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A STUDY OF THE REACTION $\pi^- p \rightarrow \phi\phi n$ AT 16 GeV/c

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ABSTRACT

The reaction $\pi^- p \rightarrow \phi\phi n$ has been isolated at 16 GeV/c and its cross section determined to be $(40 \pm 10)\text{nb}$. The $\phi\phi$ mass spectrum shows a threshold enhancement between 2.1 and 2.5 GeV. A successful description of the angular content of the $\phi\phi$ system requires two interfering $J^P = 2^+$ states.

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1. INTRODUCTION

In this paper we study the properties of the reaction $\pi^- p \rightarrow \phi\phi n$ at 16 GeV/c. This reaction according to the Okubo-Zweig-Iizuka (OZI) rule is expected to be suppressed. The prominent feature is a low $\phi\phi$ mass bump first observed at BNL [1]. In particular we analyse, with good acceptance, the decay angular distribution of the $\phi\phi$ system.

2. THE EXPERIMENT

The experiment was performed using the Omega Spectrometer at the CERN SPS. A 16 GeV/c π^- beam with a mean flux of 6×10^5 per burst was incident upon a 60 cm liquid hydrogen target. During 20 days of running time 3×10^6 triggers were recorded. The effective beam flux sensitivity considered in this analysis was 39 events/nb for 100% acceptance^(*).

A schematic layout of the apparatus is shown in fig. 1. The trigger used for this analysis required:

- (a) An identified π^- incident upon the target and no signal from the beam veto counter A_0 ;
- (b) At least one hit on both hodoscopes H1 and H2 satisfying a correlation matrix between the hodoscopes;
- (c) For every pair of hodoscope hits satisfying the (H1, H2) correlation matrix, an absence of light in the appropriate cells of the Cerenkov counter placed between the hodoscopes and filled with freon at one atmosphere pressure (in this way the trigger selected events producing a forward going antiproton with momentum > 2.8 GeV/c or a forward going negative kaon with a momentum between 2.8 and 9.8 GeV/c);
- (d) The absence of a γ -signal from a system of scintillator-lead-scintillator sandwich counters, designed to reduce the number of events with π^0 s;

(*) The value quoted here differs from that given in ref. [2] and is due to a detailed re-evaluation of the sensitivity.

- (e) Three or four charged particles detected by combining the signals from a cylindrical hodoscope (TS) around the target with those from MWPC 1 just downstream of the target;
- (f) Two, three or four charged particles detected in MWPC III.

The data were processed by the OMEGA pattern recognition and geometrical reconstruction program (ROMEO). Charge balancing four-prong events were selected for the subsequent analysis if the reconstructed vertex position lay within the hydrogen of the target, and at least one of the two negative particles could be identified with a trigger track. The latter was achieved by tracing the track through the magnetic field to the hodoscopes H1 and H2, and requiring (a) no light in the appropriate cell of the Cerenkov counter, and (b) for both H1 and H2 agreement between the traced hit position on the hodoscope and the element for which a hit was recorded.

After imposing these selection criteria upon the 590 000 charge balancing four-prong events, we obtained 521 000 good candidates for further analysis.

3. THE REACTION $\pi^- p \rightarrow \phi\phi n$

To isolate the process $\pi^- p \rightarrow \phi\phi n$ we assigned the kaon mass to the outgoing charged tracks, labelled $K_1^- K_2^- K_1^+ K_2^+$, from all charge balancing four-prong events after exclusion of the four-constraint channels $\pi^- p \rightarrow K^+ K^- \pi^- p$ and $\pi^- p \rightarrow \bar{p} p \pi^- p$. Labelling the triggering particle as K_1^- we plot the effective mass of $(K_1^- K_1^+, 2)$ against the effective mass of $(K_2^- K_2^+, 1)$ for those events having a missing mass lying in the neutron region (0.84 to 1.02 GeV) (fig. 2(a)). An accumulation of events is seen in the region corresponding to double ϕ production. Retaining the events which lie within the box where both $(K^+ K^-)$ effective masses are between 1.012 and 1.028 GeV we obtain 153 $\pi^- p \rightarrow \phi\phi n$ candidates. There is no evidence of a significant contamination within this region from single ϕ production. Although there are two entries/event into this plot, we find only 1 entry/event within the selected $\phi\phi$ box. The background has been estimated from the region

bordering the $\phi\phi$ box to be (35 ± 6) events $(23 \pm 4)\%$. In fig. 3 the (K^+K^-) effective mass is plotted if the complementary (K^+K^-) mass lies between 1.012 and 1.028 GeV. The ϕ peak observed is centred at 1.019 GeV and has FWHM of 8 MeV.

