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STUDY OF THE $\pi^+\pi^+\pi^-\pi^-$ SYSTEM CENTRALLY PRODUCED BY INCIDENT π^+ AND p BEAMS AT 85 GeV/c

WA76 Collaboration

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Abstract

The reactions $\pi^+p \rightarrow \pi^+(\pi^+\pi^+\pi^-\pi^-)p$ and $pp \rightarrow p(\pi^+\pi^+\pi^-\pi^-)p$, where the $(\pi^+\pi^+\pi^-\pi^-)$ system is centrally produced have been studied at 85 GeV/c. The $\pi^+\pi^+\pi^-\pi^-$ mass spectrum shows evidence for the $f_1(1285)$ meson with a mass of 1278 ± 2 MeV and width 41 ± 12 MeV which decays mainly through $\rho^0(770)\pi^+\pi^-$. The $f_1(1285)$ is also observed in the $\eta\pi^+\pi^-$ channel. There is no significant evidence for $\eta\pi\pi$ or 4π decay modes of the $f_1(1420)$. The $\rho^0\rho^0$ production is found to be small. A Dalitz plot analysis of the 3π system shows evidence for $a_2(1320)$ production and for a large contribution of the $J^{PC} = 1^{++} \rho\pi$ wave.

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1. INTRODUCTION

One of the important expectations of QCD is the existence of hadrons composed of gluons, or of mixtures of quarks and gluons, and some of these states are predicted to lie in the mass region below 2.0 GeV [1]. A few candidates for gluonium already exist but the complicated situation in light meson spectroscopy makes it difficult to establish them as gluonic states, since the possibility that they are four-quark states or radial excitations cannot be ruled out. For this reason "glueball hunting" is a rather complex matter and the understanding of light meson spectroscopy is likely to come only from an overall comparison between meson production from different dynamical sources, e.g. J/ψ radiative and hadronic decays, $p\bar{p}$ annihilation, hadron induced reactions, $\gamma\gamma$ collisions, high p_T physics and central production.

One of the problems in light meson spectroscopy is the $J^{PC} = 1^{++}$ nonet in which there are at least two important questions to be answered. The first is the so-called F/t puzzle which has led recently to the confirmation of the $J^{PC} = 1^{++}$ assignment to the $f_1(1420)$ (F) meson by different experiments [2,3]. The second question concerns the understanding of the mixing among the members of the multiplet which is related by $SU(3)$ to the masses of the resonances; in particular, the mass and width of the a_1 resonance is still a matter of investigation [4]. The possible confirmation of a new $J^{PC} = 1^{++}$ state, the $f_1(1525)$ [5], makes this multiplet difficult to understand in terms of a simple quark model. In fact, we are confronted with the possibility of having ten members of the same multiplet which could imply the existence of a new kind of meson [6].

Experiment WA76 at the CERN Ω Spectrometer was designed to study centrally produced exclusive final states with the aim of searching for signs of new mesons. As the centre of mass energy increases the so-called Double Pomeron Exchange (DPE) is one of the production mechanisms which is expected to become relatively more important and, if the Pomeron is composed of gluons, DPE can be expected to be a source of gluonium states [7].

In the present paper we investigate the production of $J^{PC}=1^{++}$ mesons coupled to the $2\pi^+2\pi^-$ and $2\pi^+2\pi^-\pi^0$ final states.

2. DATA SELECTION

The data come from the WA76 Experiment performed at CERN using the Ω Spectrometer in the H1 beam which contains approximately equal numbers of π^+ and protons at 85 GeV/c. Details of the trigger conditions and the data processing have been given in previous publications [3].

