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# STUDY OF THE REACTION $\pi^- + p \rightarrow \rho^0 + \pi^- + p$ AT 6 BeV/$c$†

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Two peaks in the $\rho^0\pi^\pm$ effective-mass distribution in the region between 1.0 and 1.4 BeV have recently been reported.[1] These two mass peaks, which have been named the $A_1$ and $A_2$ mesons, have been observed in $\pi$-$p$ reactions involving four charged particles in the final state. Several theoretical interpretations[2-4] of the $A_1$ results have attributed this peak to the kinematic features of the $\pi$-$p$ reaction.

The purpose of this paper is to report the results of a study of the $\rho^0\pi^-$ system in the final state of the reaction $\pi^- + p \rightarrow \pi^- + \pi^- + \pi^+ + p$ at 6 BeV/$c$. These results show (a) no peak in the $A_1$ region when background events involving $N^*(1240)$ production are removed, and (b) that the events in the $\rho^0\pi^-$ mass region between 1.0 and 1.2 BeV are consistent with peripheral production of the $\rho^0$ via a one-pion-exchange model. In contrast to the results for the $A_1$, the $A_2$ meson is clearly evident and is not associated with the above-mentioned type of $\rho^0$ production. The $A_2$ meson is observed at a mass of $1290 \pm 10$ MeV with a full width at half-maximum, $\Gamma$, of $70 \pm 10$ MeV. The results of a spin-parity analysis for events in the $A_2$ region favor $J^P = 2^-$ ($p$ wave) or $1^+$ ($s$ wave).

Approximately 4500 four-pronged events obtained from the Brookhaven National Laboratory 80-inch liquid-hydrogen bubble chamber were scanned and measured. Using track density and $\chi^2$ probability selection criteria, 691 of these events were fitted to the four-constraint $\pi^-\pi^-\pi^+p$ final state.

One feature of this final state at this energy is that more than 90% of the events involved a $\pi^+\pi^-$ effective mass $M(\pi^+\pi^-)$ in the $\rho^0$ region or a $\pi^\pm p$ effective mass $M(\pi^\pm p)$ in the $N^*(1240)$ region. The $M(\pi^+p)$, $M(\pi^-p)$, and $M(\pi^+\pi^-)$ distributions are shown in Figs. 1(a), 1(b), and 1(c). Strong $N^{*++}$ formation is evident in the $M(\pi^+p)$ plot, with approximately 35% of the combinations falling in the region between 1110 and 1370 MeV. The $M(\pi^-p)$ plot indicates that the $N^{*0}$ production is less strong with a much larger background present. This background is influenced, in general, by the fact that each event is plotted twice and, at higher values, by the peripheral nature of the interaction [a beamlike particle ($\pi^-$) and a targetlike particle ($p$) tend to have a high effective mass]. However, the production of the $N^{*0}\rho^0$ and the $N^{*0}f^0$ final states is apparent from a comparison of Figs. 1(d) and 1(e), which show the $M(\pi_2^-\pi^+)$ and $M(\pi_1^-\pi^+)$ distributions, respectively, when $M(\pi_1^-p)$ is in the $N^*(1240)$

region.

In studying the $\rho^0\pi^-$ system (produced in the $\rho^0\pi^-p$ final state) it is desirable to suppress that background which is due to the following final states: (1) $\rho^0 N^{*0}$, and (2) $N^{*++}\pi^-\pi^-$. In view of the results shown in Figs. 1(d) and 1(e), this can be substantially accomplished in the case of (1) by removing the events in which the $M(\pi^-p)$ value falls in the $N^*(1240)$ region. However, the suppression of that background which is due to state (2) is not unambiguously accomplished by a removal of events which have a $M(\pi^+p)$ combination in the $N^*$ region. This is noted in Fig. 1(f) which shows that more than half of the $\pi^+$ involved in such a $M(\pi^+p)$ combination are also associated with a $M(\pi^+\pi^-)$ in the $\rho^0$ region.[5] In view of this ambiguity, the $\rho^0\pi^-$ system was examined with and without the subtraction of the above type of $N^{*++}$ events.

