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($KN\pi\pi\pi$) Final States in Interactions of 3.0 GeV/c K^+

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I. Introduction

In a 3.0 GeV/c K^+ exposure of the 80cm Saclay HBC at the CERN proton synchrotron, the following reactions were studied :

$$K^+p \rightarrow K^+p\pi^+\pi^-\pi^o \qquad (1)$$

$$\rightarrow K^o p\pi^+\pi^+\pi^- \qquad (2)$$

The cross-sections for these reactions are 0.8 mb., and 0.4 mb., respectively, where the decay corrections for reaction (2) have been taken into account. The samples measured, yielded 312 events of reaction (1), and 113 events of reaction (2) (in which the K^o decay was visible), identified and processed through the standard CERN analysis programmes. Each event was examined on the scanning table for compatibility of ionisation with the result of the fitting programme.

II. Investigation of Reaction $K^+p \rightarrow K^+p\pi^+\pi^-\pi^o$

From the study of this reaction, we appear to have strong production of $N^*(1238)$ in conjunction with the two charge states of $K^*(890)$,

$$\text{i.e. } K^+p \rightarrow K^{*o}N^{*++}\pi^o$$

$$\rightarrow K^{*+}N^{*++}\pi^-$$

In Fig.1, the mass distribution for $p\pi^+$ is shown, the shaded area representing those events in K^{*o} and the cross-hatched area representing events in K^{*+}, where the K^* band is defined as $0.86 \leq M(K\pi) \leq 0.94$ GeV. It may be seen that if one substracts the events which are produced with K^*, the remainder of the $p\pi^+$ spectrum is in agreement with phase space (Fig.2), and it may also be remarked that the shaded region of Fig.1 has the general form of the Breit-Wigner for the N^*. From these considerations we find that about half of the events in this reaction go through the formation of $N^*(1238)$.

Fig.3 shows the mass distribution for the $(K^+\pi^0)$ combination, where the shaded region represents events falling inside the N^* band, i.e. $1.15 \leqslant M(p\pi^+) \leqslant 1.3$ GeV. It may be clearly seen that there is production of $K^*(890)$, and that it is produced predominantly with the $N^*(1238)$. The solid line represents phase space for the $(K\pi)$ system in the $(K\pi\pi N^*)$ state, fitted to the shaded region, but neglecting the $K^*(890)$ events. A subtraction between this curve and the histogram should then leave the K^* events standing on a background distributed as $(K\pi)$ phase space from $(K\pi\pi p\pi)$ final state*. This subtraction procedure avoids the statistical uncertainty of each interval of the data. In Fig.4 where this subtraction has been performed, the K^* shows up clearly but there is also an accumulation of events around 730 MeV. If one associates this excess of events with the kappa, κ, meson, there are $\sim$12 events produced in this charge state.

In Fig.5 and 6 the combination $(K^+\pi^-)$ is treated similarly. The presence of $K^*(890)$, and the production together with the N^* are in evidence again, in Fig.5, while the excess of events around 730 MeV persists in the neutral charge state. Here, the excess is $\sim$10 events.

The effective mass of the three pions is plotted in Fig.7, where the solid line gives the shape of the phase space distribution. The production of $\sim$40 ω^0 events may be clearly seen. It should be noted that no production of a recoiling K^+p resonance system is observed in the ω^0 reactions. The ω^0 events have not been subtracted out of the $(K\pi)$ distributions discussed above, as they distribute themselves over the $K\pi$ spectrum in a manner consistent with phase space.

Thus, it has been seen that this five-body reaction proceeds through many channels, and by the production of many resonances. The production cross-section for the resonances, and the partial cross-sections for the various channels are given in Table I.

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* It has been noted in this experiment, and others, that the phase space distribution is little affected when one combines the K or π from K^*, or π from N^*, to form a $K\pi$ non-resonant system.

III. Investigation of Reaction $K^+p \rightarrow K^0 p\pi^+\pi^+\pi^-$, $K^0 \rightarrow \pi^+\pi^-$

For reaction (2) we observe that about half of the events proceed through the formation of $N^*(1238)$, with the predominant reaction channel being

$$K^+p \rightarrow K^{*+}N^{*++}\pi^- .$$

The effective mass plot for the $(p\pi^+)$ combinations is shown in Fig.8 where the solid line again gives the shape of the phase space distribution. The plot is consistent with the production of ~ 50 N^* events. (The shaded region represents events in the K^* band $(0.86 \leqslant M(K\pi) \leqslant 0.94$ GeV) analogous to the treatment in the analysis of reaction (1).) The mass distribution for the $(K^0\pi^+)$ combinations is shown in Fig.9, where the shaded area represents events falling in the N^* band, $1.15 \leqslant M(p\pi^+) \leqslant 1.3$ GeV. That is, for an event in which the $(p\pi^+_1)$ combination falls inside the N^* band, the mass of combinations $(K^0\pi^+_2)$ is shaded, and vice versa. This plot indicates that there is an appreciable production of $K^{*+}N^{*++}\pi^-$ states, where $K^{*++} \rightarrow K^0\pi^+_{1,2}$ and $N^{*++} \rightarrow p\pi^+_{2,1}$. As was done in analysis of $K\pi$ states in reaction (1), this shaded region was fitted to the phase space distribution taking into account the presence of N^*, and the subtraction performed (Fig.10). This shows clearly the production of $K^*(890)$, and also enhances the effect around 730 MeV.

