CERN/EP 80-1
11 January 1980

OBSERVATION AND QUANTUM NUMBERS DETERMINATION OF THE

E(1420) MESON IN $\pi^- p$ INTERACTIONS AT 3.95 GeV/c

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ABSTRACT

In a high statistics (90 events/ μb) bubble chamber experiment, the reactions $\pi^- p \rightarrow K_S^0 K^{\pm} \pi^{\mp} n$ have been studied at 3.95 GeV/c. A significant enhancement is observed in the $(K\bar{K}\pi)$ system which we attribute to the production of the E(1420) meson. For its mass, M , and width, Γ , we find: $M = 1426 \pm 6$ MeV and $\Gamma = 40 \pm 15$ MeV. The E(1420) quantum numbers are determined to be $I^G J^P = 0^+ 1^+$ with a branching ratio $E \rightarrow K \bar{K}^* + \text{c.c.}/E \rightarrow [\delta\pi + (K \bar{K}^* + \text{c.c.})] = .86 \pm .12$, where $\delta \rightarrow K\bar{K}$. The cross section for the reaction $\pi^- p \rightarrow En$, with $E \rightarrow K^0 K^{\pm} \pi^{\mp}$, is $(8.2 \pm 1.0)\mu\text{b}$. Forward and backward productions are observed in the approximate ratio 2:1. The SU(3) assignment of the E(1420) meson is discussed.

Submitted to Nuclear Physics B

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(**) Work supported by the Swedish Natural Science Research Council.

1. INTRODUCTION

In the Particle Data Group tables (PDG) [1], the E(1420) meson is considered not to be well established. The reason being that since it was observed decaying into $K_S^0 K^\pm \pi^\mp$ in $\bar{p}p$ annihilations at rest [2] no other statistically satisfying confirmation has been obtained. Subsequent analysis [3] of the $\bar{p}p$ experiment indicated the E(1420) isospin to be 0 while the observation of the decay mode $K_1^0 K_1^0 \pi^0$ established its charge conjugation to be $C = +1$ and therefore $I^G = 0^+$. In the same analysis a determination of the spin parity resulted in a preference of the $J^P = 0^-$ versus the 1^+ assignment.

With poorer statistical significance, the E(1420) meson has also been observed in $\pi^- p$ interactions [4] and in $\bar{p}p$ annihilations at 0.7 and 0.76 GeV/c [5,6]. These experiments, while agreeing with the $I^G = 0^+$ determination, prefer a $J^P = 1^+$ assignment when able to do a spin-parity analysis [4,5,7].

As a result of these conflicting J^P assignments, the E meson has been accepted not only as the companion isosinglet to the well-established D(1285) meson in the 1^{++} SU(3) nonet, but has also been considered [8] to be a more natural member of the pseudoscalar nonet than the $\eta'(958)$. More recently it has been proposed [9] that it could well be a member of a new pseudoscalar nonet having as other members the newly suggested $K'(1400)$ [10] and $\eta'(1260)$ [11] resonances. The pseudoscalar assignment would also be attractive from the point of view of models proposing the existence of four quark states [12].

In this paper we analyze the properties of the E meson after presenting the evidence for its production in $\pi^- p$ interactions at 3.95 GeV/c.

The following reactions have been investigated:

$$\pi^- p \rightarrow K_S^0 K^+ \pi^- n \quad 1652 (1797) \text{ events} \quad (1a)$$

$$\pi^- p \rightarrow K_S^0 K^- \pi^+ n \quad 1520 (1650) \text{ events} \quad (1b)$$

with the decay $K_S^0 \rightarrow \pi^+ \pi^-$ seen.

The two numbers given for each reaction refer to the events observed after applying the selection criteria described later and, in brackets, to those obtained after weighting them to correct for decay losses.

The plan of the paper is the following. The description of the data used is presented in sect. 2. The evidence for the E(1420) meson and its decay Dalitz plot are shown and discussed in sect. 3. The determination of the E(1420) quantum numbers, mass and width, branching ratios and production cross section are the object of sect. 4. After a brief comment on the E production characteristics in sect. 5, we discuss in sect. 6 some SU(3) implications of our results. The conclusions of the paper are summarized in sect. 7.

2. EXPERIMENTAL PROCEDURES

The data come from an analysis of a series of exposures of the CERN 2m hydrogen bubble chamber to π^- beams of 3.95 GeV/c average momentum. The total sensitivity is around 90 events/ μ b. The general details of the experiments are given in ref. [13].

We recall here that, in order to ensure good scanning and measurability conditions, a limited fiducial region was imposed. To take into account scanning biases, only K^0 's with a projected decay length of more than 3 mm were kept for further analysis. Appropriate weights corrected both for the events thus lost and for those escaping the selected fiducial volume; the average K^0 weight being ~ 1.09 .

The reactions under study having an undetected neutron (1C reactions) are affected by kinematical ambiguities with other 1C reactions or with each other, if the two charged secondaries have high momentum. With a loose probability acceptance criterion, 1%, $\sim 70\%$ of the accepted events give ambiguous fits after estimates of track ionization have been used. Nevertheless it is worth mentioning that an important fraction of the ambiguities arises from the very low probability level at which kinematical hypotheses are initially accepted. This because stricter criteria can only be safely established after a critical evaluation of the ambiguities.

The nature of these and the procedures used to resolve them are described now.

In each final state $\sim 35\%$ of the events are ambiguous with the reaction $\pi^- p \rightarrow \pi^+ \pi^- K_S^0 \Lambda$ and $\sim 10\%$ with $\pi^- p \rightarrow \pi^+ \pi^- K_S^0 \Sigma^0$ when the Λ decay is not seen.

