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Neutral three-pion resonance production in 15-GeV/c π^+-deuteron collisions

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The production of $\pi^+\pi^-\pi^0$ events allows the study of pure $I = 1$ exchange without the complicating presence of the $\Delta(1236)$ which appears with proton targets. A total of 4218 events, corresponding to 8.5 events/μb, were analyzed from an exposure of the SLAC 82-inch deuterium bubble chamber. The low-mass resonances [η, ω, A_2, and $\omega(1675)$] are clearly observed. In addition, enhancements due to possible higher-mass resonances are observed by using the technique of $p_\perp$ cuts.

INTRODUCTION

The production of neutral (3π) resonant states, in pion-deuteron collisions at energies greater than several GeV, is always a small fraction of the total cross section. This is in contrast to the neutral dipion $(\pi^+\pi^-)$ spectrum from π^+d interactions, as well as the charged (3π) states induced in $\pi^\pm p$ collisions. In some measure, the relative dearth of netural (3π) resonant production in π^+d interactions reflects the fact that neither pion charge exchange nor pion diffractive dissociation can result in the production of the $\pi^+\pi^-\pi^0$ system at the pion vertex. The purpose of this article is to present our results concerning the odd-G-parity bosons produced in the reaction $\pi^+d \to pp\pi^+\pi^-\pi^0$. Our attention will focus on the production of states more massive than the ω (1675).

EXPERIMENTAL DETAILS

The data of this experiment were obtained from an 890 000-picture exposure of the SLAC 82-inch, deuterium-filled bubble chamber in an rf-separated π^+ beam of 15 GeV/c. (The sample for this reaction comes from the measurement of four-prong events with spectators and some three-prong events with a possible proton candidate chosen during the scanning process.) The first 40% of the events were measured on a Hough-Powell device while the remainder were measured on a spiral reader. Every positive particle below 1.5 GeV/c momentum was identified by ionization. In addition, all events that had a four-constraint fit ($\pi^+d \to \pi^+\pi^-pp$, $\pi^+d \to K^+K^-pp$, and $\pi^+d \to ppp\bar{p}$) were removed from the sample. Figure 1 shows the square of the missing mass $(\text{MM})^2$ where a clear π^0 peak is observed. Unfortunately, neutral η decays produce a shoulder at $(\text{MM})^2 = 0.3$ GeV thereby making the separation of single π^0 events from multi-π^0 events and η events a little more difficult. In addition, only those events with a χ^2 fit probability of $\geqslant 2\%$ and $-0.2 < (\text{MM})^2 < 0.24$ GeV^2 were included in the sample. 4218 events survived the cuts, with about 10% being multi-π^0 or $\eta \to \gamma\gamma$ events. This corresponds to $\sigma(\pi^+d \to \pi^+\pi^-\pi^0pp) = 495 \pm 30$ μb, giving a

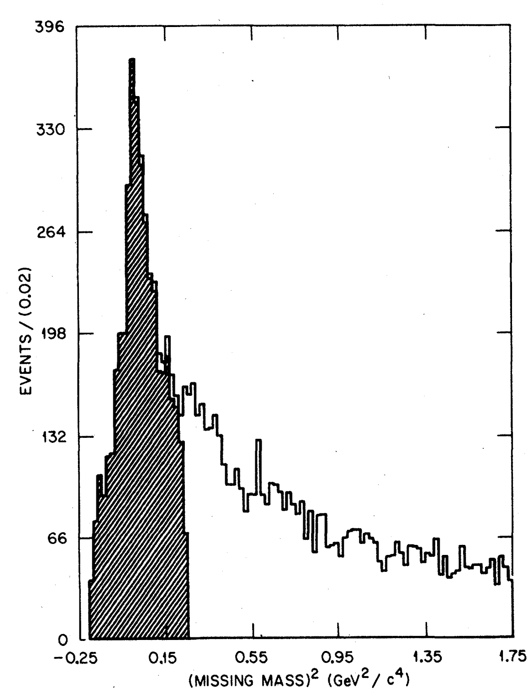

FIG. 1. Distribution of the square of the missing mass for events without a four-constraint fit. The shaded area corresponds to those events which were selected as π^0 fits ($\pi^+d \to pp\pi^+\pi^-\pi^0$).

