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INTERFERENCE EFFECTS IN $K^-p \rightarrow K^-K^+\Lambda$ AT 4.2 GeV/c
AND THE THRESHOLD $K\bar{K}$ S WAVE AMPLITUDE

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ABSTRACT

We study the interference phenomena between the ϕ meson and the underlying K^-K^+ S wave in the reaction $K^-p \rightarrow K^-K^+\Lambda$ at 4.2 GeV/c. We perform an amplitude analysis of the double multipole moments and investigate the $K\bar{K} \rightarrow K\bar{K}$ S wave amplitude.

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1. INTRODUCTION

The spectrum of $J^{PC} = 0^{++}$ mesons below about 1.5 GeV continues to be of considerable interest. In addition to the quark model $q\bar{q}$ $L = 1$ nonet of 0^{++} mesons, it has been proposed [1] that there may be a low lying $qq\bar{q}\bar{q}$ nonet and even gluonium 0^{++} states. The experimental identification of scalar mesons has proved to be very difficult. At present firm evidence [2] exists for S^* , δ , ϵ , [3,4] and κ [5] states. For the $I = 0$ states the information comes mainly from the pion exchange $\pi\pi$ and $K\bar{K}$ production processes (for example, $\pi N \rightarrow 0^- 0^- N$). Information on the $K\bar{K} \rightarrow K\bar{K}$ channel would be of particular value in studying the dynamical nature and properties of these mesons. However, in comparison to the π exchange reactions, it is much more difficult [4] to isolate K exchange in $K\bar{K}$ production processes. The reaction $K^- p \rightarrow K^- K^+ \Lambda$ offers a unique opportunity of investigating this problem. The Λ decay acts as a polarization analyser and assists in the isolation of K exchange. Moreover in the threshold region the data are dominated by the ϕ resonance. Thus by studying S-P wave interference in the ϕ mass region we can investigate the magnitude and phase of the S wave $K\bar{K}$ amplitudes, which could be attributable to the S^* and δ resonance effects.

In this paper we present the results of a study of the reaction $K^- p \rightarrow K^- K^+ \Lambda$ at 4.2 GeV/c. In this final state we find the ϕ is strongly produced in the forward direction with an important unnatural-parity-exchange cross section. The data show evidence for small, but significant, interference effects in some of the relevant moments of the joint decay distributions of the Λ and $(K^- K^+)$ systems. We present these data in sect. 2. In sect. 3 we describe a model independent S and P wave amplitude analysis of the data in the ϕ mass region. The results are discussed in sect. 4.

2. EXPERIMENTAL DATA

The data for this analysis come from the study of 3.1×10^6 photographs taken at the CERN 2m HBC exposed to an electrostatically separated K^- beam of average momentum 4.15 GeV/c. The final sample, representing a statistical sensitivity of 133 events/ μ b, is used in this study.

The events for the final state of interest, $K^-K^+\Lambda$, come from the two-prong plus vee topologies. Event separation criteria have been discussed elsewhere [6]. As a result of a careful analysis of the different ambiguities it was found that events for which the χ^2 probability of the ΛK^+K^- fit was bigger than 0.5% could be safely attributed to this final state. To further purify the sample the following requirements were imposed:

- (a) only 4C fits at the production vertex were accepted,
- (b) the χ^2 probability of the fit was larger than 1%,
- (c) the missing mass squared was in the range $-0.0024 \leq MM^2 \leq 0.001 \text{ GeV}^2$,
- (d) The error on the missing mass squared was smaller than 0.0025 GeV^2 .

A total of 4424 unweighted events satisfied these criteria. They correspond to 4889 weighted events.

At low values of the K^-K^+ effective mass this final state is dominated by the production of the ϕ , see fig. 1, with no contamination from N^* or E^* reflections. As fig. 2 shows the ϕ resonance is preferentially produced in the forward hemisphere. In the following the analysis of the K^-K^+ system will be restricted to the peripheral region, $\cos\theta_{p\Lambda} > 0.5$.

In order to investigate the S-P wave interference effects in the ϕ mass region we take the joint moments, H , of the Λ and K^-K^+ decay angular distributions

$$H(LM\ell m) = \sum_i D_{MO}^L(\Omega_i) D_{mo}^P(\Omega'_i) W_i \quad (1)$$

where the sum extends over all the events in a given mass interval. The solid angles Ω and Ω' measure the directions of the K^- and decay proton in the K^-K^+ and Λ rest frames respectively, and W_i represents the weight of the i^{th} event. We use s channel helicity decay angles.

