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RESONANCE IN THE $K\bar{K}\pi$ SYSTEM BELOW $1.6 \text{ GeV}/c^2$

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INTRODUCTION

In my talk I shall report the present experimental status on the $K\bar{K}\pi$ final state below $1.6 \text{ GeV}/c^2$ in $K\bar{K}\pi$ effective mass. In this low mass range the $K\bar{K}\pi$ system is dominated by the production of 3 resonances: the D, the E/π and the D' recently reported¹. They are all isoscalar, D and D' have $J^{PC} = 1^{++}$; the J^{PC} of the E/π is under discussion, between 0^{-+} and 1^{++} . The possibility of having around the E mass two different states 0^{-+} and 1^{++} has been also envisaged². The D and D' could be identified as the two isoscalar of the 1^{++} SU(3) nonet but if the E is a 1^{++} , we will have 3 candidates for two isoscalars. In ref. 1 it is noticed that the couple D, D' fits better the SU(3) nonet than any other couple (see table 2). On the other hand, if E/π is a 0^{-+} it enters in no well established nonet.

E/π MESON SITUATION

$\bar{p}p$ annihilation at rest

This experiment, which is a CERN-Collège de France-Institut du Radium Collaboration^{3,4}, discovered the E meson in the reaction

$$\bar{p}p \rightarrow E\pi\pi$$

where the $\bar{p}$ is at rest. The statistics is fairly high compared to the other experiments. In ref. 4 we have:

$$600 \text{ events in } \bar{p}p \rightarrow E\pi^+\pi^- \quad (1)$$

$$\quad \quad \quad \downarrow$$

$$\quad \quad \quad \rightarrow K_1^0 K^\pm \pi^\mp$$

$$273 \text{ events in } \bar{p}p \rightarrow E^0\pi^0\pi^0 \quad (2)$$

$$\quad \quad \quad \downarrow$$

$$\quad \quad \quad \rightarrow K_1^0 K^\pm \pi^\mp$$

At the Paris Conference⁵ and at this conference a new analysis of those data were presented using the maximum likelihood technique on 536 events coming from reaction (1).

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That experiment concludes to:

$$J^{PC} = 0^{-+} ** ; \quad I = 0 ***$$

Decay branching ratio K^*K 43%, $\delta\pi$ 40%, $KK\pi$ 13% interference
 $\delta\pi K^*K$ 4%.

The *'s were put according to the degree of confidence we may have on the result. There is *** on the isospin determination because E is not seen in the charged mode which should have been quite numerous in case of $I > 0$. For J^{PC} there is only ** because its determination depends on the presence of the K^*K decay mode. In fig. 1 we have the basic plot leading to the discovery of the E. Fig. 1(c) displays the $KK\pi$ neutral mass distribution in $pp \rightarrow K_1^0 K^+ \pi^- \pi^+$. There are always two neutral combinations per event. The scatter plot of fig. 2 shows that there is nearby always one of these combinations in the E mass region. About 10% of the events have both neutral combination compatible with the E. In order to eliminate the effect of the unwanted combination, in fig. 1(a) we subtract the doubly-charged combination from the neutral one. On fig. 1(a) we see a nice Breit-Wigner type of distribution. This, together with the scatter plot fig. 2, leads to the assumption of 100% E production in reaction (1) without any background. Figs 1(b) and 1(d) give the $K\bar{K}$ and $K\pi$ mass distribution when the $KK\pi$ combination inside the E mass band is selected. The full curve corresponds to $J^{PC} = 0^{-+}$ and the dotted to 1^{++} . Fig. 3 is the Dalitz plot of the E decay. On these plots one sees that 0^{-+} fits better than 1^{++} . The main feature are a strong $K\bar{K}$ low mass enhancement and probably a K^* production. For the latter case the situation is confused because the low KK mass region happens to be also the kinematical region where the two possible $K\pi$ combinations are compatible with the $K^*(890)$. Fig. 4 shows the $K\pi$ and the $K\bar{K}$ angular distributions in the $K^*(890)$ and $\delta(980)$ mass region. Fig. 4(b) indicates a non uniform angular distribution for the δ decay in $K\bar{K}$. This implies an interference with an other decay mode and the best candidate for it is the decay of E in K^*K . Fig. 4(a) is incompatible with a flat distribution for decay of the K^* and agrees with a cosine squared type as expected for 0^{-+} . The accumulation near 1 is due to the overlapping of K^* 's. In fact the curve calculated for 0^{-+} fits much better than the one calculated in the 1^{++} hypothesis for the E. The curves shown in figs 1-4 are the result of the maximum likelihood. The parameter values are indicated in table 1 in the case of the best fit 0^{-+} . The value found for the logarithm of the likelihood was 298 for 0^{-+} , 230 for 1^{++} . 330 is the value to be found if the hypothesis were totally correct.