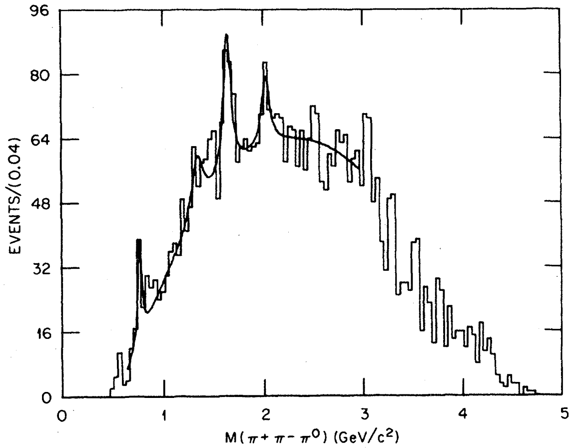

FIG. 2. Full $\pi^+\pi^-\pi^0$ mass spectrum.

sensitivity of 8.5 events/μb. Other published results[1] from this film include additional experimental details.

THE NEUTRAL ODD-*G*-PARITY BOSONIC SPECTRUM

In Fig. 2, we present the full $\pi^+\pi^-\pi^0$ spectrum from our data. Aside from the lower-mass states (η, ω), the evidence for 3π states in this histogram is less than compelling. Nevertheless, the spectrum has been fitted with Breit-Wigner resonances for the η, ω, A_2, $\omega(1675)$, and $A_2^*(2030)$ and with a polynomial background including terms quadratic in mass, from threshold to 3 GeV. Because background in the η region is essentially zero and because of the paucity of events in this region, the cross section for η production is obtained by merely counting events. Further, with such a small sample, mass and width measurements would not be particularly meaningful. Because of the poor quality of the A_2 signal in this spectrum, its mass and width were constrained so they would not exceed 1370 and 150 MeV, respectively. In addition, the quality of the fit is enhanced by the inclusion of a higher-mass state at ~2050 MeV with a width of 100 MeV. The production cross sections together with the fitted masses and widths are given in Table I. As was mentioned in the Introduction, 3π resonance production does not appear to be a dominant effect in the spectrum. These well-established states contribute only about 40 μb. Because of the rather structureless nature of the spectrum in the A_2 region, we show in Fig. 3 the 3π spectrum, where all events with any $p\pi$ mass less than 1.7 GeV/c^2 have been removed. Although this removes about 70% of our sample, the resulting spectrum displays convincing evidence for both A_2 and $\omega(1675)$ production. Furthermore, in this latter

TABLE I. Boson productions for the reaction $\pi^+ d \rightarrow pp\pi^+\pi^-\pi^0$. The cross-section determination refers only to those decays which appear in the $\pi^+\pi^-\pi^0$ final state. The mass and width of the A_2 has been constrained not to exceed the values shown in the table. Similarly the $A_2^*(2030)$ width was required to be no less than 100 MeV.

3π state	Cross section (μb)	Mass (MeV)	Width (MeV)
η	2.5 ± 0.6	~550	
ω	5.4 ± 1.6	784^{+70}_{-12}	45 ± 21
A_2	10.4 ± 3.1	1370	150
$\omega(1675)$	15.0 ± 3.8	1679 ± 13	92 ± 37
$A_2^*(2030)$	8.0 ± 3.0	2064 ± 24	100

spectrum, the η and ω become more pronounced features of the data. However, at this level of analysis there appears to be no structure beyond the $\omega(1675)$.