Allowing for S and P wave K^-K^+ production there are eighteen independent observable double moments ($L < 2$). In fig. 3 we show these moments corresponding to 4 MeV mass bins and $\cos\theta_{p\Lambda} > 0.5$. The $L = 0, 2$ moments contain (PP^*) and, for $L = 0$, also small (SS^*) contributions; whereas the six moments with $L = 1$ give information on the interference, (SP^*), between the S and P wave K^-K^+ amplitudes.

The Λ decay acts as a valuable polarization analyzer. The twelve moments with $\ell = 1$ occur by virtue of its parity violating decay. These $\ell = 1$ moments are pure imaginary, whereas the moments with $\ell = 0$ are real.

3. AMPLITUDE ANALYSIS

The observed moments, $H(LM\ell m)$, of the (K^-K^+) and Λ decay distributions allow an almost complete $K^-p \rightarrow (K^-K^+)\Lambda$ amplitude analysis to be performed. In table 1 the moments are expressed in terms of the eight independent S and P wave (helicity) amplitudes, $S_{++}^0, P_{++}^0, P_{++}^\pm$ where the $\pm$ subscripts denote the Λ and incident proton helicities, $\pm \frac{1}{2}$. The superscripts specify the (K^-K^+) helicity; S^0 and P^0 correspond, respectively, to the production of an S and P wave helicity-zero K^-K^+ system, which can only be produced by unnatural-parity-exchange. The amplitudes $P^\pm$ are defined by the following combinations of helicity $\lambda = \pm 1$ amplitudes

$$P^\pm \equiv \frac{1}{\sqrt{2}} (P^{\lambda=1} \pm P^{\lambda=-1}), \quad (2)$$

so that $P^\pm$ describe helicity-one P wave K^-K^+ production by natural, unnatural parity-exchange respectively, to leading order in energy.

Table 1 relates the 18 observables to 16 amplitude components, which we take to be the magnitudes and phases of the amplitudes. Clearly the overall phase cannot be determined. Further since the target proton is unpolarized there will be a one-parameter ambiguity in the solution.

To study the S-P interference effects we analyse the double moments in the three mass bins centred on 1016, 1020 and 1024 MeV using a constant S wave and a ϕ Breit-Wigner resonance form. Explicitly the $K\bar{K}$ mass (m) dependence of the P wave amplitudes is taken to be

$$P^\lambda = P^\lambda(m_R) \frac{m_R \sqrt{\Gamma(m_R)} \Gamma(m)}{m^2 - m_R^2 - im_R \Gamma(m_R)} \quad (3)$$

with

$$\Gamma(m) = \Gamma(m_R) \left(\frac{q}{q_R} \right)^3 \left(\frac{1 + q_R^2 R^2}{1 + q^2 R^2} \right)$$

where $P^\lambda(m_R)$, the magnitude of P^λ at the resonant mass, is to be determined by the data, and where q is the magnitude of the kaon c.m. momentum; $q^2 = m^2/4 - m_K^2$. Various values of the Breit-Wigner parameters were studied; the results presented correspond to

$$m_R = 1020 \text{ MeV}, \Gamma(m_R) = 4.8 \text{ MeV}, R = 3.5 \text{ GeV}^{-1}.$$

The theoretical forms for the moments were averaged over each 4 MeV mass bin before fitting to the data.

The double moments in the three mass bins were fitted in terms of the 14 amplitude components. For the P wave we use the components of $P^\lambda(m_R)$ of eq. (3). The results are shown in table 2. The overall phase was fixed by setting the phase of $P_{+-}^0(m_R)$ to be 90° . The one-parameter family of solutions is displayed in table 2 as a function of the phase of S_{+-}^0 .

Each solution gives an identical fit to the data, which is shown in fig. 3. Also listed in the table are the values of the invariants

$$\begin{aligned} |L^\lambda|^2 &\equiv |L_{++}^\lambda|^2 + |L_{+-}^\lambda|^2 \\ \text{Pol}(L^\lambda) &\equiv 2\text{Im}(L_{++}^\lambda \cdot L_{+-}^{\lambda*}) / |L^\lambda|^2, \end{aligned} \quad (4)$$

which may be regarded as the cross section and baryon polarisation associated with the production of spin L, helicity λ meson states.

