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π^+–p Scattering at 10–35 MeV in a Diffusion Cloud Chamber

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Abstract. An investigation has been made of π^+–p scattering at incident pion energies of $20(^{+15}_{-10})$ MeV, using a hydrogen filled diffusion cloud chamber in a magnetic field. Fifteen π^+–p scattering events were observed and the incident pion spectrum and path length were determined from measurements on π–μ decays. The results were analysed by using the values for the phase shifts $\alpha_{33} = 0 \cdot 235\eta^3$, $\alpha_{31} = 0$ and assuming that α_3 is directly proportional to η. The phase shift α_3 was then found to be $-(0 \cdot 13 \pm 0 \cdot 035)\eta$ radians, where η is the pion momentum in mass units.

§ 1. Introduction

THE low energy scattering of π-mesons by protons is of great interest, since at these energies the S-wave scattering is not masked by the P-wave scattering and the small S-wave phase shifts can be found. A knowledge of these phase shifts is important and at the time when the present experiment was in progress there was a discrepancy between the values obtained from experiments on the Panofsky ratio and low energy pion–nucleon scattering. The difference between the results is now within the experimental errors and any small disagreement which may remain can possibly be explained by the failure of isotopic spin conservation at low energies (Noyes 1956).

At low energies pion–nucleon scattering experiments are difficult because the cross sections are small and the short ranges of all the particles necessitate the use of thin targets. Counter techniques have only been used above 30 MeV for elastic scattering (Angell and Perry 1953 a, b, c, Barnes *et al.* 1953, Leonard and Stork 1954, Sachs *et al.* 1955) and above 20 MeV for charge exchange scattering (Spry 1954, Tinlot and Roberts 1953, 1954). For elastic scattering experiments at 20–30 MeV nuclear emulsions have been used. Orear *et al.* (1954 a), Orear (1955 a) have observed scattering events occurring in the emulsion and Whetstone and Stork (1956) have used an emulsion stack to detect pion scattering by a liquid hydrogen target. The first method has the disadvantage that the target is not pure and in the second the actual scattering event is not observed. In both methods the identification of events is difficult and the emulsions require specialized scanning.

A study of negative pion–proton scattering at 0 to 25 MeV has been made by Rinehart *et al.* (1955) using a hydrogen filled diffusion cloud chamber in a magnetic field. The gas filling of such a chamber is almost a pure proton target and the scanning although tedious is straightforward. Scattering events can be easily

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identified and the measurement of π–μ decay events gives a simple and accurate method of obtaining the pion path length and spectrum. This method of obtaining scattering events is very slow since the gas density is low and the repetition rate is limited by the slow recovery of the cloud chamber. Liquid hydrogen bubble chambers would obviously be more efficient detectors for this type of experiment and they will undoubtedly be used in the future.

The values of the phase shifts obtained in the earlier experiments have been summarized by Orear (1954, 1955 b) and the later work by Whetstone and Stork (1956).
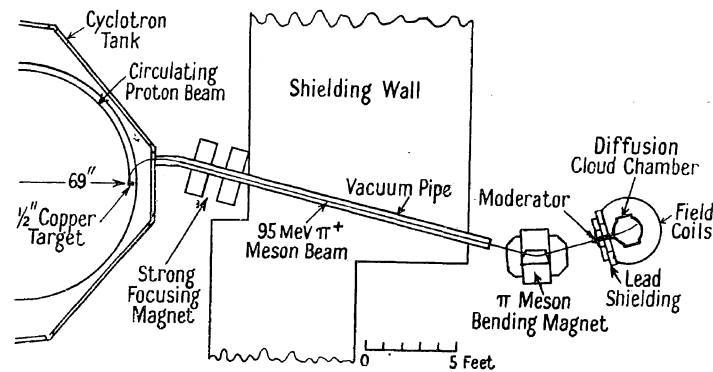

Figure 1. Experimental arrangement.
Operating conditions of the diffusion cloud chamber :

Run	Pressure (lb in^{-2})	Mean gas density (mg cm^{-3})
1	348	2·54
2	378	2·74
3	365	2·64

Mean temperature in sensitive region $-35°$c.

Moderator: 1st run: 1·532 in. of copper=35 g cm^{-2};
2nd & 3rd runs: 9·75 in. of polythene=22·6 g cm^{-2}.

