INELASTIC INTERACTION OF PIONS WITH HELIUM NUCLEI AT APPROXIMATELY 300 Mev

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Interaction of positive and negative π mesons with helium nuclei at corresponding energies 273 Mev and 330 Mev was studied with the aid of a diffusion cloud chamber. Quasifree scattering on neutrons and protons, multiple scattering and absorption of the mesons were discriminated. The total inelastic interaction cross sections were $(145 \pm 15) \times 10^{-27}$ cm^2 for $E_\pi = 273$ Mev and $(103 \pm 10) \times 10^{-27}$ cm^2 for $E_\pi = 330$ Mev. The relative probabilities for quasifree scattering on neutrons and protons through angles of 45° in the laboratory coordinate system are found to agree with the corresponding probabilities for scattering on free nucleons. The probabilities for multiple scattering processes were found equal to 0.24 ± 0.06 for $E_\pi = 273$ Mev and 0.29 ± 0.05 for $E_\pi = 330$ Mev.

The experimental results confirm current ideas concerning the main role of n-p pairs in absorption of π mesons by nuclei. The angular distribution of inelastically scattered π mesons is compared with the Watson-Zemach calculations.

INTRODUCTION

THE basic phenomena that occur when fast pions are scattered by nuclei are adequately described in first approximation by the Serber-Goldberger model.[1,2] In this model the inelastic scattering is considered as a result of the interaction between the pion and individual nucleons of the nucleus. The nucleons of the nucleus are represented as an aggregate of non-interacting particles, located in a potential well and having a certain momentum distribution.

The absorption of the pions by the nuclei fits the framework of the mechanism of absorption by nucleon pairs, and the principal role is apparently played by n-p pairs.[3-6]

More detailed experimental research is necessary for further development of the notions of the mechanism of interaction between fast pions and nuclei. In particular, it is very important to establish by direct experiment the degree to which the free and bound nucleons exhibit identical properties in the scattering, the role of the interaction processes in which more than one nucleon participates, etc. Such investigations entail great experimental difficulties. The problem becomes somewhat simpler if targets of light nuclei are used and the experiments performed with both positive and negative pions.

The present work covers inelastic interactions between $\pi^\pm$ mesons and helium nuclei at approximately 300 Mev.

EXPERIMENTAL PROCEDURE AND APPARATUS

The interaction between pions and helium nuclei was investigated with a high pressure diffusion chamber using pion beams from the synchrocyclotron of the Joint Institute for Nuclear Research. The arrangement of the experimental apparatus when working with negative and positive pions is shown in Figs. 1 and 2 respectively.

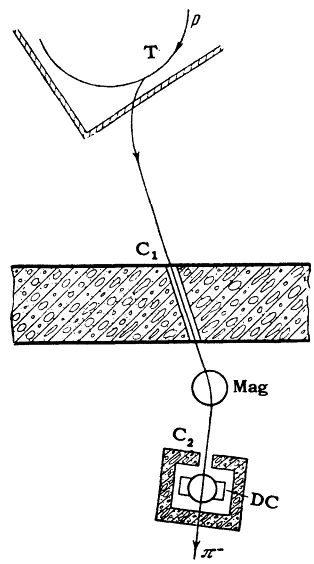

FIG. 1. Setup for the experiment with negative pions.

Negative pions were produced with a carbon target T, placed inside the accelerator chamber along the circular path of a 670-Mev proton beam. The negative pions accelerated in the stray magnetic field of the accelerator, passed through a steel

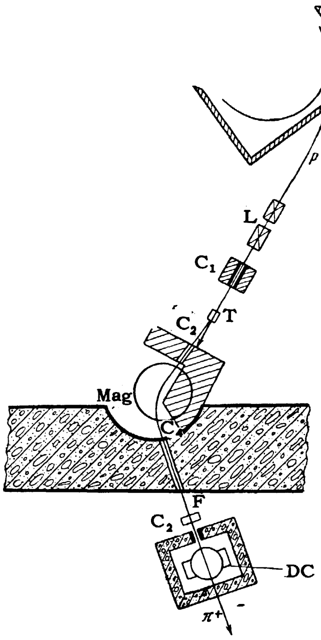

FIG. 2. Setup for the experiment with positive pions.

collimator C_1, 100 mm in diameter, in a four-meter concrete shield, were again deflected by a clearing magnet Mag by 22° and entered the diffusion chamber DC.

Positive pions were produced with the proton beam extracted from the accelerator chamber. A polyethylene target T 200 mm thick was placed at the focus of quadrupole magnetic lenses L past a collimator C_1. A monochromatic beam of positive pions from the reaction $p + p \rightarrow \pi^+ + d$, traveling at an angle of 9° to the direction of the proton beam, was gathered with the aid of collimators C_3 and C_4 and analyzing magnet Mag. The diffusion chamber, as in the first case, was placed in the experiment room behind a four-meter concrete shield.

In both cases, a collimator C_2, with a cross section equal to the size of the inlet window of the diffusion chamber (30×60 mm) was placed in front of the chamber. To clear the positive pion beam of protons having the same momenta as the mesons, a carbon filter F 60 mm thick was placed in front of collimator C_2. To reduce the background of extraneous particles the diffusion chamber was surrounded by additional lead and concrete shields.

The pion energy was determined by simulating their trajectories with a flexible current-carrying conductor. The positive-pion beam was used in addition to plot a range curve in copper. It follows from these measurements that, allowing for ionization losses in the absorber and the chamber walls, the energies of the positive and negative pions were (273 ± 7) and (330 ± 6) Mev respectively.