In conclusion the best interpretation to date of the $\bar{p}p$ experiment is 100% E production in reaction (1) decaying in K^*K and $\delta\pi$ with $J^{PC} = 0^{-+}$. Another interpretation like $J^{PC} = 1^{++}$ with similar decay mode has a probability lower by 10^{-30} .

SLAC experiments, radiative production of the E/ψ

Two experiments at SLAC found the E/ψ in the J/ψ radiative decay at SPEAR: the MARK-2⁶ and the Crystal Ball⁷ collaborations. It was found in the following decay chain:

$$e^+e^- \rightarrow \gamma/\psi + \dots$$

$$\quad \quad \quad \downarrow E\gamma$$

The statistics are limited, 130 events in the case of the Crystal Ball and much less in the MARK-2 experiments. The analysis of the E/ψ comes mainly from the Crystal Ball data⁸. They reach the following assignment:

$$J^{PC} = 0^{-+} \quad ***; \quad I = 0 \quad **$$

$$\text{Decay } K^* K \quad 25\% \quad \delta\pi \text{ dominant}$$

The background is negligible for the MARK-2 data and remains small for the Crystal Ball. A caveat has to be put on the analysis of the Crystal Ball data: it seems that they have a poor $K\bar{K}$ effective mass resolution. This should not affect the spin-parity analysis because it relies mainly on the production mechanism. These are well known since the E/ψ is produced in a two-body decay of the J/ψ where all the spins and parities are known except those of the E/ψ . It would nevertheless seriously affect the decay analysis of the E/ψ which is very dependent on the precise situation around the low $K\bar{K}$ effective mass where we have also the two $K\pi$ combinations both compatible with the $K^*(890)$. Figs 5-6 show the $K\bar{K}\pi$ mass plot for the two SLAC experiments. It can be seen that the MARK-2 data (fig. 5) has a good signal for the E/ψ with no background. They are looking at the E through the reaction:

$$e^+e^- \rightarrow J/\psi + \dots \quad (3)$$

$$\quad \quad \quad \downarrow E\gamma$$

$$\quad \quad \quad \downarrow K_1^0 K^+ \pi^-$$

The Crystal Ball (fig. 6) are looking at the reaction:

$$e^+e^- \rightarrow J/\psi + \dots \quad (4)$$

$$\quad \quad \quad \downarrow E\gamma$$

$$\quad \quad \quad \downarrow K^+ K^- \pi^0$$

They have also a good signal with more events than MARK-2 but with a background level not negligible. In fig. 7 we find the Dalitz plot for events compatible with the E/ψ . Although they claim a 100% $\delta\pi$ decay mode for the E/ψ , this plot shows, in the low $K\bar{K}$ mass value, an accumulation of events less pronounced than in reaction (1). By looking at fig. 8 where the $K\bar{K}$ mass distribution of the E/ψ decay is

displayed for the two SLAC experiments, one can see that MARK-2 shows a low $K\bar{K}$ mass accumulation sharp enough to be compatible with the $p\bar{p}$ experiment at rest while the Crystal Ball data indicates a larger bump. Since the events are very similar in both experiments, one may conclude that the resolution of the Crystal Ball is much poorer than that of the MARK-2. This lack of resolution may explain why the strong accumulation seen in $p\bar{p}$ annihilation is washed out in the Crystal Ball Dalitz plot. Then it is understandable why the Crystal Ball is not able to separate $\delta\pi$ decay from K^*K decay. An additional support for that interpretation comes from the measurement done by the Crystal Ball of the reaction

