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Multiple Pion Production by 1.89-BeV/c π^- †

R. CHRISTIAN,* A. R. ERWIN, H. R. FECHTER,‡ F. E. SCHWAMB,§ S. H. VEGORS,§ AND W. D. WALKER
Physics Department, University of Wisconsin, Madison, Wisconsin
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A report is given of a study of pion-proton interactions in a liquid-hydrogen bubble chamber. A 1.89-BeV/c negative-pion beam incident upon a 14-in.-diam chamber caused interactions from which those with four charged secondaries were selected and measured. Fits were attempted to the following states: $3\pi+p$, $3\pi+p+\pi^0$, and $4\pi+n$. The branching ratios for these three reactions were found to be $(64.9\pm3.3)\%$, $(21.5\pm1.7)\%$, and $13.9\pm1.3)\%$, respectively. The $3\pi+p$ reaction was found to be dominated by the production of the $\frac{3}{2}$-$\frac{3}{2}$ pion-nucleon isobar, $(43\pm3)\%$ of these events going via this channel. Evidence for the η and ω mesons was found in the $3\pi+p+\pi^0$ final state, $(9.0\pm2.2)\%$ of these events going via the η channel, and $(14.0\pm2.8)\%$ via the ω channel.

I. INTRODUCTION

THE experiment reported here is similar to that of Satterblom *et al.*[1] The incident-beam momentum in this experiment is 1.89 ± 0.07 BeV/c.[2] The adjusted beam momentum obtained from fitted events was 1.895 ± 0.026 BeV/c. As the experiment reported here was performed at the same time as the one in Ref. 1, the liquid-hydrogen chamber, arrangement of the pion beam, scanning procedures, measuring, spatial reconstruction, and analysis are similar for both.

Events were considered to be of the type $3\pi+p$ if they had χ^2 values of less than 15 for this reaction. Events having χ^2 values >15 for the $3\pi+p$ reaction were considered to be of the type $3\pi+p+\pi^0$ or $4\pi+n$ if their χ^2 values for these reactions were <3.0. All the events were classified according to their values of χ^2.

With these limits, less than 1% of the four-constraint events and less than 8% of the one-constraint events should have been rejected. Plots of the experimental χ^2 distribution of the four-constraint and one-constraint events (not shown) are in good agreement with the theoretical distribution.

The neutral-mass distribution for each of the three types of reactions gave neutral masses of -36 ± 40 MeV for the $3\pi+p$ reaction, 130 ± 42 MeV for the $3\pi+p+\pi^0$ reaction, and 936 ± 32 MeV for the $4\pi+n$ reaction. These distributions were quite clean, indicating that there was very little contamination of one type of event by another.

Ambiguous events were of two types. Those where the ambiguity was in deciding which of the particles in the $3\pi+p$ reaction was the proton were resolved by using the event with the smallest χ^2. This type of ambiguity occurred in 5% of these events. This same type of ambiguity occurs in the $3\pi+p+\pi^0$ events. For these, the events with the smallest value of χ^2 were used. This ambiguity occurred in 4% of these events. The other type of ambiguity was where the values of χ^2 for a $3\pi+p+\pi^0$ or a $4\pi+n$ interpretation of the same event were approximately the same. This occurred in 4% of these events. In those cases the events were eliminated.

The mass resolution was checked by plotting the error in the invariant mass as printed out by the computer calculation.[1] The results so obtained were consistent with the choice of 20-MeV bin widths used for the various invariant-mass distributions.

II. RESULTS

A. Gross Features

The number of acceptable events of each reaction type and their respective branching ratios are

$$\pi^-+p\rightarrow\pi^-+p+\pi^-+\pi^+;\quad 604 \text{ events};\quad (64.9\pm3.3)\%;\qquad(1)$$

$$\rightarrow\pi^++p+\pi^-+\pi^++\pi^0;\quad 200 \text{ events};\quad (21.5\pm1.7)\%;\qquad(2)$$

$$\rightarrow\pi^-+\pi^++\pi^-+\pi^++n;\quad 129 \text{ events};\quad (13.9\pm1.3)\%.\qquad(3)$$

Based on a total cross section for the four-prong events of 2.44 ± 0.24 mb,[3] the cross sections for reactions (1), (2), and (3) were found to be 1.58 ± 0.30, 0.52 ± 0.14, and 0.34 ± 0.11 mb, respectively. The (π^+,p) isobar was found to dominate reaction (1). The η and ω resonances were found in reaction (2). The ρ resonance was not seen. In reactions (2) and (3) hardly any phase space is available for this channel (ρ resonance) because of the relatively low momentum of the incident π^- beam, 1.89 BeV/c. In reaction (1) the ρ is not seen because of the dominance there of the (π^+,p) isobar.

