Diffractive and Nondiffractive A_1, A_3, and A_4 Production in π^+p Interactions at 15 GeV/c

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We have studied the spin-parity structure of the 3π system produced opposite a proton or Δ^{++} in π^+p interactions at 15 GeV/c. Our results suggest that the broad enhancement at 1.1 GeV, traditionally associated with the A_1, does not have the properties usually associated with a resonant state. We obtain similar results for the A_3 and A_4 enhancements.

The quark model predicts the existence of an axial-vector meson state with odd G parity. This state is traditionally associated with the A_1, a broad enhancement observed around 1.1 GeV in the invariant mass of the diffractively produced 3π system. However, the resonant interpretation of the A_1 is not clear since its position coincides with that of the $(\rho\pi)$ Deck effect.[1-5]

In this Letter, we report on a study of the resonant properties of the 3π system produced in π^+p interactions. We have performed an energy-independent spin-parity decomposition of the 3π system using a partial-wave–analysis program which we have developed for this purpose.[1]

Our data have been derived from an 866 000-picture exposure of the Standord Linear Accelerator Center 82-in. hydrogen bubble chamber to an rf-separated 15-GeV/c π^+ beam. The sensitivity of the exposure was determined to be 43.3 $\pm$0.5 events/μb. All interactions were measured on the Columbia University Hough-Powell Device operated in an automatic pattern-recognition mode. The present analysis is based on the two reactions[1,6]

$$\pi^+p \to p\pi^+\pi^+\pi^- \quad (25\,991 \text{ events}), \tag{1}$$

$$\pi^+p \to \Delta^{++}\pi^+\pi^-\pi^0 \quad (7728 \text{ events}). \tag{2}$$

We have selected Δ^{++} production in Reaction (2) by requiring at least one $p\pi^+$ mass combination below 1.4 GeV.

The invariant mass of the $\pi^+\pi^-$ system produced in Reaction (1) shows clear peaks due to ρ, f, and g production. If we select the $\pi^+\pi^-$ mass in the ρ and f regions, the $\rho\pi$ and $f\pi$ invariant-mass distributions show broad, low-mass enhancements due to the A_1 and the A_3. Similarly, the $g\pi$ mass distribution shows an enhancement near 2.2 GeV, which was first seen in this experiment[6] and called the A_4. The A_1 and A_3 enhancements are clearly visible in the uncut 3π mass distribution (Fig. 1); the A_4, however, has much smaller cross section and does not show up significantly.

We describe the 3π system in the spirit of the isobar model[1,7] as being the sum of di-pion states with angular momentum l and relative orbital angular momentum of the third π with respect to the di-pion, L. The 3π system has spin and parity J^P, t-channel helicity M, and isospin I. The $(p\pi^+)$ system in Reaction (2) is characterized by its spin-parity state $J_2^{P_2}$ and t-channel helicity M_2.

The decay of the 3π system is described in terms of two Dalitz-plot variables and three Euler angles. For Reaction (2), we have added three more variables to describe the decay of the $p\pi^+$ system: the invariant mass of the $p\pi^+$ system, $m_{p\pi^+}$, and the polar angles of the proton in the $p\pi^+$ rest frame.

The probability density function for a fixed region of total energy $\sqrt{s}$, 3π mass $m_{3\pi}$, and momentum transfer t' can be written in terms of the generalized density matrix ρ. We have adopted for the density matrix the "minimal parametriza-

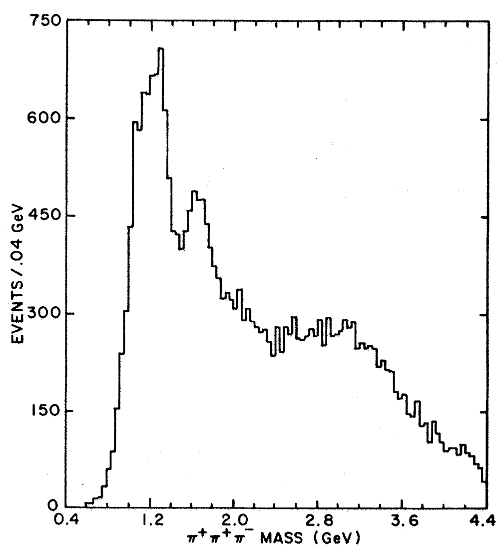

FIG. 1. Invariant-mass distribution of the 3π system from Reaction (1).

tion" suggested by Chung and Trueman.[8] By imposing the proper rank condition on the density matrix, the number of free parameters in the fit increases linearly with the number of amplitudes, rather than quadratic as one might expect in a density-matrix analysis.[2-5] None of the amplitudes included in our fits have been forced to be coherent. The extended maximum-likelihood method[9] has been used to estimate the real and imaginary parts of all density-matrix elements from the data.