To show the quality of the recoiling neutron signal for events within the selected double ϕ region we plot the missing mass to the four outgoing kaons for all charge balancing events lying within this region (fig. 4). Between 0.84 and 1.02 GeV there is an estimated background of (34 ± 11) events $(22 \pm 4)\%$ under the neutron peak.

The $(\phi\phi)$ mass spectrum (fig. 5) shows a threshold bump with a width of 0.4 GeV, and a sharp drop at 2.5 GeV. These features are similar to those obtained at BNL [1]. The four-momentum transfer squared distribution t'_{p+n} (fig. 6) is described for $t' < 0.3$ by the parametrisation $\exp(bt')$ where $b = -(12 \pm 2)\text{GeV}^{-2}$ and $t' = |t - t_{\min}|$. Thus the reaction is dominated by the peripheral production of a $\phi\phi$ pair.

The cross section for the reaction $\pi^-p \rightarrow \phi\phi n$ is estimated to be $(40 \pm 10)\text{nb}$ on the basis of 118 events above a background of 35 events, after correcting for the trigger and reconstruction efficiency of 0.6, the geometrical acceptance of 0.55 (sect. 4), and the branching ratio for $\phi\phi \rightarrow K^-K^+K^-K^+$ of 0.24.

4. SPIN-PARITY ANALYSIS OF THE $(\phi\phi)$ THRESHOLD ENHANCEMENT

In order to study the spin-parity of the $(\phi\phi)$ threshold enhancement, we have limited the sample to those events with low $(\phi\phi)$ mass (< 2.7 GeV) and low t' ($< 0.3 \text{ GeV}^2$) (see fig. 2(b) and the shaded parts of figs 3 and 4). This selection reduces the background of non- $\phi\phi n$ events to $(15 \pm 5)\%$, leaving 95 events in the low-mass $(\phi\phi)$ region. Using this data sample we attempt to describe the $(\phi\phi)$ threshold enhancement in terms of a single spin-parity state. We compare the experimental angular correlations with predictions from pure J^P states modified by the experimental acceptance.

The total spin J of the $(\phi\phi)$ system is constructed in the standard manner by vectorial addition of L and S , where L is the orbital angular momentum between the two ϕ mesons and S is the vector sum of the spins of the two ϕ mesons. The parity of the $(\phi\phi)$ system is then given by $P = (-1)^L$.

Since the $\phi\phi$ system is an $I = 0$ state formed from two identical particles, the space part of the state vector has to be symmetric under the exchange of the two ϕ 's; from this follows that $(-1)^{L+S} = 1$ (or $L + S = \text{even}$). The allowed states for $I < 2$ and $L \leq 2$ are listed in table 1. The expansion of the state vector and the definition of the co-ordinate frames in which the six decay variables α , $\cos\beta$, α_1 , $\cos\beta_1$, α_2 , $\cos\beta_2$ are measured are given in the Appendix.

The experimental angular distributions uncorrected for acceptance are shown in fig. 7(a) for the selected data sample. To take account of identical particle symmetry the α_1 and α_2 distributions (and similarly the $\cos\beta_1$ and $\cos\beta_2$ distributions) have been added and denoted by α_i ($\cos\beta_i$).

Fig. 7(b) shows the dependence of the experimental acceptance upon the angular variables α , $\cos\beta$, α_i and $\cos\beta_i$. This dependence was computed using isotropic angular distributions, a flat distribution in $(\phi\phi)$ mass from 2.1 to 2.5 GeV, and the observed t' distribution.

To extract information concerning J^P for the $(\phi\phi)$ state, the correlations in the 6-dimensional decay angular space have been studied. These correlations are represented by "triple moments", as defined by equation (A3) of the Appendix. We restrict our analysis to the moments $\langle 00, 20, 00 \rangle$, $\langle 00, 20, 20 \rangle$, $\langle 00, 21, 21 \rangle$ and $\langle 00, 22, 22 \rangle$, since for these moments the dependence on the $(\phi\phi)$ polarisation is weak (arising only from acceptance effects). Table 2 shows these moments for the data. The significant negative $\langle 00, 20, 00 \rangle$ moment reflects the $\sin^2\beta_i$ structure observed in fig. 7(a).

