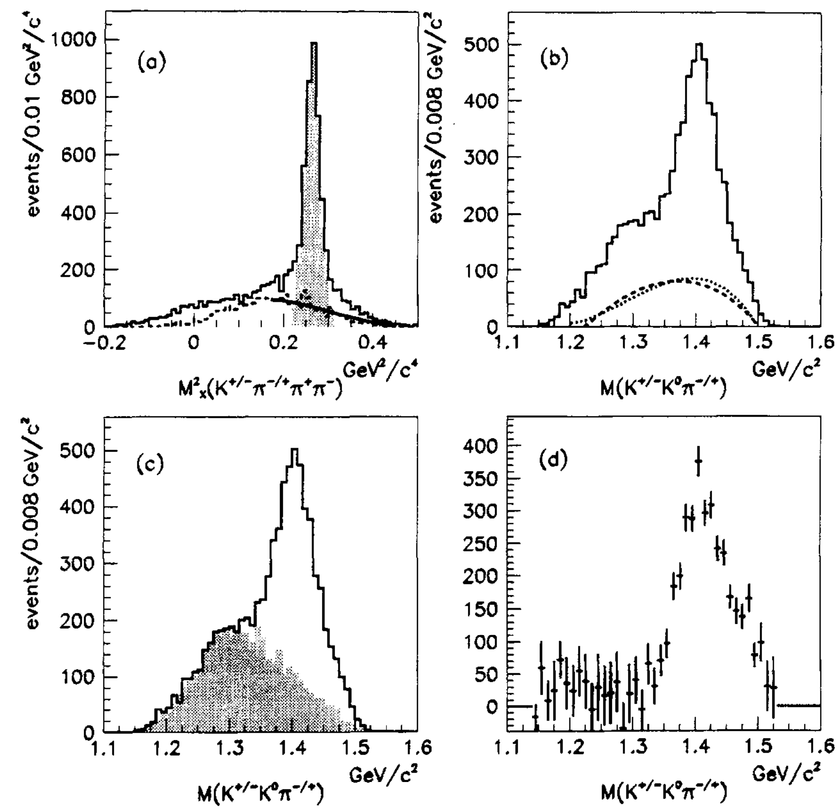

Fig. 1. Squared missing mass of the $K^\pm\pi^\mp\pi^+\pi^-$ selected events (solid line): the hatched area shows the events selected by kinematical fit with C.L. > 90% to the $K^\pm K^0\pi^\mp\pi^+\pi^-$channel. The shape of the fitted background contribution is also shown (continuous line), whereas the dashed line shows the $K^\pm\pi^\mp\pi^+\pi^-$ squared missing mass for $K^\pm K^\mp\pi^+\pi^-\pi^0$ Monte Carlo events which survive the same selection criteria as the real events; b) $K\bar{K}\pi$ invariant mass for kinematically selected $K^\pm K^0\pi^\mp\pi^+\pi^-$events (two entries per event): real data (solid line), $K^\pm K^0\pi^\mp\pi^+\pi^-$phase-space Monte Carlo events (dotted line), real data with low confidence level ($0.002 \leq$ C.L. ≤ 0.01) (dashed line); c) $K\bar{K}\pi$ invariant mass for real data (continuos line) and double charged $K^\pm K^0\pi^\pm$ combination (shaded area); d) $K\bar{K}\pi$ invariant mass for real data after the double charged $K^\pm K^0\pi^\pm$ subtraction and acceptance correction.

kaon momentum (cut below 200 MeV/c). Actually, a charged K^* is produced together with a charge conjugated kaon and decays into a neutral kaon. On the contrary, a neutral K^* is produced together with a neutral kaon, and decays into a charged kaon. In the first case, the charged kaon recoiling against the K^* would be too slow to be detected by the apparatus, whereas, in the second case, the momentum of the charged kaon, produced in the decay of the neutral K^*, is above the detection threshold and the parent K^* can be detected.

The 3940 selected events were then submitted to both a global fit and a partial wave analysis. In the framework of the isobar model the reaction is considered as a chain of two-body decays. Using the fitted 4-momenta of the final state, the analysis was performed with two independent programs, one based on the Zemach tensor formalism [20], the other one on the helicity formalism [21]. Their results were found to be in complete agreement.