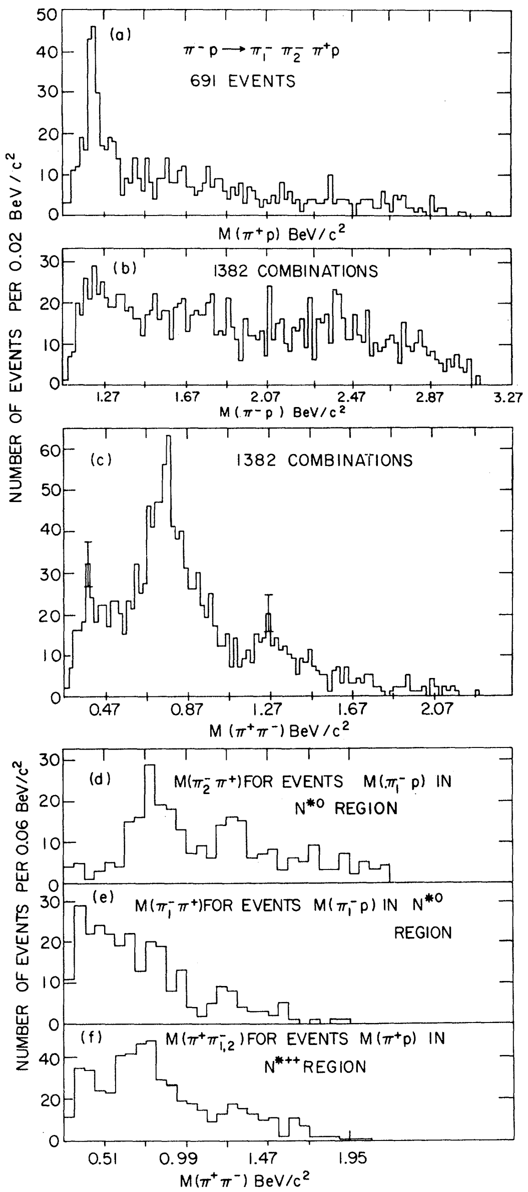


FIG. 1. Effective-mass distribution of (a) $\pi^+p$, (b) $\pi^-p$, and (c) $\pi^+\pi^-$ for all events which fit $\pi^-+p \to \pi^-+\pi^-+\pi^++p$. Figure (d) shows the effective-mass distribution of $\pi^+\pi^-$ pairs produced together with $N^{*0}$. Figure (e) is the effective-mass distribution of those $\pi^+\pi^-$ pairs for which the $\pi^-p$ invariant mass is in the $N^{*0}$ region. Figure (f) is the effective-mass distribution of $\pi^+\pi^-$ pair for which the $\pi^+p$ invariant mass is in the $N^{*++}$ region.

The $M(\rho^0\pi^-)$ distribution for the 452 events in which at least one $M(\pi^+\pi^-)$ combination was in the $\rho^0$ region (600-880 MeV) is shown in Fig. 2(a). A broad enhancement is seen for these events in the region below 1.4 BeV. When background due to $N^{*0}(1240)$ production is removed as discussed above, a sharp peak is observed in the $A_2$ region in the distribution for the remaining 311 events. However, no evidence of peaking is observed in the region in which the $A_1(1080)$ was previously reported. Furthermore, when the $N^{*++}$ type events are subtracted, the mass distribution is flat in the $A_1$ region.[6]

