Elastic Scattering of 26-Mev Negative Pions by Hydrogen in Emulsion*

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Standard Ilford G5 plates were exposed to a fairly monoenergetic 30-Mev π^--meson beam obtained by slowing down the Chicago 90-Mev beam with absorber and then using magnetic analysis. Range curves were taken indicating a 35 percent contamination from muons and electrons in this geometry. This figure was independently determined from the grain density distribution of tracks in the emulsion. A flux of 2.2×10^5 tracks per cm^2 was used for area scanning. The average beam energy in the plates is (26 ± 2) Mev as determined from measuring the recoil proton energies in the 5 pion-proton scatterings which were found. An equivalent pion path length of 13×10^4 cm was scanned giving a cross section of (1.15 ± 0.6) mb for the 5 events. This cross section is for scatterings greater than 50°. Smaller angle scatterings were not considered because of the possibility that such short recoil protons might be missed by area scanning. Various scanning efficiency checks indicate a scanning efficiency above 90 percent. The data are analyzed to give $(4.7°\pm2.7°)$ for the phase shift combination $(2\alpha_1+\alpha_3)$.

I. INTRODUCTION

PION–PROTON elastic scattering experiments using hydrogen targets and counters have been limited to energies above 30 Mev because of the short range of pions under 30 Mev. Two other techniques have been used successfully in the low-energy region: the hydrogen diffusion cloud chamber[1] and the nuclear emulsion technique of area scanning for hydrogen collisions.[2]

The energy region below 30 Mev is quite important in that such information is necessary for a reliable determination of the scattering lengths for the phase shifts in pion-nucleon scattering. At the time this experiment was initiated the experimental evidence led some workers to discuss the possibility that the *s*-wave phase shifts were proportional to the pion momentum only for energies under 10 Mev. There was some speculation that the *s*-wave phase shift $\alpha_3(T=\frac{3}{2})$ might change sign in the region of 20 to 30 Mev.[3] Such a phase shift behavior would predict roughly 8 mb as the result for this experiment rather than the observed 1.15 mb.

The results of this experiment, along with other recent information, now permit the simpler interpretation that α_3, α_1, and α_{33} behave as momentum to the power $(2l+1)$ up to 80 Mev. This interpretation is discussed in detail in the following paper.[4]

This experiment gives (1.15 ± 0.6) millibarns for the elastic $(\pi^-\text{-}p)$ scattering cross section between 50° and 180° in the center-of-mass system. Such a low value would be expected by extrapolating down the phase shifts obtained at 40,[5] 61.5,[6] or 120 Mev[7] using the momentum to the power $(2l+1)$ dependence. At the low energies studied by the Columbia cloud chamber group,[1] one would expect this cross section to increase considerably due to a constructive Coulomb interference. Quantitatively, the Columbia cloud chamber preliminary results are consistent with our 26-Mev result.[4]

Details of exposure geometry and beam analysis are given in Sec. II. As described in Sec. III, the plates were area scanned under 350× magnification for single proton beginnings. Then each proton beginning was examined for an incoming and scattered pion. Three-pronged events of this type, but not due to hydrogen, were rejected on the basis of two tests: coplanarity of the three prongs, and angular correlation of the two scattering angles to satisfy energy-momentum conservation. A total of 5 hydrogen events with $\chi>50°$ was found. χ is the pion scattering angle in the center-of-mass system. In each of these events the recoil proton did not leave the emulsion, thus permitting a measurement of the incoming pion energy.

II. EXPOSURE

Since there is no external pion beam of the Chicago cyclotron under 40 Mev, it is necessary to slow down higher-energy pions with absorber. Slowing down a higher-energy beam to the region of 26 Mev results in a considerable energy and angular spread of what was initially a fairly monoenergetic and parallel beam. In order to obtain a workable degree of energy resolution and parallelism of tracks, we found it necessary to use magnetic analysis after the beam leaves the absorber. In order to achieve parallelism of beam tracks suitable for area scanning, it is necessary to expose the plates a

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[1] Rinehart, Sargent, Rogers, and Lederman in *Proceedings of the Fourth Rochester Conference* (University of Rochester Press, Rochester, 1954); and (private communication).

[2] Orear, Lord, and Weaver, Phys. Rev. **93**, 575 (1954).

[3] H. P. Noyes and A. E. Woodruff, Phys. Rev. **94**, 1401 (1954).

[4] J. Orear, following paper, Phys. Rev. **96**, 176 (1954).

[5] J. Tinlot and A. Roberts, Phys. Rev. **95**, 137 (1954).

[6] Bodansky, Sachs, and Steinberger, Phys. Rev. **93**, 1367 (1954).