For the energy part of the amplitudes, both relativistic Breit-Wigner functions, as well as amplitudes constructed in the scattering length approximation, due to the different characteristics of the resonances involved, were used. To build the overall amplitude the following assumptions were made:

- the presence of one or more resonances in the neutral $K\bar{K}\pi$ system, which could decay to $a_0\pi$, $K^*\bar{K}$, $(K\bar{K})_S\pi$, and $(K\pi)_S\bar{K}$, where $(K\bar{K})_S$ and $(K\pi)_S$ represent a dimeson in S-wave. The following parametrization for the neutral $(K\bar{K}\pi)$ system

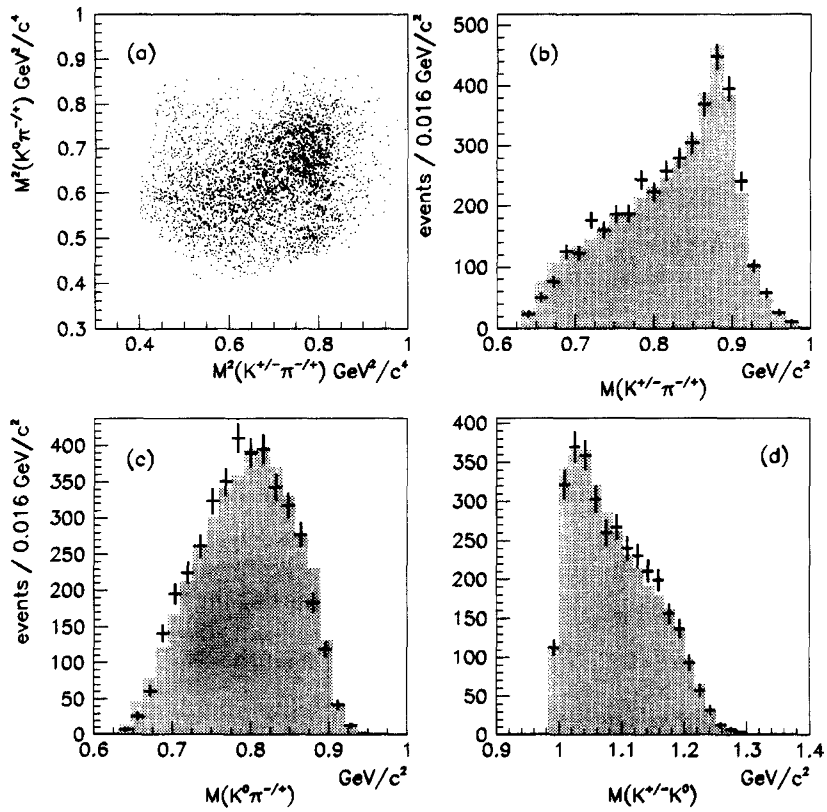

Fig. 2. a) $K\bar{K}\pi$ Dalitz plot, b) $K^{\pm}\pi^{\mp}$ invariant mass, c) $K^0\pi^{\pm}$ invariant mass, d) $K^{\pm}K^0$ invariant mass. For all distributions $M(K^{\pm}K^0\pi^{\mp}) > 1.380$ GeV/c^2. The experimental points (crosses) are superimposed to the results of the best fit of the spin-parity analysis (shaded areas).

and its isobar decomposition was used:

1. The resonant $K\bar{K}\pi$ neutral system and the K^* were described by a relativistic Breit-Wigner function (BW).
2. The $K\bar{K}$ enhancement at threshold (Fig. 2d) was identified either with the $a_0(980)$ resonance - and therefore described by a Flattè formula ($F(a_0)$) [22], with mass and width taken from the Review of Particle Properties [23] - or with a $(K\bar{K})_S$ final state interaction, parametrized in the scattering length approximation ($S_0(K\bar{K})$).
3. The S-wave $K\pi$ system ($(K\pi)_S$) was described in the scattering length approximation ($S_0(K\pi)$) [24].

Furthermore it was seen that:

- the $\pi^{\pm}\pi^{\mp}$ dipion distributions, recoiling against $K\bar{K}\pi$, could not be reproduced simply by phase space. Due to the fact that in this case the $\pi^{\pm}\pi^{\mp}$ invariant mass is ≤ 0.5 GeV/c^2, it is natural to expect that the $(\pi^{\pm}\pi^{\mp})$ interaction should occur mainly with relative orbital angular momentum $l = 0$. Introducing the Au-Morgan-Pennington (AMP) parametrization of the $(\pi\pi)_S$ amplitude, the data description improved significantly, but the fit was not yet satisfactory, probably due to the fact that in the low mass region the existing fits to experimental data are not completely reliable.

A satisfactory fit was obtained by introducing a scattering length function, or by generalizing the AMP amplitude in the N/D approximation [25]. In the first case, the parameters were determined by fitting the phase shifts from Ref. [26], whereas, in the second case, they were determined from our data. These parameters were then used in all the subsequent fits, being quite independent from the description of the $K\bar{K}\pi$ neutral system. A possible contribution of $\rho^0 \to \pi^+\pi^-$ turned out to be negligible.