In order to study the origin of the enhancement in the $\rho^0\pi^-$ system below 1.4 BeV, it is helpful to compare the events in the $A_1$ mass region (1020-1220 MeV) with the events in the $A_2$ region (1220-1420 MeV) with respect to the following distributions: (i) the pion scattering angle $\theta$ relative to the incident pion direction in the $\rho^0$ rest frame; (ii) the Treiman-Yang angle for the $\rho^0$; and (iii) the four-momentum transfer, $\Delta^2(\rho^0)$, of the $\rho^0$. The conclusions drawn from the above comparisons are not dependent upon what background subtraction is made; therefore only the distributions for the sample of events without $N^*(1240)$ production are shown in Fig. 3. The pion scattering angle for the events in the $A_1$ mass region [Fig. 3(a)] exhibits the strong $\cos^2\theta$ feature which is characteristic of the decay of a $J=l=1$ resonance. This angular distribution—showing strong alignment between the $\rho^0$ and the incident pion—and the isotropic nature of the Treiman-Yang angle distribution [Fig. 3(c)] are consistent with the view that the $\rho$'s associated with the events in the $A_1$ mass region are produced via one-pion exchange and not as the decay product of a high-

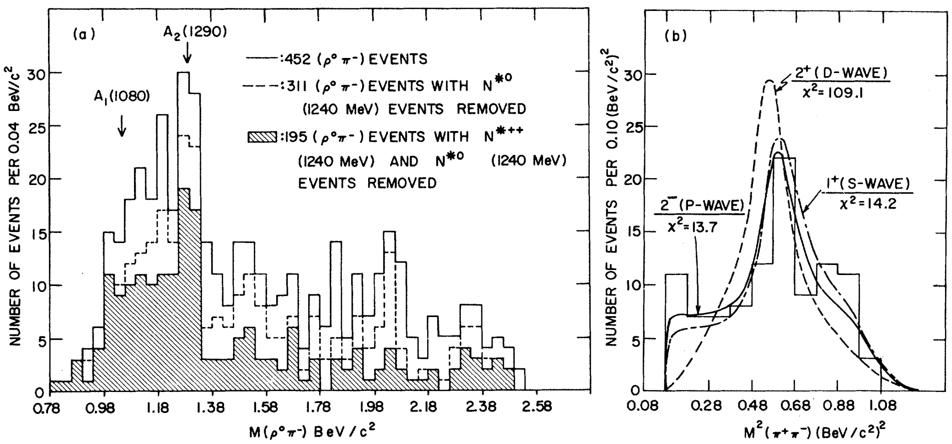


FIG. 2. (a) The solid line is the histogram of the $\rho^0\pi^-$ effective mass for all events. The broken line is the histogram of the $\rho^0\pi^-$ effective mass for events where $N^{*0}$ is removed. The shaded histogram is the $\rho^0\pi^-$ effective mass distribution for events where both $N^{*0}$ and $N^{*++}$ are removed. (b) Spin-parity analysis of $A_2$ meson assuming that all events in the mass region 1220 MeV $< M(\rho^0\pi^-) <$ 1420 MeV are $A_2$ mesons.

er resonant state. In contrast, the $\rho$'s from the events in the $A_2$ region show no alignment with the incident pion [see Fig. 3(b)] and have a Treiman-Yang angle distribution [Fig. 3(d)] which deviates, comparatively, much more from isotropy. These results concerning the $\rho$'s associated with the $A_2$ events support the evidence, from the $M(\rho\pi)$ plot, that they are produced as decay products of a higher resonant state.[7] Figures 3(e) and 3(f), and Figs. 3(g) and 3(h), which show, respectively, the $\Delta^2(\rho)$ distribution for the two mass regions and the $M(\rho\pi)$ plots for those events with $\Delta^2(\rho) < 40\mu^2$ and $>40\mu^2$, where $\mu$ is the rest mass of the $\pi^0$, indicate that the $\rho$'s for events in the $A_1$ region are produced much more peripherally than those for events in the $A_2$ region. All the above results for the events in the $A_1$ region are in agreement with the interpretation, suggested by Deck,[2] of the $A_1$ as a kinematic effect due to peripheral production of the $\rho^0$, which predicts that the kinematic peak should become broader as the incident pion energy is increased.