We have attempted fits with all partial waves with spin ≤ 3, helicity $|M|=0, 1$, and orbital angular momentum $l+L \leq 3$. The notation $\epsilon\pi$, $\rho\pi$, $f\pi$, or $g\pi$ identifies, respectively, the angular momentum of the di-pion $l=0$, 1, 2, or 3. For Reaction (2), in addition to amplitudes with isospin $I=1$, we have considered amplitudes with $I=0$ and we have also included the 3^- $(\rho\pi)\, f_{I=0}$ and 3^- $(g\pi)\, p_{I=0}$ states.

To determine the dependence of different spin-parity states on $m_{3\pi}$, we have made fits in $m_{3\pi}$ intervals up to 2.5 GeV in Reaction (1) and between 0.9 and 2.0 GeV in Reaction (2). We have used the t' cut: $t'<0.5$ GeV^2 for Reaction (1) and $t'<0.8$ GeV^2 for Reaction (2). In order to describe the data with a relatively small number of amplitudes (i.e., $J \leq 3$), we have eliminated events from Reaction (1) with at least one $p\pi^+$ mass combination $m_{p\pi^+}<1.5$ GeV and events from Reaction (2) for which both $m_{p\pi^+}$ mass combinations were below 1.4 GeV. All cuts have been properly taken into account in the fitting procedure.[1] After all cuts were applied, we were left with 11 720 events in Reaction (1) and 6576 events in Reaction (2).

Only states belonging to the unnatural-parity series were found to be important in Reaction (1). The only exception is the 2^+ $(\rho\pi)$ d wave in the region of the A_2^+ resonance. Also, all unnatural-parity states are produced with helicity $M=0$ in the Gottfried-Jackson frame, corresponding to natural-parity exchange in the t channel. A complete description of our method and the results of our analysis are given in Ref. 1. In the following, we will summarize some of the results regarding A_1, A_3, and A_4 production.

In Fig. 2, we show the mass dependence of some of the most important waves contributing to Reaction (1). The A_1, A_2, A_3, and A_4 are clearly visible as enhancements in the 1^+ $(\rho\pi)$ s, 2^+ $(\rho\pi)$ d, 2^- $(f\pi)$ s, and 3^+ $(g\pi)$ s waves. We have used a nonrelativistic Breit-Wigner shape to fit the mass distributions in Fig. 2. The best fits are shown in the figure (solid line) and the corresponding