The elementary amplitudes for $\bar{p}p \to E/\iota\ \pi^+\pi^-$ were then constructed as follows:

1. $E/\iota \to K^*\bar{K}$:

$$A_k = A(\pi\pi)BW(E/\iota)[BW(K^{*\pm})D(K^{*\pm}) + G \cdot BW(K^{*0})D(K^{*0})] \quad (1)$$

2. $E/\iota \to (K\bar{K})_S\pi$:

$$A_k = A(\pi\pi)BW(E/\iota)F(a_0)D(a_0) \quad (2)$$

or

$$A_k = A(\pi\pi)BW(E/\iota)S_0(K\bar{K})D(K\bar{K}) \quad (3)$$

3. $E/\iota \to (K\pi)_S\bar{K}$:

$$A_k = A(\pi\pi)BW(E/\iota)[S_0(K^\pm\pi^\mp)D(K^\pm\pi^\mp) + G \cdot S_0(K^0\pi^\mp)D(K^0\pi^\mp)] \quad (4)$$

Here $A(\pi\pi)$ is the S-wave dipion interaction, G is the E/ι G-parity, D describes the angular part in the helicity or Zemach formalisms, according to the angular momenta decomposition. The values of angular momentum between E/ι and dipion, and inside dipion were restricted, in the fit, to 0 and 1.

Direct production processes like $\bar{p}p \to K^*\bar{K}\pi\pi$, $a_0\pi\pi\pi$, were also taken into account. Since in this case there are, in principle, many possible angular momentum and isospin decompositions, they were added incoherently summing over all spin components.

The contamination from other reactions to the $K^\pm K^0\pi^\mp\pi^+\pi^-$channel (~20%), described above, was distributed as phase space: therefore it was assumed not to interfere with other amplitudes. This hypothesis was checked on real data by selecting events with a low confidence level ($0.002 \leq$ C.L. ≤ 0.01) for the $K^\pm K^0\pi^\mp\pi^+\pi^-$channel. One can assume that these events well represent the background shape and indeed their distribution turned out consistent with a phase space-like behaviour (see Fig. 1b). The shape of the distribution well agrees with that obtained from Monte Carlo simulation of the contaminating reactions and its quantitative estimation is in good agreement with what obtained from the results of the spin parity analysis.

A global fit of 8-dimensional space was performed. Given a point y in such space the squared modulus of the total amplitude is written as

$$|M(y)|^2 = \sum_{J^{PC}} |A_{J^{PC}}(y)|^2, \quad (5)$$

where the sum is over all possible $\bar{p}p$ J^{PC} states, and

$$A_{J^{PC}}(y) = \sum_k x_k e^{\phi_k} A_k(y), \quad (6)$$

is the sum of elementary amplitudes, with x and ϕ free parameters.

Within the P (or Q) matrix formalism [27] for resonance production, the relative phases between different decay channels of the same resonance are fixed at the same value.

Data were fitted by the maximum likelihood method by minimizing the function

$$\mathcal{L} = -2\log(L) = -2\sum_{i=1}^{N} \log[(1-f)\frac{|M(y_i)|^2}{\int |M(y)|^2 dy} + f] \quad (7)$$

where f describes an incoherent phase space-like background contribution. Masses and widths of E/ι were free parameters.

In the channel $\bar{p}p \to E/\iota(\pi\pi)$, since the E/ι mass is much greater than the dipion mass, the $(\pi\pi)$ system is in S-wave and the relative angular momentum between the E/ι and the dipion is also equal to zero. This was verified on the data and brings an important implication: a 0^{-+} resonance can only come from a $^1S_0$ $\bar{p}p$ state and a 1^{++} resonance from a $^3P_1$ $\bar{p}p$ state.

The strategy followed during the analysis was to look for the minimum set of amplitudes which provides the best description of the data. The attempt to fit the data by phase space plus the direct production channels $\bar{p}p \to K^*\bar{K}\pi\pi$, $a_0\pi\pi\pi$ was rejected by the fit. Also the fit with an axial vector resonance was unsuccessful.

One or more resonant 0^{-+} states in the $K\bar{K}\pi$ system with isospin $I = 0$ had to be introduced.

Three major groups of fits were performed. Both the likelihood function and the pseudo-χ^2 calculated on a subset of histograms were considered as criteria for the goodness of the fit. The selected histograms were the most sensitive to the chosen amplitude parametrization.