The study and comparison of the missing mass, pulls and probability distributions obtained for the two fits have shown that accepting events with a χ^2 fit probability greater than 6% for the hypothesis $K_S^0 K^\pm \pi^\mp n$ leads to a good resolution of the Λ/Σ^0 ambiguities. 85% of these ambiguous events are thus assigned to the neutron hypothesis with a contamination estimated to be $\leq 6\%$.

The good quality of this separation has been verified a posteriori by checking that the number of events attributed to these Λ/Σ^0 channels agree well with those expected from the independently studied $\pi^- p \rightarrow \pi^+ \pi^- K_S^0 \Lambda/\Sigma^0$ reactions in which both the K_S^0 and Λ were observed to decay.

Around 10% of the events fitting reaction (1a) are ambiguous with the hypothesis $\pi^- p \rightarrow \pi^- K_S^0 K^0 p$. A study analogous to that just mentioned has led to the conclusion that about half of these events belong to the neutron hypothesis the separation being obtained with the highest probability criterion. The estimated wrong assignment of events is less than 5%.

Again the number of events attributed to the proton hypothesis agree well with those deduced from that obtained in the $\pi^- K_S^0 K_S^0 p$ final state when the two $K^0 \rightarrow \pi^+ \pi^-$ decays are seen.

A final important ambiguity affecting $\sim 20\%$ of the events is that between the two reactions (1a) and (1b). The best discriminatory criterion we have found consists in comparing the probabilities of the two hypotheses. In $\sim 65\%$ of the cases the ratio of probabilities was greater than 5 and thus a reliable separation could be obtained. In the remaining 35% of the sample this ratio was not far from one. The best separation of the hypotheses corresponds to the one based on the highest probability choice.

Any possible important effect on the final results of the small residual contaminations has been carefully studied. None has been found.

Finally the missing mass squared spectra for the selected samples are shown in figs 1(a) and 1(b). The two distributions are symmetrical, well centred at the neutron mass and their widths agree with the average experimental resolution, showing the good quality of our selection.

The cross sections obtained after correcting for the K^0 unseen decay modes are $(67 \pm 5)\mu\text{b}$ and $(62 \pm 4)\mu\text{b}$ for $\pi^- p \rightarrow K^0 K^+ \pi^- n$ and $K^0 K^- \pi^+ n$, respectively.

3. OBSERVATION OF THE E(1420) MESON

The evidence for the E(1420) meson is shown in figs 2(a), 2(b) and 2(c) which display the mass spectra of the $K_S^0 K^+ \pi^-$ (2(a)), $K_S^0 K^- \pi^+$ (2(b)) and combined $K_S^0 K^\pm \pi^\mp$ (2(c)) systems.

In addition to the well-established D(1285) meson, a sharp peak is seen centred at around 1430 MeV. We will assume that it is a manifestation of the E(1420) meson.

Other main features of both final states are: production of $K^*(890)$, $\bar{K}^*(890)$, $\Delta^+(1232)$, $A_2^\pm(1310)$ and a shoulder at the threshold of the $K^\pm K_S^0$ mass. In reaction (1a) production of $\Lambda(1520)$, partially associated to $K^*(890)$, is also observed. Reaction (1b) presents an accumulation of events at the $K^- n$ threshold whose nature is under study.

Although, as we will soon show events in the E(1420) peak are strongly correlated with $K^*(890)$ and $\bar{K}^*(890)$ production and with the $K^\pm K_S^0$ threshold effect, their overlap with other resonances is very small.

Since the E meson shows up with similar characteristics in the two reactions we will from now on consider the events from both of them together.

The Chew-Low plot does not show a very distinctive t dependence for events in the peak and the background and therefore, at this stage, there is no suitable t cut to improve the signal over background ratio.

The decay Dalitz plot and the $K_S^0 \pi^\pm$, $K^\pm \pi^\mp$ and $K_S^0 K^\pm$ mass squared spectra for events in the region $1.39 \leq M(K\bar{K}\pi) \leq 1.47$ GeV are given in figs 3(a) and 3(b). The Dalitz plot is not uniformly populated and shows clear evidence for the production of $K^*(890)$'s. The $M^2(K\bar{K})$ of fig. 3(b) indicates an enhancement near the threshold. It could be due either to a constructive interference between the $K^*(890)$'s or to the decay $E \rightarrow \delta(980)\pi$, where $\delta \rightarrow K\bar{K}$, or a combination of the two effects. This question is examined in detail in sect. 4.2.

4. E(1420) MESON QUANTUM NUMBERS DETERMINATION

4.1 Isospin

Our evidence, favouring the generally accepted isospin zero assignment, comes from the non-observation of a charged ($K\bar{K}\pi$) mode in the reactions

$$\pi^- p \rightarrow K_S^0 K^- \pi^0 p \quad 1283 \text{ (1392) events,} \quad (2a)$$

$$\pi^- p \rightarrow K_S^0 \pi^- (K^0) p \quad 1363 \text{ (1477) events,} \quad (2b)$$

where (K^0) denotes that the decay was not seen.

Figs 4(a) and 4(b) show the ($K\bar{K}\pi$) mass spectra for these reactions; neither exhibit an enhancement in the E(1420) mass region.

Although the production mechanism of the E(1420) meson is not known, it appears reasonable to assume that in the forward direction the reaction $\pi^- p \rightarrow E^0 n$ is dominated by t channel exchange mechanisms, hence by $I = 1$ meson exchange. We can predict the number of forward events expected from $I = 1$ exchange in reactions (2a) and 2(b) assuming $I = 1$ or $I = 2$ for the E(1420) meson according to different decay hypotheses. Table 1 gives these numbers.