The reactions

$$\pi^+ p \rightarrow \pi^+_f (\pi^+\pi^+\pi^-\pi^-) p_s \quad (1)$$

and

$$pp \rightarrow p_f (\pi^+\pi^+\pi^-\pi^-) p_s \quad (2)$$

where the subscripts f and s refer to the fastest and slowest positive particles in the laboratory system, have been isolated from the sample of the events with six outgoing tracks in the final state. The slow proton, which triggered a 14-slab scintillation counter, was identified by means of the pulse-height momentum correlation. The fast particle was assumed to be of the same nature as the incident beam. The four remaining tracks were required, if reaching the Cherenkov system, to have a mass assignment compatible with the pion.

Momentum balancing events were selected by requiring $|\text{missing } P_x| < 3.00 \text{ GeV/c}$, $|\text{missing } P_y| < 0.10 \text{ GeV/c}$ and $|\text{missing } P_z| < 0.08 \text{ GeV/c}$. Energy balance was obtained by requiring the Δ function, defined as

$$\Delta = MM^2(\pi^+_f/p_f p_s) - M^2(\pi^+\pi^+\pi^-\pi^-)$$

(shown in fig. 1) to be $|\Delta| < 2.0 \text{ GeV}^2$.

The final sample consists of 43 960 events of which 65% come from the p beam and 35% come from the π^+ beam. The Feynman- x_F distributions (for π^+ beam) are shown in fig. 2 for the slow proton, the central system and the fast particle.

3. Mass spectra

3.1 The $2\pi^+ 2\pi^-$ channel

The four-body, three-body and two-body effective mass spectra relevant to the present study are shown in figs 3 and 4 separated for the two different reactions. The four-pion mass spectra in both π^+ and p beams, (figs (3a,b)) show a narrow enhancement around 1.28 GeV suggesting evidence for the $f_1(1285)$ meson. In addition, structures can be observed in the low mass region which are found to result from reflections coming from the $\eta\pi^+\pi^-$ channel (sect. 3.1). The three-pion mass spectra (four entries per event) (figs. 3c,d) have a "triangular shape" and show evidence for the $a_2(1320)$ resonance. The two-pion mass spectra (four entries per event) (figs (4a,b)) show clear $\rho^0(770)$, signs of $f_2(1270)$ and K^0 contamination from the $K_S^0 K_S^0$ and $K_S^0 K^\pm \pi^\mp$ channels not removed by the Δ function cut. The mass spectra which include the fast particle are shown in fig. 4(c,d) (two entries per event) for π^+ and p beams respectively and show evidence for forward produced resonances such as the $\rho^0(770)$, $f_2(1270)$ and $\Delta^{++}(1232)$. The other mass spectra (not shown) do not show significant resonance production.

3.2 The $\eta \pi^+ \pi^-$ channel

The source of the structures seen in the low mass region of the four-pion spectra can be understood from a study of the $\eta\pi^+\pi^-$ final state. These structures are due to the reflections of the $\eta\pi^+\pi^-$ decay modes of the $\eta'(958)$ and $f_1(1285)$ mesons where the π^0 from the η decay to $\pi^+\pi^-\pi^0$ is slow and falls inside the momentum and energy balance cuts. The layout used in the present experiment did not

allow the detection of γ 's so that π^0 's can be reconstructed only as missing particles with large errors due to the relatively high momentum of the incident beam.

The reactions

$$\pi^+ p \rightarrow \pi^+ f (\pi^+\pi^+\pi^-\pi^-\pi^0)p_s \quad (3)$$

and

$$pp \rightarrow pf (\pi^+\pi^+\pi^-\pi^-\pi^0)p_s \quad (4)$$

have been selected from the sample of events having six outgoing tracks. The momentum balance events have been antiselected and the missing mass squared to the six outgoing particles was computed and is shown in fig. 5(a). A clear peak at the π^0 mass squared with a signal to background of $\approx 2/1$ can be seen. The π^0 has been selected by requiring the missing mass squared to be in the region $|MM^2| < 0.2 \text{ GeV}^2$ and has then been assigned the missing momentum three-vector and the π^0 mass.