(i) In the first group of fits, the decay channels $E/\iota \rightarrow a_0(980)\pi$ and $K^*\bar{K}$ were taken into account. The one-pseudoscalar resonance hypothesis did not provide a satisfactory fit.

When a second pseudoscalar resonance was introduced, a big decrease in the likelihood function (about 400 units) was observed. The main aspects of the fit results were that the low mass state decayed preferably to $a_0\pi$, whereas the high mass state decayed mainly to $K^*\bar{K}$.

However, although with two resonances a significant improvement in the fit was observed, data description appeared not yet satisfactory: χ^2 was 3 for the fit with one 0^{-+} and 2 for the fit with two 0^{-+}. In particular, a systematic discrepancy between fitted and experimental data in the $(K\bar{K})$ mass distribution at threshold was observed. This suggested a different parametrization for the $(K\bar{K})_S$ system in terms of a scattering length formula.

(ii) In the second group of fits, the decays $E/\iota \rightarrow (K\bar{K})_S\pi$ and $K^*\bar{K}$ were assumed. The results are reported in Table 1.

The $K\bar{K}$ scattering length in S-wave was a free parameter and it turned out $a_{K\bar{K}} = -0.5 \pm 0.1$ GeV^{-1}. Due to the smallness of this number, this amplitude cannot be interpreted as referring to the $a_0(980)$ resonance.

Once more there was a consistent improvement of the fit when a second resonance with $J^{PC} = 0^{-+}$ was introduced, as can be seen from Table 1.

It is interesting to notice that, independently from the description of the $K\bar{K}$ system ($a_0(980)$ or $S_0(K\bar{K})$) to describe the decay of the low mass pseudoscalar, the high mass resonance decays, in both cases, only to $K^*\bar{K}$. Fractions are quite stable, as well as masses and widths.

In order to test whether the E/ι is produced, in $\bar{p}p$ at rest, not uniquely from initial $p\bar{p}$ $^1S_0$ state, initial $^3S_1$ and $^3P_1$ states were also considered. A slight improvement in the likelihood was observed and, as expected, the $^3S_1$ and $^3P_1$ contributions turned out to be suppressed with respect to $^1S_0$: $^1S_0 \sim 84\%$, $^3S_1 \sim 6\%$, and $^3P_1 \sim 10\%$. The introduction of these initial states reduced slightly the background fraction, which resulted $\sim$15%. On the other hand, the relative weight of the two resonances remained stable, with

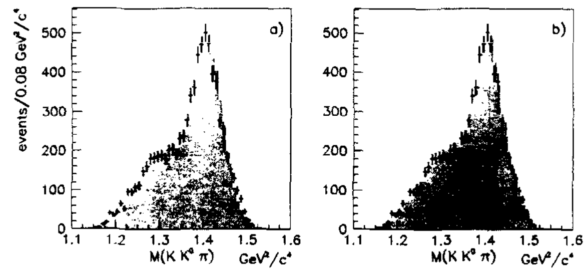

Fig. 3. $K\bar{K}\pi$ invariant mass (experimental points) with superimposed the result of the best fit from spin-parity analysis (shaded area) under the hypothesis of $E/\iota \rightarrow a_0\pi, K^*\bar{K}, (K\pi)_S\bar{K}$, $(K\bar{K})_S\pi$ with: (a) one pseudoscalar and (b) two pseudoscalar states.

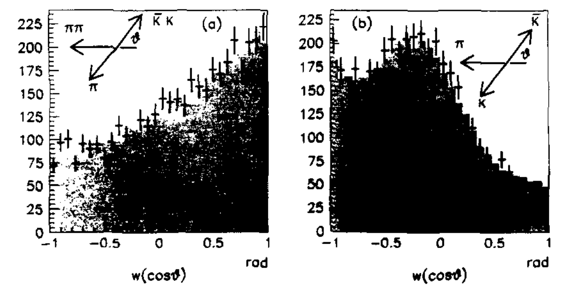

Fig. 4. Decay angular distribution of: (a) E/ι recoiling against the dipion in the $\bar{p}p$ rest frame and b) one pion recoiling against the $(K\bar{K})$ system in the E/ι rest frame; superimposed is the result of the best fit for two resonances (shaded area).

$E/\iota(2)/E/\iota(1) \sim 0.4$.

