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[7]We have used unpublished data of Peter Newcomb and Wilson F. Powell (Lawrence Radiation Laboratory), on π^+ interactions at 740 Mev/c, it being assumed that this angular distribution is not significantly different from that at 812 Mev/c. These data indicate an inelastic cross section approximately 25% of the total. We are grateful to the above authors for permission to use their data in advance of publication.

[8]This number is a weighted average of results quoted by L. B. Okun, Ann. Rev. Nuclear Sci. 9, 61 (1959), and our own measurements on stopping K^+ mesons. In both cases the branching ratio obtained for these decay modes was $b_1 = 0.061 \pm 0.003$.

[9]The uncertainty in the path length by this method comes from the reproducibility of the count, the determination of the contamination, and the statistics of the number of tracks.

[10]Here $v_{\mathrm{rel}} = v_{\mathrm{lab}}$ of the K meson. This is essentially the relativistic form given by F. Solmitz [Phys. Rev. 94, 1799 (1954)] in the small-angle region.

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π-π RESONANCE IN π^--p INTERACTIONS AT 1.25 Bev*

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It has become apparent that π-π interactions are important in π-p collisions in the Bev region. Several experiments on single-pion production[1-6] have shown that there is an excess of nucleons at low laboratory kinetic energies over that which would be expected on a statistical or isobar theory. Goebel[7] has pointed out that such an excess would be indicative of a π-π interaction. Fraser and Fulco[8] showed that a π-π resonance in an $I=1$, $J=1$ state could explain features of electron-nucleon scattering, and suggested a resonance at $w^2 \simeq 10\mu^2$, where w is the total energy of the two pions in the π-π rest frame, and μ is the pion rest mass ($w = Q + 2\mu$). Later calculations[9] suggested that the resonance was at $w^2 \simeq 22\mu^2$. Indications of a π-π resonance in π-p interactions have been obtained in several experiments,[5,6,10-12] but the results were limited by low incident pion energies, or by statistics. With the higher statistics available in the present work, strong evidence is obtained for a π-π resonance in an $I=1$ state.

As part of a study of π-p interactions, using the bubble chamber technique, we have measured 4000 π^--p events at 1.25-Bev incident pion energy. 968 events of the type

$$\pi^- + p \to \pi^- + \pi^+ + n, \tag{1}$$

and 566 of the type

$$\pi^- + p \to \pi^- + \pi^0 + p, \tag{2}$$

have been identified using the GUTS kinematic fitting program, and ionization density measurements.

Comparison of the pion momentum spectra with the predictions of the extended isobar model[13] indicate that pion production through isobar formation is not the dominant process at this energy.

The nucleons from both reactions are produced predominantly backward in the c.m. system, and thus are peaked at low laboratory kinetic energies. Figures 1(a) and (b) show the nucleon laboratory kinetic energy, T, for reactions (1) and (2), respectively. The curves in Fig. 1 were computed assuming a constant π-π cross section, $\sigma_{\pi-\pi}$, from the equation given by Chew and Low[14]:

$$\frac{\partial^2\sigma}{\partial\Delta^2\partial w^2} \xrightarrow[\Delta^2\to-\mu^2]{} \frac{f^2}{2\pi}\frac{\Delta^2/\mu^2}{(\Delta^2+\mu^2)^2}\frac{w}{q_{1L}}(\tfrac{1}{4}w^2-\mu^2)^{1/2}\sigma_{\pi-\pi}, \quad (3)$$

where Δ is the four-momentum transfer to the nucleon ($\Delta^2=2MT$), f^2 is the renormalized pion coupling constant and q_{1L} is the laboratory momentum of the incident pion. The theoretical curves are normalized to the total numbers of events in the histograms. The theoretical and experimental distributions seem to agree at low momentum transfers, but the histograms are more sharply peaked than would be expected.[15]