A diffusion chamber of 270 mm diameter, filled with helium at a pressure of 15 atmos, was used in the experiments.[7] The working liquid was methyl alcohol. The height of the sensitive layer was 5 – 6 cm at a bottom temperature of – 65° C and a vapor source temperature of + 10° C. The sensitive layer was illuminated on both sides by parallel beams of light. The chamber was photographed at an angle of 90° to the direction of the illumination by a stereo camera having lenses with parallel axes and a base of 120 mm. Lenses of focal length F = 35 mm and of relative aperture 1 : 7 were used. 35 mm Pankhrom X with a sensitivity $S_{0.85} = 1000$ GOST units and contrast $\gamma = 1.6$ was used.

During the exposure of the diffusion chamber the accelerator operated in the control mode customary for such experiments. The particle flux through the chamber was regulated by varying the number of acceleration cycles and amounted on the average to approximately 20 particles per photograph. The operating cycle was determined to a considerable extent by the background conditions and ranged from 7 or 10 seconds in the negative-meson beam to 15 or 18 seconds in the positive-meson beam.

2. PROCESSING OF THE PHOTOGRAPHS AND IDENTIFICATION OF INTERACTION EVENTS

The interaction events were selected by scanning the photographs twice through a stereo magnifier. The necessary angles and lengths of the particle ranges were measured on a reprojector.[8] Two angles were measured for all secondary particles: the angle between the direction of the primary and secondary particles, θ, and the azimuth angle φ. Most measurements could be made directly by simply reading the dials of the instrument. For this purpose the axis of rotation of the screen was made to coincide with the direction of the track of the primary particle, after which the position of the scattering plane was found by rotating the screen about this axis. The true position of the track in space was established by making its two projections on the screen coincide. If the secondary-particle track was located in a region in which a stereo projection cannot be obtained in this manner, the axis of rotation was turned by 90° in the horizontal plane, and the angles φ' and θ', connected with φ and θ by the simple relations

$$\sin\theta = \cos\theta' / \cos\varphi, \qquad \tan\varphi = \tan\theta' \sin\varphi',$$

were measured. Here φ' is the projection of the angle θ on the vertical plane, and θ' is the angle between the track of the secondary particle and the axis of rotation.

Whenever the track fell in the "dead zone" of the reprojector, it became necessary to make the measurements by the coordinate method.′ The angle at the vertex of the "dead-zone" cone was approximately 40°.

An important role was played in the identification of interaction events by measurements of the ranges and by the specific ionization of the particles. The length of the range was taken to be the distance between the point of interaction (corresponding to the point of intersection of the fast-particle tracks) and the end of the track of the stopped particles, reduced by one half the width of the track. The length obtained in this manner was reduced by another 5%, in view of the change in scale that arises when the image is reprojected, owing to the shrinkage of the film. A careful analysis was made every time to ascertain whether the particle range terminated in the illuminated region of the chamber. The accuracy with which the particle energy was determined in this manner was verified by comparing the measured ranges of the recoil α particles, formed in elastic scattering, with those calculated by the Bethe formula. The average error did not exceed 15%.

The ionization was measured by relative photometry, i.e., by comparing the photograms of tracks made by particles of known and unknown ionization.[9] The ionization was measured only when a visual estimate was found to be insufficient for identification purpose and more exact data were needed.

The chamber contained, along with the helium, methyl alcohol vapor CH_3OH. This admixture, however, was small in the sensitive layer. Estimates show that the ratio of the number of interactions with hydrogen to that with helium should not exceed ~ 0.002 for negative pions and ~ 0.01 for positive pions; the contributions due to events produced by oxygen or carbon should not exceed ~ 0.02. It was therefore assumed in the analysis of the observed events that all, with the exception of the obvious carbon and oxygen stars, are due to interactions with helium nuclei.

Before we proceed to describe the procedure of identifying different interaction processes between $\pi^{\pm}$ mesons and helium nuclei, let us list the principal reactions:

$\pi^- + He^4 \rightarrow \pi^- + He^1$,	elastic scattering	(1)
$\pi^- + He^4 \rightarrow \pi^- + n + He^3$		(2)
$ \pi^- + p + H^3$,	inelastic scattering	(3)
$ \pi^- + (2n,\ 2p)$		(4)
$\pi^- + He^4 \rightarrow \pi^0 + n + H^3$	exchange scattering	(5)
$ \pi^0 + (3n,\ 1p)$,		(6)
$\pi^- + He^4 \rightarrow n + n + d$	non-radiative capture	(7)
$ 3n + p$,		(8)
$\pi^+ + He^4 \rightarrow \pi^+ + He^4$,	elastic scattering	(1′)
$\pi^+ + He^4 \rightarrow \pi^+ + n + He^3$		(2′)
$ \pi^+ + p + H^3$,	inelastic scattering	(3′)
$ \pi^+ + (2n,\ 2p)$,		(4′)
$\pi^+ + He^4 \rightarrow \pi^0 + p + He^3$	exchange scattering	(5′)
$ \pi^0 + (1n,\ 3p)$,		(6′)
$\pi^+ + He^4 \rightarrow p + p + d$	non-radiative capture	(7′)
$ n + 3p$,		(8′)

The nucleon combination included in the parentheses may be a deuteron with two free nucleons or else four free nucleons. The elastic scattering events (1) and (1′) were segregated by kinematic particle divergence, as described in detail in references 10 and 11.