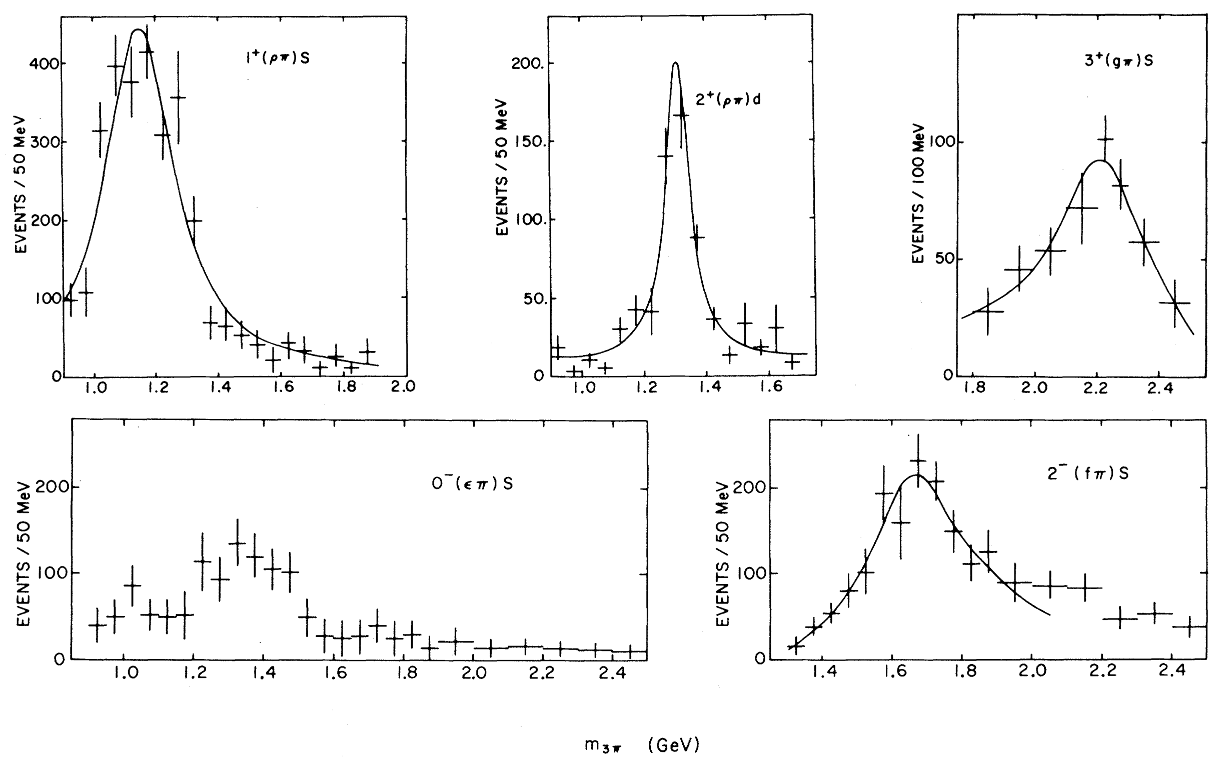

FIG. 2. Dependence on $m_{3\pi}$ of several partial waves from Reaction (1).

TABLE I. Mass, width, and cross section for all enhancements from Reaction (1).

State	Mass (GeV)	Width (GeV)	Cross section (μb)
A_1: $1^+ (\rho\pi) s$	1.152 ± 0.009	0.264 ± 0.011	129.8 ± 7.8
A_2: $2^+ (\rho\pi) d$	1.311 ± 0.008	0.099 ± 0.012	30.7 ± 2.9
A_3: $2^- (f\pi) s$	1.662 ± 0.010	0.285 ± 0.060	52.5 ± 10.0
A_4: $3^+ (g\pi) s$	2.214 ± 0.015	0.355 ± 0.021	15.6 ± 3.0

parameters are given in Table I. The fit required no background under the A_1 and only a small background under the A_2, A_3, and A_4.

The only state showing an enhancement above 2 GeV in Reaction (1) is the $3^+ (g\pi) s$ (Fig. 2). The position of the peak coincides with the A_4 seen in the $(g\pi)$ invariant mass [Fig. 1(d)]. We identify therefore the spin-parity state of the A_4 to be 3^+ and its decay 100% to $(g\pi)$, in the 3π channel.

Our analysis is sensitive to the interference phase between different amplitudes. The only wave whose phase shows a Breit-Wigner type of variation is the $2^+ (\rho\pi) d$ amplitude (Fig. 2) in the region of the A_2^+ resonance.[1] We have examined all interference phases of the $1^+ s$, $2^- s$, and $3^+ s$ waves with background amplitudes. None of the A_1, A_3, and A_4 enhancements are associated with a resonant phase increase. We show in Fig. 3 the mass dependence of some of the interference phases which have smaller errors. In particular, our data do not support the claim of a resonant phase increase of the $2^- (f\pi) s$ wave in the 1.6–1.8-GeV region.[4,5] Our results, which for the A_1[2-5] and A_3[2,3] are consistent with previous experiments, suggest that the A_1, A_3, and A_4 enhancements are not simple Breit-Wigner resonances, like the A_2 for instance.

If the A_1, A_3, and A_4 are resonant states, they should also be produced by charge exchange in

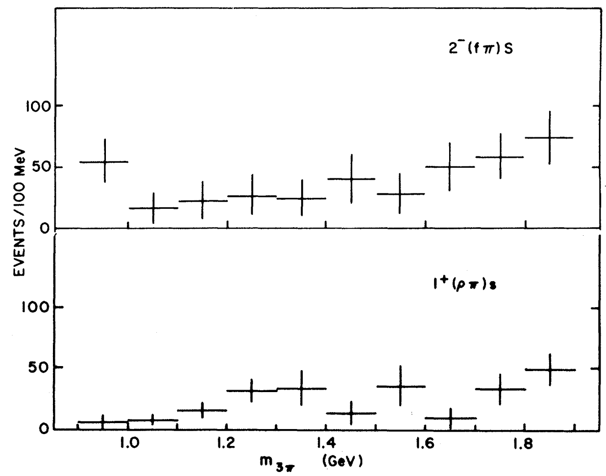

FIG. 4. Dependence on $m_{3\pi}$ of the $1^+ (\rho\pi) s$ and $2^- (f\pi) s$ isovector waves from Reaction (2).