§ 2. EXPERIMENTAL PROCEDURE

The arrangement of the apparatus is shown in figure 1. The 18 in. diameter diffusion cloud chamber already described (Alston *et al.* 1956) was filled with approximately 25 atmospheres of hydrogen and a steady magnetic field of 2·3 kilogauss was applied. The pressure and the mean temperature of the gas in the sensitive region of the chamber were carefully monitored throughout the experiment to obtain the mean gas density. A 95 mev beam of π^+-mesons was produced by the proton bombardment of a $\frac{1}{2}$ in. thick copper target placed in the cyclotron tank at a radius of 69 in. This beam was moderated at the focus of the π-meson magnet and entered the chamber through a phosphor bronze window 2 in. × 3 in. × 0·018 in.

It is difficult to obtain a moderated beam with the required characteristics. The track measurements would be simplified if a monoenergetic beam were available and for the reliable detection of π–μ decays the track density should be low and uniform throughout the sensitive region of the chamber. A monoenergetic beam could only be obtained by attenuating the original beam in front of the π-meson magnet and this procedure yielded a low energy beam of insufficient intensity. To obtain a beam in which the tracks are well separated

a heavy moderator would be preferable since the multiple scattering angle is large. In a preliminary run a copper moderator was used but a very diffuse pion spectrum was obtained and a polyethylene absorber was used in the two subsequent runs. This gave a moderated beam with a less diffuse spectrum which extended from 0 to 40 mev and was peaked at 20 mev. The synchrocyclotron produced 100 beam pulses per second and a small number of these were used per picture. Unfortunately the radio-frequency pulser was unreliable and the beam intensity was small and variable. The average number of beam pulses per picture was three and the π^+-meson intensity, in the energy range 10–35 mev, was seven per picture for an average length of 35 cm. There was also a contamination of 30% which consisted of μ-mesons, electrons and π-mesons outside the accepted energy range.

During the experiment a sensitive depth of $2\frac{1}{2}$–3 in. was maintained with a repetition rate of 30 sec. 5400 pictures were taken on 70 mm Ilford 5G91 film using a stereoscopic camera with its lens axes inclined at 7° to the vertical. A photograph of a π^+–p scattering event is shown in figure 2 (Plate).

2.1. Measurement of the Tracks

The pictures were reprojected through the camera lenses on to a screen which could be moved into any plane. Both pictures of a stereo pair were scanned for π^+–p and π–μ decay events with the screen horizontal.

The true radius of curvature and dip angle of a decaying pion were measured if the projection of the decay angle on to the horizontal plane from either lens was equal to or greater than 5° and the incident energy was between 5 and 40 mev. From these measurements and a knowledge of the gas density and π-meson life-time the π-meson spectrum and the scanned path length in g cm^{-2} could be computed (Fowler *et al.* 1953).

Scattering events were identified by kinematics and were accepted if the scattering angle in the centre-of-mass system was greater than 60° ($\sim$52° in the laboratory system) and if the incident energy was between 10 and 35 mev. If the curvature of the incident track could not be measured it was estimated from the proton range and/or the curvature of the scattered meson track. The cut-off in angle and the lower cut-off in energy were applied so that the ranges of the proton recoils from acceptable scattering events were greater than 5 mm. This ensured that π–p events were not missed and that there was no confusion between π–μ decays with associated δ-rays and true scattering events. The high energy cut-off was imposed because there were relatively few π–μ decays above 35 mev and also because accurate measurement of the track curvature was difficult.

All the pictures were rescanned for π–p events only and the combined scanning for scattering events was then considered to be 100% efficient. 1000 pictures were rescanned very carefully for π–μ decays to obtain the efficiency of the first scan. The π–μ decay events obtained in the two scans were compared and when they had been suitably combined it was assumed that all the decays with projected angle greater than 5° had been found. The mean efficiency for finding π–μ decay events was found to be 82% for the first scan and 94% for the second. The efficiency appeared to be uniform over the spectral range and showed no systematic variations.

2.2. *Results*

During the first scan 2841 $\pi-\mu$ decays in the energy range 5–40 MeV were measured. Corrections are applied to the spectrum obtained (table 1) to allow

Table 1. The Incident π^+-Meson Spectrum

(1)	(2)	(3)	(4)	(5a)	(5b)	(6)
5–10	465	$1 \cdot 20 \times 10^5$	317	6	6	388
10–15	601	$1 \cdot 98 \times 10^5$	522	8	3	657
15–20	655	$2 \cdot 58 \times 10^5$	677	10	2	896
20–25	559	$2 \cdot 51 \times 10^5$	659	12	1·5	900
25–30	262	$1 \cdot 32 \times 10^5$	348	13·5	1	486
30–35	215	$1 \cdot 20 \times 10^5$	312	15·5	1	447
35–40	84	$0 \cdot 50 \times 10^5$	132	17	0·5	192
Total						
10–35	2292	$9 \cdot 59 \times 10^5$	2518			3386

