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Inelastic Scattering of 160 mev Pions on Emulsion Nuclei

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The angular and energy spectra of pions inelastically scattered on photographic emulsion nuclei have been obtained. The average energy of pions scattered backwards ($\theta > 90°$) was found to be 64.2 ± 3 mev. Inelastic scattering of 160 mev negative pions on emulsion nuclei was calculated by the Monte Carlo method on the assumption that the picture of individual meson-nucleon collisions is valid. The problem of the sensitivity of the results obtained to the assumed characteristics of the interaction of pions with the nucleus is considered in detail. By comparing the calculated results with the experimental data, the average potential energy of the interaction of the pion with the nucleus was determined at $E_\pi = 160$ mev as $V = -(24 \pm 6)$ mev.

INTRODUCTION

THE interaction of high-energy nucleons and pions with the nucleus can be regarded as a convenient tool for studying the properties of nuclei. One can expect that, when the wavelength of the incident particle is less than or comparable with the internucleonic distances in the nucleus, experiments on the interaction of these particles with nuclei will be sensitive to the distribution of nucleons in the nucleus, to the energy spectrum of the nuclear nucleons, and to the interaction potential of the particles in question with the nucleus. In view of the fact that we know too little about the structure of the nucleus, an exact calculation of the interaction of nucleons and pions with the nucleus does not appear to be feasible. Therefore we can establish our conclusions about nuclear properties for the present only on the basis of model representations, the extent of whose validity is determined by comparing the results of calculation with experiment.

One of the possible models for the interaction of the fast particles with the nucleus is the hypothesis of nucleon-nucleon or meson-nucleon collisions in the nucleus[1-3]. There are the more reasons for such a model, the smaller the wavelength of the incident particle is in comparison with the internucleonic distances and the greater the momentum transferred to a nuclear nucleon in a collision. Theoretical estimates indicate that the model of individual collisions of these particles with nucleons of the nucleus possesses adequate validity[2] at an energy $\gtrsim$ 50-100 mev of the nucleons and pions. The results of experiments on the interaction of fast nucleons with heavy nuclei[4-8], on the scattering of fast protons on light nuclei[9-11], and on the production of pions in nuclei by protons[12] lead to the same conclusion. The interaction of fast pions with nuclei has been investigated less fully. In the published work, no quantitative analysis of the experimental results has been carried out; qualitatively, however, the experiments in question do not contradict the picture of individual meson- nucleon collisions in the nucleus. In short, the results of experiments on the interaction of pions of 100-200 mev with nuclei lead to the following[13-22]; 1) pions are efficiently absorbed ny nuclei; 2) in scattering on nuclei pions lose a large part of their energy, which can be explained by their being scattered on the moving nucleons of the nucleus.

Usually experiments on elastic scattering of fast particles by nuclei are described in terms of the optical model. According to this model, the potential energy of the interaction of the particle with the nucleus is assumed to have the form of a square well with real and imaginary parts: $U = V + i\sigma$. The real part V represents the average potential energy of the interaction of the pions (or nucleons) with the nucleus. Obviously the quantity V must be taken into account also in calculating the inelastic interaction of fast particles with the nucleus, inasmuch as the deviation of the average interaction potential brings it about that upon entering the nucleus the particle changes its energy by an amount V.

In the present article the inelastic scattering of 160 mev negative pions by emulsion nuclei is calculated under the assumption that the idea of meson-nucleon collisions in the nucleus is correct; this calculation is compared with experiment.

It is to be noted that the calculation of the interaction of fast pions with the nucleus is presented mainly in comparison with the analogous calculations of the interaction of fast nucleons.

We remark that the calculation of the interaction of fast pions with the nucleus offers the advantage over the analogous calculations for fast nucleons that in this case it is not necessary to consider the nucleonic part of the intranuclear cascade. The fact that, because of the efficient absorption of pions in the nucleus, pions escaping from the nucleus undergo few collisions with nuclear nucleons, also simplifies the calculation.

1. EXPERIMENTAL RESULTS

In this work a beam of negative pions with an energy $E_\pi = 188 \pm 5$ mev, brought out of the chamber of the synchrocyclotron of the Institute for Nuclear Physics of the Academy of Sciences, USSR, was used. After passing through a deflecting magnet and a collimator the negative pion beam entered an emulsion stack composed of 30 strips of NIKFI type R emulsion, each 395μ thick and 70 mm in diameter. In order to facilitate the following of tracks passing through several emulsion strips, a common coordinate grid with lines about 35μ thick and spaced about 3 mm apart was applied to the emulsion by means of x-rays. During processing, we selected stars so located in the emulsion that the pions which had produced the stars had traveled 4.4 ± 0.9 cm in the emulsion, having lost at the same time 26 ± 6 mev. Thus the experimental results obtained apply to a pion energy of 162 mev.