B. Details of Each Reaction

1. $\pi^-+p\rightarrow\pi^-+p+\pi^-+\pi^+$

The dominant feature of this reaction is the production of the (π^+,p) isobar or Δ (1238 MeV). The (π^+,p)

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* Present address: Physics Department, Purdue University, Lafayette, Indiana.

‡ Present address: Boeing Company, Seattle, Washington.

§ Physics Department, Idaho State University, Pocatello, Idaho.

[1] P. H. Satterblom, W. D. Walker, and A. R. Erwin, Phys. Rev. **134**, B207 (1964).

[2] A. Erwin, R. March, W. Walker, and E. West, Phys. Rev. Letters **6**, 628 (1961).

[3] This value was supplied by W. D. Walker (unpublished work).

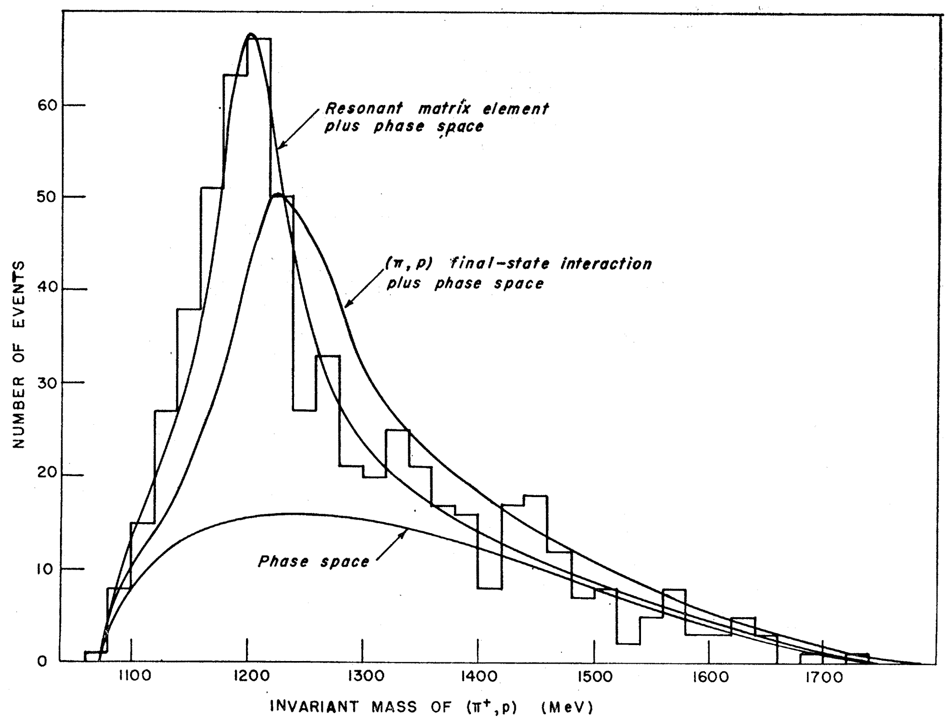

FIG. 1. The (π^+,p) invariant-mass distribution in the reaction $\pi^-+p\rightarrow\pi^-+\pi^++\pi^-+p$. Shown as solid curves are: (a) the phase-space distribution, (b) phase space plus a Breit-Wigner resonance (resonant matrix element) and (c) phase space plus final-state (π^+,p) interaction.

effective-mass distribution is shown in Fig. 1. A resonant matrix element of the Breit-Wigner form was used in an attempt to determine the relative amounts of isobar production and phase-space background. The solid curve shown in Fig. 1 gave a least-squares best fit with $(43\pm3)\%$ isobar production. The invariant mass of the (π^+,p) isobar is 1200 MeV with $\Gamma=80$ MeV. This is consistent with the results of other experiments.[1]

An attempt to use the (π^+,p) interaction cross section and an assumed final-state interaction to fit the data did not give good results. Here the reaction was assumed to go first to the four-body final state with a constant matrix element. The (π^+,p) interaction was then assumed to occur in the final state according to the (π^+,p) total cross section. Because of an apparently statistical shift of the peak in the effective-mass distribution toward lower masses, a poor fit was obtained.