$$e^+e^- \rightarrow J/\psi + \dots \quad (5)$$

$$\quad \quad \quad \downarrow$$

$$\quad \quad \quad \eta\pi\pi\gamma$$

presented at the Paris Conference⁹. In this reaction the E should be seen in the $\eta\pi\pi$ mass distribution if it decays in $\delta\pi$ 100% of the time since the δ decays at least half of the time in $\eta\pi$. In fig. 9 the $\eta\pi^+\pi^-$ and $\eta\pi^0\pi^0$ mass distribution for radiative decay of the J/ψ is presented. There is no real evidence of E/π production. Nevertheless the data are compatible with a E/π branching ratio:

$$\frac{E \rightarrow \eta\pi\pi}{E \rightarrow K\bar{K}\pi} < 50\%$$

which is compatible with the $p\bar{p}$ analysis if

$$\frac{\delta \rightarrow K\bar{K}}{\delta \rightarrow \eta\pi} \sim 1$$

These remarks should not change the conclusion on the spin parity. It comes from an isobar type phase shift analysis and since they assumed 100% $\delta\pi$, the spin determination is made using only the E/π angular distribution. This distribution is independent of the decay hypothesis which one does and it is not affected by measurement errors. Fig. 9 shows the result of their phase shift analysis. They favour 0^{-+} in $\delta\pi$. This is confirmed in fig. 10 by the analysis of the angular distribution of the reaction:

$$e^+e^- \rightarrow J/\psi \rightarrow E\gamma \quad (6)$$

With smaller statistics than reaction (4), the angular distribution is fully compatible with 0^{-+} .

$\pi^-p \rightarrow E\pi$ at 3.95 GeV/c

This is a CERN-Collège de France-Madrid-Stockholm Collaboration¹⁰. It is a large statistics hydrogen bubble chamber experiment. The reaction looked at is:

$$\pi^-p \rightarrow E\pi \quad (7)$$

$$\quad \quad \quad \downarrow$$

$$\quad \quad \quad K^0 K^\pm \pi^\mp$$

The incident momentum of the pion was 3.95 GeV/c. A nice E signal (fig. 12) is seen. The statistics are comparable to those of the SLAC experiments (126-146 events). The background level is much higher than in the three experiments mentioned above (246-226 events under the peak). They conclude that:

$$J^{PC} = 1^{++} \quad I = 0 \quad ***$$

and the decay mode into K^*K is 86%.

Only one * is attributed to the spin parity analysis due to the high level of the background. Fig. 13 displays the decay Dalitz plot for the events in the E mass region. This Dalitz plot is very different from those in fig. 3 ($\bar{p}p$ exp.) and in fig. 8 (e^+e^- exp.). In fig. 13 the K^* 's bands are evenly populated and well marked. The interference region of the two possible K^* 's is higher than the neutral K^* 's confirming the presence of an important non-resonating background. In fig. 14 we have the result of a simplified phase shift analysis. Due to the lack of statistics and because the initial state is not an angular momentum eigenstate, a complete isobar type of analysis is difficult to perform. Only a Dalitz plot analysis was done. In this case the contributions of various amplitudes may interfere only within the same partial wave. Since the final state is not well defined one may also add incoherently some amplitudes in the same wave. The results are presented in fig. 14. The determination of the spin-parity of the E comes from the presence of a bump in the 1^{++} state. The authors claim that this solution at the E mass is unique because they try several starting points for the minimisation. They claim also that when they try to reverse the 1^{++} and 0^{-+} amplitudes, the probability of the fit drops by 50. On fig. 15 one can see the angular distribution in the E mass region. The curves are the predictions when one is forcing the E to be 1^{++} or 1^{-+} . The 0^{-+} is not plotted because it does not differ from 1^{++} on these plots.

Conclusion on the E

As a conclusion, the E in the π^-p at 3.95 GeV/c experiment is declared to be 1^{++} with a 86% K^*K branching ratio. This experiment suffers from high background and from low statistics. As a consequence, they were not able to do a complete isobar type of phase shift analysis. The attribution 1^{++} for the J^{PC} and 86% $K\bar{K}$ branching ratio is totally incompatible with the $\bar{p}p$ result. In the $\bar{p}p$ at rest experiment, when leaving free the K^*K and $\delta\pi$ branching ratio one finds 0^{-+} much more preferred than 1^{++} , the drop in probability being 10^{30} . In both cases, a high K^*K branching ratio similar to the π^-p experiment is rejected by the data.