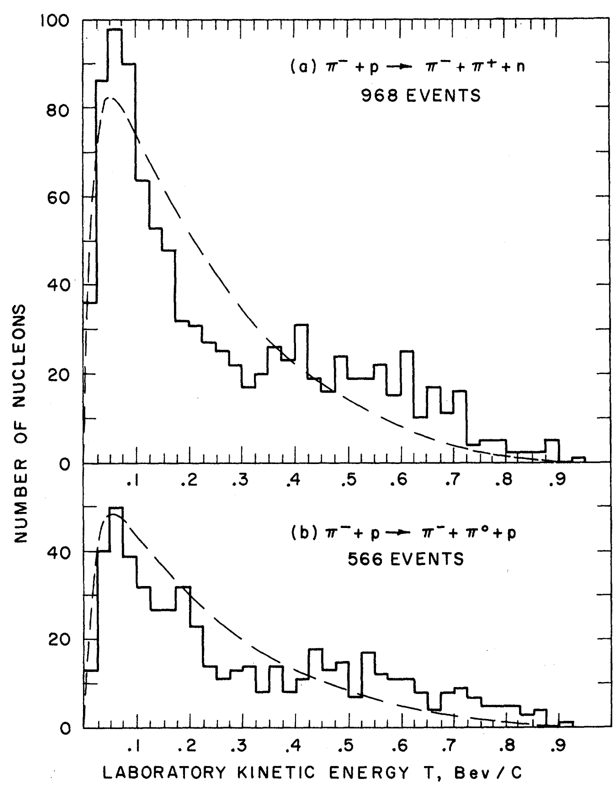

FIG. 1. Histogram of nucleon laboratory kinetic energies. The curve was calculated from the Chew-Low equation, for constant $\sigma_{\pi-\pi}$.

There is also a group of high-momentum-transfer events, not expected on a one-pion exchange model.

Figure 2 shows Q values for π^--π^+ and π^--π^0 systems, and also the prediction of the statistical model. The isobar prediction is similar to the latter. Both histograms exhibit well-defined peaks at the same Q value. The agreement in position of the two Q peaks suggests that the same π-π resonance state is dominant in both reactions. It follows, therefore, that isotopic spin $I=0$ is excluded for this state.

The branching ratio for reactions (1) and (2), $R=\sigma(2)/\sigma(1)=0.585\pm0.031$, and the ratio, $R_{\pi-\pi}$, for events in the $Q_{\pi-\pi}$ peaks (400 Mev $< Q_{\pi-\pi} <$ 550 Mev), is 0.50 ± 0.04. The one-pion exchange model predicts that $R_{\pi-\pi}=\frac{1}{2}$ for a π-π interaction