The backward peaking of the isobar is apparent from the distributions shown in Fig. 2. The (π^+,p) effective-mass distributions shown indicate substantially more isobar production relative to phase space for events with $\cos\theta<-0.7$ as opposed to those with $\cos\theta>-0.7$, where θ is the angle between the (π^+,p) momentum vector and the incident-pion momentum. The invariant mass of the (π^+,p) isobar for $\cos\theta<-0.7$ is 1180 MeV with $\Gamma=50$ MeV. For $\cos\theta>-0.7$, the invariant mass of the (π^+,p) isobar is 1200 MeV with $\Gamma=60$ MeV.

Since the phase-space distribution is obtained strictly from kinematical (or statistical) considerations, it is seen that the number of events in the phase-space distribution for a given angular segment is directly proportional to the solid angle in the center-of-mass system subtended by that segment. Thus since the solid angle subtended by events where $\cos\theta>-0.7$ is 3.4π, whereas the solid angle subtended by events where $\cos\theta<-0.7$ is 0.6π, the number of phase-space events associated with the first distribution should be 85% of 343 (the number of phase-space events in the distribution shown in Fig. 1) or 292 events, and the number of phase-space events associated with the second distribution should be 15% of 343 or 51 events. The phase-space distributions shown in Fig. 2 were so normalized.

The strong isobar production is reflected in other kinematic distributions producing distortions which are explained well by the combined effects of the isobar and phase space. The absence of $\rho(\pi^-,\pi^+)$ production, for instance, is due to the competing effects of the isobar.

In addition to the (π^+,p) invariant-mass distribution, all other possible invariant-mass combinations were plotted and examined. Also the momentum distributions of the π^-, π^+ and p were examined. The following comments are pertinent to these distributions. In the (π^-,p) invariant-mass distribution 21 events in excess of the phase-space distribution could be attributed to the Δ(1238 MeV). Thus the ratio of the production of the $\frac{3}{2}$, $\frac{3}{2}$ state of the Δ to its $\frac{3}{2}$, $-\frac{1}{2}$ state is 260/21 or 12.4 ± 2.7. This is in reasonable statistical agreement with the value of 9 predicted by isotopic-spin considerations. Some slight evidence is seen for the N (1688 MeV) in the (π^-,p) invariant-mass spectrum, but none was seen for the N (1512 MeV). The (π^-,π^-,p) invariant-mass