As a rule, reactions (2) and (2′) appear on the photographs as two-prong stars with uncorrelated prongs. The pion should have an ionization close to minimum. The He^3 nucleus is slower in this reaction, and its range terminates in most cases in the illuminated region. Quite similar in external appearance to the processes (2′) are certain exchange-scattering events, when a fast proton is emitted in reaction (5′). To segregate such events, we measure the ionization of the fast particle. We had in mind the fact, shown by kinematic calculations, that the ionization produced by the forward-flying fast proton cannot, with any discernible probability, be lower than twofold.

True, another possibility, which is much less probable for reactions (2) and (2′), is a single-prong star, formed whenever the He^3 nucleus has a very small momentum and its range is not discernible in the photograph. Such events are distinguished from reactions (8) and (5′) also by ionization measurements.

Somewhat greater difficulties arise in the identification of processes (3) and (3′). In fact, most events (3) and (3′) are three-prong stars. But processes (4), (4′), (6′), (7′), and (8′) also produce tridents. Therefore, the identification calls for an all-inclusive analysis, which takes into account all the singularities of these reactions.

The easiest to segregate from the bulk of the tridents are events in which at least one neutral particle is emitted; it is seen from these events immediately that the emitted three particles are not in a position to balance the initial momentum. This manifests itself either in the fact that the charged particles move into the rear hemisphere, or in the fact that the projections of the directions of the charged particles on the azimuth plane lie in one half plane.

The next step in the identification of tridents is also based on the conservation of momentum. If only three particles are emitted in the final state, then the measured angles φ and θ, together with the value of the initial momentum, make it possible to calculate the momenta of these particles. If neutral particles are emitted in this reaction together with the three charged particles, such a calculation does not give the true value of the momentum. In this case the expression for the calculated momentum p_n' can be represented in the form

$$p_n' = p_n - q_n.$$

Here p_n is the true momentum of the n-th particle and q_n is a rather complicated function of many quantities and can assume both positive and negative values. One can therefore consider that a sufficient condition of the emission of at least one neutral particle is the appearance of negative values for p_n'.

The purpose of further identification was to segregate from among the remaining tridents cases in which only three particles are emitted, namely (3), (3′), and (7′). For this purpose, the obtained values of the momenta were used to verify the energy balance, and whenever a particular track could not be assigned to a particular particle, different possible assumptions were made concerning the natures of the particles. In addition to the energy balance, the angular correlation between the pion and the proton in (3) and (3′), or between the two protons in (7′), were examined under the assumption that the initial momentum is represented by the difference $\mathbf{p}_0 - \mathbf{p}_{H^3}$ or $\mathbf{p}_0 - \mathbf{p}_d$ respectively. The angular correlation was verified with a special instrument, which readily simulated the vectors of all the momenta in space. Finally, we verified the correspondence between the values of the calculated momenta of the slow particles, and the values determined from the ranges, or their lower bounds.

In segregating events (3), (3′) and (7′), owing to the great variety of the measurement conditions, we did not use any particular selection rules, since an accurate determination of these events was a highly difficult matter. Instead, a thorough individual analysis was made in each specific case of the possible errors in the measurements of φ and θ, and the sensitivity of the calculated values of the particle momenta and energies to these errors was verified. As a result of such an approach, the inaccuracy in the energy balance did not exceed ±50 Mev for most of the selected three-particle events. The events identified with greatest reliability were those in which the ranges of the H^3 nuclei or of the deuterons terminated in the illuminated region of the chamber.

We also classified as processes (3) and (3′) certain of the two-pronged stars, in which the kinematic conditions of two-particle (π-p) divergence are satisfied. It was assumed that in these cases the H^3 nucleus, owing to its very small momentum, does not leave a visible track in the chamber. After separating the three-particle reactions, the remaining tridents were classified as (4), (4′), (6′), and (8′). Cases of inelastic scattering of positive pions (4′) were selected from among the processes with emission of neutral particles by measuring the ionization produced by the fast particles. We were unable to devise separation methods for the analogous exchange-scattering (6′) and non-radiative capture (8′) processes. A similar situation obtains in the identification of exchange scattering (5) and (6) and non-radiative capture, (7) and (8) of negative pions (all these cases are single-prong stars). We merely attempted here to separate the reaction (8) from events in which a fast proton was emitted (this will be discussed in Sec. 5). Typical photographs of individual reactions are given in Figs. 3, 4, and 5.

3. RESULTS OF IDENTIFICATION AND ABSOLUTE CROSS SECTIONS

We obtained 24,000 photographs in the beam of negative pions and 11,000 photographs in the beam of positive pions. The results of the scannings disclosed a total of 321 and 229 interaction events due to negative and positive pions respectively, of which 222 and 152 were due to inelastic interaction. The results of the identification of these events are listed in Table I.

