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OBSERVATION AND PROPERTIES OF THE NEUTRAL A_2 MESON*

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From a 250 000-picture exposure of 3.65-BeV/c π^+ mesons in the Brookhaven 20-inch bubble chamber, we have obtained 2993 events of the type

$$\pi^+ + d \to \pi^+ + \pi^- + \pi^0 + p + p$$

with both protons visible. The three-pion mass spectrum shows an enhancement at about 1300 MeV which we interpret as the $A_2^0(1300)$ meson. Further analysis of the data shows its subsequent decay into $\rho^\pm\pi^\mp$. The properties of the A_2^0 appear to be consistent with those expected for the neutral member of the A_2 triplet, the charged members of which have been observed[1,2] in the reactions $\pi^\pm + p \to A_2^\pm + p$. The branching ratios of the A_2^0 indicate an $I=1$ state which strongly prefers $\rho\pi$ (as opposed to direct 3π) decay. The Dalitz plot density favors a spin-parity assignment of 2^+.

There is no substantial peaking in the $A_1(1080)$ mass region. A comparison with $\pi^- p$ data indicates that the A_1 and A_2 may have different production mechanisms. This can be interpreted as support for the idea that a kinematical (e.g., Deck) effect is present in A_1 production.[3]

Event selection.—The events were analyzed using the TRED and GRIND programs and have χ^2 probability and track ionizations consistent with the hypothesis $\pi^+ + d \to \pi^+ + \pi^- + \pi^0 + p + p$. The spectator protons (defined in each event as the proton of lower momentum) have a range of 1 mm or greater. Of these spectators, 28% have a momentum greater than 250 MeV/c which exceeds our prediction of 9%, based on the Hulthén wave function for the deuteron. No significant correlation was found between the momentum of the spectator proton and the characteristics of the three pion states.

An additional 550 events having a possible proton track with momentum greater than 1.7 BeV/c but also fitting $\pi^+ + d \to \pi^+ + \pi^+ + \pi^- + p + n$ have not been included. This possible bias against events with high Δ^2 (four-momentum transfer squared) from the deuteron to the pp system does not materially affect the reactions discussed here, which are primarily low-Δ^2 processes.

General mass spectra.—The invariant mass of the $\pi^+\pi^-\pi^0$ system is shown in Fig. 1. In addition to the η^0- and ω^0-meson peaks, a broad enhancement is seen around 1300 MeV. Previous studies[4] of this peak in similar experiments have not been able to demonstrate that it was substantially due to $A_2^0 \to \rho^\pm + \pi^\mp$. The lower histogram and smooth curve are discussed later in the text.

The two-body pion-pion and pion-proton mass plots (not shown) give evidence for ρ^+, ρ^0, and ρ^- production and for production of the two-body final states $\rho^+ + N^{*0}(1238)$ and $\rho^0 + N^{*+}(1238)$. There is no evidence for the $\rho^- N^{*++}$ final state. This is perhaps explained by the fact that ρ^+ and ρ^0 can be produced in $\pi^+ n$ collisions by one-pion exchange but ρ^- cannot. The Δ^2 distribution shapes and total numbers of events for the

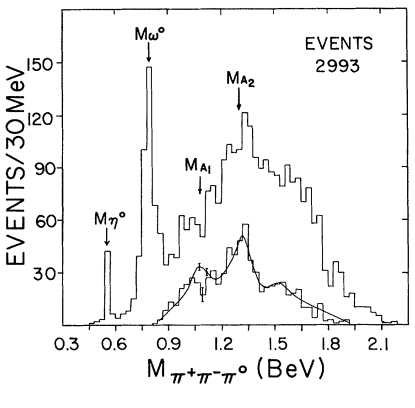

FIG. 1. Effective mass of $\pi^+\pi^-\pi^0$ for all events from $\pi^+ + d \to \pi^+ + \pi^- + \pi^0 + p + p$. The subsample of our events with ρ^+ or ρ^- and $\Delta^2(\to 3\pi) \leq 0.85$ (BeV/c)^2 is shown with a smooth curve taken from a compilation of $\pi^\pm + p \to \rho^0 + \pi^\pm + p$ data.

ρ^+N^{*0} and ρ^0N^{*+} states are in excellent agreement with being identical, as predicted by the one-pion-exchange diagrams. The ρ region is taken throughout this report as 650-850 MeV, and the $N^*(1238)$ region is defined throughout as 1140-1340 MeV.