On the other hand the data coming from e^+e^- through the radiative decay of the J/ψ and the data coming from $\bar{p}p$ at rest appear to lead to compatible results. They reach the same conclusion on the spin-parity. Their difference in branching ratio (K^*K 43% $\delta\pi$ 40% for $\bar{p}p$ and $K^*K < 25\%$ and $\delta\pi$ 100% for e^+e^-) can be understood when it is noticed the poor resolution of the Crystal Ball in the $K\bar{K}$ effective mass

determination which makes the $\delta\pi$ and the K^*K separation difficult. This is confirmed by the upper limit given by the Crystal Ball on the branching ratio of the E into $\eta\pi\pi$ which implies the branching ratio cannot be higher than the value found in $\bar{p}p$ at rest.

THE D' RESONANCE

Experimental evidence for the D'

A new resonance in the $KK\pi$ was claimed recently¹ in the reaction

$$K^- p \rightarrow K^0 K^+ \pi^- \Lambda^0 \quad (8)$$

at 4.2 GeV/c K incident beam. This resonance was seen when the $K\bar{K}\pi$ system was emitted forward in the incident K^- rest frame. Fig. 16 shows the $K\bar{K}\pi$ mass distribution and the evidence for such a resonance. Fig. 17 displays the Dalitz plot for events in the resonance bump. The two K^* bands are uniformly populated except when they overlap. Due to different kinematical conditions, the overlapping region is more in the middle of the plot than in the E case; it is more populated than the non-overlapping area indicating a constructive interference pattern between the K's. Using this, we may conclude that the $K\bar{K}$ is in an even angular momentum state which implies a G quantum number + and since the isospin as we will see is 0, we can already attribute a C-parity + to the D'. Moreover the uniform population in the K^* band favours an S wave for the K^*K system which leads to a probably spin-parity assignment for the D' of $J^{PC} = 1^{++}$. Fig. 18 shows the presence of the D' associated with the $\Sigma^0(1385)$ and its absence when it is associated to the $\Sigma^+(1385)$. Hence one concludes to I = 0. Fig. 19 shows the evidence of D' in the $K_1^0 K_1^0 \pi^0$ system and confirms the $C(D') = +$ quantum number attribution. Fig. 20 shows the same type of phase shift analysis than the one done for the E in $\pi^- p$ at 3.95 GeV/c. There is a spike at the D' mass in the 1^{++} wave. Fig. 21 shows the result of the fit for the histograms associated to the D' bins. The agreement is good.

SU(3) classification

In the same publication (1), a fit of the 1^{++} SU(3) nonet was included. The different possible isoscalar combinations were tried taking two states out of the possible three (E, D and D'). The result is in table 2. The best fit is for D and D' as the two isoscalars of the 1^{++} SU(3) nonet. So whatever is the spin parity associated to the E meson, the E remains a problem for any SU(3) classification.

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TABLE 1 - Parameter found for the E/π meson decaying in $K\bar{K}\pi$

Experiment	Mass MeV	Width MeV	J^{PC}	I	Branching ratio	
					$K^* K$	$\delta\pi$
$\bar{p}p$ at rest ³⁻⁵	1425 ± 7	80 ± 10	$0^{-+} **$	0 ***	43%	40%
$+ -$ 6,7 e e SLAC	1440 ± 20	60 ± 10	$0^{-+} **$	0 ***	< 25%	Dominant
$\pi^- p$ at 3.95 GeV/c ¹⁰	1425 ± 6	40 ± 15	$1^{++} *$	0 ***	86%	

TABLE 2 - SU(3) fit¹ result

SU(3) nonet 1^{++} members	X^2/N_D
$A_1, C/B_1, D, D'$	5/3
$A_1, C/B_1, E, D'$	46/3
$A_1, C/B_1, E, D$	15/3

$$p\bar{p} \rightarrow K_1^0 K^\pm \pi^\mp \pi^+ \pi^- \text{ at rest}$$

— $J^{PC}(E) \ 0^{-+}$
 - - - $J^{PC}(E) \ 1^{++}$

Fig. 1 Basic histogram for the reaction $\bar{p}p \rightarrow K_1^0 K^\pm \pi^\mp \pi^+ \pi^-$, refs 3-5.