To investigate further the $K\pi$ mass spectrum, we take the double $(K^0\pi^+_{1,2})$ combinations and subtract from it the $(K^0\pi^-)$ mass distribution. This latter distribution is T=3/2, and shows no deviations from phase space (Fig.11)*. The subtraction, shown in Fig.12, has therefore only one entry per event and the false $(K^0\pi^+)$ combination (which should be phase-space-like), has been removed. This distribution shows clearly the production of $K^*(890)$, and again accentuates the effect around 730 MeV. If this is associated with the κ, it implies the production of ~ 10 kappa events.

As in reaction (1), the final state discussed above involves the production of the N^* and K^* resonances. The partial cross-sections for each channel, together with the resonance production cross-section are given in Table II.

* This indicates that the enhancement has I-spin 1/2.

IV. Examination of 730 MeV Region

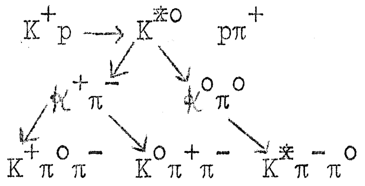
The effective mass distributions for the $K\pi$ states discussed above have shown systematically an excess of events in the region around 730 MeV, very near to the mass value assigned to the kappa meson. This resonance has been reported in $\pi^- p$ and $K^- p$ interactions at (1.51 - 2.36) GeV/c[1], and (1.0 - 1.7) GeV/c[2], respectively, but has never been regarded as well established. Again, in the $K^+ p$ interactions discussed here, identification of this state is made difficult by the shape of the phase space distribution which peaks just in this mass region. Below we attempt an examination of the enhancement around 730 MeV in the data presented above.

In Fig.13, the effective mass distribution for all of the T=1/2 ($K\pi$) combinations is shown. Fig.14 shows the spectrum for those events which belong to the positively charged system (i.e. $K^o\pi^+$ and $K^+\pi$). The solid line in Fig.13 represents the addition of the phase space distribution when the K^* is ignored, and a P-wave Breit-Wigner shape centred at 890 MeV and with a width of 50 MeV. This spectrum shows an effect of ~ 3-4 standard deviations, at 730 MeV.

Further enhancement may be obtained if the events produced in conjunction with N^* are removed (i.e. $K^+p \rightarrow KN^*\pi\pi$). As in the analysis described in Sections II and III above, this subtraction was performed by fitting an appropriate phase space to the events associated with the production of an N^*, neglecting the effect of the $K^*(890)$. This was done for all three charge states, $K^+\pi$, $K^o\pi^+$, $K^+\pi^o$ separately, and the combined histogram shown in Fig.15, where the curve is an attempted fitting of the 5-body phase space distribution to the background. It may be noted that the excess over background in both Fig.13 and 15 is ~40 events, indicating that this enhancement is not produced in conjunction with the N^*.

If we believe that this effect is indeed due to the kappa - K(730), then the branching ratio between the $K\pi^o$ and $K^o\pi^+$ channels may provide information on the I-spin of the κ, as the amplitudes may be predicted from the Clebech-Gordan coefficients. In Table III the branching ratios into these channels for the K^* (890) and κ(730) are given, together with the prediction for different isospin values. The data are in reasonable agreement with isospin 1/2, for both systems.

An additional interesting study may be made on these events. The decay of the $K^* \rightarrow \kappa + \pi$ is energetically possible and may be used to throw some light on the spin parity of the κ. If the κ's observed in the reaction above come from K^* decay, then we would expect them to be derived from the following reactions:



The parent K^* would be found in the following reactions :

$$K^+p \rightarrow K^+\pi^- \; p\pi^+ \qquad (3)$$

$$K^o\pi^o \; p\pi^+ \qquad (4)$$

From the total number of $K^*(890)$ found in reactions (3) and (4), one can place an upper limit of 0.06 on the ratio $\frac{K^* \rightarrow \kappa+\pi}{K^* \rightarrow K+\pi}$. By examining the mass spectrum of the $\kappa\pi$ combinations, the branching ratio may be further delimited by an order of magnitude (i.e. in the $\kappa\pi$ mass spectrum $\leq 1/10$ of the events are found in the K^* band, and each of these is assumed to be a real K^* despite the 'phase-space-like' shape of the spectrum). Thus, we arrive at a value for the ratio

$$R = \frac{K^* \rightarrow \kappa+\pi}{K^* \rightarrow K+\pi} \leq 0.006.$$

V. Conclusion

The five-body final states in the 3.0 GeV/c K^+ interactions appear to be an extremely rich field of resonance production. Among those produced, the $N^*(1238)$ is strongly in evidence, and the production of $K^*N^*\pi$ states is shown to be an important channel in both charge states of the K^*. The data also clearly shows an effect in the $K\pi$ mass spectrum around 730 MeV, which may be associated with the kappa meson.