Rho-pi mass spectra.—The three-pion mass spectrum has been broken into eight parts to search for decays into $\rho^+ + \pi^-$, $\rho^0 + \pi^0$, $\rho^- + \pi^+$, and 3π without ρ. Plotted in Figs. 2(a), 2(b), and 2(c) are the $\pi^+\pi^-\pi^0$ invariant mass distributions for those events having one and only one $\pi\pi$ invariant mass in the ρ region. Plotted in Figs. 2(d), 2(e), and 2(f) are those events with exactly two $\pi\pi$ mass combinations in the ρ region. Fig. 2(g) contains events with three simultaneous combinations in the ρ region. The three-pion mass spectrum for the 1288 events with no $\pi\pi$ mass combination in a ρ region is not shown here. It is smooth except for the η^0 and ω^0 peaks.

In order to estimate the distortion of the three-pion mass spectrum caused by this eight-way cut in the data, a three-pion phase-space background estimate was made and plotted on the histograms. To obtain the curves, we calculated the expected density of points on a symmetrized Dalitz plot[5] at a particular three-pion mass by dividing the number of events predicted from a three-pion phase-space curve by the total area of the plot. The curves in Fig. 2 are then calculated assuming that this density is constant over the entire plot for a given three-pion mass. The positions of the ρ bands on the symmetrized Dalitz plot at $M_{3\pi} = 1.0$ and 1.3 BeV are shown in Figs. 2(h) and 2(i). The normalization for the resulting curves has been chosen from the non-ρ events at $M_{3\pi} = 1.7$ BeV (not shown).

Branching ratios of the A_2^0.—Neutral meson states of definite isospin $I = 0$ (1 or 2) which decay (with $\vec{I}$ conservation) into $\rho + \pi$ should decay with the ratios $\rho^+\pi^-:\rho^0\pi^0:\rho^-\pi^+$ of 1:1:1 (1:0:1 or 1:4:1). We note that Figs. 2(a), 2(b), and 2(c) show a narrow peak at $M_{3\pi} \approx 1.3$ BeV in the ρ^+ and ρ^- plots. A much broader and somewhat shifted peak appears in the ρ^0 plot. The shaded events of Fig. 2 result from an attempt to remove background events. The shaded events are those which remain after the removal of nonperipheral events with $\Delta^2(\to 3\pi)$ (i.e., from the beam to the three-pion system) >0.85 $(\text{BeV}/c)^2$, plus peripheral events with $\rho^+N^{*0}(1238)$ and $\rho^0N^{*+}(1238)$. The ρN^* events are removed only if $\Delta^2(\to \rho)$ is less than 0.6 $(\text{BeV}/c)^2$. To obtain a quantitative estimate of the decay branch-

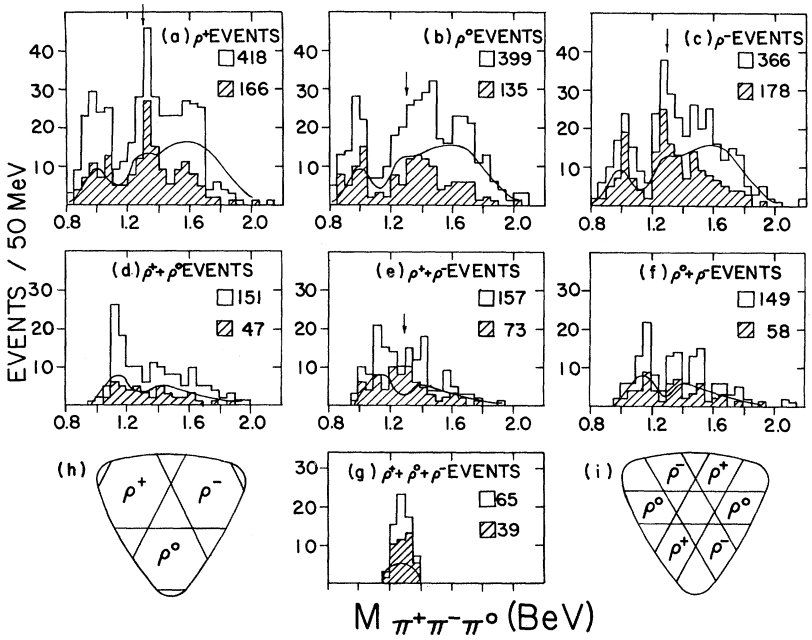

FIG. 2. Effective mass of the $\pi^+\pi^-\pi^0$ system for events with (a) only ρ^+, (b) only ρ^0, (c) only ρ^-, (d) ρ^+ and ρ^0, (e) ρ^+ and ρ^-, (f) ρ^0 and ρ^-, and (g) ρ^+ and ρ^0 and ρ^-. The solid curve shows the number of three-pion phase-space events lying in each ρ band. The locations of the ρ bands are shown on the Dalitz plot (h) at $M_{3\pi} = 1.0$ BeV and (i) at $M_{3\pi} = 1.3$ BeV. The shaded events are explained in the text.