(iii) Finally, in the third group of fits, the additional $(K\pi)_S\bar{K}$ decay mode was introduced: $E/\iota \rightarrow a_0\pi, K^*\bar{K}, (K\pi)_S\bar{K}, (K\bar{K})_S\pi$

The results are shown in Table 2 and Figs. 3 and 4. A big difference in the likelihood between one and two states, which decay dominantly to $(K\pi)_S\bar{K}$ and to $K^*\bar{K}$, respectively, can be observed. Since the low energy $(K\pi)_S$ system is not resonant, the E/ι decay mode to $(K\pi)_S\bar{K}$ is practically equivalent to the three-body $(K\bar{K}\pi)$ direct decay. The same can be said if the $(K\bar{K})_S$ threshold enhancement is described, not by a resonance (a_0), but by a scattering length amplitude, in which the scattering length takes a small value. Therefore, the decay mode $(K\pi)_S\bar{K}$ and $(K\bar{K})_S\pi$ are indeed equivalent, as indicated by a comparison of the fit results shown in Table 2 (last two fits).

Direct three-body decays, or quasi-two-body, in which the isobar is a weakly interacting system (as for instance the $\eta(\pi\pi)_S$ system), were also observed,

Table 1
Fractional contributions from the fits with $E/\iota \rightarrow (K\bar{K})_S\pi$, $K^*\bar{K}$, in the hypotheses of one and two 0^{-+} resonances (masses and widths are in GeV/c^2), with the corresponding values of the maximum likelihood function $\mathcal{L}$, the pseudo-χ^2 and the number of fitting parameters N_f.

$\mathcal{L}$	χ^2	N_f	$E/\iota(1) \rightarrow$		$E/\iota(1)$		$E/\iota(2) \rightarrow$		$E/\iota(2)$		$K^*\bar{K}\pi\pi$	Background
			$(K\bar{K})_S\pi$	$K^*\bar{K}$	m	Γ	$(K\bar{K})_S\pi$	$K^*\bar{K}$	m	Γ		
one-resonance fit $((K\bar{K})_S\pi, K^*\bar{K})$												
−2420	2.6	7	0.46 ± 0.03	0.23 ± 0.03	1.426 ± 0.002	0.078 ± 0.004	-	-	-	-	0.11 ± 0.03	0.20 ± 0.03
two-resonance fit $((K\bar{K})_S\pi, K^*\bar{K})$												
−2630	1.3	12	0.47 ± 0.04	< 0.01	1.416 ± 0.002	0.052 ± 0.004	< 0.01	0.22 ± 0.03	1.466 ± 0.007	0.108 ± 0.014	0.05 ± 0.03	0.23 ± 0.02

Table 2
Fractionals contributions from the fits with $E/\iota \rightarrow a_0\pi$, $K^*\bar{K}$, $(K\pi)_S$, $(K\bar{K})_S\pi$, in the hypotheses of one and two 0^{-+} resonances (masses and widths are in GeV/c^2), with the corresponding values of the maximum likelihood function $\mathcal{L}$, the pseudo-χ^2 and the number of fitting parameters N_f.

$\mathcal{L}$	χ^2	N_f	$E/\iota(1) \rightarrow$				$E/\iota(1)$		$E/\iota(2) \rightarrow$				$E/\iota(2)$		$K^*\bar{K}\pi\pi$	Back-ground
			$a_0\pi$	$K^*\bar{K}$	$(K\pi)_S\bar{K}$	$(K\bar{K})_S\pi$	m	Γ	$a_0\pi$	$K^*\bar{K}$	$(K\pi)_S\bar{K}$	$(K\bar{K})_S\pi$	m	Γ		
one-resonance fit $(a_0\pi, K^*\bar{K}, (K\pi)_S\bar{K})$																
−2310	2.6	6	0.04 ±0.02	0.23 ±0.05	0.30 ±0.06	-	1.410 ±0.002	0.056 ±0.006	-	-	-	-	-	-	0.04 ±0.02	0.38 ±0.03
two-resonance fit $(a_0\pi, K^*\bar{K}, (K\pi)_S\bar{K})$																
−2606	1.3	11	0.09 ±0.04	< 0.01	0.44 ±0.07	-	1.414 ±0.002	0.046 ±0.005	< 0.01	0.20 ±0.05	< 0.01	-	1.450 ±0.006	0.098 ±0.014	-	0.27 ±0.02
two-resonance fit $(a_0\pi, K^*\bar{K}, (K\bar{K})_S\pi)$																
−2660	1.3	14	0.04 ±0.02	0.02 ±0.01	-	0.49 ±0.06	1.416 ±0.002	0.052 ±0.004	< 0.01	0.15 ±0.04	-	< 0.01	1.466 ±0.007	0.108 ±0.014	0.07 ±0.03	0.22 ±0.02

when such amplitude was taken explicitly into account, in hadro production process [28] as well as in J/ψ decay [16].