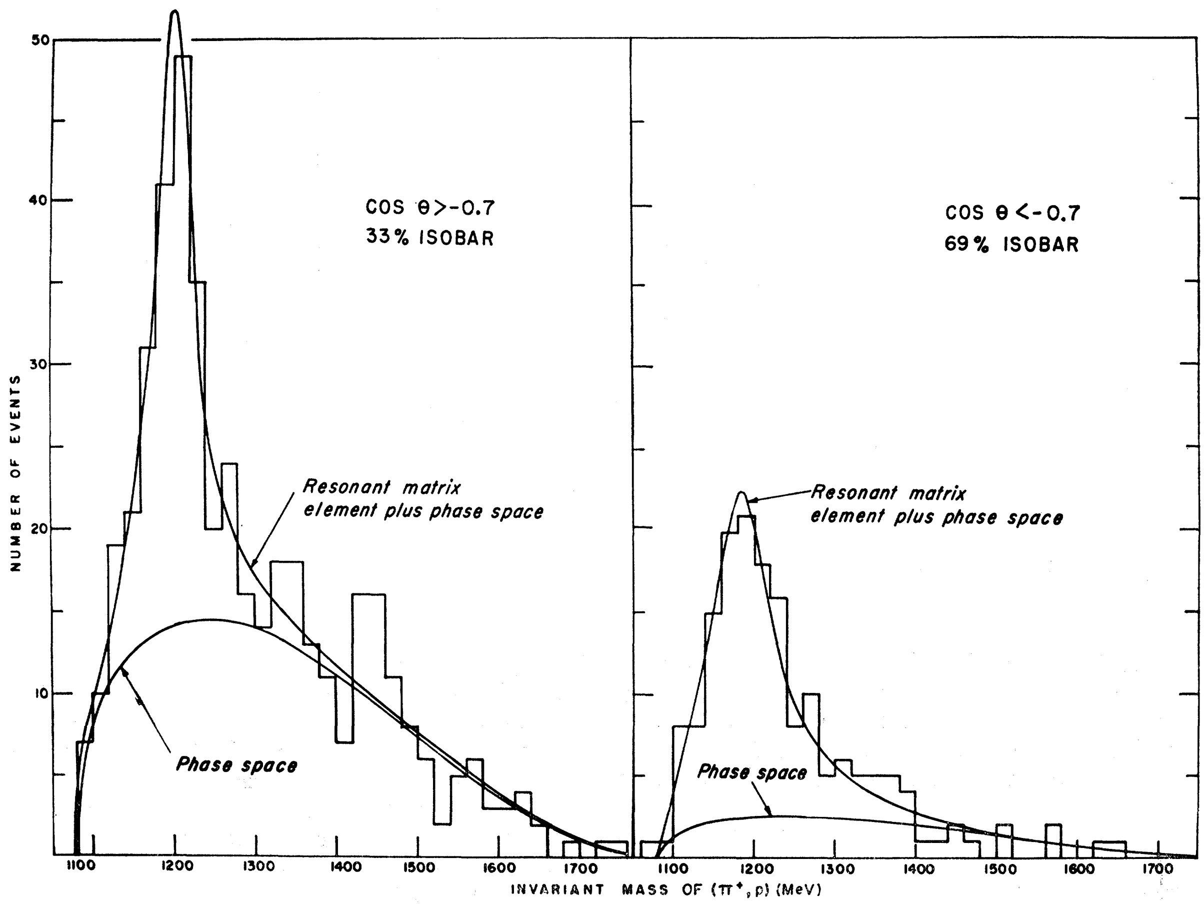

FIG. 2. $\Delta(1238)$ isobar production as a function of the center-of-mass angle θ between the incident π^- beam and the momentum vector of the isobar.

distribution is distorted from pure phase space, with larger values of invariant mass being preferred. This again shows the influence of the dominating (π^+,p) isobar. Finally, the π^+ momentum spectrum shows a substantial deviation from phase space with lower values of momentum being preferred as expected from the presence of the (π^+,p) isobar. All the other invariant-mass and momentum distributions showed no meaningful deviations from phase space.

Analysis of the angular distributions of the p, π^+, π^- and the (π^+,p) isobar showed predominance of protons and the isobar in the backward direction (see Fig. 2). The π^+ angular distribution was isotropic and the π^- angular distribution was peaked in the forward direction.

2. $\pi^-+p \to \pi^-+p+\pi^-+\pi^++\pi^0$

The most interesting feature of the data from this reaction is the production of neutral three-pion resonant states as observed in the (π^-,π^+,π^0) effective mass dis-distribution. Figure 3 shows a histrogram of this distribution. The solid curve is a least-squares fit obtained with the combination of two resonant matrix elements and phase space. The unusually large values of Γ for the η(548 MeV) and ω(782 MeV) resonances are caused by the fact that the momentum spread in the incident beam was rather large. Because of the poor statistics due to the small number of events, the values of Γ quoted for the η(548 MeV) and ω(782 MeV) are subject to rather large errors. This fit gives the result that $9.0\pm2.2\%$ of the events in this reaction go by the η(548 MeV) channel and that $14.0\pm2.8\%$ of them go by the ω(782 MeV) channel. This yields a cross section for the production of the η(548 MeV) by this channel,

$$\pi^-+p \to \pi^-+p+\eta \to \pi^-+p+\pi^-+\pi^++\pi^0,$$

of 0.047 ± 0.017 mb, or a total η cross section corrected for nonobserved decay modes[4] of 0.172 ± 0.043 mb. The ω(782 MeV) cross section in the channel

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

is then 0.073 ± 0.024 mb or a total ω cross section corrected for nonobserved decay modes[4] of 0.085 ± 0.028 mb.