[7] Anderson, Fermi, Martin, and Nagle, Phys. Rev. **91**, 155 (1953).

considerable distance behind the absorber. Both the 45-Mev and 90-Mev π^- beams were tried with the 90-Mev beam giving much better results. The intensity and energy resolution were improved somewhat by making use of the horizontal focusing properties of the Chicago 45° magnetic wedge. The absorber and plates were placed at conjugate foci as shown in Fig. 1. This geometry gave an intensity of about 1/80 of the intensity with no absorber. A six-hour exposure was required to obtain a flux of 2.2×10^5 tracks per cm^2.

Another difficulty in obtaining external low-energy pion beams is the high contamination of muons and electrons. In our case this contamination was determined by two independent methods. An absorption curve was taken at the time of the exposure using thin counters. Analysis of this curve gave a pion content of (64±3) percent. Then both scanning groups independently counted grain densities of 100 successive tracks over a length of 480 microns each. Figure 2 shows the histogram obtained by the Chicago group. The grain densities cluster into three distinct groups as would be expected for electrons, muons, and pions of

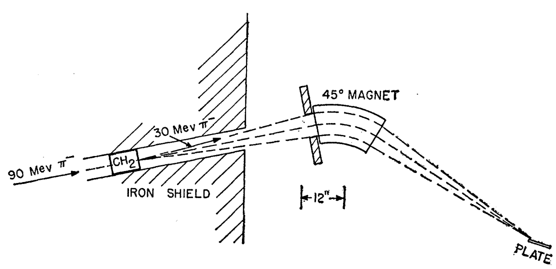

FIG. 1. Experimental setup. Paraffin absorber and plate are at conjugate foci of 45° magnetic wedge.

the same momentum. This analysis gives a pion content of (65±4) percent.

III. SCANNING

The scanning technique is the same as described in previous papers.[2,8] This technique is quite time-consuming for cross sections as low as was encountered in this experiment. Scanning continued until all the emulsion which had been exposed was covered. The scanners were responsible for observing all proton beginnings confined to a square region 250×250 microns which is defined by a whipple disk reticle. Since there is some possibility of overlooking short proton tracks, we limited ourselves to scatterings greater than 50°, or proton tracks greater than 40 microns in length. Also the regions within 15 microns of either surface were excluded. All scanning was done by the authors who have previous experience in this type of pion-proton scanning. The scanners personally felt that their scanning efficiencies were greater than 90 percent. In addition two types of quantitative checks were made. Strips were rescanned independently by a second scanner. Also

[8] J. Orear, Phys. Rev. **92**, 156 (1953).

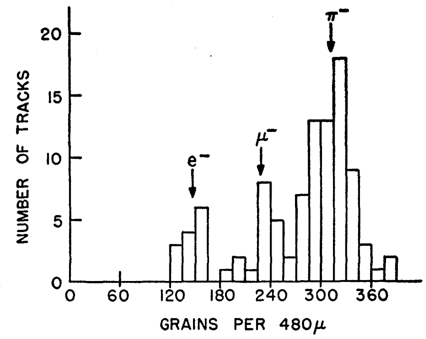

FIG. 2. Grain density distribution of beam tracks.

scanning tests were devised by selecting strips which contained events which either were pion-proton scatterings or else looked similar to them. Out of 15 possibilities, no events were missed.

IV. RESULTS

If L_π is the total pion path scanned, n_H the density of hydrogen in the plates, and N the number of events found, then

$$\sigma=(1/L_\pi n_H)N.$$

The value $n_H=(3.34\pm0.1)\times10^{22}$ protons/cm^2 is specified by Ilford, where the uncertainty is that caused by moisture content of the emulsion. For the region scanned L_π was determined to be $(1.3\pm0.1)\times10^5$ cm. Five pion-proton scatterings were found with $\chi>50°$. This gives

$$\sigma(\chi>50°)=(1.15\pm0.6) \text{ millibarns.}$$

The 5 events are listed in Table I.

The energies of the incoming pions were calculated by measuring the range of the recoil protons. Fortunately in all 5 cases the protons stopped in the emulsion. This method of determining the pion beam energy superimposes an artificial energy spread mainly due to inaccuracies in the determination of χ. According to the range curves taken at the time of the exposure, the primary beam was about 30 Mev. Since this beam entered 600-micron emulsion at about 8° inclination to the surface, the average value of (26±2) Mev obtained from the five events is consistent with the range curve determination.

These results can give some useful information about the s-wave phase shifts. At these low energies the elastic

TABLE I. Energies and angles of the $(\pi^- - p)$ scatterings.