ing ratios, all shaded events in Figs. 2(a), 2(b), and 2(c) are counted between 1.2 and 1.4 BeV. A subtraction of 24 background events is made from the number of events in each of the three intervals. An additional subtraction of 14 events is made from the single-ρ^- events since these also lie in the N^{*++} region. This is necessary because similar ρN^* events were previously removed from the ρ^+ and ρ^0 events. This gives for the branching ratios

$$\rho^+\pi^-:\rho^0\pi^0:\rho^-\pi^+ = (1.3\pm 0.4):(0.5\pm 0.3):1.$$

The errors include an uncertainty of five events in the background subtraction. The results favor an $I=1$ state assignment. Because the observed position (1310 ± 10 MeV) and width (110 ± 45 MeV) of this state and the $I=1$ assignment agree with those found for the $A_2^{\pm}$, we conclude that the peak at 1.3 BeV is the A_2^0.

In the non-ρ events no peak above the general background at the A_2 mass is observed. The subsample of non-ρ events with $\Delta^2(\to 3\pi)\leq 0.85$ $(\mathrm{BeV}/c)^2$ still shows no evidence for A_2^0. We obtain the following upper limit for the branching ratio

$$(A_2^0\to 3\pi)/(A_2^0\to \rho^+ +\pi^- \text{ or } \rho^- +\pi^+)\leq 0.17.$$

We use for the numerator the square root of the events with $\Delta^2(\to 3\pi)\leq 0.85$ $(\mathrm{BeV}/c)^2$ in the A_2 region (1.2-1.4 BeV) and outside the ρ^+ or ρ^- bands, multiplied by 2.1. This is the factor (estimated from phase space) that would be used to obtain the total number of $A_2^0\to 3\pi$ from a hypothetical peak observed in those events outside the ρ^+ or ρ^- bands. The denominator is taken as the number of A_2^0 events above background as described below and shown in the lower histogram of Fig. 1.

A_2^0 production mechanism.—Assuming that we are observing the A_2^0, a test of ρ exchange as a production mechanism can be made. The cross section for $\pi^+ +n\to A_2^0 +p$ at a given energy should be twice that for $\pi^- +p\to A_2^- +p$, based on the ratio of the isospin vector addition coefficients at the $n\rho p$ and $p\rho p$ vertices. An additional factor of 2 for the observed ratio of A_2^0/A_2^- results from the fact that both $\rho^+\pi^-$ and $\rho^-\pi^+$ decays are observed in this experiment, whereas only $A^-\to\rho^0+\pi^-$ (and not $A^-\to\rho^-+\pi^0$) is normally observed in $\pi^- p$ experiments.

We have made a comparison of this experiment with our data from $\pi^- +p\to\pi_1^- +\pi_2^- +\pi^+ +p$ also at 3.65 BeV/c.[6] In each set of data, $\Delta^2(\to 3\pi)\leq 0.85$ $(\mathrm{BeV}/c)^2$ is required. Additionally in the $\pi^+ d$ data, ρ^+ or ρ^- is required, and in the $\pi^- p$ data, ρ_1^0 or ρ_2^0 is required. For the $\pi^+ d$ data the cross section per event is 1.3 ± 0.2 μb/event.[7] Counting the events above $\rho\pi$ phase space for the two experiments, we obtain

$$\left.\frac{\sigma(A_2^0)}{\sigma(A_2^-)}\right|_{\text{observed}} = \frac{190\pm 50\ \mu\mathrm{b}}{90\pm 30\ \mu\mathrm{b}} = 2.1\pm 0.8,$$

which is more than two standard deviations below 4.0, as predicted by the simple argument above. The 0.8 error includes a 20% uncertainty in normalization for $\sigma(A_2^0)$ and 10 and 14% uncertainties in the normalization of the two phase-space curves, but no error for uncertainty in the shape of the background.

We compare A_1^0 production with $A_1^{\pm}$ production in the lower histogram of Fig. 1. Peripheral events with ρ^+ or ρ^- are shown with a smooth curve taken from $\pi^{\pm}+p\to\rho^0+\pi^{\pm}+p$ data[6,8] and normalized arbitrarily. The fact that there are fewer events in the neutral A_1 region than would be predicted from this curve seems to indicate a fundamental difference in the production mechanism for the events in the A_1 and A_2 regions. If the Deck effect[3] is present in A_1 production, one would expect a diminished value for A_1^0 production due to the requirement of charge exchange at the nucleon vertex.