To determine the absolute cross sections, we selected the photographs of highest quality containing not more than 20 particles per frame. The total number of interactions of events in these selected photographs of positive and negative meson beams was approximately 100 in each selected group. These photographs were subjected to careful scanning, with simultaneous calculation of the number

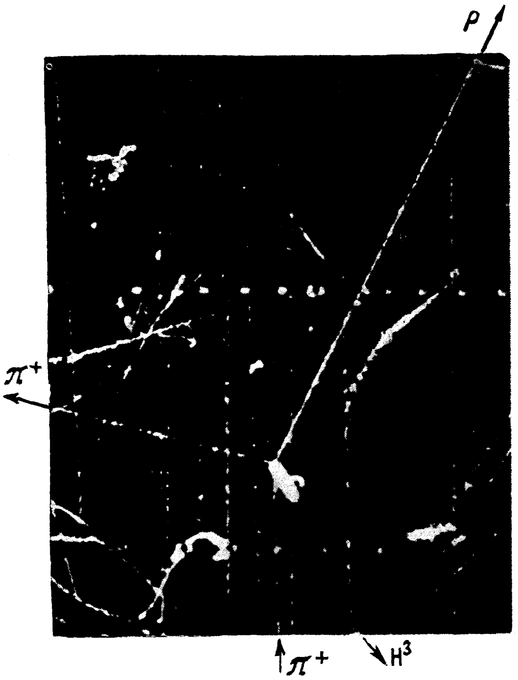

FIG. 3. Photograph of quasifree scattering of a positive pion by a proton.

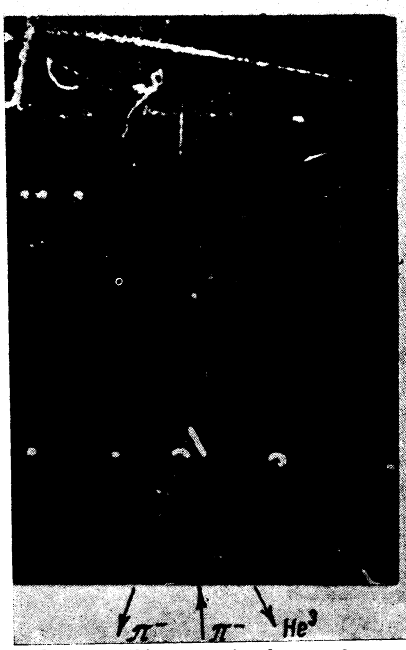

FIG. 4. Photograph of quasifree scattering of a negative pion by a neutron.

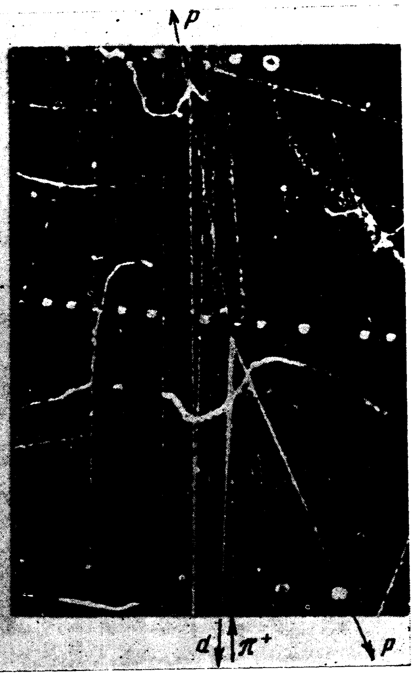

FIG. 5. Photograph of capture of a positive meson by an n-p pair.

of particles passing through the chamber. This number did not include the particles deviating from the beam direction by angles greater than the divergence angle of the beam. Nor were particles included whose ionization, as estimated visually, exceeded the minimum value. The admixture of muons and fast electrons in the negative-pion beam was estimated by observing the (π-μ) decays in flight in the same beam,[7] and was assumed to equal 6%. The same admixture in the positive-pion beam was determined from the range curve and amounted to 10%. In the calculations of the absolute cross section the gas density was assumed to correspond to the temperature of the midpoint of the sensitive layer, and the effective thickness of the track in the chamber was taken to be 23 cm. The total absolute cross sections of interaction of 330-Mev negative pions and

TABLE I

Positive pions, E_π = 273 Mev			Negative pions, E_π = 330 Mev		
Process	Number of events	Cross section, 10^{-27} cm²	Process	Number of events	Cross section, 10^{-27} cm²
1	2	3	4	5	6
(1′)	77	75±9	(1)	99	47±5
(2′) total	14 [5]*	14±4	(2) total	72	34±4
track of He³ invisible	—		track of He³ invisible	4	
(3′) total	51 [10]	50±7	(3) total	27 [7]	13±3
track of H³ invisible	1		track of H³ invisible	4	
(4′)	21 [12]	20±4	(4)	41 [6]	19±3
(5′) total	35 [10]	34±6	(5), (6), (7), (8) total	70	33±4
track of He³ invisible	[2]				
(7′) total	8 [1]	8±3	with emission of fast protons	20	9±2
track of d invisible	—				
(6′), (8′)	13 [5]	13±4			
Cases of interaction with oxygen or carbon	2		Cases of interaction with oxygen or carbon	4	
Unidentified events	8		Unidentified events	8	
Total	229	220±20	Total	321	150±15

*The numbers in square brackets indicate the events in each group with lower reliability of identification, owing to poor measurement conditions.

of 273-Mev positive pions with helium nuclei were found to be $(150 \pm 15) \times 10^{-27}$ and $(220 \pm 20) \times 10^{-27}$ cm^2, respectively. The partial cross sections of different processes are listed in columns 3 and 6 of Table I. The cross sections are indicated with relative statistical errors.