To amplify our search for higher-mass 3π states, we invoke a method suggested by Hagopian *et al.*[2] and subsequently exploited by Deutschmann *et al.*[3] in their search for massive states produced in πp collisions. These authors have observed that higher mass resonances become enhanced in multiparticle spectra when only those events are included for which the transverse momentum of each decay particle exceeds some specified minimum value. In their study of the reaction $\pi^+ p \rightarrow \pi^+\pi^+\pi^- p$ at 16 GeV/c, Deutschmann *et al.*[3] observed the usual structure in the complete 3π spectrum at the A_1, A_2, and A_3 mass regions. However, as the acceptable minimum value for the transverse momentum of each pion (p_T) increases from zero to 0.3 GeV/c in steps of 0.05 GeV/c, the relative amounts of A_1, A_2, and A_3 in the spectra change.

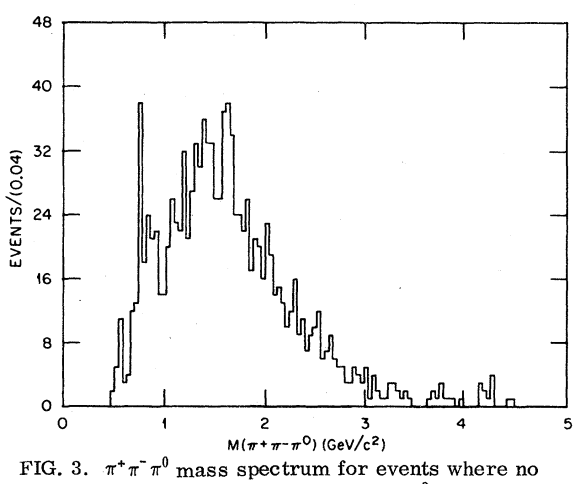

FIG. 3. $\pi^+\pi^-\pi^0$ mass spectrum for events where no pion-nucleon mass is less than 1.7 GeV/c^2.

At the highest p_T cut, the A_1 has disappeared while the A_3 is more prominent than the A_2. This contrasts to the state of affairs at the lesser p_T cuts or in the unselected spectrum. In addition, at the highest p_T cut $[\langle p_T\rangle = 0.3\ \mathrm{GeV}/c]$, a new structure appears at a mass of 1.8 GeV/c^2, for which additional analysis suggests at least a partial $f^0\pi$ decay.

In order to effect a comparison between the π^+p experiment alluded to in the previous paragraph and our π^+d experiment, all of our subsequent presentation will refer to data for which no (πp) mass lies in the $\Delta(1236)$ region $(1.0 \leq M_{p\pi} \leq 1.36$ GeV/$c^2)$. While our data are relatively insensitive to such a restriction, such a selection is patently desirable when analyzing π^+p interactions because of the dominance of $\Delta(1236)$ production.

In Fig. 4, we plot the neutral 3π spectra for those events where the squared transverse momentum (p_T^2) for each pion exceeds the minimum values 0.04, 0.06, 0.08 GeV^2/c^2. At the smallest p_T^2 cut, only the $\omega(1675)$ among the well-established particles is manifest, while evidence for the A_2 is marginal, at best. This is in sharp contrast with the π^+p data where, for a similar p_T cut, it is still a prominent feature of the (3π) mass spectrum. This undoubtedly reflects the difference in production mechanisms of the charged and neutral A_2 mesons.[4] At the larger p_T^2 cuts [Figs. 4(b) and 4(c)], not only does the $\omega(1675)$ become relatively more dominant, but also higher-mass structures appear to be present.

For reasons of statistics, we have chosen to fit the intermediate (p_T^2) spectrum $(p_T^2 > 0.06$ GeV^2/$c^2)$ rather than the one with the most restrictive transverse-momentum selection. Our best fit, using a background including terms quadratic in mass, was obtained by employing Breit-Wigner resonances for the $\omega(1675)$ and three higher-mass states [smooth curve, Fig. 4(b)]. The parameters determined from this fit are given in Table II. The inclusion of a cubic-mass term in the background has negligible effect on the fitted parameters. A fit of somewhat lesser probability is obtained when the two higher-mass states are coalesced into a single, broad state.