Event	χ, deg	Pion energy, Mev
1	55	32
2	87	22
3	97	26
4	97	22
5	104	26

π^- scattering in terms of the phase shifts is

$$\frac{d\sigma}{d\omega}=\lambda^2\left[\left(\frac{2\alpha_1}{3}+\frac{\alpha_3}{3}+\frac{2\alpha_{33}}{3}\cos\chi+\frac{1}{137\beta\pi(1-\cos\chi)}\right)^2+\frac{\alpha_{33}{}^2}{9}\sin^2\chi\right].$$

This is under the assumption $\alpha_{31}=\alpha_{13}=\alpha_{11}=0$. This equation can be solved for $(2\alpha_1+\alpha_3)$ if the value of α_{33} at 26 Mev is known. There is good evidence that $\alpha_{33}=0.235\eta^3$ in this energy region.[4] Using this value for α_{33} we have $2\alpha_1+\alpha_3=(4.7°\pm2.7°)$ at 26 Mev. The upper and lower limits are the values corresponding to a cross section of 1.7 and 0.6 mb, respectively, for scatterings greater than 50°.

This result when combined with other recent results lead to the conclusion that the simple energy dependence of momentum to the power $(2l\pm1)$ is quite reasonable for the phase shifts α_3, α_1 and α_{33} up to 80 Mev. The following paper develops this conclusion in detail.

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Low-Energy Behavior of the Phase Shifts in Pion-Proton Scattering*

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A best fit has been made to all pion-proton scattering phase-shift information under 80 Mev assuming the energy dependence of the phase shifts is momentum to the power $(2l+1)$ which would be the case for strong short-range interactions. The values obtained for the Fermi-type solutions are $\alpha_{33}=0.235\eta^3$, $\alpha_3=-0.11\eta$, and $\alpha_1=0.16\eta$. These phase shifts, along with Coulomb forces, fit all scattering experiment data quite closely including the 5-Mev cloud chamber results at Columbia. However, at zero energy they predict $(\alpha_1-\alpha_3)=0.27\eta$, while recent photoproduction results and the Panofsky effect as evaluated here predict $(\alpha_1-\alpha_3)=0.21\eta$ with rather large uncertainties.

INTRODUCTION

NECESSARY parameters for devising a theory of meson-nucleon forces are the scattering lengths, which in principle can be determined from low-energy pion-proton scattering experiments. Recently, considerable low-energy pion-proton scattering information has become available, and has been analyzed in terms of s- and p-wave phase shifts. At low energies the energy dependence of such phase shifts can be expanded in powers of the momentum, where the first term is the power $(2l+1)$. Furthermore, wave mechanics shows that if the two particle interaction is strong compared to the kinetic energy in a region $r<r_0$ and if there is essentially no interaction beyond this region, then for $kr_0\ll1$ the first term of the expansion in momentum is much larger than the higher order terms. In this energy region we would expect

$$\alpha_l \propto \eta^{2l+1}, \tag{1}$$

where η is the center-of-mass momentum divided by $m_\pi c$. Empirically the phase shifts up to 80 Mev seem to follow this energy dependence. We have taken such an empirical approach in selecting 80 Mev as the upper energy limit of the available data which is used in obtaining a best fit to the theoretical shape η^{2l+1}.

The scattering results have fairly successfully been fitted with s- and p-wave phase shifts assuming conservation of isotopic spin. In the various phase shift solutions at low energies there are two fairly large s-wave phase shifts α_3 and α_1 (corresponding to $T=\frac{3}{2}$ and $T=\frac{1}{2}$) and one large p-wave phase shift. We shall consider only that type solution (commonly called the Fermi-type solution) where α_{33} $(T=\frac{3}{2}, J=\frac{3}{2})$ is the largest p-wave phase shift.[1] We shall make the additional restriction that α_{33} be positive. This choice is based on preliminary 115-Mev π^+-p scattering results which show a destructive Coulomb interference.[2] Also the solutions with negative α_{33} are inconsistent with Eq. (1).

At the 1954 Rochester Conference, Bethe[3] and Noyes[3] discussed the possibility of a Jastrow-type potential for α_3 which had previously been suggested by Marshak.[4] Such a potential would cause α_3 to depart violently from Eq. (1) at about $\eta=0.3$ and in some of the proposals it would change sign at about $\eta=0.5$.[3,5] Bethe and de Hoffman discuss the possibility that $\alpha_3\sim0$ up to $\eta\sim0.3$ in their forthcoming book.[6] One of the motiva-

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[6] H. A. Bethe and F. de Hoffmann, *Mesons and Fields* (Row, Peterson and Company, Evanston, to be published).