A more complete treatment of these reactions (1) and (2), including information on the angular distributions for production and decay of the resonant states, and a study of the $K\pi\pi$ systems will be presented at the Conference.

References : (1) D.H. Miller et al, Physics Letters 5, 279 (1963)
(2) S. Wojcicki et al, Physics Letters 5, 283 (1963)

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Figure Captions

Fig.1 The mass spectrum of the $p\pi^+$ in reaction $K^+p \rightarrow K^+p\pi^+\pi^-\pi^o$. The shaded area represents events inside the K^{*o}, while the cross-hatched area represents events inside the K^{*+}, where the K^* band is defined as $(0.86 \leq M(K\pi) \leq 0.94$ GeV).

Fig.2 The $p\pi^+$ mass spectrum from reaction $K^+p \rightarrow K^+p\pi^+\pi^-\pi^o$, when events inside the K^{*o} and K^{*+} have been subtracted out. The solid line represents phase space distribution for the $K^*p\pi\pi$ state.

Fig.3 The $K^+\pi^o$ mass distribution for reaction $K^+p \rightarrow K^+p\pi^+\pi^-\pi^o$. The shaded area represents events in which an N^* is produced, where the N^* band is defined as $(1.15 \leq M(p\pi^o) \leq 1.3$ GeV). The solid line is the phase space distribution for $K\pi\pi N^*$ final state, fitted to the shaded area, neglecting the $K^*(890)$.

Fig.4 The $K^+\pi^o$ mass spectrum obtained after subtraction of the fitted phase space spectrum from the total $K^+\pi^o$ data. This spectrum shows clearly the production of $K^*(890)$, and indicates an effect around 730 MeV, in the $K\pi$ system.

Fig.5 The mass spectrum for $(K^+\pi^-)$ from the reaction $K^+p \rightarrow K^+p\pi^+\pi^-\pi^o$. The shaded area represents events in which an N^* is produced, where the N^* band is defined as $1.15 \leq M(p\pi) \leq 1.3$ GeV. The solid line is the phase space distribution for a $K\pi\pi N^*$ final state, fitted to the shaded area, neglecting the $K^*(890)$.

Fig.6 The $K^+\pi^-$ spectrum obtained from the subtraction of the fitted phase space spectrum from the data. This histogram shows the production of $K^*(890)$, and the presence of the enhancement around 730 MeV, in the neutral mode.

Fig.7 The effective mass distribution of $(\pi^+\pi^-\pi^o)$ from the reaction $K^+p \rightarrow K^+p\pi^+\pi^-\pi^o$. The solid line shows the expected shape of the distribution as given by phase space for 5-body final state. The figure clearly shows the production of ω^o events, at 780 MeV.

Fig.8 The $p\pi^+$ mass spectrum for the reaction $K^+p \rightarrow K^o p\pi^+\pi^+\pi^-$. Each event has two combinations entered on the distribution. The shaded area represents events in which $(K^o\pi^+_{1,2})$ are in a K^{*+}; that is the shaded area represents the corresponding $(p\pi^+_{2,1})$ combinations for that event. The solid line is an attempted fitting of the 5-body phase space shape, to the total data. The fitting shows that there is considerable productions of $N^*(1238)$.

Figure Captions (contd.)

Fig.9 The mass spectrum for the two $K^o\pi^+$ combinations from the reaction $K^+p \to K^o p\pi^+\pi^+\pi^-$. The shaded area represents events in which one of the π^+ is in an N^* with the proton : in this case the mass value of the combination of the K^o with the other π^+ is shaded. ($p\pi^+_{1,2}$ in N^* : shaded area represents $K^o\pi^+_{2,1}$.) The solid line is a fitting of the 4-body phase space ($K\pi\pi N^*$), to the shaded area, neglecting the $K^*(890)$ events.

Fig.10 The mass spectrum for ($K^o\pi^+$) obtained from the subtraction of the fitted phase space (to the events produced in conjunction with N^*), from the total data. The $K^*(890)$ is prominent, and an excess of events around 730 MeV is indicated.