In the table we give also the upper limits (at the 95% of confidence level) to the numbers of E^- that can be determined from a fit to the $(K\bar{K}\pi)^-$ mass histograms in the forward hemisphere (not shown). Their comparison with the numbers expected clearly rules out the $I = 1$ and $I = 2$ hypotheses.

4.2 J^{PC} and branching ratios

In the present experiment the final state $K^0\bar{K}^0\pi^0n$ is not accessible, therefore we cannot determine directly the charge conjugation of the E effect. This determination will be obtained nevertheless through the spin-parity analysis we proceed to describe.

The available statistics permit only a simplified mass independent partial wave analysis. We use the method described in detail in ref. [14]. The analysis involves maximum likelihood fits to the Dalitz plots for successive $K\bar{K}\pi$ mass slices. For the decay amplitudes, in the spirit of the non-unitary isobar model, the $K\bar{K}\pi$ system will be composed of quasi two-body amplitudes constructed using the Zemach representation [15]. We have introduced, as possible decay modes for the $E(1420)$ meson, the $K^*\bar{K} + c.c.$ and the $\delta(980)\pi$ ones, with $\delta \rightarrow K\bar{K}$.

Therefore the two-body isobars included in the fit were the $K^*(890)$, represented by a p wave relativistic Breit Wigner function, with mass and width fixed at the Particle Data Group values, and the $\delta(980)$. For the $\delta(980)$ two representations have been tried: a scattering length of 2.5 fm [1] and a coupled channel parametrization [16] with the parameters of ref. [17] i.e. $M_\delta = 981$ MeV, $\Gamma_\delta = 55$ MeV. The latter was our final choice but the results do not depend on it.

From the fit we get simultaneously the spin parity and the branching ratios.

The analysis was limited to $K\bar{K}\pi$ masses below 1.63 GeV because at higher values the $\Delta^\pm(1232)$ and $\Lambda(1520)$ reflections become important and high J^P waves are needed. These facts would require more amplitudes without adding information about the $E(1420)$ region.

The J^P analysis has been performed in the following four $K\bar{K}\pi$ mass regions:

1.31 - 1.39 GeV: "first control region",

1.39 - 1.47 GeV: "E meson region",

1.47 - 1.55 GeV: "second control region",

1.55 - 1.63 GeV: "third control region".

When adding the two reactions (1a) and (1b) to get better statistics for the J^P analysis, we have two possibilities: either we consider together $K^*\bar{K}$ and $\bar{K}^*K$ [i.e. $(K^+\pi^-$ and $K^0\pi^+)$ and $(\bar{K}^0\pi^-$ and $K^-\pi^+)$] or K^* charged K and K^* neutral K ; [i.e. $(K^0\pi^+$ and $K^0\pi^-)$ and $(K^+\pi^-$ and $K^-\pi^+)$]. Based on the observation of a different amount of K_{ch}^* and K_{ne}^* production, we chose the second procedure in order to increase the difference between background and resonant events. In fact G parity eigenstates have a Dalitz plot population symmetrical in all the $K\pi$ mass combinations while different K_{ch}^* and K_{ne}^* production can be expected for the background events. Nevertheless, we have checked that the final results of the J^P analysis do not depend on the choice made.

We started from a simple set of waves of definite J^P and G parity with $L \leq 2$; L being the angular momentum between the isobar and the remaining particle. The amplitude was

$$\begin{aligned} \text{COH (coherent waves)} &= \delta\pi[0^-; 1^+; 2^-] + \\ &+ (K_{ch}^*K + G K_{ne}^*K) [0^-; 1^+S, D; 1^-; 2^-; 2^+]. \end{aligned} \quad (3)$$

The interference between K_{ch}^*K and K_{ne}^*K is fixed by C parity: constructive ($G = +1$) for $C = +1$; destructive ($G = -1$) for $C = -1$.

The interference between $[K_{ch}^*K + G K_{ne}^*K]$ and $\delta\pi$ waves of the same spin parity were left free in the fit. K_{ch}^*K 's (K_{ne}^*K 's) are functional forms depending on the assumed spin and parity. The explicit expressions are given in table 2. To take into account the incoherent K_{ch}^*K and K_{ne}^*K production, coming from the background, we added incoherently K_{ch}^*K and K_{ne}^*K waves. That this is needed is qualitatively visible in figs 3(a) and 3(b) where the K_{ch}^*K appears to be more strongly produced than the K_{ne}^*K in the E region.

All the incoherent waves up to $L = 2$ which gave an important increase to the likelihood were added to the set. Only 1^+S and 1^-P , both K_{ch}^*K and K_{ne}^*K , were found to do so. The following incoherent amplitude was finally added to eq. (3):

$$\begin{aligned} \text{INC (incoherent waves)} = & K_{ch}^* K[1^+S] + K_{ne}^* K[1^+S] + K_{ch}^* K[1^-P] + \\ & + K_{ne}^* K[1^-P] + \text{phase space } (K\bar{K}\pi), \end{aligned} \quad (4)$$

where only the fraction of each wave has been fitted. So that the following final amplitude was fitted

$$A = \text{COH} + \text{INC} \quad (5)$$

with COH and INC given by eqs (3) and (4) respectively.

Two kinds of fits have been performed according to the C parity hypothesis.

4.2.1 C = +1: constructive interference between K^* 's

The final result of this fit (fit (a)) is shown in fig. 5, where only the contributing waves have been plotted.