Reaction (2), where the Deck background is suppressed. The partial-wave analysis of Reaction (2) shows clear evidence for the resonant behavior of the $2^+ (\rho\pi) d_{I=1}$ and $3^- (\rho\pi) f_{I=1}$ amplitudes, associated with A_2^0 and $\omega'(1675)$ production.[1] However, we see no evidence for A_1^0 or A_3^0 production in the $1^+ (\rho\pi) s$ and $2^- (f\pi) s$ waves (Fig. 4). The $1^+ (\rho\pi) s$ wave has very little contribution in both isospin states. In particular, in the A_1 region ($m_{3\pi} \sim 1.1$ GeV). The isovector $1^+ s$ state is within 2 standard deviations of zero. The 1σ upper limit for A_1^0 production at a mass of 1.1 GeV is $\sigma_{A_1^0} < 0.5$ μb, for an A_1 width of 200 MeV. This value can be compared with cross sections for A_1^0 production in Reaction (2), recalculated recently by Haber and Kane.[10] Using "reasonable" assumptions, they predict a signal about ten times larger than our 1σ upper limit. Their absolutely lowest limit, including the charge-exchange Deck effect at 1.1 GeV, is 1.2 μb. This is $2\frac{1}{2}$ standard deviations higher than what we observe from the data (Fig. 4). By comparison,

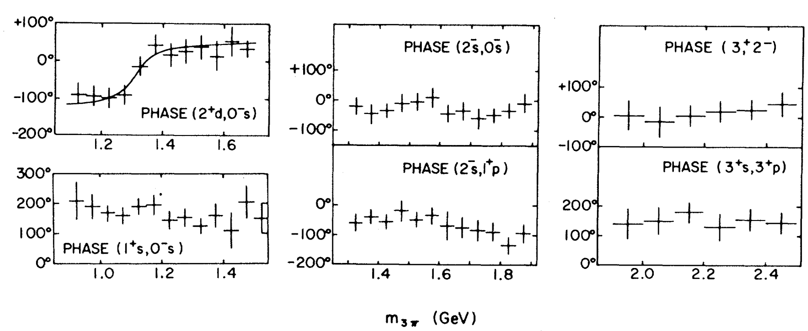

FIG. 3. Dependence on $m_{3\pi}$ of several interference phases from Reaction (1).

our cross section for A_2^0 production in Reaction (2) comes out to be 11.6 ± 1.6 μb.[1]

Several analyses have used an unitarized model to describe the diffractive data in terms of an A_1 resonance in the presence of a Deck background.[11] Their results are indicative of the presence of an A_1 resonance of mass ranging between 1300 and 1500 MeV and width of 200–400 MeV. If such a resonance exists, it should be visible in the nondiffractive 1^+ $(\rho\pi)$ s amplitude (Fig. 4). There is no evidence in our data for a high-mass A_1^0. The highest upper limit in the interval $m_{3\pi} \leq 1.5$ GeV can be set at 1.3 GeV: $\sigma_{1.3} < 3$ μb, consistent with the cross section expected for an A_1 resonance of this mass.[10] The phase of the 1^+ $(\rho\pi)$ s wave shows no evidence for a resonant increase at 1.3 GeV, however, the absolute value of the amplitude is too small below $m_{3\pi} = 1.2$ GeV for an accurate measurement. For the A_3^0, the 1σ upper limit in Reaction (2) is $\sigma_{A_3^0} < 1$ μb.

In conclusion, we have isolated for the first time the wave responsible for the A_4 enhancement: 3^+ $(g\pi)$ s. Within the framework of our analysis, none of the A_1, A_3, or A_4 enhancements is associated with the Breit-Wigner type of phase variation which characterizes the well-established resonances such as the A_2. Also none of the A_1^0, A_3^0, or A_4^0 is produced by charge exchange in Reaction (2). Our upper limit for A_1^0 production at a mass of 1.1 GeV is more than one order of magnitude smaller than the cross section for A_2^0 production in the same process. However, our data do not rule out a higher-mass A_1, i.e., $m_{A_1} \sim 1.3$ GeV.

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Study of Heavy-Ion–Induced Reactions on Uranium with Use of Mica Detectors

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Multifragment reactions are directly observed in heavy-ion–induced reactions using mica track detectors in 2π geometry. Sequential fission is found to be the major reaction channel in the reaction 800-MeV ^{84}Kr + U; however, binary decay can still be identified. A small contribution of reactions with four fragments is observed for the first time in ^{84}Kr- and ^{136}Xe-induced reactions with uranium.

Fission at low and moderate excitation energy is essentially a binary decay process. Theoretical arguments have been presented over a long period of time suggesting that ternary fission should be a possible reaction channel too. Fleischer *et al.* describe the discovery of such a decay mode for Ar-induced reactions.[1] The measured cross section σ_{3F} has always been small: $\sigma_{3F} \leq 0.05\sigma_R$, σ_R being the total reaction cross section.[2]

Recently, heavy ions like Kr or Xe became available for nuclear reaction studies. A new type of reaction was observed, very often named "strongly damped collision."[3] Radiochemical