Our first observation concerning these high-p_T^2 spectra is that there appears to be no neutral object present at a mass of ~1.8 GeV/c^2 corresponding to the charged state observed by Deutschmann *et al.*[3] This suggests that the principal production mechanism of the charged state is either diffractive or a process similar to A_2 production, whereby A_2^0 production in higher-energy π^+n collisions is considerably inhibited relative to $A_2^\pm$ production in $\pi^\pm p$ reactions.[4,5]

Higher-mass odd-G-parity bosons have recently

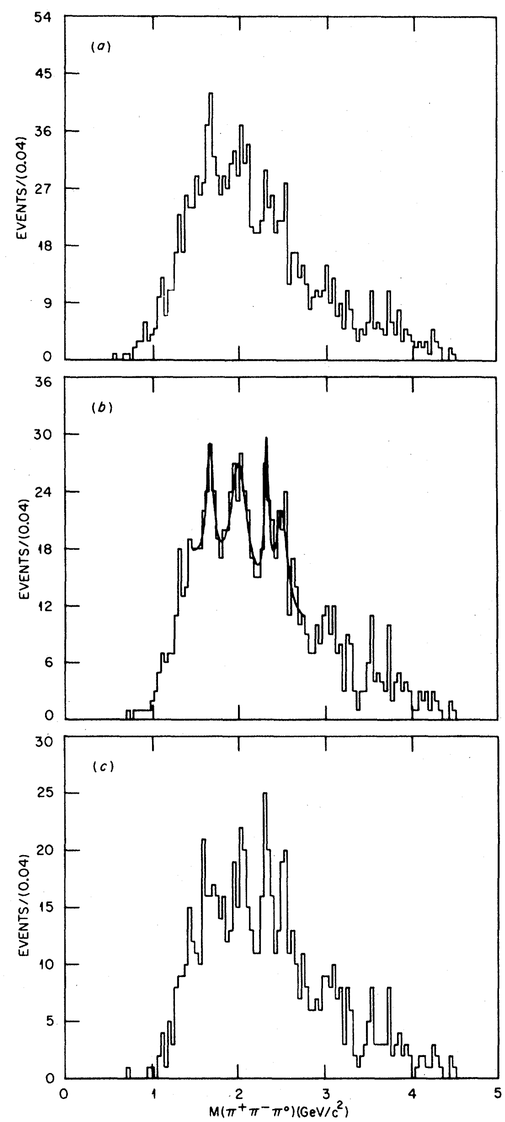

FIG. 4. $\pi^+\pi^-\pi^0$ mass when each pion has a squared transverse momentum greater than (a) 0.04 GeV^2/c^2; (b) 0.06 GeV^2/c^2; (c) 0.08 GeV^2/c^2.

been reported at 1942 MeV $(\Gamma = 57.6$ MeV),[6] 1900 MeV,[7] 2340 MeV $(\Gamma = 180$ MeV),[8] ~1900 MeV $(\Gamma \sim 200$ MeV),[9] and 2030 MeV $(\Gamma = 510 \pm 20$ MeV).[10] The states most relevant to our observations would appear to be those of mass in excess of 2 GeV/c^2. The state at 2.34 GeV decays primarily into $\rho\rho\pi$ and has isospin of at least one. Our five-pion data from the channel, $\pi^+d \to pp\pi^+\pi^+\pi^-\pi^-\pi^0$, have been examined for signals in the $\rho^0\rho^0\pi^0$, $\rho^+\rho^0\pi^0$ and $\rho^-\rho^0\pi^0$ spectra (not shown) without detecting

TABLE II. Mass, width, and production cross sections for states appearing in high-p_T^2 data. If the two most massive states are combined, we find a production cross section of 21 ±4 μb with a mass of 2467±39 MeV and a width of 385±85 MeV.

State	Mass (MeV)	Width (MeV)	Cross sections (μb)
ω(1675)	1695±19	97±60	5.8±2.1
$A_2^*(2030)$	2032±27	238±68	15.5±3.3
	2355±15	61^{+50}_{-20}	3.3±1.3
	2530±30	157^{+90}_{-53}	7.8±2.4

any significant enhancements. Since this 2.34-GeV/c^2 state decays into 3π less than 10% of the time, it is clear that none of the neutral enhancements observed here can be identified with it.