The 1^+S solution is strongly favoured since only the 1^+ coherent wave shows a deviation from a smooth behaviour and it does so in the E mass region. We tested the uniqueness of the solution by varying the intervals width and playing with different starting values of the parameters. For a quantitative estimate we performed other fits, only in the E region, in which we eliminated alternatively the 0^- coherent wave (fit (b)) and the 1^+S coherent one (fit (c)). We can compute L_{ab} and L_{ac} as the differences in log likelihood, between the fit (a) and the fit (b) and (c) respectively in the E region. The theorem of likelihood ratios [18] implies that $2 L_{ab}$ [$2 L_{ac}$] is χ^2 distributed under the hypothesis $1^+S(0^-)$. In other words, we can give χ^2 probabilities for the 0^- and 1^+ solutions.

We obtain $P(\chi^2)_{1^+S} \sim 85\%$ and $P(\chi^2)_{0^-} \sim 1\%$ and thus our data prefer the 1^+S assignment. As a check we have tested that this solution represents well all possible one-dimensional distributions (figs 6(a) and 6(b)). The fact that the 0^- solution (not shown) reproduces almost equally well the different one-dimensional distributions, illustrates well the poor discriminatory power of analyses based on them only.

4.2.2 C = -1: destructive interference between K^* 's

The same fits with $C = -1$ give a much worse value of the likelihood function than that obtained in the previous 1^{++} fit. Moreover, neither the 1^{+-} nor the 0^{--} assignments reproduces well the experimental distributions. This is seen in figs 6(a) and 6(b) where only the 1^{++} (fit a) and the 1^{+-} (fit a') projections are shown; the 0^{--} being much worse than the 1^{+-} ones.

Therefore $C = +1$ is confirmed and our data favours the 1^{++} assignment for the J^{PC} of the E(1420) meson.

This result disagrees with that obtained in the $\bar{p}p$ at rest experiment [4] which preferred the $J^{PC} = 0^{-+}$ solution.

4.2.3 Branching ratios

Finally, as a result of the partial wave analysis, we obtain for the E(1420) meson the following branching ratio:

$$\frac{E \rightarrow K \bar{K}^* + \text{c.c.}}{E \rightarrow [(K \bar{K}^* + \text{c.c.}) + \delta\pi]} = .86 \pm .12, \quad (6)$$

where $\delta \rightarrow K\bar{K}$.

Thus in the $K\bar{K}\pi$ final state, the E meson would appear to be mostly due to the $K \bar{K}^* + \text{c.c.}$ decay with the $K\bar{K}$ threshold enhancement being the result of the constructive interference between $K \bar{K}^*$ and $\bar{K}^* K$.

In an attempt to find other possible decay modes and guided by the knowledge of the 4π decay of the D(1285) meson [19], we have studied the reaction $\pi^- p \rightarrow \pi^+ \pi^+ \pi^- \pi^- n$. The data come from the same experiment and correspond to a sensitivity of ~ 15 events/ μb . More experimental details can be found in ref. [20], where the difficulties in observing the $D^0 \rightarrow 4\pi$ decay over a large $f^0 \rightarrow 4\pi$ background are pointed out. We derive an upper limit of

$$\frac{E \rightarrow 4\pi}{E \rightarrow K \bar{K}^* + \text{c.c.}} < .90$$

with 95% confidence level.

4.3 Mass and width

The E(1420) meson is produced over a large and fast rising background. We have tried to determine it using a multichannel likelihood analysis which gives in particular the reflections on the $K\bar{K}\pi$ mass distribution of resonances occurring in other mass combinations. In this attempt we have failed to reproduce the high $K\bar{K}\pi$ mass region, around 1700 MeV, which may indicate that decays difficult to establish, like $g \rightarrow K\bar{K}\pi$, may also be feeding the same final state. This problem, together with the fact that the E lies ~ 40 MeV above the K^*K nominal threshold, makes it difficult to determine its mass and width from the complete $K\bar{K}\pi$ sample.

To improve the signal over background ratio we can take advantage of the $K^*K + c.c.$ dominant decay mode. This is done by considering only the events with a $K\pi$ mass combination in the $K^*(890)$ region and $\cos\theta_{K^*}$ bigger than .5; θ_{K^*} being the polar decay angle in the s channel helicity frame. In the E mass region this $\cos\theta_{K^*}$ cut is equivalent to selecting events preferentially in the K^* 's interference region.

The result of this selection is shown in fig. 7: the signal shows up quite nicely over a very small background.

The parametrization of a resonance which not only occurs close to the two-particles decay threshold, but also goes through a quasi two-body decay mode is not straightforward. In fact, in the usual two-body decay amplitude [21] the width Γ varies with mass roughly as

$$\Gamma(M, M_0) \simeq \Gamma_0 \left(\frac{q}{q_0} \right)^{2\ell + 1},$$

ℓ being the orbital angular momentum and q the momentum available in a normal two-body decay. It is clear that in a quasi two-body decay the q of the decay isobar (the K^* in our case) is no longer precisely defined; furthermore, because of the finite K^* width, neither is the K^*K threshold well defined and the q momentum available in a normal two-body amplitude may become unphysical ($q^2 \leq 0$).