4. ANALYSIS OF THE INELASTIC AND EXCHANGE SCATTERING PROCESSES

a) Role of multiple scattering processes. The reactions (2), (2′), (3), (3′), and (5′) can be considered as the results of a quasifree scattering by individual bound nucleons, considering that the residual nuclei do not participate directly in the interaction with the incoming pions. Analyzing these reactions, we can verify that the momenta of the He^3 and H^3 nuclei are of the same order of magnitude as the intranuclear momenta of the nucleons; their values range essentially from 0 to 300 Mev/c. The angular distributions of these nuclei (detailed data on which will be published later) also agree with the foregoing scheme. In addition, the momenta and the angles of the mesons and protons in (3) and (3′) are correlated and are close to the correlation that takes place in scattering by free nucleons.

Thus, the singularities of these reactions, together with their high probability (see Table I), illustrate the correctness of the point of view that the pion-nucleon interaction at these energies has essentially a one-nucleon character.

The remaining cases of inelastic scattering (4), (4′), (6), and (6′), in which more than three particles are emitted in the final state, can be interpreted in two ways. Firstly, these cases may be the result of simultaneous interaction between the pions and complexes of nucleons. This assumption can be corroborated partially by the fact that a noticeable probability of non-radiative pion capture exists, in which at least two nucleons participate. The fact that not a single event of a type (π, d, d) reaction was registered cannot serve as a refutation of this point of view, since the probability of emission of a group of nucleons in the bound state may prove to be small.

Secondly, these cases may be the result of the development of a cascade in the nucleus. The few observed events, in which two charged particles (apparently protons) diverge at an angle of 90°, indicates that the cascade processes do take place, at least in those cases. Actually, it is probable that both mechanisms are in operation. To clarify their relative role, the experimental results must be supplemented by cascade calculations.

The processes that proceed via these two channels we shall tentatively call multiple-scattering processes. The relative probability of multiple scattering in inelastic scattering ϵ can be determined directly from the number of cases that correspond to the reactions (2), (2′), (3), (3′), (4) and (4′):

$$\varepsilon_{E_\pi=273} = N_{4'} / (N_{2'} + N_{3'} + N_{4'}) = 0.24 \pm 0.06;$$

$$\varepsilon_{E_\pi=330} = N_4 / (N_2 + N_3 + N_4) = 0.29 \pm 0.05.$$

In exchange scattering this probability cannot be determined, since the corresponding reactions were not identified.

b) Relations between quasifree scattering processes. One can hope that the results obtained for the quasifree scattering by neutrons and protons will throw light on the question whether the properties of the free and bound nucleons that appear in the scattering are identical. In particular, owing to the great difference in the interaction of pions with nucleons in various isotopic states, one can attempt to obtain, by comparison with the corresponding quantities for the free nucleons, information on the purity of the isotopic states in quasifree scattering processes. However, one must bear in mind here several circumstances which make such an analysis difficult. The first of these is that the interaction between pions and nucleons is not confined to quasifree processes. Therefore, for comparison purposes, it would be desirable to separate all the cases that result from pairwise interaction with neutrons and protons, cases due to collective interactions or interference phenomena, and to establish whether the latter influence in a unique manner the probability of interaction with neutrons and protons. In actuality, this cannot be done on the basis of experimental data.

The second difficulty lies in the fact that there is a certain indeterminacy in the choice of the energy for which the cross sections of interaction with free nucleons are to be taken. The comparison could be made within the framework of some theory that describes sufficiently well the entire complex of interactions between pions and nucleons. Unfortunately, no such theory exists. Nevertheless, a comparison of the relative probabilities of scattering by free and bound nucleons can be made under certain simplifying assumptions.

We shall assume that the corrections to the relation between the quasifree processes due to multiple scattering and absorption of pions are small. The influence of elastic scattering can be excluded by using in the comparison cross sections in that range of angles where there is practically no elastic scattering (> 45°). For exchange scattering

TABLE II

Pion energy, Mev	Process	Cross sections, 10^{-27} cm² total	Cross sections, 10^{-27} cm² θ>45°	Cross section ratio total	Cross section ratio θ>45°
1	2	3	4	5	6
		Scattering by free protons			
$E_\pi = 330$	I) $\pi^+p \to \pi^+p$	56	25.1	$\sigma_I / \sigma_{II} = 5.1$	3.9
	II) $\pi^-p \to \pi^-p$	11	6.4	$\sigma_I / \sigma_{III} = 3.7$	
	III) $\pi^-p \to \pi^0 n$	15	—		
$E_\pi = 273$	I	96	49.0	$\sigma_I / \sigma_{II} = 7.4$	6.0
	II	13	8.2	$\sigma_I / \sigma_{III} = 4.0$	
	III	24	—		
$E_\pi - V_R = 296$	I	76	34.8	$\sigma_I / \sigma_{II} = 6.3$	5.1
	II	12	6.8	$\sigma_I / \sigma_{III} = 3.6$	
	III	21	—		
$E_\pi - V_R = 244$	I	118	68.2	$\sigma_I / \sigma_{II} = 7.4$	6.6
	II	16	10.4	$\sigma_I / \sigma_{III} = 3.9$	
	III	30	—		
		Quasifree scattering			
$E_\pi = 330$	(2)	34±4	25±4	$\sigma_{(2)} / \sigma_{(3)} = 2.6 \pm 0.7$	4.2±1.3
	(3)	13±3	6±2		
	(5)	—	—		
$E_\pi = 273$	(3′)	50±7	39±6	$\sigma_{(3')} / \sigma_{(2')} = 3.6 \pm 1.1$	4.9±2.0
	(2′)	14±4	8±3	$\sigma_{(3')} / \sigma_{(5')} = 1.5 \pm 0.3$	
	(5′)	34±6	—		

this need not be done, since any interaction that leads to a change in charge of an α particle is an inelastic process.