A_2^0 spin-parity test.—A spin test for the A_2^0 was made from the Dalitz-plot density within the ρ^+ and ρ^- bands. No knowledge of the production mechanism is needed for this test. The theoretical equations of Frazer, Fulco, and Halpern[9] which are based on a simplest matrix element approach have been used. The ρ^+ or ρ^- half-width (Γ' of Ref. 9) is taken to be 0.150 BeV^2. This corresponds to a full width in mass of 200 MeV, which includes our experimental $\pi^{\pm}\pi^0$ resolution of 60 MeV. Except for experimental parameters of this type, the predictions for the A_2^0 are exactly the same as for the $A_2^{\pm}$. The interference terms for a given J^P between ρ^+ and ρ^- are the same as those between ρ_1^0 and ρ_2^0 in the $\pi^{\pm}p$ data. Previous Dalitz-plot spin-parity tests with $\pi^{\pm}p$ data[2] have resulted in possible assignments of $J^P=1^+$ s wave, 2^-, or 2^+. If the A_2 decays to $K\bar{K}$ as observed by Chung et al.,[2] then the choice is limited to $J^P=2^+,\ 4^+,\cdots$.

Figure 3(a) shows $M^2(\pi^-\pi^0)$ for A_2^0 events with ρ^+ (650-850 MeV). One might expect the

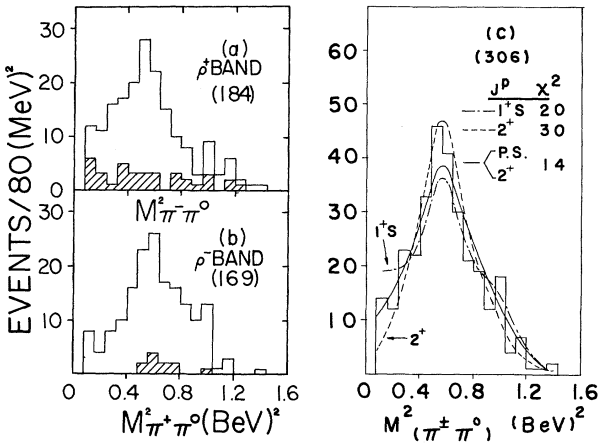

FIG. 3. (a) and (b) Mass-squared distributions for events in ρ bands with $1.2 \leq M_{3\pi} \leq 1.4$ BeV and $\Delta^2(\rightarrow 3\pi) \leq 0.85$ (BeV/c)^2. (c) Sum of events in (a) and (b) less the shaded events as explained in the text. Theoretical curves are for $J^P = 1^+$ s wave and 2^+ both without background, and 2^+ with 37% background distributed according to phase space.

background for these events to be similar to $\pi^\pm p$ data since the ρ^+ in our $\pi^+ n$ experiment, like the ρ^0 in $\pi^\pm p$, can be produced through pion exchange. Figure 3(b) shows $M^2(\pi^+\pi^0)$ for our events with ρ^-, which cannot be produced in pion exchange. A comparison of these distributions with $\pi^\pm p$ data shows in fact that Fig. 3(a) does have a shape similar to $\pi^\pm p$ data while Fig. 3(b) has fewer events in the low-$M^2(\pi\pi)$ region. The events having $\rho^+ N^{*0}$ or $\rho^0 N^{*+}$ with $\Delta^2 \rightarrow \rho \leq 0.6$ (BeV/c)^2 are shaded. They are distributed approximately according to phase space in Fig. 3(a) but can lie only in the ρ overlap regions of Fig. 3(b). Figure 3(c) is the sum of (a) and (b) excluding the shaded events. As required for the theoretical curves, events with both ρ^+ and ρ^- are included twice in this plot but both of them do not fall, in general, at the same mass value.

Three of the theoretical curves are shown in Fig. 3(c). If we do not take into account the presence of background, the three best assignments, with (J^P, χ^2 probability), are (2^+, 0.01), (1^+ s wave, 0.25), and (2^-, 0.02). From the 3π mass plots for these events, the background level is estimated to be 37%. With the addition of this background distributed according to phase space, the above J^P assignments become (2^+, 0.55), (1^+ s wave, 0.02), and (2^-, 0.002) for 16 degrees of freedom. Thus with the assumptions of our experimental parameters, and the distribution of background according to phase space, our data definitely favor the 2^+ assignment over all other J^P with $J \leq 2$. It is interesting that for $J^P = 1^+$ s wave and 2^-, the minimum values of χ^2 are reached with 0% background, but for 2^+ the χ^2 is minimized at 32% background.

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