If the fit is extrapolated outside the fitted mass range a satisfactory description of the data is obtained, except for the moments $H(0000)$ and $H(0011)$ for which the prediction off-resonance is of too large a magnitude. As can be seen from table 1, these are the only moments containing amplitude contributions of the form (SS^*) . Indeed if the mass bins above resonance are included in the amplitude analysis the only

essential change is a suppression of the S wave amplitudes, which leads to a much poorer description of the $L = 1$ (S-P wave interference) moments. In fact the $|S|^2$ contribution is reduced to 1% of the cross section.

4. DISCUSSION

A major objective in the study of the reaction $K^-p \rightarrow K^-K^+\Lambda$ is to isolate K exchange, and so obtain information on $K\bar{K}$ scattering. Now K exchange contributes to the helicity-zero amplitudes and, except in the very near forward direction $\cos\theta_{p\Lambda} > 0.95$, dominantly populates the baryon flip (rather than the non-flip) s channel amplitudes, S_{+-}^0 and P_{+-}^0 . If we assume K exchange is the dominant contribution to these amplitudes then a solution specifies both the magnitude and the phase of the S wave $K^-K^+ \rightarrow K^-K^+$ amplitude in terms of the known ϕ resonance amplitude.

The expectations for the relative magnitude and phase can be written

$$\frac{S_{+-}^0}{P_{+-}^0} = \frac{3}{\sqrt{3}} \frac{(S^* + \delta)}{\phi} \quad (5)$$

where S^* and δ are used to denote the isospin $I = 0$ and $I = 1$ S wave $K\bar{K}$ amplitudes, and ϕ the $I = 0$ P wave $K\bar{K}$ amplitude. The $\sqrt{3}$ is the factor $\sqrt{2L+1}$ occurring in P wave $K\bar{K}$ production. At $m = 1.02$ GeV typical estimates of these amplitudes are shown in fig. 4; where S^* is the prediction from the $\pi\pi$, $K\bar{K}$ coupled channel analysis of ref. [4], and δ is taken from ref. [7]. Using these values in eq. (5) gives

$$S_{+-}^0/P_{+-}^0 (m_R) = 0.6 \exp(i 25^\circ). \quad (6)$$

Table 2 shows that, within the large errors, a solution, compatible with this estimate, exists; however for $\phi(S_{+-})$ in the required region of 115° we see $|S_{+-}|$ is smaller than that given by eq. (6). This is just the range of $\phi(S_{+-})$ for which S_{++} gives the more important contribution. The size of the non-flip amplitudes are a measure of the importance of unnatural parity non-K exchange contributions. That such contributions are appreciable is also evident from the non-zero polarisations (eq. (4) and table 2) found in the S^0 and P^0 sectors. It is clear that with sufficient statistics the analysis could be put on a much firmer basis by determining the amplitudes as a function of t .

In summary, we observe $K\bar{K}$ S-P wave interference effects in $K^-p \rightarrow K^-K^+\Lambda$ data. The (K^-K^+) and Λ decay angular distributions allow an almost complete amplitude analysis of the data; we obtain a one-parameter family of solutions. The values of the amplitudes S_{+-}^0 and P_{+-}^0 can be used to give information on the S wave $K^-K^+ \rightarrow K^-K^+$ amplitude in the ϕ mass region. Such information is invaluable for resolving the properties of the S^* and δ resonant structures. In practice we find appreciable non-K exchange (K^-K^+) production in the unnatural parity exchange sector, which, with the available statistics, leads to large uncertainties in the K exchange predictions. With improved statistics the t dependence of the $K^-p \rightarrow (K^-K^+)\Lambda$ amplitudes could be studied, the K exchange amplitudes isolated and definitive information on the $K\bar{K} \rightarrow K\bar{K}$ S wave obtained.

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TABLE CAPTIONS

TABLE 1 Relations between $K^-p \rightarrow (K^-K^+)\Lambda$ double moments and helicity amplitudes. The moments $H(LM\ell m)$ are defined by eq. (1); (LM) and (ℓm) refer to the (K^-K^+) and Λ decays respectively. The Λ decay asymmetry is taken to be $\alpha_\Lambda = 0.647$ in the $\ell = 1$ moments. For $\ell = 0$ and $\ell = 1$ H is used to denote $\text{Re}H$ and $\text{Im}H$ respectively.