The $\pi^+\pi^-\pi^0$ effective mass distributions for reactions (3) and (4) (four entries per event) are shown in figs 5(b,c) where shoulders can be seen at the η and ω masses. In order to estimate the combinatorial background, new $\pi^+\pi^-\pi^0$ spectra have been formed by using event mixing. After subtraction of this background (normalized to three of the four combinations) we obtain the spectra (dashed histograms) shown in figs 5(b,c) where the η and ω are now clearly seen.

To obtain the $\eta \pi^+ \pi^-$ final state we have selected the η by choosing all combinations in the region $0.51 < m(\pi^+\pi^-\pi^0) < 0.59 \text{ GeV}$ and for a $\pi^+\pi^-\pi^0$ combination in this mass region we have summed the three-vectors of the three particles and assigned the η mass. The resulting $\eta \pi^+ \pi^-$ mass spectra are shown in fig. 6(a) (π^+ incident), fig. 6(b) (p incident) and fig. 6(c) (sum) where these mass spectra have been weighted with the inverse of the number of combinations. The total sample consists of 6656 events (70% belonging to the p beam and 30% to the π^+ beam).

The spectra for both reactions show clear signals for $\eta'(958)$ and $f_1(1285)$. A fit of the $\eta\pi^+\pi^-$ mass spectrum has been performed by using simple Breit–Wigner formulas to describe the $\eta'(958)$ and the $f_1(1285)$. The background has been described by a formula of the form

$$dN/dm = \alpha(m - m_{th})^\beta e^{-\gamma m - \delta m^2}, \quad (5)$$

where m_{th} is the threshold mass. A Breit–Wigner to describe the $f_1(1420)$ has also been included in the fit with a mass fixed to the value obtained from the fit of the $K^0_S K^\pm \pi^\mp$ mass spectrum (sect.3.2) and a width which takes into account the experimental resolution ($\sigma \approx 45$ MeV) in this mass region. The $f_1(1285)$ mass obtained from the fit is 1288 ± 5 MeV. The fit probability changes from 70% to 67% when the $f_1(1420)$ is removed from the fit and we compute an upper limit for $f_1(1420)$ production of $f_1(1420) \rightarrow \eta\pi\pi/f_1(1285) \rightarrow \eta\pi\pi < 0.1$ (95% c.l.).

3.3 The $f_1(1285)$ meson

We have performed a fit of the $2\pi^+2\pi^-$ mass spectrum for the combined reactions. In order to take into account the reflections coming from the $\eta\pi^+\pi^-$ final state, the $2\pi^+2\pi^-$ mass spectrum has been extracted from reactions (3) and (4) for the case where $m(\eta\pi\pi) < 1.35$ GeV. The fit involves a simple Breit–Wigner to describe the $f_1(1285)$ meson, the background reaction (5) and the histogram representing the $\eta\pi\pi$ reflections for which the overall size has been left as a free parameter. Various fits have been performed and we have found that the presence of reflections largely affects the $f_1(1285)$ width which can be determined only with large systematic errors. The fitted parameters of the $f_1(1285)$ meson are found to be

$$m = 1278 \pm 2 \text{ MeV},$$

$$\Gamma = 41 \pm 12 \text{ MeV},$$

and the fit has a $\chi^2/ND\Gamma = 223/188$. The experimental resolution has been estimated to be $\sigma \approx 10$ MeV at the $f_1(1285)$ mass. The results of the fit are shown in fig. 7 where a large contribution to the χ^2 can be seen to come from the E/t region.