Fig. 2 Scatter plot of the lowest mass $K_1^0 K^+ \pi^-$ combination versus the highest in the reaction $\bar{p} p \rightarrow K_1^0 K^+ \pi^- \pi^+ \pi^-$, refs 3-5.

$$1.370 < M(K_1^0 K^\pm \pi^\pm) < 1.450 \text{ GeV}$$

Fig. 3 Dalitz plot of the E decay from $\bar{p}p$ at rest, refs 3-5.

Fig. 4 Angular distributions of the E decay in $\bar{p}p$ at rest, refs 3-5.

SLAC - MARK II

Fig. 5 $K\bar{K}\pi$ mass distribution coming from the MARK II experiment⁶ showing evidence for E/ψ production in $e^+e^- \rightarrow J/\psi + \dots$

Fig. 6 $K\bar{K}\pi$ mass distribution coming from the crystal ball experiment, ref. 7.

Fig. 7 Dalitz plot of the E coming from the Crystal Ball, ref. 7.

Fig. 8 Comparison of the two $K\bar{K}$ mass distributions in the E decay. One is coming from the Crystal ball, the other from Mark 2, ref. 8.

Fig. 9 Results of the Crystal ball⁸ phase shift analysis using the isobar model.

- (a) is the number of events coming from the $K\bar{K}\pi$ in 0^{-+} with a $K\bar{K}\pi$ flat distribution on the E Dalitz plot.
- (b) is the number of events coming from $K\bar{K}\pi$ in 1^{++} assuming 100% K^*K .
- (c) is the number of events coming from $K\bar{K}\pi$ in 0^{-+} assuming 100% $\delta\pi$.

SLAC - Crystal ball

Fig. 10 Angular distribution of the J/ψ decaying in $E\gamma$ from the reaction $e^+e^- \rightarrow J/\psi \rightarrow E\gamma$. The curve corresponds to $J^{PC}(E) = 0^{-+}$.

Slac - Crystal ball

Fig. 11 $\eta\pi\pi$ mass distribution in $e^+e^- \rightarrow J/\psi + \dots$. The plot is coming from the Crystal ball, ref. 9. $\eta \rightarrow \pi\pi\gamma$

Fig. 12 $K\bar{K}\pi$ mass distribution in $\pi^- p$ at 3.95 GeV/c showing the evidence for the D and the E, ref. 10.

Fig. 13 Decay Dalitz plot of the E, ref. 10.

$\pi^- p$ 3.95 GeV/c (Dionisi et al)

Fig. 14 Phase shift analysis of the $KK\pi$ system from ref. 10.

$\pi^- p$ 3.95 GeV/c (Dionisi et al)

$1.39 \leq M(K_S^0 K^\pm \pi^\mp) \leq 1.47$ GeV

Fig. 15 Angular distributions of the E decay produced in the $\pi^- p$ at 3.95 GeV/c [10]. Comparison with $J^{PC}(E) = 1^{++}, 1^{-+}$.

Fig. 16 $K_1^0 K^\pm \pi^\mp$ mass distribution coming from $K^-p \rightarrow K_1^0 K^\pm \pi^\mp \Lambda^0$ at 4.2 GeV/c incident beam¹. The dotted histogram corresponds to the total sample, the dashed area is the $KK\pi$ forward contribution. The curve is the result of the phase shift analysis.

Fig. 17 Decay Dalitz plot of the D' , ref. 1.

Fig. 18 $K_1^0 K_1^0 \pi^0$ mass distribution for the $K\bar{K}\pi$ system emitted forward in the $K^- p \rightarrow K_1^0 K_1^0 \pi^0 \Lambda^0$ reaction at 4.2 GeV/c incident beam.

Fig. 19 Comparison of the $K\bar{K}\pi$ distribution when produced in
 $K^- p \rightarrow K^- K_S^0 \pi^0 \Sigma^+(1385)$ and when produced in
 $K^- p \rightarrow K^- K_S^0 \pi^0 \Sigma^+(1385)^+$, ref. 1.

Fig. 20 Result of the $K\bar{K}\pi$ phase shift analysis coming from ref. 1.

$K^- p$ 4.2 GeV/c
 (Gavillet et al)
 $1.47 < M(KK\pi) < 1.59 \text{ GeV}/c^2$

Fig. 21 Decay mass distribution of the D' produced in $K^- p \rightarrow K^0 K^\pm \pi^\mp \Lambda^0$
 when the $K\bar{K}\pi$ system is emitted forward, ref. 1.