One major consideration from Tables 1 and 2 is that the second pseudoscalar decays dominantly to $K^*\bar{K}$, quite independently from the decay of the first state.

The contribution of a 1^{++} resonance, with mass and width similar to that reported by the MARK III Collaboration [15], did not improve the quality of the fit. The upper limit for the presence of such resonance turned out ~2.5%.

The same can be said for possible contributions from $f_1(1285)$ and/or $\eta(1290)$, which did not introduce improvements in the fit.

The fit results with $G = -1$ were much poorer than those with $G = +1$, so that the E/ι G-parity was fixed to $+1$ in the amplitudes.

In the tables, as background are indicated all unaccounted non-resonant contributions to the selected channel, plus the contamination from other competing reactions feeding through the selection criteria. Moreover, the variations observed in the background intensity in the different fitting hypotheses are presumably due to contributions from unaccounted small components of the amplitude. The coincidence of a good likelihood with a low value of the background (which turned out slightly higher than the contamination coming from other reactions) is an indication that the most important waves were correctly taken into account.

An important characteristics of the selected $K^{\pm}K^0\pi^{\mp}\pi^+\pi^-$channel is that there are two combinations contributing to the $(K\bar{K}\pi)$ system, due to the presence of two identical pions. If one plots one combination against the other, two kinematical regions can be distinguished: one where the masses of both combinations fall both in the resonant region (1.37–1.50 GeV/c^2), and another where only one combination is in the region of resonant behaviour (there are two such non-overlapping regions). The relevant dynamics observed in our final state, i.e. the appearence of K^* and the threshold enhancement in the $K\bar{K}$ mass distribution, are kinematically suppressed in the overlapping region. This feature was taken into account in a partial wave analysis (PWA): by performing a fit of the data using those events of a given $(K\bar{K}\pi)$ mass bin which belonged only to the non-overlapping $(K\bar{K}\pi)$ mass regions. In this case, the amplitude used for the fit is well suitable to describe a system with

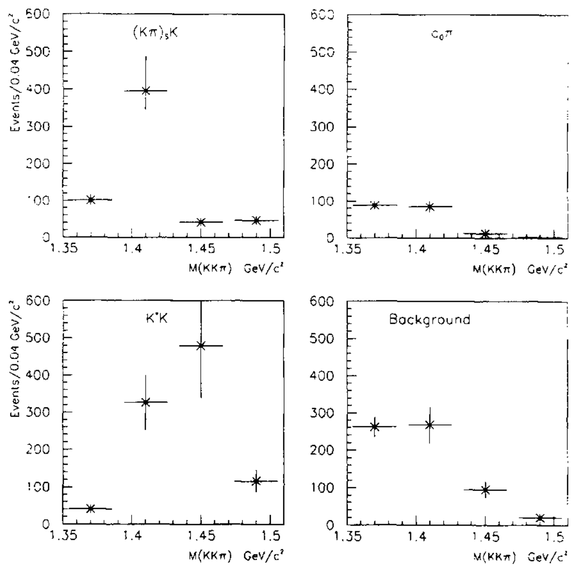

Fig. 5. Results of the partial wave analysis: partial wave intensities and background contribution.

only one entry per event, the background containing, in this case, also the combinatorial contribution.

Using a set of interfering amplitudes, the intensities, as well as the relative phases, were estimated with a maximum likelihood fit for different $(K\bar{K}\pi)$ mass intervals. Only the dominant $\bar{p}p$ $^1S_0$ initial state and an incoherent background distributed as phase space were taken into account. The intensities were calculated from the relative fractions of each elementary amplitudes, with the total sum normalized to the number of events in the given mass bin.

In order to obtain a stable solution against possible ambiguities in the binning procedure, the analysis was carried out for different non-overlapping mass bin sizes, requiring a smooth link of the relative phases between neighbouring mass bins.

The intensity of each partial wave is shown in Fig. 5. As expected, the background intensity distribution had a shape similar to the combinatorial background one (double charged $K^{\pm}K^0\pi^{\pm}$) combination. The weak $0^{-+}a_0\pi$ wave intensity seemed also not to have any remarkable structure and it was similar to the shape of the combinatorial background: for that reason this wave was chosen as the reference wave. The $0^{-+}(K\pi)_S\bar{K}$ wave intensity showed a peak in the region of 1.4 GeV/c^2, while the $0^{-+}K^*\bar{K}$ was more prominent at higher mass values (around 1.45