To solve this problem we have chosen the solution that consists in assuming that the energy dependence of Γ is proportional to the integral of the decay matrix element over the available area of the Dalitz plot for each $K\bar{K}\pi$ mass value. Our prescription for the S orbital angular momentum case is

$$\Gamma_E(M_{K\bar{K}\pi}; M_E) = \Gamma_0 \frac{\int_{\text{Dalitz plot } (M_{K\bar{K}\pi})} D_{K^*}^2 d\phi}{\int_{\text{Dalitz plot } (M_E)} D_{K^*}^2 d\phi} \quad (7)$$

with

$$D_{K^*} = |BW_{K_{12}^*} \vec{t}_3 + BW_{K_{13}^*} \vec{t}_2|, \quad (8)$$

where $BW_{K_{ij}^*}$ are the usual wave relativistic Breit Wigner functions [21] with the K^* mass and width fixed at the Particle Data Group values and $\vec{t}_i$ are the Zemach vectors describing the spin 1 content; they are given in table 2.

The final amplitude chosen to fit the mass and width was

$$B[E \rightarrow 1^+ S(K^* \bar{K} + \text{c.c.})] = BW_E \cdot D_{K^*} \quad (9)$$

with

$$BW_E = \frac{1}{(M_E^2 - M_{K\bar{K}\pi}^2) - iM_E \Gamma_E}, \quad (10)$$

where for Γ_E and D_{K^*} we use eq. (7) and (8) respectively and M_E, Γ_0 are the parameters to be fitted.

With this amplitude the multidimensional likelihood fit on the cut data has been performed to get the mass and width values. In this way the effects that the K^* and the $\cos\theta_{K^*}$ cuts might introduce in the background are safely taken into account. The full curve in fig. 7 shows the projection of this fit on the $K\bar{K}\pi$ mass histogram while the dotted line represents the background contribution.

The following values are obtained:

$$M_E = 1426 \pm 6 \text{ MeV} ; \quad \Gamma_E = 40 \pm 15 \text{ MeV} ,$$

where the errors are statistical only. The experimental mass resolution (8 MeV FWHM) for $M(K\bar{K}\pi) < 1.63 \text{ GeV}$ has not been folded in.

To calculate the production cross section, we have to correct for the K^* selection and for the $\cos\theta_{K^*}$ cut. This has been estimated by generating Monte-Carlo events with and without the selections.

The production cross section for the process $\pi^- p \rightarrow E n$ with $E \rightarrow K^0 K^\pm \pi^\mp$, turns out to be $(8.2 \pm 1.0) \mu\text{b}$. To go from $\sigma_E(K^0 K^\pm \pi^\mp)$ to $\sigma_E(K\bar{K}\pi)$ we multiply by a factor 1.5 to correct for the other undetected $(K\bar{K}\pi)$ decay modes using the isospin and G parity of the E : $I^G = 0^+$.

We obtain $\sigma_E(K\bar{K}\pi) = (12.3 \pm 1.5) \mu\text{b}$.

We have also fitted the uncut data in the D(1285) region, where the background is small, with a relativistic three-body Breit Wigner and a polynomial background. We get

$$M_D = 1283 \pm 3 \text{ MeV} ; \quad \Gamma_D = 29 \pm 10 \text{ MeV}$$

in good agreement with the PDG values [1]. For the cross section we get $\sigma_D(K^0 K^\pm \pi^\mp) = (3.9 \pm .4) \mu\text{b}$ and $\sigma_D(K\bar{K}\pi) = (5.8 \pm .6) \mu\text{b}$.

5. PRODUCTION PROPERTIES

To study the production angular distribution of the E(1420) meson we have used only the sample restricted by the K^* and $\cos\theta_{K^*}$ cuts. The Chew-Low plot for these events is given in fig. 8; whereas a peak can be seen in the forward direction, the distribution in the backward hemisphere appears to be fairly uniform. The slope of the differential cross section in the forward hemisphere is $b = .9 \pm .4 \text{ GeV}^{-2}$ and the ratio between forward and total cross sections is found to be $.7 \pm .2$.

It is worth mentioning that the backward production of others axial vector mesons (A_1 , B, C/Q_1 , D) has recently been observed in a $K^- p$ experiment at 4.2 GeV/c [22,23,24,19].

6. SU(3) IMPLICATIONS

Having established the E(1420) meson as a good candidate for the missing isosinglet of the SU(3) 1^{++} nonet, it is natural to relate its decay properties to those of the other known axial vector mesons both in the $J^{PC} = 1^{++}$ (A_1 , C/Q_1 , D) and 1^{+-} (B , Q_2) multiplets using SU(3).

We have done this with the SU(3) scheme already used in previous attempts [25,26,27] and which allows mixing of the strange members of the two multiplets.

Complete details of the method can be found in ref. [27]. Here we just recall that it relates the S wave decay parameters of the axial vector mesons decaying into a vector and a pseudoscalar particles. The partial decay widths, Γ_i , are assumed to be related to the reduced coupling, γ_i , obeying exact SU(3) symmetry, by the formula

$$\Gamma_i = \frac{\langle q_i \rangle}{M_i^2} \gamma_i^2 \quad (11)$$

with $\langle q_i \rangle$, the phase space factor, defined by

$$\langle q_i \rangle = \frac{\int dm q_i(m, M_i) BW_V(m)}{\int dm BW_V(m)} \quad (12)$$

Here the integral in the numerator is over all values of m which allow physical momenta i.e. $q_i^2(m, M_i) \geq 0$, while that in the denominator is over the whole undistorted Breit-Wigner shape (BW_V) of the daughter vector meson resonance [27].

The data used as input are shown in table 3; they are: the ACNO results [22,23] on backward produced A_1 and C/Q_1 , the SLAC information [28] on the diffractively produced Q_2 and the results on the E(1420) meson presented in this paper.

