about 36 mb. This is about twice that attributable to a $j=5/2$ resonance; however, the uncertainty in the magnitude of the nonresonant intensity, the possibility that σ_{el}/σ_{tot} is less than 0.4 for the resonant interaction, and the possibility of interference between the resonant and nonresonant amplitudes do not permit exclusion of $j=5/2$ for the upper resonance.

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† On the staff of the University of California Radiation Laboratory during the performance of this experiment.

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π^--p SCATTERING BELOW 1 Bev

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We have carried out measurements of π^--p total and differential elastic cross sections in the energy range 400 to 800 Mev. This work was done by exposing a propane bubble chamber in a pion beam at the Brookhaven Cosmotron.

The chamber had an active volume of 12 in. ×6 in.×6 in. which was viewed with two cameras at right angles. The right-angle stereoscopy permits more accurate angle measurements than do more conventional small-angle stereo systems.

Since the intensity of the Cosmotron was not under our control, it was necessary to sacrifice momentum resolution for beam intensity. Therefore, only one analyzing magnet was used which gave pions of momenta 590 ± 50, 750 ± 50, and 890 ± 75 Mev/c. In all, we took about 60 000 pictures.

During the process of scanning, all pion interactions were counted and placed in the following categories: elastic scattering, quasi-elastic scattering, charge exchange, pion production (i.e., apparently in a π^--p collision), diffraction scattering, and carbon stars. All the apparently elastic events were measured and calculated. Because of the right-angle stereo, visual discrimination is usually good and about 70% of the calculated events were consistent with being π^--p elastic scatterings. Thus we have the number of π^--p elastic scatterings and all other events. From this and the total π^--p [1] and π^--C [2,3] cross sections we can deduce the total elastic π^--p cross section. We estimate the π^--p inelastic and π^--p charge exchange from the ratios observed. It is certain that perhaps 30-40% of these inelastic and charge exchange events are the result of collisions with protons bound in carbon. We assume that the ratios on free and bound protons are roughly the same. McCormick and Baggett[4] have measured σ_{el}, σ_{inel}, and σ_{ex} at 810 Mev. They find ratios of these three quantities to be 14.3, 15.5, 6.4, and we find at 760 Mev the ratios 16.7, 13.5, 7.35. Likewise our 460-Mev results have been closely confirmed by unpublished measurements in hydrogen by Stranahan, Ashkin, and DeBenedetti.[5]

The results of our measurements are shown in Figs. 1 and 2. It is perhaps necessary to point out again that the elastic cross sections were measured on the basis of the kinematics alone; that is, on the basis of coplanarity, angle measurement, and, in a considerable fraction of cases, the range of the protons. There is a small background due to quasi-elastic scatterings. We estimate from the angular dispersion of the quasi-elastic events that this background is less than 5%. Our selection criteria and measurements are essentially the same as those used by Pless[6] who finds a similar background in p-p scatterings in a hydrocarbon chamber at a comparable momentum in a very well resolved beam.