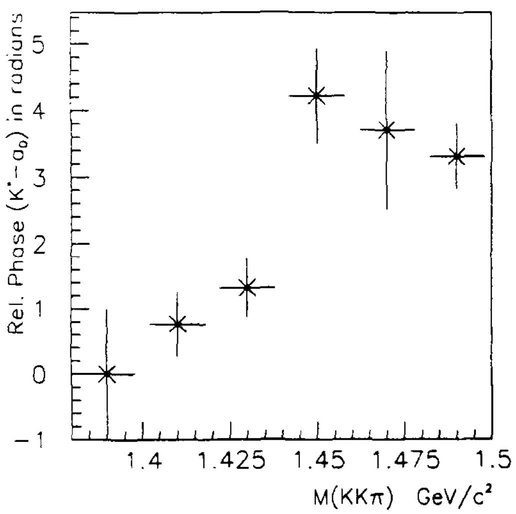

Fig. 6. Phase motion of the 0^{-+} $K^*\bar{K}$ wave.

GeV/c^2). A fit of these intensities with Breit-Wigner provides results in agreement with those of the global fit ($m = 1.403 \pm 0.006$ and $\Gamma = 0.04 \pm 0.01$ GeV/c^2, $m = 1.44$–1.46 and $\Gamma = 0.066$–0.120 GeV/c^2).

In the region ~1.38–1.43 GeV/c^2 the phase motion of the $0^{-+}(K\pi)_S\bar{K}$ wave with respect to the $0^{-+}a_0\pi$ wave resulted almost constant, which means that both waves are resonating together, or that none is resonating. From the existence of a clear enhancement observed in the $0^{-+}(K\pi)_S\bar{K}$ intensity, the first hypothesis seems more probable, i.e. a resonant behaviour of both waves can be argued. Indeed, from the global fit, a small resonant contribution from the $0^{-+}a_0\pi$ wave was observed.

The phase of the $0^{-+}K^*\bar{K}$ wave relative to the $0^{-+}a_0\pi$ wave shows a rapid forward motion (Fig. 6) in the same mass region where the intensity of the $0^{-+}K^*\bar{K}$ wave has a peak (around 1.44–1.46 GeV/c^2). This provides a clear indication of the presence of a resonance in that wave.

The result of PWA is that there is a resonant structure in the $K\bar{K}\pi$ mass region around 1.4 GeV/c^2 with a main decay mode $(K\pi)_S\bar{K}$, together with a second resonance, decaying to $K^*\bar{K}$, at higher mass values (1.44–1.46 GeV/c^2).

In conclusion, from the fit of 3940 $\bar{p}p$ annihilation in liquid hydrogen into the final state $K^{\pm}K^0\pi^{\mp}\pi^+\pi^-$, – a data sample exceeding previous data in $K\bar{K}\pi$ by a factor six – performed with two independently developed analysis programs, good evidence for the existence of two resonances in the mass region of the E/ι meson was obtained, both resonances being definitely established to be pseudoscalars.

The channel reaction proceeds mostly from $^1S_0$ initial state: the P-wave contribution turned out to be no more than ~10%. The channel is dominated by resonant production (80 to 90%).

Concerning the low mass resonance, the fit with a small $K\bar{K}$ S-wave scattering length was definitely better than the one with the a_0 resonance. Moreover, also a dominance of $E/\iota \rightarrow (K\pi)_S\bar{K}$, and again a small contribution of $a_0\pi$ was found. Due to the smallness of $a_{K\bar{K}}$ and $a_{K\pi}$ scattering lengths, and since $K\pi$ and $K\bar{K}$ mass spectra cover a limited mass region starting from threshold, the decay channels $(K\bar{K})_S\pi$ and $(K\pi)_S\bar{K}$ can be considered equivalent and very similar to a phase space-like behaviour. This means that the low mass resonance seems to decay mainly to $K\bar{K}\pi$, possibly with final state interactions, with a small contribution coming from $a_0\pi$, and a negligible one from $K^*\bar{K}$. Mass and width are $m = 1.416 \pm 0.002$ GeV/c^2 and $\Gamma = 0.050 \pm 0.004$ GeV/c^2.

Concerning the higher mass resonance, results were quite stable, indicating a dominant decay to $K^*\bar{K}$, with an intensity approximately 1/2–1/3 of the first resonance. Mass and width are $m = 1.46 \pm 0.01$ GeV/c^2 and $\Gamma = 0.105 \pm 0.015$ GeV/c^2.

Masses, widths and decay modes are in agreement with the analysis of J/ψ radiative decay performed by the Mark III Collaboration [15].

The dominant three-body decay mode of the lighter 0^{-+} is observed here for the first time. Additional contributions from direct production reactions $\bar{p}p \rightarrow K^*\bar{K}\pi\pi$ and $a_0\pi\pi\pi$ turned out to be very small.