TABLE 2 The $K^-p \rightarrow (K^-K)\Lambda$ production amplitudes at $m = 1.02$ GeV. The overall phase is specified by $\phi(P_{+-}^0) \equiv 90^\circ$ and the table lists the one-parameter (taken to be $\phi(S_{+-}^0)$) family of solutions to the $(K^-K^+)\Lambda$ double moment data. The errors, shown in brackets for the solution with $\phi(S_{+-}^0) = 120^\circ$, are the average of the MINOS errors obtained using the CERN Minuit programme. $|L^\lambda|^2$ and $\text{Pol}(L^\lambda)$ are defined in eq. (4), and are the same for all solutions.

TABLE 1

$$\begin{aligned}
 H(0000) &= |S_{++}^0|^2 + |S_{+-}^0|^2 + |P_{++}^0|^2 + |P_{+-}^0|^2 + |P_{++}^-|^2 + |P_{+-}^-|^2 + |P_{++}^+|^2 + |P_{+-}^+|^2 \\
 H(2000) &= \frac{2}{5} (|P_{++}^0|^2 + |P_{+-}^0|^2) - \frac{1}{5} (|P_{++}^-|^2 + |P_{+-}^-|^2 + |P_{++}^+|^2 + |P_{+-}^+|^2) \\
 H(2100) &= \frac{\sqrt{6}}{5} \operatorname{Re}(P_{++}^0 P_{++}^{-*} + P_{+-}^0 P_{+-}^{-*}) \\
 H(2200) &= \frac{1}{5} \sqrt{\frac{3}{2}} (|P_{++}^-|^2 + |P_{+-}^-|^2 - |P_{++}^+|^2 - |P_{+-}^+|^2) \\
 H(2110) &= \frac{\alpha}{5} \sqrt{\frac{2}{3}} \operatorname{Im}(P_{++}^+ P_{++}^{0*} + P_{+-}^+ P_{+-}^{0*}) \\
 H(2210) &= \frac{\alpha}{5} \sqrt{\frac{2}{3}} \operatorname{Im}(P_{++}^+ P_{++}^{-*} + P_{+-}^+ P_{+-}^{-*}) \\
 H(0011) &= \frac{\alpha}{3} \sqrt{2} \operatorname{Im}(S_{+-}^0 S_{++}^{0*} + P_{+-}^0 P_{++}^{0*} + P_{+-}^- P_{++}^{-*} - P_{+-}^+ P_{++}^{+*}) \\
 H(2011) &= \frac{\alpha}{15} \sqrt{2} \operatorname{Im}(2 P_{+-}^0 P_{++}^{0*} + P_{+-}^+ P_{++}^{+*} - P_{+-}^- P_{++}^{-*}) \\
 H(211\pm 1) &= \frac{\alpha}{5\sqrt{3}} \operatorname{Im}(P_{+-}^0 P_{++}^{-*} - P_{++}^0 P_{+-}^{-*} \mp P_{++}^0 P_{+-}^{+*} \pm P_{+-}^0 P_{++}^{+*}) \\
 H(221\pm 1) &= \frac{\alpha}{5\sqrt{3}} \operatorname{Im}(P_{+-}^+ P_{++}^{+*} + P_{+-}^- P_{++}^{-*} \pm P_{+-}^+ P_{++}^{-*} \pm P_{+-}^- P_{++}^{+*}) \\
 H(1000) &= \frac{2}{\sqrt{3}} \operatorname{Re}(S_{++}^0 P_{++}^{0*} + S_{+-}^0 P_{+-}^{0*}) \\
 H(1100) &= \sqrt{\frac{2}{3}} \operatorname{Re}(S_{++}^0 P_{++}^{-*} + S_{+-}^0 P_{+-}^{-*}) \\
 H(1110) &= \frac{\alpha}{3} \sqrt{\frac{2}{3}} \operatorname{Im}(P_{++}^+ S_{++}^{0*} + P_{+-}^+ S_{+-}^{0*}) \\
 H(1011) &= \frac{\alpha}{3} \sqrt{\frac{2}{3}} \operatorname{Im}(S_{+-}^0 P_{++}^{0*} - S_{++}^0 P_{+-}^{0*}) \\
 H(111\pm 1) &= \frac{\alpha}{3\sqrt{3}} \operatorname{Im}(S_{+-}^0 P_{++}^{-*} - S_{++}^0 P_{+-}^{-*} \mp S_{++}^0 P_{+-}^{+*} \pm S_{+-}^0 P_{++}^{+*})
 \end{aligned}$$