To take into account the change in the relative energy due to intranuclear motion of the nucleons, we shall average the total cross sections for the interaction between pions and free protons over the function of momentum distribution of the nucleons in the nucleus. If the distribution function is taken in the form $A \exp(-p^2/p_0^2)$ with a value $p_0 = 150$ Mev/c, and we use the experimental energy dependence of the π-p interaction cross section,[12-15] then the calculated effective cross sections hardly differ from the cross sections of the corresponding processes on protons at rest at the same energies in the laboratory system of coordinates. Thus, in this range of energies one can disregard the effect of the intranuclear motion of the nucleons on the value of the relative meson energy.

Finally, we can also take into account the presence of a repelling nuclear potential, which reduces the kinetic energy of the pions in the nucleus. The values of the real part of the average nuclear potential V_R can be assumed to be 29 and 34 Mev for the energies 273 and 330 Mev respectively (more details on this will be reported later). The results of the comparison of the corresponding cross sections are given in Table II. The data pertaining to interaction between $\pi^\pm$ mesons and protons were taken from the literature,[14,15] and the angular distributions were taken for values of energy close to those under consideration, and normalized to the corresponding total cross sections.

The quantities in Table II evidence clearly the influence of the factors considered on the results of the comparison. In accordance with the considerations advanced above, one must compare the values listed in column 6 for $E_\pi - V_R$ and quasifree scattering. For both pion energies considered, the average values of the relative scattering probabilities by bound neutrons and protons is undervalued. However, owing to the large statistical errors, the reliability of this fact is low. If we consider in addition the roughness of the scheme adopted for the comparison, and also the possible systematic errors in the separation of quasifree scattering cases, it is obvious that the results obtained give no grounds for doubting the purity of the isotopic states in quasifree scattering of pions.

TABLE III

Energy, Mev		γ
$E_\pi =$	300	0.63±0.06
	273	0.53±0.06
$E_\pi - V_R =$	296	0.47±0.05
	244	0.44±0.05

Table III lists the values of the coefficient γ, which characterizes the summary influence of the bond on the absolute cross section of interaction with bound nucleons. It is equal to the ratio of the total cross section of inelastic scattering between pions and He^4 nuclei to the sum of cross sections of interaction with free nucleons.

c) Angular distributions. The angular distributions of inelastic scattering in the laboratory system of coordinates are shown in Figs. 6 and 7.

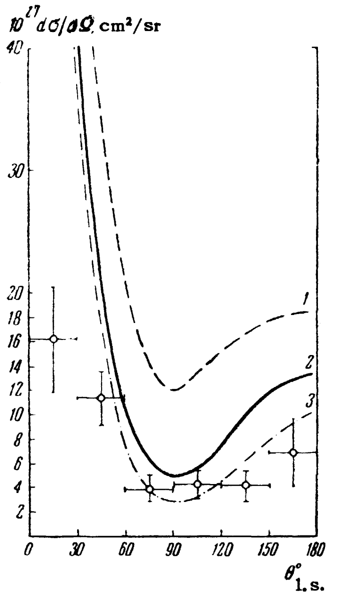

FIG. 6

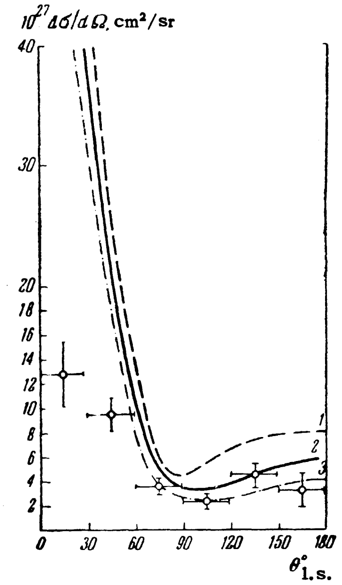

FIG. 7

FIG. 6. Angular distribution of inelastic scattering of π^+ mesons by He^4 at E = 273 Mev; curves – calculated: 1 – values of 2Σ for $E_\pi - V_R$ = 244 Mev, 2 – $(F/F_f) \times 2\Sigma$ at $E_\pi - V_R$ = 244 Mev, 3 – $(F/F_f) \times 2\Sigma$ at E_π = 273 Mev.

FIG. 7. Angular distribution of inelastic scattering of negative pions by He^4 at E = 330 Mev. The curves have been calculated by the same formulas as the corresponding curves of Fig. 6, but at the following energies: 1 – $E_\pi - V_R$ = 296 Mev, 2 – $E_\pi - V_R$ = 296 Mev, 3 – E_π = 330 Mev.

These include both quasifree and multiple-scattering events. The dotted lines in the same figures show the sums (multiplied by two) of the differential cross sections of the scattering of pions by free neutrons and protons[14,15]

$$2\Sigma = 2\,[d\sigma(\pi^- p \rightarrow \pi^- p)/d\Omega + d\sigma(\pi^+ p \rightarrow \pi^+ p)/d\Omega]$$

for energies $E_\pi - V_R$. The relative variation of the differential cross section of scattering by free nucleons is very similar to the angular dependence of inelastic scattering of pions by He^4. Exceptions are the region of small angles ($\theta < 40°$), where the inelastic scattering is noticeably suppressed. This phenomena can be understood by considering that the inelastic scattering by nuclei is forbidden at a relatively small energy transfer to the bound nucleons, as indeed happens in the case of scattering at small angles.