To compare these experimental moments with those predicted for each of the $|J^P_{LS}\rangle$ states listed in table 1 we have generated each state separately according to formula (A2) of the Appendix assuming $\rho_{00} = 1$. The generated events were weighted by the acceptance and the moments subsequently calculated by the same method employed to calculate the experimental moments. The comparison of experimental with predicted triple moments is shown in table 3. No single $|J^P_{LS}\rangle$ state gives an acceptable χ^2 , one of the difficulties being the description of the $\cos\beta_i$ distribution.

Apart from acceptance effects the only contributions to the $\cos\beta_i$ distribution that do not come from pure $|J^P_{LS}\rangle$ states come from the interference between states of the same J^P but different L, S (Appendix). A contribution of this type can arise from the interference between the two $J^P = 0^+$ states and the three $J^P = 2^+$ states (table 1).

Allowing the $J^P = 0^+$ S and D waves to interfere we have computed the moments by the Monte-Carlo method. The D to S wave amplitude ratio $A(0^+22)/A(0^+00)$ has been adjusted to minimise the χ^2 from the comparison of the predicted moments with the experimental moments. The amplitude ratio has been kept real. Introduction of a phase does not improve the χ^2 . The results are presented in table 4. It is seen that $J^P = 0^+$ does not describe the data.

Similarly we have considered each of the three pairs of $J^P = 2^+$ states. As seen from table 4, all three fits can explain the experimental moments.

5. CONCLUSIONS

The reaction $\pi^- p \rightarrow \phi\phi n$ has been observed at 16 GeV/c incident momentum with a measured cross section of $(40 \pm 10)\text{nb}$. The $\phi\phi$ mass spectrum shows a threshold enhancement between 2.1 and 2.5 GeV. The four-momentum transfer squared $t'_{p \rightarrow n}$ distribution is described by the function $\exp(bt')$ where $b = -(12 \pm 2)\text{GeV}^{-2}$ for the t' region below 0.3 GeV^2 .

The correlations of the ϕ decay angles which are represented by the triple moments $\langle 00, 20, 00 \rangle$, $\langle 00, 20, 20 \rangle$, $\langle 00, 21, 21 \rangle$ and $\langle 00, 22, 22 \rangle$ are used to analyse the spin properties of the low mass, low t' , $(\phi\phi)$ system. We find that the data cannot be explained by a single $|J^P_{LS}\rangle$ state with $J < 2$ and $L < 2$. However, an adequate description of these moments is obtained in terms of two interfering $J^P = 2^+$ states. We note, however, that our description of the data does not exclude the possibility of a higher angular momentum assignment to the $(\phi\phi)$ system or of a more extensive degree of interference between contributing states.

APPENDIX

ANGULAR MOMENTUM EXPANSION OF A $1^- 1^-$ STATE

In the rest frame of the $\phi\phi$ system with coordinate axes (x,y,z) as explained in fig. A.1 (Gottfried-Jackson axes), the direction of flight of meson ϕ_1 with momentum p is given by $\Omega = (\alpha, \beta)$.

Fig. A.1

Fig. A.2

In the rest frames of each ϕ meson, the coordinate axes (x_1, y_1, z_1) and (x_2, y_2, z_2) are chosen as in fig. A.2 with anti-parallel helicity axes z_1 and z_2 and with parallel x_1 and x_2 . The azimuthal and polar angles of the K^- in each ϕ rest frame are denoted by $\Omega_1 = (\alpha_1, \beta_1)$ and $\Omega_2 = (\alpha_2, \beta_2)$ and the K^- momenta are denoted as p_1 and p_2 .

The space part of the state vector of two 1^- mesons with given decay angles is expanded in a series of angular momentum eigen vectors:

$$|p\Omega, p_1\Omega_1, p_2\Omega_2\rangle = \sum_{JM} \sum_{\lambda_1\lambda_2} D_{M\lambda}^J(\Omega) D_{\lambda_1 0}^1(\Omega_1) D_{\lambda_2 0}^1(\Omega_2) \cdot \sum_{LS} \sqrt{2L+1} (L0, S\lambda | J\lambda) (1\lambda_1, 1-\lambda_2 | S\lambda) |J^P M L S\rangle \quad (A1)$$

where J, P, L, S are explained in the text. M is the projection on the Z axis of the total angular momentum. λ_1, λ_2 are the helicities of each ϕ meson. $\lambda = \lambda_1 - \lambda_2$.