Fig.11 The effective mass distribution for ($K^o\pi^-$) combinations from $K^+p \to K^o p\pi^+\pi^+\pi^-$ reactions. The solid line is the 5-body phase space shape, normalised to the total number of events.

Fig.12 The mass spectrum for $K^o\pi^+$, when the $K^o\pi^-$, or phase space, is subtracted from the ($K^o\pi^+_1 + K^o\pi^+_2$) spectrum. In this manner, the false $K^o\pi^+$ combination is removed, showing clearly the production of $K^*(890)$, and also enhancing the effect around 730 MeV.

Fig.13 The mass distribution for all the T=1/2, $K\pi$ combinations produced in the reactions $K^+p \to K^{o,+} p\pi^+\pi^-\pi^{+,o}$ (i.e. $K^o\pi^+$, $K^+\pi^o$, $K^+\pi^-$). The solid line is the sum of 5-body phase space (normalised at the wings), and a P-wane Breit-Wigner centred at 890 MeV, and with a width of 50 MeV. The distribution is in good agreement with the fit, except for the production of 40 events in mass region $0.70 \lesssim M(K\pi) \lesssim 0.75$ GeV.

Fig.14 The ($K\pi$) mass distribution, where only the positively charged combination is taken. The solid curve is the sum of 5-body phase space (normalised at the wings), and a P-wave Breit-Wigner centred at 890 MeV, and with a width of 50 MeV.

Fig.15 The ($K\pi$) mass spectrum obtained from the subtraction of ($K\pi\pi N^*$) phase space (fitted to those events in which an N^* is produced), from the total ($K\pi$) data. The shaded region represents the positively charged combination only. The $K^*(890)$ and the 730 MeV enhancement show up very clearly on this plot.

TABLE I

Partial Cross-Sections for $K^+p \rightarrow K^+p\pi^+\pi^-\pi^o$

Channel	No. Events	Cross-Section
$K^+p \rightarrow K^+p\ \pi^+\ \pi^-\ \pi^o$	~65	~170μb
$K^+\ N^{*++}\ \pi^-\ \pi^o$	~40	~100μb
$K^{*o}N^{*++}\ \pi^o$	~60	~150μb
$K^{*+}\ N^{*++}\ \pi^-$	~45	~130μb
$K^{*o}\ p\pi^+\ \pi^o$	~25	~ 78μb
$K^{*+}\ p\pi^+\ \pi^-$	0	0
$K^+\ p\ \omega^o$	~40	~100μb
$\mathcal{K}^+\ p\pi^+\ \pi^-$	~15	~ 45μb
$\mathcal{K}^o\ p\pi^+\ \pi^o$	~13	~38μb
$\mathcal{K}^+\ N^{*++}\pi^-$	0	0
$\mathcal{K}^o\ N^{*++}\pi^o$	0	0
N^{*++} Production	147	~380μb
K^{*+} "	~ 45	~ 227μb
K^{*o} "	~ 85	~127μb
ω^o "	40	~ 105μb
$\mathcal{K}^+$ "	15	~ 45μb
$\mathcal{K}^o$ "	13	~ 38μb

TABLE II

Partial Cross-Sections for for $K^+p \rightarrow K^o p\pi^+\pi^+\pi^-$

Channel	No. Events	Cross-Section
$K^+p \rightarrow K^o p\,\pi^+\,\pi^+\,\pi^-$	~45	~140 μb
$K^o\,\pi^+\,\pi^-\,N^{*++}$	~20	~60 μb
$K^{*+}\,N^{*++}\,\pi^-$	~30	~93 μb
$K^{*+}\,p\pi^+\,\pi^-$	~10	~31 μb
$\kappa^+\,p\,\pi^+\,\pi^-$	~12	~36 μb
$\kappa^+\,N^{*++}\,\pi^-$	~0	0
N^{*++} Production	~50	~154 μb
K^{*+} "	~40	~124 μb
κ^+ "	~12	~36 μb

TABLE III

$K^*(890)$ and $\kappa(730)$ Branching Ratios

State	$K^*(890)$	$\kappa(730)$
$K^o\pi^+$	69 ± 10 *	20 ± 8 *
$K^+\pi^o$	45 ± 8	15 ± 6
Branching Ratio	1.5 ± 0.4	1.3 ± 0.7 +
Expected Branching Ratio for I = 1/2	2.0	
Expected Branching Ratio for I = 3/2	0.5	

* These figures have been corrected for the invisible decay modes of the K^o, and for the different size of the measured sample. There is a factor of 0.55 against the $K^o p\pi^+\pi^+\pi^-$ reaction in fiducial volume and fraction of experiment analysed.

\+ Further evidence for the I = 1/2 character of the $\kappa(730)$ comes from the 'phase-space-like' distribution of the $K^o\pi^-$ spectrum in Fig.11.