Watson and Zemach[16] have made an attempt to take into account theoretically the influence of coherent processes on inelastic scattering of pions by nuclei. Actually they have approximately taken account of the variation in the kinematic factors, due to the fact that the mesons are scattered in a medium where the potential differs from zero and varies with the pion energy. The differential scattering cross sections by free $(d\sigma/d\Omega)_f$ and bound $(d\sigma/d\Omega)_b$ nucleons they were able to relate by means of the simple equation

$$(d\sigma/d\Omega)_b = (F/F_f)\,(d\sigma/d\Omega)_f.$$

The factor F/F_f is a function of the angle θ, and also depends on the initial pion energy and on the value of the optical potential. In accordance with the theory considered, the angular dependence of this factor for meson energies of 273 and 330 Mev is shown in Fig. 8. On the basis of this dependence,

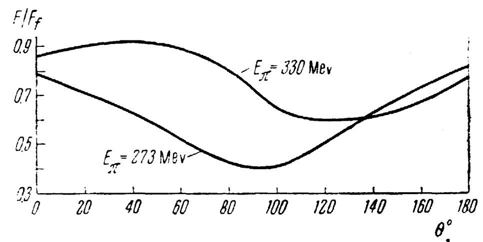

FIG. 8

we calculated the angular distributions of inelastic scattering of pions by He^4 nuclei. The calculations were made for two versions. In the first version $(d\sigma/d\Omega)_f$ were taken for the pion energy in the laboratory system. In the second version, we took into account the change in the pion energy by an amount V_R.

It is seen from Figs. 6 and 7 that the results of the calculations are in good agreement with the experimental points, particularly for $E_\pi = 330$ Mev. A great discrepancy is observed only in the region of small angles. But this is to be expected, since in the Watson-Zemach calculation no account was taken of the Pauli exclusion rule. Such a success of these calculations appears somewhat strange, since firstly the theory contains a large number of rough approximations, and secondly it does not reflect many factors which undoubtedly influence the size of the inelastic scattering cross section. In particular, the screening action of the nucleons is disregarded.

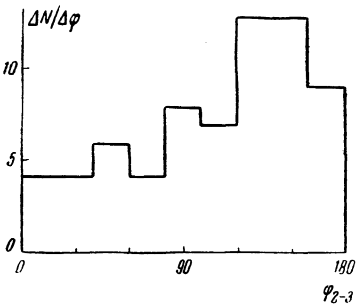

FIG. 9. Dependence of the number of events on the relative azimuth angle φ_{2-3} of the proton and H^3 nucleus in reactions $\pi^\pm + He^4 \to \pi^\pm + p + H^3$.

d) Correlation in the divergence of nucleons and residual nuclei. Figure 9 shows the distribution of the number of cases of quasi-elastic scattering of $\pi^\pm$ mesons by protons as a function of the angle between the projections of the proton and H^3 momenta on the azimuth plane. This distribution indicates that the proton and H^3 have a tendency to diverge in opposite directions (19 cases of travel in the same direction and 49 of travel in opposite directions). A possible interpretation of this phenomenon may be that the scattering of the mesons gives rise to an excited α-particle level, the existence of which is indicated by many experiments.[17] If we adopt this point of view and calculate the value of the excitation energy Q, its average is found to be approximately 20 Mev (Fig. 10) i.e., exactly the expected level. Errors in the determination of Q are quite large, and therefore one must not attach great significance to this result, since the agreement may be quite accidental. In addition, the observed correlation can be understood qualitatively within the framework of the Goldberger model. In fact, at the instant of collision between the pion and the proton, the latter has a momentum equal and opposite to the momentum of the H^3 nucleus. Since the momentum transferred by the meson to the proton by scattering is of the same order as the intranuclear momenta of the nucleons, the initial direction of motion of the proton should be conserved to the some extent.

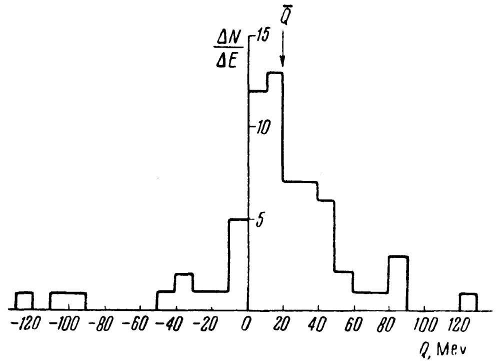

FIG. 10. Distribution of the values of Q for the reactions $\pi^\pm + He^4 \to \pi^\pm + p + H^3$.