The D 's are the Wigner rotation functions. The Clebsch-Gordan coefficients exhibit the $L-S$ coupling scheme.

The 6-dimensional angular distribution is then obtained from (A1) by introducing the production density matrix ρ and decay amplitudes A :

$$\frac{d\sigma}{d\Omega d\Omega_1 d\Omega_2} = \sum_{JM} \sum_{\lambda_1\lambda_2} D_{M\lambda}^J(\Omega) D_{M'\lambda'}^{J*}(\Omega) D_{\lambda_1 0}^1(\Omega_1) D_{\lambda_1' 0}^{1*}(\Omega_1) \cdot D_{\lambda_2 0}^1(\Omega_2) D_{\lambda_2' 0}^{1*}(\Omega_2) \sum_{LS} \sqrt{2L+1} \sqrt{2L'+1} (L0, S\lambda | J\lambda) (L'0, S'\lambda' | J'\lambda') \cdot (1\lambda_1, 1-\lambda_2 | S\lambda) (1\lambda_1', 1-\lambda_2' | S'\lambda') \rho_{J'P'M'}^{JPM} A_{LS}^{JP} A_{L'S'}^{J'P'*} \quad (A2)$$

The one-dimensional projection on $\cos\beta_1$ is obtained by integrating (A2) over all other angles.

$$\frac{d\sigma}{d\cos\beta_1} = \sum_{\lambda_1} [d_{\lambda_1 0}^1(\beta_1)]^2 \sum_{\lambda_2} \sum_{LS} \sum_{L'S'} A_{LS}^{JP} A_{L'S'}^{J'P'*} \sum_M \rho_{J'P'M'}^{JPM} \cdot \sqrt{2L+1} \sqrt{2L'+1} (L0, S\lambda | J\lambda) (L'0, S'\lambda' | J'\lambda') (1\lambda_1, 1-\lambda_2 | S\lambda) (1\lambda_1', 1-\lambda_2' | S'\lambda') \quad (A3)$$

where cross-terms with different parities no longer appear because of the symmetry properties of the Clebsch-Gordan coefficients.

It is seen further that (A3) is independent of the helicity M and that no cross terms with different values of J occur. The angular distribution (A2) can be expressed in terms of three D-functions with coefficients called "triple moments":

$$\frac{d\sigma}{d\Omega d\Omega_1 d\Omega_2} = \sum_{Imk} \sum_{S_1 m_1} \sum_{S_2 m_2} D_{mk}^{I*}(L) D_{m_1 0}^{S_1*}(\Omega_1) D_{m_2 0}^{S_2*}(S_2) \langle D_{mk}^I D_{m_1 0}^{S_1} D_{m_2 0}^{S_2} \rangle \quad (A4)$$

where

$$k = m_1 - m_2 \text{ and}$$

S_1, S_2 may have only the values 0 and 2.

From parity conservation in the reaction it follows that the moments have to be real. In the text we use the abbreviation:

$$\langle Im, S_1 m_1, S_2 m_2 \rangle \equiv \langle D_{mk}^I D_{m_1 0}^{S_1} D_{m_2 0}^{S_2} \rangle$$

REFERENCE

- [1] A. Etkin et al., Phys. Rev. Lett. 40 (1978) 422.
- [2] T.A. Armstrong et al., Phys. Lett. 85B (1979) 304.

TABLE CAPTIONS

- TABLE 1 The allowed $|J^P LS\rangle$ states of the $\phi\phi$ -system ($J \leq 2$ and $L \leq 2$).
The prediction for the $\cos\beta_1$ distribution is also given.
- TABLE 2 Experimental triple moments (uncorrected for acceptance) for
 $M(\phi\phi) < 2.7$ GeV and $t' < 0.3$ GeV².
- TABLE 3 Predicted triple moments for states with $J \leq 2$ and $L \leq 2$.
- TABLE 4 Predicted triple moments for 0^+ and 2^+ allowing two states to
interfere. The results for the amplitude ratios are also given.