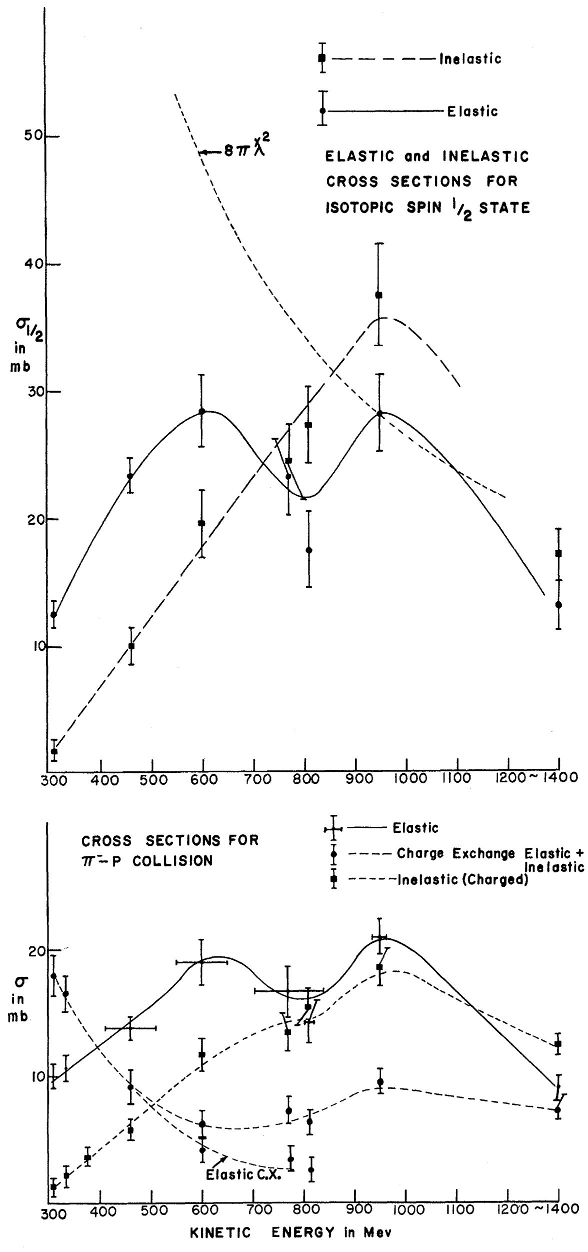

FIG. 1. Partial cross sections for the π^--p system and the isotopic spin 1/2 system. The data at 307, 330, and 375 Mev are the Russian work[7]; at 810 Mev they are from Berkeley[4] and have been normalized to a total cross section of 36 mb. The data at 950 Mev[8,9] and 1.4 Bev are from earlier bubble chamber, diffusion chamber, and emulsion experiments.