For the partial width $\Gamma(E \rightarrow K^* \bar{K} + c.c.)$ we cannot simply use eq. (6) since there only the decay $\delta \rightarrow K \bar{K}$ has been taken into account. We have calculated the branching ratio $R = \delta \rightarrow KK / \delta \rightarrow \eta\pi$ using the published ACNO data [17] and obtained: $R = 0.24 \pm 0.07$. Then eq. (6) is replaced by

$$\frac{E \rightarrow K^* \bar{K} + c.c.}{E \rightarrow [\delta\pi + (K^* \bar{K} + c.c.)]} = 0.54 \pm 0.22 . \quad (13)$$

From this we obtain, as an upper limit, $\Gamma(E \rightarrow K^* \bar{K} + c.c.) \leq 22 \pm 8$ MeV, since other decay modes of the E(1420) meson may exist.

The experimental couplings have been then fitted to their SU(3) expressions (table 4). These are function of 4 parameters: g_A and g_B , which describe, respectively, the antisymmetric and symmetric octet coupling for axial vector + pseudoscalar decay; θ_Q is the mixing angle of the C/Q_1 and Q_2 mesons and θ_A the octet-singlet mixing angle of the 1^{++} isosinglets. To our knowledge, this is the first time that an attempt is made to determine θ_A .

The results of least-square fits (fits 1 and 2) are given in table 5. They are compatible with those obtained in ref. [27] and constitute a satisfactory interpretation of the data in terms of the SU(3) mixing scheme. The value obtained for the octet-singlet mixing angle is $\theta_A \geq 67^\circ \pm 6^\circ$; this being only a lower limit since only an upper limit can be determined for the partial width $\Gamma(E \rightarrow K^* \bar{K} + c.c.)$.

We have made other fits (fits 3 and 4) imposing as an additional constraint the Gell-Mann-Okubo mass formula

$$\cos^2 \theta_A = \frac{4Q_A^2 - 3D^2 - A_1^2}{3(E^2 - D^2)} , \quad (14)$$

where the particles names stand for their masses.

The fits become worse and show therefore an unpleasant incompatibility between the mass formula and the SU(3) constraints on the resonance widths. It has to be emphasized, however, that we have assumed that the masses, determined experimentally from Breit-Wigner fits, are not far from the pole positions. This may be a bad approximation for broad resonances like the A_1 and the Q 's and may thus be the reason for the observed discrepancy.

Magic mixing of the E and D mesons with the E being ϕ -like would correspond [29] to $\theta_A = 35^\circ$. The result of the best fit gives $\theta_A \geq 67^\circ \pm 6^\circ$ and indicates that the E meson is not made of strange quarks only. This conclusion is reinforced by the observation of a large production cross section in $\pi^- p$ reactions which would otherwise be in contradiction with the Zweig rule.

7. CONCLUSIONS

From a high statistics experiment we have observed a significant $K_S^0 K^{\pm} \pi^{\mp}$ enhancement which we attribute to the production of the E(1420) meson in $3.95 \text{ GeV}/c \pi^- p$ interactions.

The I^G quantum numbers are confirmed to be 0^+ .

A mass independent partial wave analysis of the $K\bar{K}\pi$ decay Dalitz plots strongly favours the 1^+ assignment for the spin parity.

The mass and width are $1426 \pm 6 \text{ MeV}$ and $40 \pm 15 \text{ MeV}$, respectively, with a production cross section for the process $\pi^- p \rightarrow E n$; $E \rightarrow K^0 K^{\pm} \pi^{\mp}$ of $(8.2 \pm 1.0) \mu\text{b}$.

The following decay branching ratio is obtained:

$$\frac{E \rightarrow K^* \bar{K} + \text{c.c.}}{E \rightarrow [(K^* \bar{K} + \text{c.c.}) + \delta\pi]} = .86 \pm .12 ,$$

where $\delta \rightarrow K\bar{K}$, as well as an upper limit of

$$\frac{E \rightarrow 4\pi}{E \rightarrow K^* \bar{K} + \text{c.c.}} < .90$$

with 95% of confidence level.

In the production mechanism of the E we find evidence both for forward and backward productions in the ratio 2:1.

Combining the available information on A_1 , C/Q_1 , Q_2 and that provided in this paper on the E(1420) meson, we have used an SU(3) scheme to determine the parameters characterising the decays of axial vector mesons into a pair of vector and pseudoscalar particles. Although a satisfactory fit is obtained for the resonance widths with in particular a D-E mixing angle $\theta_A \geq 67^\circ \pm 6^\circ$, we find the Gell-Mann-Okubo mass formula to disagree with this value of θ_A . The deviation of this value from that expected from "magic" mixing ($\theta_A = 35^\circ$) may be explained if the E-meson is not a pure $(s\bar{s})$ state. This conjecture is supported by the relatively large production cross section observed in our experiment.

Acknowledgements:

We wish to thank Prof. J.D. Jackson for fruitful discussions. We also wish to thank the operating crews at the CERN Proton Synchrotron and the 2 m hydrogen bubble chamber and the designers and constructors of the beam. We are also indebted to the scanning, measuring and computing staffs at our laboratories.

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TABLE CAPTIONS

Table 1 Predicted numbers of E^0 events if $I = 1, 2$.

Table 2 E^0 decay amplitudes for $K_{ch}^* K + K_{ne}^* K$ and $\delta(980)\pi$ modes.

Table 3 Data on C/Q_1 , Q_2 , A_1 and E used in the $SU(3)$ analysis.

Table 4 $SU(3)$ expressions.

Table 5 The results of the $SU(3)$ fits.