The center of the $A_2$ mass peak is found to be at 1290 ± 10 MeV from a Gaussian ideogram (not shown), and its full width at half-maximum,

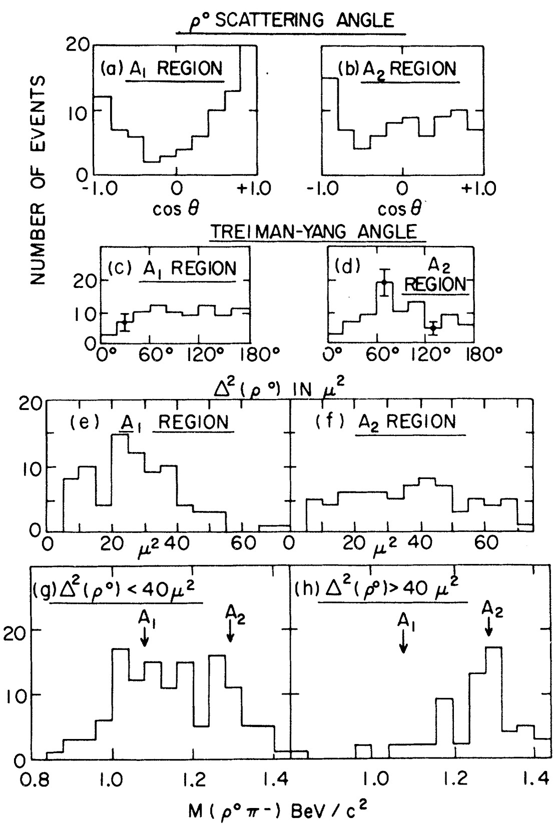


FIG. 3. (a) Distribution of the $\rho^0$ decay angle with respect to the $\pi^-$ beam direction in the $\rho^0$ center of mass, for events in the $A_1$ mass region, and (b) the same for $A_2$ meson. (c) and (d) Treiman-Yang angle distributions for the $\rho^0$'s from $A_1$ and $A_2$ regions, respectively. Distributions of the momentum transfer to the $\rho^0$ are shown in (e) for the $A_1$ region and in (f) for the $A_2$ region. (g) and (h) The $\rho^0\pi^-$ effective-mass plots for events with low momentum transfer to the $\rho^0$ and high momentum transfer, respectively.

$\Gamma$, is $70 \pm 10$ MeV. In order to determine the spin-parity ($J^P$) of the $A_2$ meson from its $\rho^0\pi^-$ decay mode, the di-pion density distribution in the $\rho^0$ band of the $3\pi$ Dalitz plot has been analyzed as suggested by Zemach.[8] The projection of this distribution for the sample of events without $N^{*0}(1240)$ production is shown by the histogram in Fig. 2(b); the smooth curves in that figure are the theoretical distributions based on various spin-parity assignments. The theoretical curves are obtained assuming no background and are normalized to the total number of events. However, the $\rho^0\pi^-$ background in our data comprises about 50% of the total number of events in the $A_2$ mass region. Nevertheless, the $\chi^2$ values, for nine degrees of freedom shown in Fig. 2(b), indicate that, if background effects do not dominate, the $1^+$ ($s$-wave) and $2^-$ ($p$-wave) assignments are favored over the $2^+$ ($d$-wave) assignments.

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[6]It has been suggested for the $\pi^+p$ reaction (Ref. 3), that if the $A_1$ peak were caused by an interference effect due to the symmetrization of the matrix element of a $(\pi_a{}^+\pi_b{}^+\pi^-)$ system, then a double subtraction of $N^*(1240)$ events from a $M(\rho\pi)$ distribution would result in the enhancement of such a peak, since this subtraction would reduce the $\rho\pi$ background. Our results are inconsistent with this conjecture when applied to the $\pi^-p$ reaction in that the mass distribution becomes flatter when such a double subtraction is made.

[7]A further analysis of the $\pi^\pm$-$p$ results at 3.7 BeV/$c$ [B. C. Shen et al., Phys. Rev. Letters 15, 731 (1965)] is in agreement with these results for the $A_2$ from this experiment. In addition, they conclude that the $A_1$ enhancement observed in their data results from diffraction scattering of virtual pions.

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