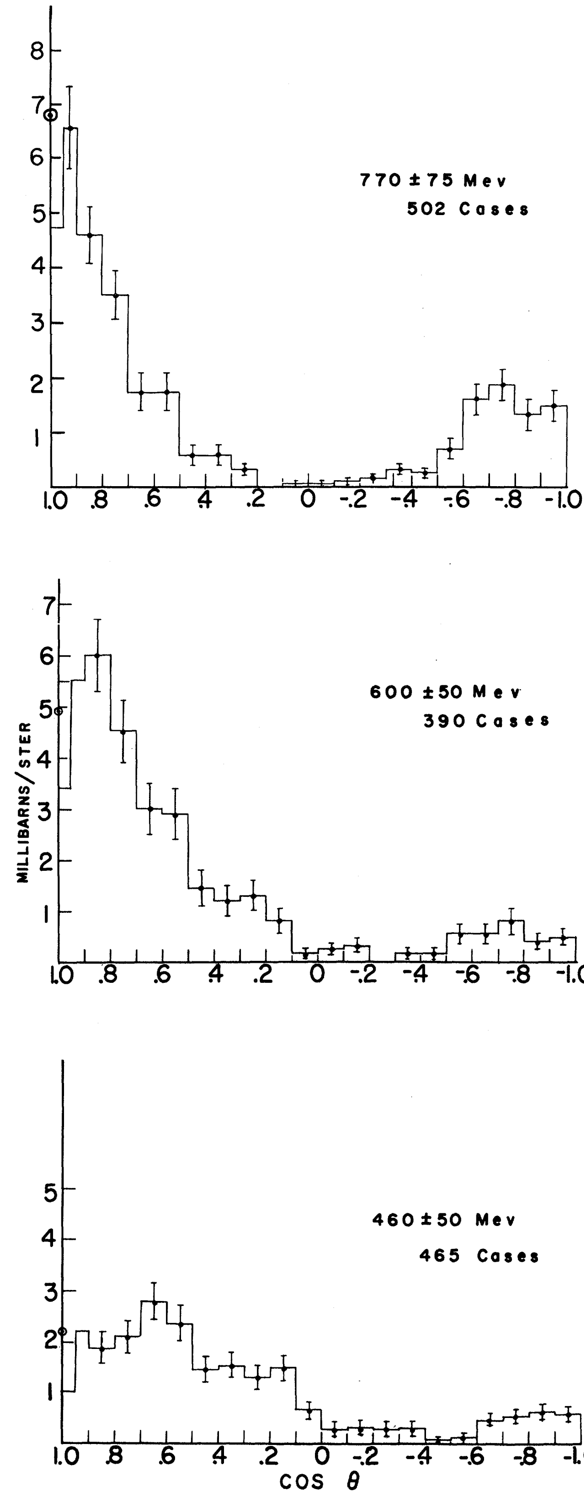

FIG. 2. Differential π^--p elastic scattering cross sections. In most cases the most nearly forward interval (1.0 - 0.95) is not very trustworthy. The circles on the ordinate are the dispersion relation predictions as calculated by Sternheimer from the data of Cool et al.[1]

We give in Fig. 2 our differential angular distributions. It should be noted that at all energies above 300 Mev,[7] the distributions are not apparently dominated by a single J state. At 460 Mev, for example, s, p, and d waves contribute comparable fractions to the elastic cross section. There is quite a marked change in angular distribution between energies of 600 and 760 Mev. A large bump in the backward hemisphere develops. Of the order of 35% of the total elastic cross section is contained in the backward hemisphere. Previously Walker et al.[8] and Erwin and Kopp[9] have commented on the possible origin of the rise as being due to spin-flip scattering. On the basis of the present data we would say that either a $T = 1/2$ phase shift has changed sign or goes through 90° in the neighborhood of 600 Mev. It is also possible that the rapid growth of the f-wave phase shift has caused the change.

Recent work on photoproduction of pions in the same energy range at the California Institute of Technology and Cornell University[10] gives indications of a resonant state which should show up around 600 Mev in a π^--p scattering. Our data are certainly consistent with such a picture. The elastic cross section comes up before the inelastic cross section and shows a slight maximum at about 600 Mev. The marked change in shape in the differential elastic cross section between 600 and 760 Mev is likewise consistent with a resonance.

We have extracted the $T=1/2$ cross sections by subtracting out the $T=3/2$ contribution. This is possible because of recent data on π^+-p interactions of Willis et al.[11] and Erwin and Kopp.[12] In order to calculate the $T=1/2$ inelastic cross section it is necessary to know, in addition to the inelastic processes giving charged particles, the inelastic charge exchange cross section, i.e., $\pi^- + p \rightarrow 2\pi^0 + n$. We have measured the amount of $1\pi^0$ and $2\pi^0$ production at 460 and 600 Mev. We did this by counting the number of pairs within four centimeters from the stopping point. This gives the average number of γ rays produced per charge exchange which is simply related to the number of π^0's. At 810 Mev and 760 Mev we use the isobar model,[13] which is consistent with the data, to compute the $2\pi^0$ cross section.

To see in detail which, if any, state resonates at about 600 Mev is a very difficult problem. At 600 Mev, $8\pi\bar{\lambda}^2$ (the maximum cross section for a $J=3/2$ state) is twice the observed elastic cross section in the $T=1/2$ state. This shows that if the peak in the cross section is produced by a $J=3/2$ wave then the wave must be strongly absorbed. Preliminary efforts at a phase-shift analysis by one of the authors (W.D.W.) supports this view. The phase-shift analysis requires an enhanced $d_{3/2}$ phase shift.[14] A large positive α_{13} seems excluded because of the relatively small amount of charge exchange scattering. The humped appearance of the differential cross section at 460 Mev is characteristic of constructive interference between p- and d-wave spin-flip terms. At 460 Mev preliminary estimates of the $T=1/2$ phase shifts give for the real part of the phase shifts $\alpha_1 = +20°$, $\alpha_{11} = +30°$, $\alpha_{13} = -10°$, $\delta_{13} = +23°$, $\delta_{15} = -5°$. To account for the large peak in the forward direction at 600 Mev, δ_{13} must be considerably increased.