[4] A. H. Rosenfeld *et al.*, Rev. Mod. Phys. **36**, 977 (1964).

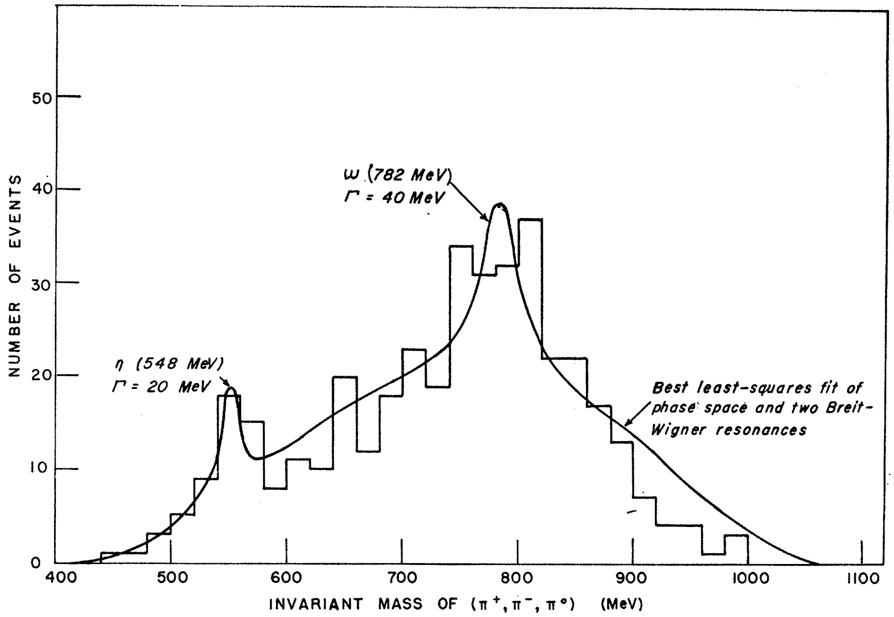

FIG. 3. The (π^-,π^+,π^0) invariant-mass distribution in the reaction $\pi^-+p \rightarrow \pi^-+\pi^+ +\pi^-+p+\pi^0$. The solid curve is phase-space plus two Breit-Wigner resonances.

As previously, the invariant-mass distributions for all possible combinations of particles produced in the reaction were examined. In the (π^+,p), (π^-,p), and (π^0,p) invariant-mass distributions the formation of the Δ (1238 MeV) does not dominate. This is illustrated in Fig. 4 which also shows that isobar production is most predominant in the (π^-,p) distribution. This is in agreement with the results of Satterblom.[1] No evidence is seen for the η or ω resonances in either the (π^-,π^-,π^0) or the (π^-,π^-,π^+) invariant-mass distribution as predicted by the fact that each of these resonances has isotopic-spin zero. The ρ resonance is not seen in the (π^-,π^0), (π^-,π^+), or the (π^+,π^0) invariant-mass distributions because of lack of phase space at the "mass" of this resonance.

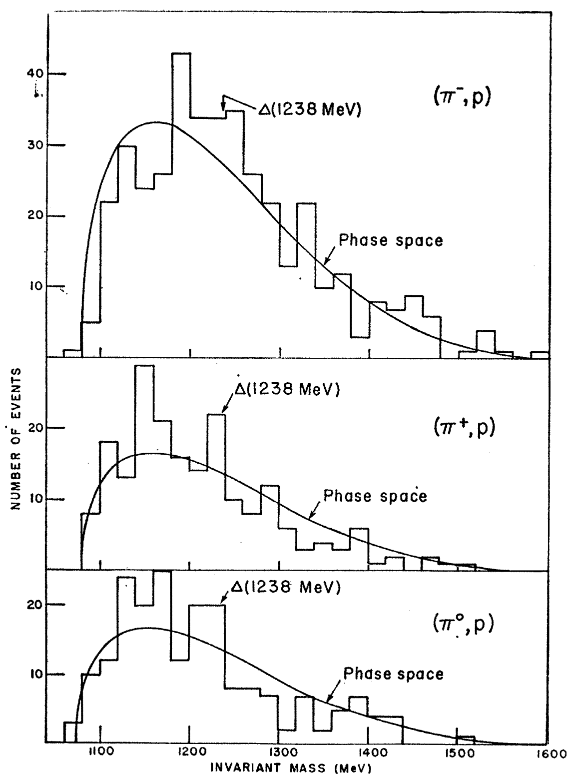

FIG. 4. (π^-,p), (π^+,p) and (π^0,p) invariant-mass distributions in the reaction $\pi^-+p \rightarrow \pi^-+\pi^++\pi^-+p+\pi^0$.