TABLE 1

		$K_S^0 K^{\pm} \pi^{\mp} n$	$K_S^0 K^{\mp} \pi^0 p$	$K_S^0 (K^0) \pi^{\mp} p$
	Observed ^(a)	152 ± 25	< 10	< 14
Predictions for $I = 1$	Expected if 100% $K^* K$		38 ± 7	53 ± 10
	Expected 100% $(K\bar{K})\pi$ with $I_G^{\pm} = 1^-$ for $K\bar{K}$		38 ± 7	13 ± 2
	Expected if 100% $(K\bar{K})\pi$ with $I_G^{\pm} = 1^+$ for $K\bar{K}$		38 ± 7	38 ± 7
Predictions for $I = 2$	Expected if 100% $(K\bar{K})\pi$ with $I_G^{\pm} = 1^-$ for $K\bar{K}$		342 ± 56	342 ± 56
	Expected if 100% $(K\bar{K})\pi$ with $I_G^{\pm} = 1^+$ for $K\bar{K}$		342 ± 56	114 ± 19

(a) in the forward direction.

TABLE 2

		Amplitudes	
J^P	Decay modes	Coup.Ch. (δ) (a)	$E \rightarrow \pi_1^+ K_2^- K S_3$
0^-	$\delta \pi$		$\vec{t}_i$ is the vector part (in E c.m.) of
	$K^* K$	$BW(K_{12}) \vec{t}_3 \cdot \vec{P}_3 + G BW(K_{13}) \vec{t}_2 \cdot \vec{P}_2$	$P_j^\mu - P_k^\mu - \left[\frac{m_j^2 - m_k^2}{m_{jk}^2} \right] [P_j^\mu + P_k^\mu]$
1^+	$K^* K$	$BW(K_{12}) \vec{t}_3 + G BW(K_{13}) \vec{t}_2$	$\vec{P}_i$ ($i = 1, 2, 3$) are the vector parts of the three decaying particle 4-momenta in the E c.m. system $G = \pm 1$
	$\delta \pi$	Coup.Ch. (δ) $\vec{P}_1$	
	$K^* K$	$BW(K_{12}) \left[\vec{P}_3 \cdot (\vec{t}_3 \cdot \vec{P}_3) - \frac{1}{3} (\vec{P}_3 \cdot \vec{P}_3) \vec{t}_3 \right] + G BW(K_{13}) \left[\vec{P}_2 \cdot (\vec{t}_2 \cdot \vec{P}_2) - \frac{1}{3} (\vec{P}_2 \cdot \vec{P}_2) \vec{t}_2 \right]$	
1^-	$K^* K$	$BW(K_{12}) (\vec{t}_3 \times \vec{P}_3) + G BW(K_{13}) (\vec{t}_2 \times \vec{P}_2)$	
2^-	$K^* K$	$BW(K_{12}) \left[\frac{1}{2} (\vec{t}_3 \cdot \vec{P}_3^j + P_3^j \cdot \vec{t}_3^j) - \frac{1}{3} (\vec{t}_3 \cdot \vec{P}_3) \delta^{ij} \right] + G BW(K_{13}) \left[\frac{1}{2} (\vec{t}_2 \cdot \vec{P}_2^j + P_2^j \cdot \vec{t}_2^j) - \frac{1}{3} (\vec{t}_2 \cdot \vec{P}_2) \delta^{ij} \right]$	
	$\delta \pi$	Coup.Ch. (δ) $\left[P_1^i P_1^j - \frac{1}{3} \vec{P}_1 ^2 \delta^{ij} \right]$	
2^+	$K^* K$	$BW(K_{12}) \left\{ \frac{1}{2} \left[(\vec{t}_3 \times \vec{P}_3)^i P_3^j + P_3^i (\vec{t}_3 \times \vec{P}_3)^j \right] - \frac{1}{3} \left[(\vec{t}_3 \times \vec{P}_3) \cdot \vec{P}_3 \right] \delta^{ij} \right\} + G BW(K_{13}) \left\{ \frac{1}{2} \left[(\vec{t}_2 \times \vec{P}_2)^i P_2^j + P_2^i (\vec{t}_2 \times \vec{P}_2)^j \right] - \frac{1}{3} \left[(\vec{t}_2 \times \vec{P}_2) \cdot \vec{P}_2 \right] \delta^{ij} \right\}$	

(a) Coup. Ch(δ): coupled channel amplitude of the δ meson [16].

TABLE 3

Resonance	Experiment	Mass (MeV)	Γ_{tot} (MeV)	$\Gamma_{\rho K}$ (MeV)	$\Gamma_{K^*\pi}$ (MeV)	$\Gamma_{\omega K}$ (MeV)	$\Gamma_{K\epsilon} + \Gamma_{K^*\pi}$ (MeV)	Γ_{K^*K} (MeV)
C/Q_1	ACNO	1275 ± 10	75 ± 15	57 ± 14	14 ± 11	4 ± 4		
Q_2	SLAC	$1404 \pm 3 \pm (\pm 10)$	$142 \pm 4 \pm (\pm 15)$	2 ± 1	117 ± 10	~ 0	23 ± 12	
A_1	ACNO	1040 ± 25	230 ± 50	$\Gamma_{\rho\pi} = \Gamma_{\text{tot}}$				
E	This experiment	1426 ± 6	40 ± 15					22 ± 8