The results of the partial wave analysis were substantially in agreement with those of the global fit. The phase motion of the 0^{-+} $K^*\bar{K}$ wave confirmed the existence of a second pseudoscalar state in $p\bar{p}$ annihilation at rest.

There is no indication in these data of the presence of a possible 1^{++} state, as it should be expected, due to the protonium S-wave dominance in $\bar{p}p$ annihilation at rest in LH_2.

Analyses of higher statistics data samples are needed: in order to quantify the small contributions of $a_0\pi$ and $K^*\bar{K}$ to the first resonance decay and to obtain a more precise evaluation of mass and width of the second resonance.

The confirmation of the presence of two pseudoscalars under the $\eta(1440)$ (following the notation of the Review of Particle Properties [23]), makes more meaningful the debate on their possible exotic nature.

The two pseudoscalars would have to fit into the only two $2\ ^1S_0$ available slots (the radial excitations of η and η') expected in the $q\bar{q}$ model and there is already a third candidate, the $\eta(1295)$. Thus, tentatively, one could think of one of the three states as a non-$q\bar{q}$ state. Unfortunately, one is not sure if the $\eta - \eta'$ mass difference will be reproduced in their radial excitations, nor the mixing angle between octet and singlet members of the excited nonet is known.

If the $\eta(1295)$ were the first radial excitation of the $\eta'(958)$, then it would be expected to be produced in $\gamma\gamma$ collisions. However, no evidence for the $\eta(1295)$ was seen by the Crystal Ball Collaboration [29] where, on the other hand, a large $\eta'(958)$ signal is evident in the $\eta\pi^0\pi^0$ mass spectrum. Therefore, identifying the $\eta(1295)$ with the $2\ ^1S_0(u\bar{u}+d\bar{d})$ state, radial excitation of the $\eta(548)$, seems quite natural [23,28].

The assignment of one of the two peaks to the remaining free slot $2\ ^1S_0$ $s\bar{s}$ appears to be problematic. Indeed, the $\eta(1440)$ was observed in $s\bar{s}$ depleted reactions like $\pi^- p \rightarrow \eta\pi\pi n$ [28] and $\pi^- p \rightarrow a_0(980)\pi p$ [30,31] and was not seen in $s\bar{s}$ enriched channels like $K^- p \rightarrow K^*(892)\bar{K}\Lambda$ [32]. Moreover, according to the Godfrey-Isgur model [1], the $2\ ^1S_0$ $s\bar{s}$ state should have a mass, 1.550 GeV/c^2, definitely higher than that of the $\eta(1440)$.

On the other side, the fact that the $\eta(1295)$ and the $\eta(1440)$ bumps have been seen with similar intensities [28], argues for these states being of similar nature, i.e. both radial excitations of η and η', respectively.

A reasonable conclusion is that *at least one* of the two pseudoscalars in the $\eta(1440)$ *cannot fit* with a conventional $q\bar{q}$ nonet.

Arguments in favour of a glueball interpretation of one of the two pseudoscalars under the $\eta(1440)$ have been used. Firstly, the copious production in typical gluon rich environments like J/ψ radiative decays and $\bar{p}p$ annihilations. The non-observation in $\gamma\gamma$ formation experiments [33–36] is another element in favour of a large gluon content, because very special cancellations would be required to suppress the coupling of photons to charged quarks. These two experimental evidences are usually combined and made quantitative introducing the "stickiness" parameter S [37]: for the $\eta(1440)$ $S > 45$ (compare with $S = 3.7$ for the η').

Looking for characteristics which may help in disentangling glueballs from quarkonium, the $\eta(1440)$ is also flavour blind, since in J/ψ hadronic decays has never been seen in association neither with ω nor with ϕ.

A recent analysis [38] of the structure of the $\eta(1440)$ performed using a mixing model with non-strange, strange and glueball basic states, shows that the higher mass pseudoscalar can be a partner of the radially excited isospin zero state $\eta(1295)$, whereas the lower mass resonance can be a pseudoscalar glueball.

As far as the decay modes are concerned, it has been shown [39] that a pseudoscalar glueball would decay dominantly into $K\bar{K}\pi$. Another hypothesis has also been put forward for the lighter 0^{-+}: to be a $q\bar{q}g$ hybrid state [40] made by coupling a 1^{++} $q\bar{q}$ state with a transverse electric gluon. Such a state, predicted [41] around 1.4 GeV/c^2, is expected to decay via $a_0(980)\pi$ and $\eta(\pi\pi)_S$.

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