(1) Incident energy (MeV); (2) $\pi-\mu$ decays measured; (3) measured path length L (cm); (4) measured path length x (g cm^{-2}); (5) corrections : a, projection $\alpha_p(\%)$, b, Coulomb scattering α_c; (6) corrected path length $[x/(1-\alpha_p+\alpha_c)]100/82$ (g cm^{-2}).

for the inefficiency in the scanning, 5° cut-off in decay angle, and coulomb scattering events above 5° which could have been mistaken for $\pi-\mu$ decays. The 5° cut-off corrections are smaller than for a plane projection because the lenses are inclined at 14° to each other. The corrected spectrum is shown in figure 3.
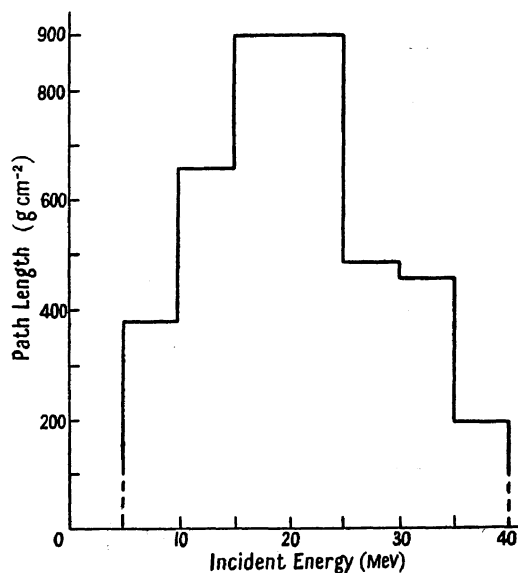

Figure 3. Corrected spectrum of incident π^+-mesons.

Fifteen π^+-p scattering events were found with incident energy in the range 10–35 MeV and with scattering angle greater than 60° in the centre-of-mass system (table 2). No events were missed due to the 5° cut-off in reprojection.

Table 2. Accepted π^+-p Scattering Events

Incident pion energy (MeV)	10–12	16	19	21	23	23	25	26
Pion scattering angle (c.m.s.) (deg.)	152	74	110	137	150	157	116	152

Incident pion energy (MeV)	26	25–27	25–27	29	31	32	31–34
Pion scattering angle (c.m.s.) (deg.)	79	78	80	114	141	70	165

The average total cross section over the accepted energy range for $\theta > 60°$ is found to be 7·4 millibarns.

The differential cross section for π^+–p scattering at low energies is given by

$$\frac{d\sigma^+}{d\omega} = \lambdabar^2 \left\{ \left[\alpha_3 + (2\alpha_{33} + \alpha_{31}) \cos\theta - \frac{\alpha}{1 - \cos\theta} \right]^2 + (\alpha_{33} - \alpha_{31})^2 \sin^2\theta \right\}$$

$$\dots\dots(1)$$

(Bethe and de Hoffmann 1955). We assume (Orear 1954)

and also
$$\alpha_{33} = 0·235\eta^3, \qquad \alpha = 1/137\beta_\pi, \qquad \alpha_{31} = 0$$
$$\alpha_3 = -q\eta \qquad\qquad \dots\dots(2)$$

where q is a constant, η the momentum of the incident pion in the centre-of-mass system in units of μc and β_π the velocity of the pion in the laboratory system in units of c.

From equations (1) and (2) and the incident pion spectrum (figure 3), the predicted number of events for various values of q is calculated and compared with the number actually found. This calculation gives a value $q = 0·13 + 0·03$, where the error is the standard deviation in the number of events only.

The systematic experimental error is estimated as 5%, arising from errors in the knowledge of scanning efficiency, gas density and the corrections applied to the spectrum. A further small error may be introduced by assuming $\alpha_{31} = 0$; however, this phase shift is known to be small and a value $\alpha_{31} = 1°$ makes less than 1% difference to the predicted number of events.

The final value obtained is

$$\alpha_3 = -(0·13 \pm 0·035)\eta. \qquad\qquad \dots\dots(3)$$

This value is in good agreement with that of Orear (1954, 1955 a, b), i.e. $\alpha_3 = -0·11\eta$ deduced mainly from results at pion energies above 40 Mev.

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↓ Beam direction

Figure 2. A picture of a π^+-p scattering event. Incident energy = 23 Mev, pion scattering angle (lab) = 152°, proton recoil angle (lab) = 12°, pion scattering angle (c.m.s.) = 157°. The picture also shows two π-μ decay events.