TABLE 4

Couplings	SU(3) expressions
$\gamma(A_1 \Rightarrow \rho\pi)$	$\frac{1}{3} \sqrt{6} g_A$
$\gamma(Q_1 \Rightarrow \rho K)$	$\frac{1}{2} g_A \cos\theta_Q - 3 \sqrt{\frac{1}{20}} g_B \sin\theta_Q$
$\gamma(Q_1 \Rightarrow K^* \pi)$	$\frac{1}{2} g_A \cos\theta_Q + 3 \sqrt{\frac{1}{20}} g_B \sin\theta_Q$
$\gamma(Q_1 \Rightarrow \omega K)$	$\frac{1}{2} g_A \cos\theta_Q \sin\theta_V + \left[\sqrt{\frac{1}{20}} g_B \sin\theta_V + g_1 \cos\theta_V \right] \sin\theta_Q$
$\gamma(B \Rightarrow \phi\pi)^{(a)}$	$\frac{1}{\sqrt{5}} g_B \cos\theta_V + g_1 \sin\theta_V$
$\gamma(B \Rightarrow \omega\pi)$	$\frac{1}{\sqrt{5}} g_B \sin\theta_V - g_1 \cos\theta_V$
$\gamma(Q_2 \Rightarrow \rho K)$	$\frac{1}{2} g_A \sin\theta_Q + 3 \sqrt{\frac{1}{20}} g_B \cos\theta_Q$
$\gamma(Q_2 \Rightarrow K^* \pi)$	$\frac{1}{2} g_A \sin\theta_Q - 3 \sqrt{\frac{1}{20}} g_B \cos\theta_Q$
$\gamma(Q_2 \Rightarrow \omega K)$	$\frac{1}{2} g_A \sin\theta_Q \sin\theta_V - \left[\sqrt{\frac{1}{20}} g_B \sin\theta_V + g_1 \cos\theta_V \right] \cos\theta_Q$
$\gamma(E \rightarrow K^* \bar{K} + K^* K)$	$g_A \cos\theta_A$

$\theta_Q = Q_A - Q_B$ mixing angle

θ_V = vector meson mixing angle; we put $\theta_V = -31^\circ \pm 3^\circ$ see ref. [27]

$\theta_A = D - E$ mixing angle

(a) For exact OZI rule we have: $B \nrightarrow \phi\pi$ and hence $g_1 = -\frac{1}{\sqrt{5}} g_B \cot\theta_Q$

TABLE 5

	Input	g_A	g_B	θ_Q	θ_A	χ^2/ND
Fit 1	$A_1 + C/Q_1 + E$	1.19 ± 0.10	-0.83 ± 0.04	$27^\circ \pm 8^\circ$	$67^\circ \pm 6^\circ$	2.2/4
Fit 2	$A_1 + C/Q_1 + E + Q_2$	1.21 ± 0.10	-0.79 ± 0.04	$49^\circ \pm 3^\circ$	$67^\circ \pm 5^\circ$	13/4
Fit 3	$A_1 + C/Q_1 + E$ + Mass formula	0.97 ± 0.10	-0.83 ± 0.03	$25^\circ \pm 7^\circ$	$44^\circ \pm 7^\circ$	21/4
Fit 4	$A_1 + C/Q_1 + E + Q_2$ + Mass formula	1.15 ± 0.06	-0.80 ± 0.03	$51^\circ \pm 3^\circ$	$51^\circ \pm 5^\circ$	37/4

FIGURE CAPTIONS

- Fig. 1 (a) Missing mass squared for the selected $\pi^- p \rightarrow K_S^0 K^+ \pi^- n$ sample.
 (b) Missing mass squared for the selected $\pi^- p \rightarrow K_S^0 K^- \pi^+ n$ sample.
- Fig. 2 (a) $K^+ K_S^0 \pi^-$ mass distribution of the reaction $\pi^- p \rightarrow K_S^0 K^+ \pi^- n$.
 (b) $K^- K_S^0 \pi^+$ mass distribution of the reaction $\pi^- p \rightarrow K_S^0 K^- \pi^+ n$.
 (c) $K^\pm K_S^0 \pi^\mp$ mass distribution of the reactions $\pi^- p \rightarrow K_S^0 K^\pm \pi^\mp n$.
- Fig. 3 (a) Decay Dalitz plot for events in the mass region
 $1.39 \leq M(K\bar{K}\pi) \leq 1.47$ GeV.
 (b) $K_S^0 \pi^\pm$, $K^\pm \pi^\mp$, $K_S^0 K^\pm$ mass squared spectra in the same region.
- Fig. 4 (a) $K_S^0 K^- \pi^0$ mass distribution of the reaction $\pi^- p \rightarrow K_S^0 K^- \pi^0 p$.
 (b) $K_S^0 (K^0) \pi^-$ mass distribution of the reaction $\pi^- p \rightarrow K_S^0 (K^0) \pi^- p$.
- Fig. 5 Results of the partial wave analysis for the fit (a) described in the text.
- Fig. 6 (a) The same as in fig. 2(b). The curves show the projections of the partial wave solutions for the fits (a) and (a').
 (b) Polar decay angular distributions in the s-channel helicity frame. The curves show the results of fit (a) and (a').
- Fig. 7 $K^\pm K_S^0 \pi^\mp$ mass spectrum after the K^* and the $\cos\theta_{K^*}$ selections described in the text. The curves show the result of the mass and width fit described in the text.
- Fig. 8 Chew Low plot for the $K_S^0 K^\pm \pi^\mp$ system after the K^* and the $\cos\theta_{K^*}$ selection described in the text.

Fig. 1(a)

MM^2 GeV²

Fig. 1(b)

Fig. 2(a)

Fig. 2(b)

Fig. 2(c)

Fig. 3(a)

Fig. 3(b)

Fig. 4(a)

Fig. 4(b)

Fig. 5

Fig. 6(a)

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

Fig. 6(b)

Fig. 7

Fig. 8