TABLE 2

$ S_{++}^0 $	ϕ	$ S_{+-}^0 $	ϕ	$ P_{++}^0 $	ϕ	$ P_{+-}^0 $	ϕ	$ P_{++}^- $	ϕ	$ P_{+-}^- $	ϕ	$ P_{++}^+ $	ϕ	$ P_{+-}^+ $	ϕ
3.5	- 98	2.9	- 150	3.4	- 47	5.8	90	5.2	- 101	6.0	1	7.5	138	7.7	- 145
2.6	- 65	3.7	- 120	5.1	- 53	4.4	90	5.7	- 114	5.5	- 9	7.0	123	8.2	- 154
2.1	- 16	4.1	- 90	6.0	- 40	3.1	90	6.1	- 108	5.1	- 9	6.7	122	8.4	- 148
1.9	33	4.1	- 60	6.3	- 22	2.3	90	6.2	- 96	4.9	- 1	6.8	129	8.3	- 135
2.1	76	4.0	- 30	6.4	1	2.2	90	6.2	- 77	4.9	13	7.0	145	8.2	- 117
2.3	118	3.9	0	6.3	24	2.4	90	6.2	- 58	4.9	27	7.2	159	8.0	- 99
2.6	158	3.6	30	6.1	47	2.9	90	6.2	- 40	4.9	39	7.5	175	7.7	- 83
3.3	- 171	3.0	60	5.1	53	4.4	90	5.7	- 42	5.4	34	8.0	172	7.1	- 87
3.8	- 148	2.2	90	3.8	54	5.6	90	5.2	- 49	6.0	27	8.4	168	6.7	- 98
4.1	- 137	2.0	120	2.8	38	6.1	90	5.0	- 61	6.1	20	8.3	161	6.7	- 111
(± 1.0)	(± 23)	(± 1.3)		(± 1.9)	(± 46)	(± 1.3)		(± 1.7)	(± 28)	(± 1.6)	(± 20)	(± 1.5)	(± 24)	(± 1.7)	(± 28)
4.1	- 128	1.9	150	2.1	12	6.3	90	4.7	- 73	6.3	14	8.3	154	6.8	- 123
3.9	- 115	2.2	180	2.2	- 18	6.3	90	4.9	- 84	6.2	10	8.1	149	7.0	- 131
$ S^2 = 20 \pm 16$			$ P^0 ^2 = 45 \pm 21$			$ P^- ^2 = 63 \pm 32$			$ P^+ ^2 = 115 \pm 10$						
$\text{Pol}(S) = 0.75 \pm 0.25$			$\text{Pol}(P^0) = -0.55 \pm 0.3$			$\text{Pol}(P^-) = -0.96 \pm 0.4$			$\text{Pol}(P^+) = -0.97 \pm 0.3$						

FIGURE CAPTIONS

- Fig. 1 The K^-K^+ effective mass distribution observed in the reaction $K^-p \rightarrow K^-K^+\Lambda$.
- Fig. 2 The $dN/d\cos\theta_{p\Lambda}$ distribution for events with $0.998 \leq m(K^-K^+) \leq 1.042$ GeV. $\theta_{p\Lambda}$ is the angle between the incoming proton and outgoing Λ in the overall centre of mass.
- Fig. 3 The eighteen observable moments, $H(LM\ell m)$, as a function of $m(K^-K^+)$ over the ϕ mass region for $0.5 \leq \cos\theta_{p\Lambda} \leq 1$. The curves are the result of the amplitude analysis of the data in the three mass bins $1.014 \leq m(K^-K^+) \leq 1.026$ GeV, see sect. 3. The $\ell = 0$ and $\ell = 1$ moments are $\text{Re}H(LM\ell m)$ and $\text{Im} H(LM\ell m)$ respectively.
- Fig. 4 S^* and δ denote respectively, the $I = 0$ and $I = 1$ $K\bar{K}$ S wave amplitudes at the ϕ mass, normalised to their respective unitarity circles. ϕ is the $I = 0$ P wave amplitude at $m = m_R$.

Fig. 1

Fig. 2

Fig. 3(a)

$K^- K^+$ Mass(MeV)

Fig. 3(b)

$K^- K^+$ Mass (MeV)

Fig. 3(c) $K^- K^+$ Mass (MeV)

Fig. 4