In order to determine the $f_1(1285)$ branching ratio we have compared its decays to $2\pi^+2\pi^-$ and $K_S^0 K^\pm \pi^\mp$. The $K_S^0 K^\pm \pi^\mp$ mass spectrum is shown in fig. 8, where clear $f_1(1285)$ and $f_1(1420)$ signals can be seen. Details of the criteria used to select the above channel can be found in ref. [3]. We note here that we used the sample of events having one particle identified as a K or ambiguous K/p. Events having the secondary vertex at less than 3 cm from the main vertex have been removed in order to reduce inefficiencies in the K_S^0 reconstruction. The ratio of the geometrical acceptances between the $K_S^0 K^\pm \pi^\mp$ and $2\pi^+2\pi^-$ decay modes has been found to be 0.49 in the $f_1(1285)$ region. In order to extract the $f_1(1285)$ and $f_1(1420)$ yields, a fit to the $K_S^0 K^\pm \pi^\mp$ spectrum using two Breit – Wigners and a background of the form (5) has been performed as shown in fig. 8. Taking into account unseen decay modes (a factor 3 for the $K\bar{K}\pi$ decay mode and a factor 3 for the 4π decay mode) and the different sensitivity of the trigger for the two reactions (a factor 2.7 in favour of the $K^\pm$ final state) we obtain a ratio

$$(f_1(1285) \rightarrow K\bar{K}\pi)/(f_1(1285) \rightarrow 4\pi) = 0.31 \pm 0.02 \pm 0.03.$$

By using the same method and fitting the $2\pi^+2\pi^-$ mass spectrum by “assuming” the presence of the $f_1(1420)$ meson we obtain

$$(f_1(1420) \rightarrow 4\pi)/(f_1(1420) \rightarrow K\bar{K}\pi) \leq 0.87 \text{ (95\% c.l.)}$$

In the calculations of the above branching ratios we have neglected contributions from other resonances seen by some experiments in this mass range such as the $\eta(1275)$, $\eta(1420)$ and $\eta(1440)$ which have been found [3] to be negligible in the kinematical region covered by this experiment.

4. CHANNEL LIKELIHOOD FIT

In order to make a quantitative analysis and to separate the different reactions which contribute to the observed final states (1) and (2), we have used the technique of the Channel Likelihood Fit [8] using a modified version of the program CHAFIT [9].

The program performs a maximum likelihood fit of different overlapping amplitudes. We have used Breit – Wigner amplitudes to describe the observed resonances. The reflections from the η' and the $f_1(1285)$ $\eta\pi\pi$ decay mode in the low mass region of the 4π mass spectrum have been parametrized as two Gaussians at masses of 800 and 1059 MeV and σ 's of 56 and 150 MeV respectively. The K^0_S was parametrized as a Gaussian centred at the K^0_S mass and having a σ of 7.5 MeV. Each amplitude has to be normalized by integration over the Lorentz Invariant Phase Space (LIPS). Our reactions, however, are confined by the trigger conditions to a limited region of phase space and it was difficult to reproduce completely, using standard Monte – Carlo techniques, the phase – space distribution in all the mass combinations. All the features of the data were reproduced by generating artificial events where each of the six outgoing tracks was randomly taken from different real events. The events resulting from this kind of Monte – Carlo generator were used as phase space to integrate the input amplitudes for the fit. The program fits the data in an iterative procedure, and at the end a likelihood function is computed and a weight assigned for each event to belong to one of the input channels in the fit. In order to check how the different resonant contributions have been described by the program, we have plotted, in figs 3 and 4 (dashed histograms), the part of the data which are found by the fit not to contain any of the resonances observed in this mass spectrum. In the $\pi^+\pi^-$ mass spectrum, for example, we have plotted all the $\pi^+\pi^-$ combinations excluding all the weights corresponding to the presence, in any of the combinations, of the K^0_S , the $\rho^0(770)$ and the $f_2(1270)$. It can be seen that the resonances have been satisfactorily taken into account by the fit. The results are summarized in table I.

We note that both reactions proceed strongly through $\rho\pi^+\pi^-$ (38%). We have included the $f_1(1285)$ with 4π and $\rho\pi\pi$ as possible decay modes. The result of the fit shows that the $f_1(1285)$ proceeds entirely through the $\rho^0(770)\pi^+\pi^-$ decay mode, in the 4π channel.