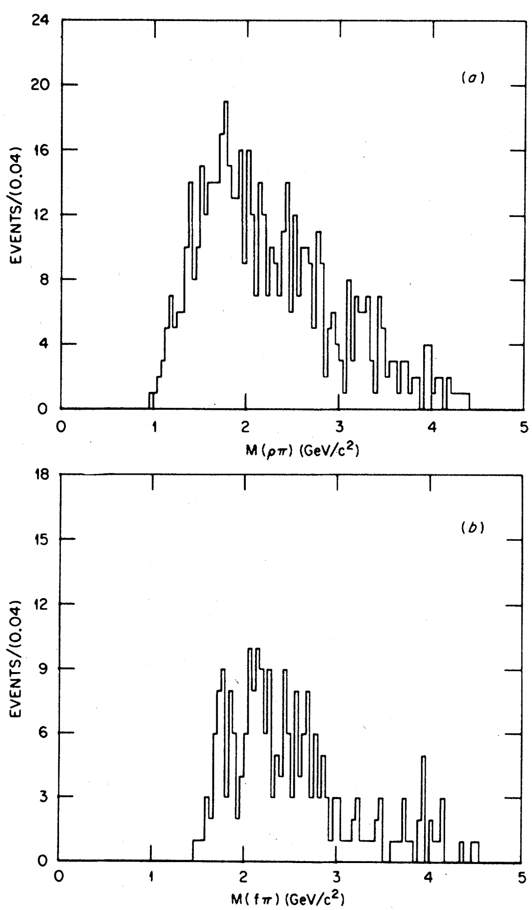

FIG. 5. (a) $(\rho\pi)^0$ mass spectrum when each pion has a squared transverse momentum greater than 0.06 (GeV/c)^2. (b) $f^0\pi^0$ mass spectrum when each pion has a squared transverse momentum greater than 0.06 (GeV/c)^2.

The other relevant state, observed by Corden *et al.*,[10] in a study of the reaction $\pi^- p \to n\pi^+\pi^-\pi^0$, using the CERN Omega multiparticle spectrometer is quite broad (Γ ~ 510 MeV). It would seem likely that the state we observe at 2037±27 MeV should be identified with this state, even though our fitted width (Γ = 238±68 MeV) is several standard deviations less than the value reported by these authors. In our data, this state appears in the (p_T^2 > 0.06 GeV^2/c^2) spectrum as a 5-standard-deviation enhancement over background. Moreover, we are not able to achieve an acceptable fit to this spectrum without the introduction of at least one, and more likely, (from χ^2 considerations) two additional states with masses of 2355±15 MeV ($\Gamma = 61^{+50}_{-18}$ MeV) and 2530±26 MeV ($\Gamma = 157^{+90}_{-53}$ MeV). Aside from the observations of Baltay *et al.*[8] on the (predominantly) ρρπ state at 2340 MeV, we are aware of no current evidence for neutral odd-*G*-parity objects in this mass region.

We have also subjected these high-p_T^2 spectra to the requirement that two of the three pions be in the ρ region (0.66 GeV/$c^2 \leq M_\rho \leq$ 0.86 GeV/c^2) [Fig. 5(a)]. None of the states at masses larger than 1.8 GeV/c^2, appears to be enhanced by the selection of either (ρ^+, ρ^-) or (ρ^+, ρ^-, ρ^0). We show only the latter result since it is to be expected that the higher-mass states will be isoscalar as they have not appeared in the much more widely investigated $\pi^+\pi^+\pi^-$ spectra. [Fig. 5(b)] shows the $f^0\pi^0$ mass spectrum (1.12 ≤ M_f ≤ 1.42 GeV/c^2) under the conditions that p_T^2 for each pion exceeds 0.06 GeV^2/c^2. While the data are obviously rather limited, statistically, this spectrum suggests that, at least, the state around 2.0 GeV may have a significant $f^0\pi^0$ decay mode. Because of the large (≈200 MeV) mass difference with the $f^0\pi$ state observed by Deutschmann *et al.*[3] it is uncertain whether the two experiments are observing the same object.

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