The π^-, π^+, p, and π^0 momentum distributions are all in good agreement with phase space. The angular distributions of the π^+, π^-, π^0, and p in the center of mass are statistically consistent with an isotropic distribution.

3. $\pi^-+p \rightarrow \pi^-+\pi^++\pi^-+\pi^++n$

The invariant mass for all possible combinations of particles was examined. Momentum-distribution plots for the π^-, π^+, and n were also made as well as angular-distribution plots in the center of mass for the π^-, π^+, and n.

In the (π^-,n) invariant-mass spectrum, the $\frac{3}{2}^-$ state of the Δ(1238 MeV) was seen. This is shown in Fig. 5. $63\pm9\%$ on these events went via the Δ channel. The invariant mass of the (π^-,n) isobar is 1230 MeV with $\Gamma=30$ MeV. The fit to these data was done in the same manner as that for the (π^+,p) data in the $\pi^-+p \rightarrow \pi^-+\pi^++\pi^-+p$ reaction.

In the (π^+,n) invariant-mass spectrum no statistically significant evidence was seen for the $\frac{1}{2}^+$ state of the Δ(1238 MeV). Also, no statistically significant evidence was seen for either the η or the ω mesons in the (π^-,π^+,π^-), $T_z=-1$ or the (π^-,π^+,π^+), $T_z=+1$ invariant-mass distributions. This is in agreement with

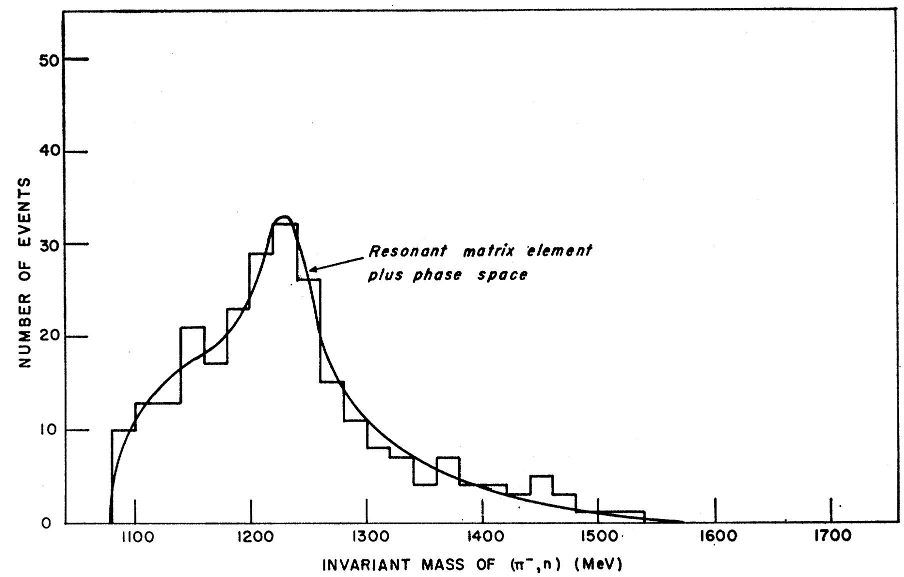

FIG. 5. (π^-,n) invariant-mass distribution in the reaction $\pi^-+p\rightarrow\pi^-+\pi^++\pi^-+\pi^++n$.

the accepted designation of the isotopic spin of each of these particles as zero. No evidence was seen for a "four-pion" resonance in the (π^-,π^+,π^-,π^+) invariant-mass distribution.

The momentum distributions for the π^-,π^+, and n were each in agreement with phase space.

The n angular distribution in the center of mass was somewhat peaked in the backward direction. The π^+ angular distribution was slightly peaked in the forward direction, while the π^- angular distribution appeared to be isotropic.

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