We note that the fit gives a small contribution of $\rho^0\rho^0$ ($2.8 \pm 0.5\%$ for the proton data and $1.3 \pm 0.7\%$ for the π^+ data) in contrast with what was found in $\gamma\gamma$ collisions [10] and radiative J/ψ decay [11]. Figure 9 shows the scatter diagram $m(\pi^+\pi^-)_{3,4}$ vs $m(\pi^+\pi^-)_{1,2}$ (two combinations per event) where no indication is seen for a large $\rho^0\rho^0$ contribution.

5. DALITZ PLOT ANALYSIS OF THE THREE – PION SYSTEM

In order to investigate the spin structure of the three – pion system we have performed a Dalitz plot analysis assuming an isobar model, where the three – pion system decays through $\rho\pi$ and $\varepsilon\pi$ in a spin configuration up to two, by using the Zemach tensor method [12]. The formalism can be found in ref. [13].

The geometrical acceptance as a function of the three – pion effective mass (fig. 10) is smooth in the region of interest and does not influence the Dalitz plot analysis which has been performed using the unweighted events. Many possible combinations of waves and interferences ($\rho\pi$, $\varepsilon\pi$ and 3π) have been tried and those contributions found to be small or not continuous over the entire 3π mass range were removed from the fit. It was found that keeping or removing the events in the Δ^{++} in the $p_f \pi^+$ spectrum (p beam) or the $\rho^0(770)$ and $f_2(1270)$ in the $\pi_f^+ \pi^-$ spectrum (π^+ beam) did not change the main results of the analysis. The results are shown in fig. 11 and can be summarized as follows:

- a. The data do not require waves other than those coupled to $\rho\pi$.
- b. The $J^{PC} = 2^{++}$ wave peaks, as expected, at the $a_2(1320)$ mass.
- c. The $J^{PC} = 1^{++}$ wave has the largest intensity and comes entirely from an S – wave $\rho\pi$ system, the D – wave contribution being insignificant.

6. CONCLUSIONS

We have studied the $2\pi^+2\pi^-$ system centrally produced by incident π^+ and p at 85 GeV/c. The $2\pi^+2\pi^-$ effective mass distribution (from both beams) shows a narrow structure having a mass of 1278 ± 2 MeV and a width of 41 ± 12 MeV which we identify as the $f_1(1285)$ meson. This confirms previous observations on the dynamics of the production of this meson which prefers to be produced centrally rather than peripherally [14,15].

A study of the $\eta\pi^+\pi^-$ system also provided evidence for the decay of the $f_1(1285)$ into $\eta\pi\pi$ and little or no evidence for the $f_1(1420)$ decay to $\eta\pi\pi$ for which we measure an upper limit $(f_1(1420) \rightarrow \eta\pi\pi)/(f_1(1285) \rightarrow \eta\pi\pi) < 0.1$ (95% c.l.).

We have determined the ratios $(f_1(1285) \rightarrow K\bar{K}\pi)/(f_1(1285) \rightarrow 4\pi) = 0.31 \pm 0.02 \pm 0.03$ and $(f_1(1420) \rightarrow 4\pi)/(f_1(1420) \rightarrow K\bar{K}\pi) \leq 0.87$ (95% c.l.). The $\rho^0\rho^0$ contribution is found to be small.

A Dalitz plot analysis of the 3π system shows the $a_2(1320)$ in the $J^{PC} = 2^{++}\rho\pi$ wave and a large contribution from the $J^{PC} = 1^{++}$ S-wave $\rho\pi$.

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TABLE 1

Results from the Channel Likelihood Fit. The amount
of each channel is given in per cent.