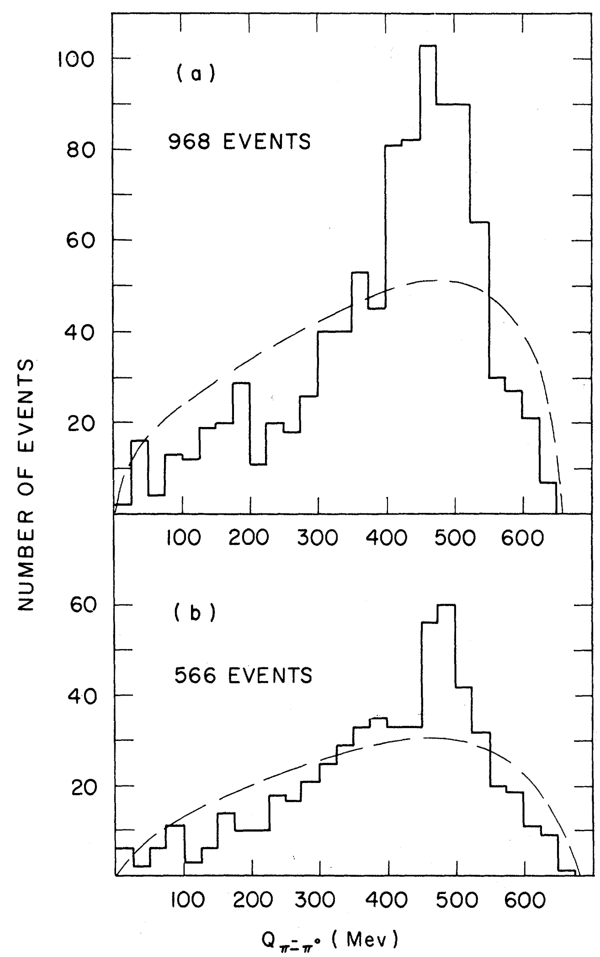

FIG. 2. Q-value distributions for π-π system for all events, for (a) $\pi^-+p\to\pi^-+\pi^++n$, (b) $\pi^-+p\to\pi^-+\pi^0+p$; the dashed curves are from statistical theory.

in a pure $I=1$ state, and $\frac{9}{2}$ for $I=2$. The model is more likely to be valid if we select events with small Δ^2. Restricting the selection of events in the Q peak to those with $\Delta^2<10\mu^2$, or $T<104$ Mev, we obtain $R_{\pi-\pi}=0.42\pm0.06$. The data are in agreement with the predictions of the model for $I=1$. This state is further suggested by the Yale π^+-p experiment at 1.26 Bev,[11] by comparing the π^+-π^0 and π^+-π^+ Q distributions.

The π-π cross section, as a function of w^2, was calculated by integrating Eq. (3) up to $\Delta^2=10\mu^2$, assuming this equation to be valid in the physical region. Comparison of the experimental and theoretical distributions in Fig. 1 indicates that this may be a reliable procedure for small Δ^2.[16] Figure 3 shows $\sigma_{\pi-\pi}$ obtained in this way, for the combined events from reactions (1) and (2). The background on the low-energy side of the resonance is associated with both reactions. This would seem to eliminate a pure $I=0$ low-energy effect. We obtain $\sigma_{\pi-\pi}=95$ mb at the peak, $w^2=29\mu^2$ ($Q=475\pm10$ Mev). The full width at half maximum is 130 Mev. These values, and the values determined at 1.74 Bev by Erwin et al.[12] agree within statistics. This agreement between results at two quite different energies implies that there is, indeed, a resonance, π^*, in the π-π system.

The decay angle, δ, between the direction of the π^- in the rest frame of π^* and the c.m. direction of π^*, was calculated. In Figs. 4(a) and (b) the distributions of events in the Q peaks show backward-forward symmetry, but a marked departure from isotropy. Restricting the selection to events with small Δ^2 shows that the anisotropy is mainly associated with such events. For events outside the Q peak, the asymmetries observed in both reactions (1) and (2) are consistent with some $(\frac{3}{2},\frac{3}{2})$ π-p isobar formation.

To investigate angular momentum states involved in the π^* resonance, the angle, α, between the direction of the π^- in the rest frame of π^* and the direction of the incident pion, was calculated. Events were selected in which π^* was emitted closely parallel or antiparallel to the incident pion direction ($|\cos\theta|\geq0.9$).[17] Provided that the Adair analysis[18] holds for this selection, and for a short-lived resonant state, the π^- angular distribution is expected to be a relatively simple function of the angular momentum state J ($a+b\cos^2\alpha$ for $J=1$). The distributions are shown in Figs. 4(c) and (d). That in 4(c), at least, is suggestive of $J=1$, rather than larger J values which would give higher powers of $\cos^2\alpha$. The distribution in 4(c)