The inelastic cross section in the $T=1/2$ state shows a relatively large peak in the neighborhood of 900 Mev. To account for the size of the cross section requires complete absorption of s, p, and d waves if these are the only waves to be considered. Complete absorption of these waves would be inconsistent with angular distribution of the elastically scattered π's at these energies (in particular the large hump in the backward hemisphere). Consequently it is certain that f waves play an important role in the 800-900 Mev region.

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THEORY OF SPIN-ORBIT INTERACTION IN NUCLEAR FORCES*

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It has repeatedly been pointed out in recent years[1-4] that a spin-orbit interaction between two nucleons is necessary to explain the observed scattering of nucleons. From a theoretical point of view the existence of a spin-orbit interaction is not at all surprising, because it has been shown by Breit[5] that in a relativistic treatment of the interaction of nucleons the spin-orbit interaction arises in a natural way. However, pion-theoretical calculations by Klein[6] and several other authors[7] show that the pion theory is unable to account for the large spin-orbit interaction, which is required to explain the experimental results. It is, therefore, necessary to look for some other explanation of the spin-orbit interaction.

Recently we have predicted[8,9] the existence of a hitherto unobserved neutral scalar meson, the ρ^0 meson, which is coupled strongly to the nucleons. Since the mass of the ρ^0 meson is considerably larger than the pion mass, it leads to a force of very short range between the nucleons. The second-order nuclear potential due to the ρ^0 meson is given by

$$V_2(\rho^0) = -\frac{g'^2}{4\pi r} e^{-\lambda' r} + \frac{g'^2}{4\pi r}\frac{1}{2\kappa^2}\frac{d}{dr}\left(\frac{e^{-\lambda' r}}{r}\right)\vec{L}\cdot\vec{S}, \quad (1)$$

where g' is the coupling constant for the interaction of ρ^0 mesons and nucleons, λ' and κ are related to the ρ^0-meson mass μ' and the nucleon mass M as $\lambda' = \mu' c/\hbar$ and $\kappa = Mc/\hbar$, and we have used the Signell-Marshak definitions[3] of $\vec{L}$ and $\vec{S}$. The coefficient of $\vec{L}\cdot\vec{S}$ in (1) can be expressed as

$$V_{LS} = \frac{V^0}{x}\frac{d}{dx}\left(\frac{e^{-nx}}{x}\right), \quad (2)$$

with

$$V_0 = \frac{g'^2}{4\pi c\hbar}\frac{\lambda c\hbar}{2}\left(\frac{\lambda}{\kappa}\right)^2, \quad (3)$$

where λ is related to the pion mass μ as $\lambda = \mu c/\hbar$, while $x = \lambda r$ and $n = \mu'/\mu$.

According to our earlier ideas,[8] the ρ^0-meson mass should be somewhat larger than twice the pion mass, and the coupling constant for the interaction of ρ^0 mesons and nucleons should have the same value as the coupling constant for pions and nucleons. Thus, we can take

$$n \approx 2, \quad g'^2/4\pi c\hbar \approx 14. \quad (4)$$

We also have

$$\lambda/\kappa = 1/6.7, \quad \lambda c\hbar = \mu c^2 = 139.4 \text{ Mev}, \quad (5)$$

where we have taken the pion mass as $273 m_e$. Substituting the above values in (2) and (3), we find

$$V_{LS} = \frac{V_0}{x}\frac{d}{dx}\left(\frac{e^{-2x}}{x}\right), \quad (6)$$

with

$$V_0 = 21.7 \text{ Mev}. \quad (7)$$

It seems to us quite astonishing that not only (6) has exactly the same form as the latest phenomenological spin-orbit interaction of Signell, Zinn, and Marshak,[4] but our theoretical value of V_0 is also remarkably close to the phenomeno-