Channels	π^+ incident	p incident
$(\pi^+/p)_f f_1(1285)(\rightarrow \rho\pi\pi) p_s$	3.0 ± 0.3	3.1 ± 0.2
$(\pi^+/p)_f \rho(770)\pi\pi p_s$	40.9 ± 2.0	37.0 ± 1.4
$\rho(770)_f \rho(770)\pi p_s$	13.5 ± 0.7	
$\Delta^{++}_f \rho(770)\pi p_s$		10.5 ± 0.5
$(\pi^+/p)_f f_2(1270)\pi\pi p_s$	10.7 ± 0.5	9.2 ± 0.4
$(\pi^+/p)_f a_2(1320)\pi p_s$	4.9 ± 0.9	3.9 ± 0.6
$\rho(770)_f 3\pi p_s$	7.4 ± 0.7	
$f_2(1270)_f 3\pi p_s$	2.5 ± 0.5	
$\Delta^{++}_f 3\pi p_s$		11.3 ± 0.5
$(\pi^+/p)_f \rho(770)\rho(770) p_s$	1.3 ± 0.7	2.8 ± 0.5
K^0 contamination	1.0 ± 0.3	1.4 ± 0.2
$\eta' (\rightarrow \eta\pi\pi)$ reflection	0.6 ± 0.1	1.0 ± 0.1
$f_1(1285) (\rightarrow \eta\pi\pi)$ reflection	6.1 ± 0.4	6.4 ± 0.3
phase space	8.0 ± 1.7	13.4 ± 1.2

FIGURE CAPTIONS

Fig. 1 Δ function distribution for the $\pi^+\pi^+\pi^-\pi^-$ channel.

Fig. 2 Feynman- x_F distribution for the slow proton, the central $\pi^+\pi^+\pi^-\pi^-$ system and the fast particle for the π^+ incident data.

Fig. 3 (a,b) $2\pi^+2\pi^-$ effective mass distributions for the π^+ and p incident data respectively;
(c,d) $\pi^\pm\pi^+\pi^-$ effective mass distributions for the π^+ and p incident data respectively.

The dashed histograms represent the results of the Channel Likelihood Fit (see text).

Fig. 4 (a,b) $\pi^+\pi^-$ effective mass distributions for the π^+ and p incident data respectively;
(c) $\pi^+_f\pi^-$ effective mass distribution for the π^+ incident data;
(d) $p_f\pi^+$ effective mass distribution for the p incident data.

The dashed histograms represent the results of the Channel Likelihood Fit (see text).

Fig. 5 (a) Distribution of the missing mass squared to the six outgoing particles for the six-prong events after having excluded reactions (1) and (2). The curve represents the estimated background under the π^0 peak.

(b,c) $\pi^+\pi^-\pi^0$ effective mass distributions for the channels $\pi^+/pp \rightarrow \pi^+_f/p_f(2\pi^+2\pi^-\pi^0)p_s$ (f entries per event) for the π^+ and p beams respectively. The dashed histograms represent the result of subtracting the combinatorial background by using the method of mixed events.

Fig. 6 $\eta\pi^+\pi^-$ effective mass distributions for: (a) the incident π^+ beam, (b) the incident p beam and (c) the sum. The line is the result of the fit described in the text.

FIGURE CAPTIONS (Cont'd)

- Fig. 7 $\pi^+\pi^+\pi^-\pi^-$ effective mass distributions for: the combined reactions (1) and (2). The line is the result of the fit described in the text. The full line histogram is the fitted contamination from the $\eta\pi\pi$ channel.
- Fig. 8 $K^0_S K^\pm \pi^\mp$ effective mass. The line is the result of the fit described in the text.
- Fig. 9 Scatter diagram $m(\pi^+\pi^-)_{3,4}$ vs. $m(\pi^+\pi^-)_{1,2}$. (two entries per event) for a sample of data for reactions (1) and (2).
- Fig. 10 $\pi^\pm\pi^+\pi^-$ acceptance as a function of the 3π effective mass.
- Fig. 11 Results from the Dalitz plot analysis of the 3π system.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

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Fig. 9

Fig. 10

Fig. 11