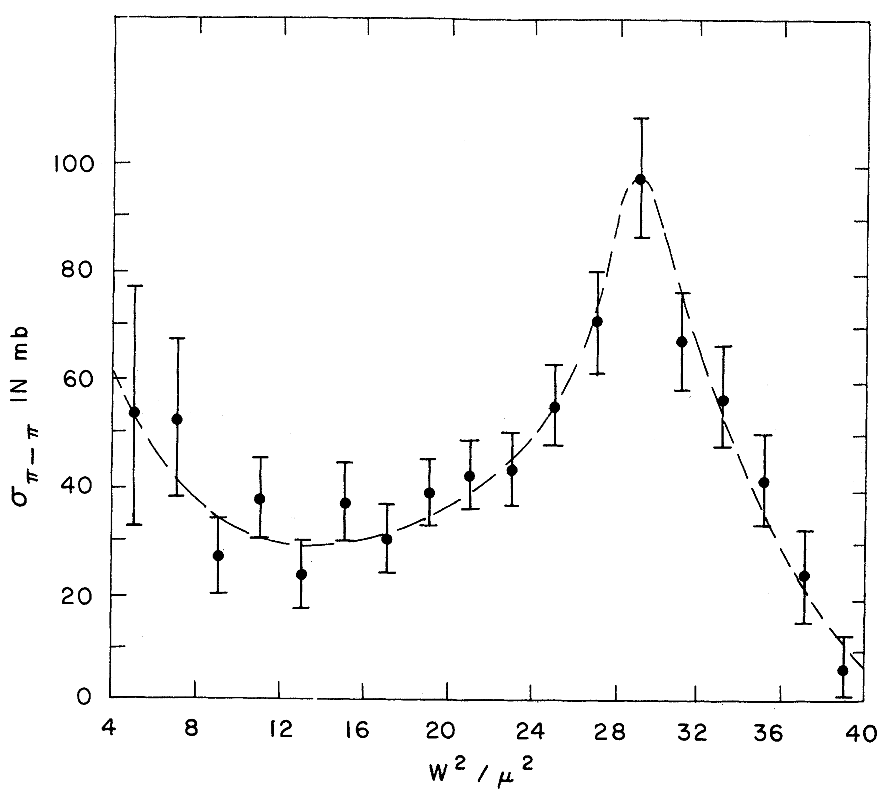

FIG. 3. Variation of cross section, $\sigma_{\pi-\pi}$ with energy, w, for the π-π system for events with $\Delta^2<10\mu^2$. The dashed curve is a free curve drawn through the points. μ = rest mass of charged pion.

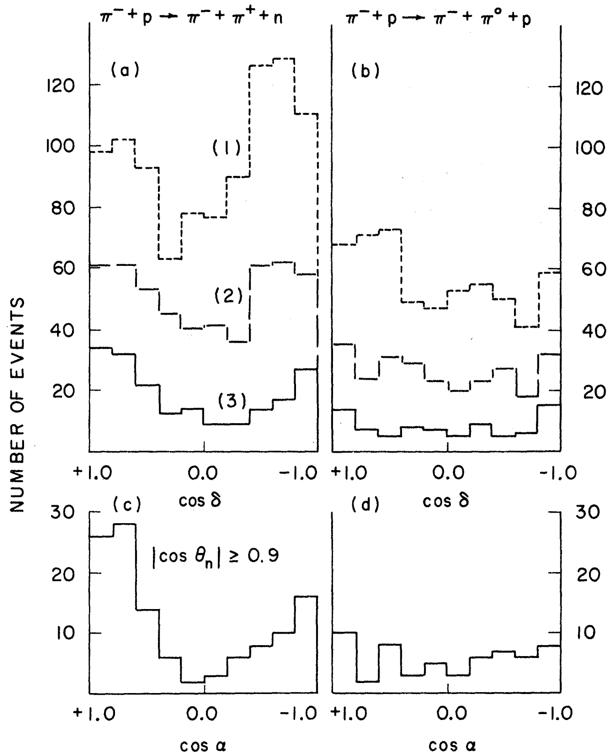

FIG. 4. Angular distributions for the π-π system. (a) and (b) show decay angles δ of π^- in π^* rest frame, relative to c.m. direction of π^*: (1) All events (dotted); (2) events with 400 Mev $\leq Q_{\pi-\pi} \leq$ 550 Mev (dashed); (3) events from (2) with $\Delta^2 < 10\mu^2$ (solid). (c) and (d) show decay angles α of π^- in π^* rest frame, relative to incident pion direction, for events with $|\cos\theta| \geq 0.9$, where θ = c.m. angle of π^*.

shows some asymmetry (backward/forward ratio = 43/76), which may indicate interference from another state.

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