TABLE 1

J^P	L	S	$f(\cos\beta_1)$
0^+	0	0	1
0^+	2	2	$1 + 3 \cos^2 \beta_1$
0^-	1	1	$\sin^2 \beta_1$
1^+	2	2	$1 + \cos^2 \beta_1$
1^-	1	1	$1 + \cos^2 \beta_1$
2^+	0	2	1
2^+	2	0	1
2^+	2	2	$1 + 9/22 \sin^2 \beta_1$
2^-	1	1	$1 + 1/6 \sin^2 \beta_1$

TABLE 2

$\langle 00, 20, 00 \rangle$	$(-.172 \pm .037)$
$\langle 00, 20, 20 \rangle$	$(.036 \pm .017)$
$\langle 00, 21, 21 \rangle$	$(-.008 \pm .013)$
$\langle 00, 22, 22 \rangle$	$(.045 \pm .017)$

TABLE 3^(a)

J^P_{LS}	$0^+ 00$	$0^+ 22$	$0^- 11$	$1^+ 22$	$1^- 11$	$2^+ 02$	$2^+ 20$	$2^+ 22$	$2^- 11$
$< 00, 20, 00 >$	-.025	.164	-.209	.091	.085	.013	-.030	-.049	-.044
$< 00, 20, 20 >$	.078	.109	.043	-.083	-.081	.005	.073	.045	-.032
$< 00, 21, 21 >$	-.079	.077	0	-.059	.064	-.002	-.089	.012	.032
$< 00, 22, 22 >$	.082	.044	-.121	-.002	-.003	.008	.088	.014	-.055
$\chi^2/N.D.F.$	14	36	24	31	33	8	16	4.3	18

(a) The uncertainties in the predicted triple moments due to the Monte-Carlo statistics are small compared with the uncertainties in the experimental triple moments (table 2).

TABLE 4

$J_1^{P_1} L_1 S_1$	0^+00	2^+02	2^+02	2^+20
$J_2^{P_2} L_2 S_2$	0^+22	2^+20	2^+22	2^+22
$\frac{A(J_2^{P_2} L_2 S_2)}{A(J_1^{P_1} L_1 S_1)}$	0.5	0.65	0.5	-1.4
$\langle 00, 20, 00 \rangle$	-.205	-.117	-.160	-.171
$\langle 00, 20, 20 \rangle$	.046	.012	.022	.039
$\langle 00, 21, 21 \rangle$	-.022	-.016	-.008	-.007
$\langle 00, 22, 22 \rangle$	.114	.061	.006	.070
$\chi^2/\text{d.o.f.}$	4.7	1.4	1.6	0.6

FIGURE CAPTIONS

- Fig. 1 Schematic layout of the OMEGA Spectrometer as used in this experiment.
- Fig. 2 (a) Scatter plot of the mass $K_1^- K_1^+$ against the mass $K_2^- K_2^+$ for the four-prong charge balancing events which, when the four charged particles have a kaon mass assigned to them, have a missing mass lying in the neutron mass region viz 0.84 to 1.02 GeV.
- (b) Same as (a) with t'_{p+n} less than 0.3 GeV² and mass of four kaons < 2.7 GeV.
- Fig. 3 $K^+ K^-$ effective mass distribution for the events used in fig. 2(a) when the other $K^+ K^-$ combination has a mass lying in the ϕ mass interval (1.012 to 1.028 GeV). The shaded area corresponds to the events used in fig. 2(b), i.e. with $t'_{p+n} < 0.3$ GeV² and $M(4K) < 2.7$ GeV.
- Fig. 4 Missing mass distribution to the four-prong charge balancing events falling in the $\phi\phi$ region of fig. 2(a) (dashed region). The shaded area corresponds to the events falling within the dashed region of fig. 2(b).
- Fig. 5 Effective mass distribution of the events which are candidates for the $\pi^- p \rightarrow \phi\phi n$, i.e. those events lying within the dashed region shown on fig. 2(a).
- Fig. 6 Four momentum squared distribution (t'_{p+n}) for the events within the dashed region ($\phi\phi$ region) of fig. 2(a).
- Fig. 7 (a) Experimental angular distributions of the angles α , β , α_i and β_i as defined in the text.
- (b) Dependence of the experimental acceptance on the angles α , β , α_i and β_i .

Fig. 1

Fig. 2a

Fig. 2 b

Fig.3

Fig. 4

Fig. 5

Fig. 6

Fig. 7a

Fig.7b