5. NON-RADIATIVE CAPTURE

As already noted in Section 4, of all the cases of non-radiative capture of positive pions, the only capture that could be identified directly was the one with emission of two protons and a deuteron in the final state (8′). In all these cases the deuterons are slow, their momenta not exceeding 200 Mev/c. The protons display on the other hand an angular and momentum correlation, corresponding to the absorption of pions by free deuterons (see Fig. 11). Thus, we can interpret reaction (8′) as the capture of a pion by a deuteron pair. For the

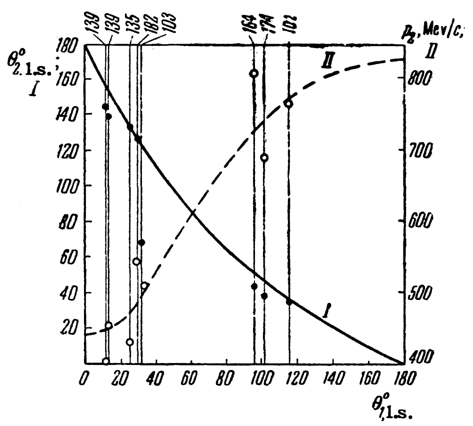

FIG. 11. Angular and momentum correlation in the reaction $\pi^+ + He^4 \to p + p + d$. The curves correspond to correlation in absorption by a free pair of nucleons; the full circles (left-hand scale) show the values of the angles θ_2, while the empty circles (right-hand scale) show the values of the momenta p_2. The numbers on top are the values of the momenta of the residual deuterons.

probability of the other possible cases of positive-pion capture, the only thing that is obtained experimentally is an upper limit. It can be estimated if all the events (6′) and (8′) (see Table I) are considered to be absorption. However, among the latter events there should be also multiple exchange-scattering events. Their fraction can be calculated by assuming that the probability of the multiple-scattering processes, both with and without charge exchange, are the same. This assumption is partially justified by the roughness of the calculation of the cascade probability in both cases, which indicates that these probabilities are approximately equal. An estimate of the number of events of multiple-exchange scattering, obtained under this assumption, corresponds to 14, where a total of 13 events (6′) and (8′) were observed. This result can be interpreted (naturally, with a reliability determined by the small statistical accuracy) as evidence of the low probability for other processes of pion absorption, including the capture of negative pions by a pair of like nucleons.

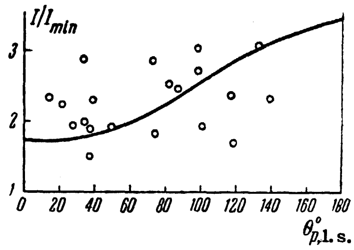

FIG. 12. Correlation between the angle of emission and ionization of fast protons in single-prong stars, produced by negative pions. The curve is obtained from kinematic calculations under the assumption that the absorption is produced by a free pair of nucleons.

We attempted to identify the absorption of negative pion processes by pairs of like nucleons directly from the correlation between the angle θ of emission of the fast proton and the ionization it produced. However, a reliable separation of the cases of absorption by a pair of like nucleons from other processes that lead to the emission of fast protons could not be attained, owing to the large error in the measurement of the ionization, and also owing to the ambiguous connection between the ionization and the angle (due to intranuclear motion). The results of the measurements are given in Fig. 12. For negative pions, as was done for the positive pions, an indirect estimate was made of the number of absorptions by a pair of like nucleons. It was assumed here, too, that the relative probabilities of capture by a deuteron pair at 273 and 330 Mev are equal. With the statistics accumulated for 300 Mev, this corresponds to 12 captures by an n-p pair, whereas an estimate of the number of absorptions by a p-p pair yields a value of 6.

The analysis of the experimental results on the capture of pions in helium indicates that apparently the pion capture is produced essentially by nucleon pairs, and the absorption by a deuteron pair is the principal process. This conclusion agrees with the results of investigation of the absorption of pions by more complex nuclei such as carbon, chlorine, and fluorine.[4-7]

6. RARE EVENTS

Five events of interaction of pions with helium were registered, and these cannot be ascribed to any of the foregoing processes. A characteristic feature of all these cases was that among the secondary products there was more than one fast particle, producing nearly minimum ionization (Fig. 13).

FIG. 13. Photograph of a probable production of a neutral pion with subsequent decay into 2e and a photon.

As noted above, in the scattering of 300-Mev pions there cannot be any protons with less than twofold ionization. These events can therefore be interpreted as the production of particles lighter than nucleons. An additional argument in favor of this statement is also the absence of angular correlation between the fast particles, which would appear in quasifree scattering of pions. Summary data on the observed events are listed in Table IV.

By virtue of the limited information, we cannot identify these events uniquely, and therefore the last column of Table IV lists only a probable interpretation. In addition to the conservation laws, we took into account in the interpretation certain considerations on the probable angles β between the electrons in the processes $\pi^0 \rightarrow 2e + \gamma$.

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TABLE IV

E_π, Mev	θ_1	θ_2	β	θ_3	θ_4	θ_5	Ionization	Probable interpretation
330	30.0	11.5	31.3	142.1	—	—	$I_1 \approx I_2 \approx I_{min}$	$\pi^- + He^4 \to \pi^0 + n + H^3$, $\pi^0 \searrow 2e + \gamma$
	162.8	19.8	146.7	116.6	—	—	$I_1 \approx I_2 \approx I_{min}$	$\pi^- + He^4 \to \pi^- + \pi^+ + (p, 3n)$
	63.5	130.5	150.0	17.4	—	—	$I_1 \approx I_2 \approx I_{min}$	
273	139.7	123.6	17.5	20.0	71.3	—	$I_1 \approx I_2 \approx I_{min}$	$\pi^+ + He^4 \to \pi^0 + p + He^3$, $\pi^0 \searrow 2e + \gamma$
	32.5	66.0	34.1	125.2	5.01	180	$I_1 \approx I_2 \approx I_3 \approx I_{min}$, $I_4 \approx (2-3) I_{min}$	$\pi^+ + He^4 \to \pi^+ + \pi^0 + p + H^3$, $\pi^0 \searrow 2e + \gamma$

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