A total of 1185 interactions of pions of the specified energy with emulsion nuclei was found. Out of these an inelastically scattered charged pion was observed in 323 cases. The interactions of pions with nuclei were found by area scanning the emulsion strips under a magnification of 450 ×. Therefore elastic interactions of pions with nuclei and 0-pronged stars, in which the scattered meson lost less than 80 mev, were not recorded effectively. We also carried out an investigation of inelastically scattered pions escaping from 0-pronged stars and found in scanning a total of 80 meters of beam pion tracks. At the same time it was found that the characteristics of the energy spectrum of pions back-scattered inelastically ($\theta \geq 90°$) do not differ appreciably from the corresponding characteristics of the spectrum of pions escaping from stars with one or more prongs and found by area scanning.

The identification of scattered pions was effected by determining the gradient of the grain density along the track. The energy of the scattered pion was determined from the grain density and from the length of the ionizing range in those cases where the entire pion track was imbedded in the emulsion stack. A graph of grain density vs. pion range for the given emulsion was plotted by following the tracks of pions stopped in the emulsion stack to the place of entry into the stack. Values of dN/dR for pions at $R = 25$ cm and $R = 16$ cm were obtained with great accuracy by measuring the grain density of tracks in the emulsion stack and after traversal of 9 cm of emulsion, respectively. A stack 10 cm in diameter of the same emulsion was used for this purpose.

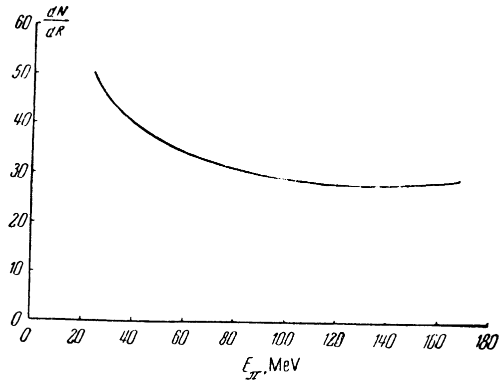

FIG. 1. Grain density *vs.* pion energy. (dN/dR is the number of grains along 80μ.)

A graph of pion energy vs. range in the emulsion was plotted from the data of Fay[23] et al. and of a series of experimental determinations of the range of protons and pions[24-26] in emulsion. For pion energies above 105 mev the graph of $E = f(R)$ was extrapolated in accordance with the calculated data for Cu and Al. The data of Fay et al. used here apply to the Ilford G-5 emulsion; however, as was shown by measuring the lengths of muon tracks in the $\pi \to \mu$ decay, the stopping power of the NIKFI type R emulsion practically coincides with that of the Ilford G-5 emulsion[27]. The graph of grain density vs. pion energy thus obtained is shown in Fig. 1.

For determining the energy of the scattered pion we selected those events, where the angle between the pion track and the plane of the emulsion did not exceed 30°, inasmuch as for large dip angles the determination of pion energy from grain density gave incorrect results. In accordance with this selection a definite statistical weight, depending on the angle between the tracks of the primary and the scattered pion, was assigned to each event of a scattered pion with a dip angle $\beta \leq 30°$. A statistical weight $k = 1/p$ is assigned to each event, where p is the probability that a particle with a given angle of scattering has a dip angle β (see Appendix).

The energy spectra of pions scattered into the angular interval $\theta = 90°$ to 180° are shown in Fig. 2.

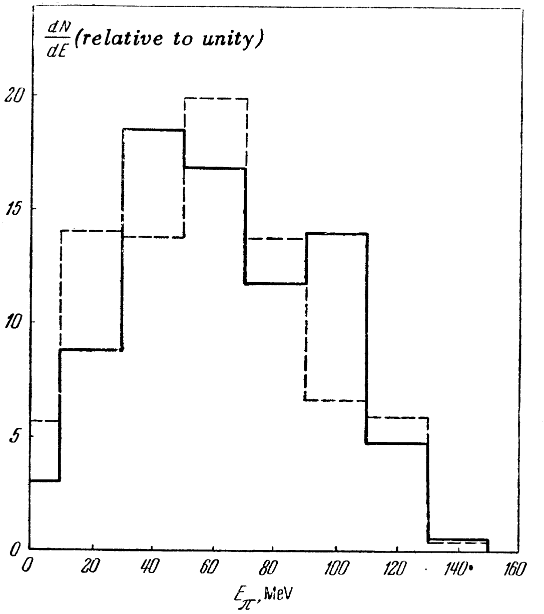

FIG. 2. Energy spectra of pions scattered on emulsion nuclei into the angular interval $\theta = 90^\circ$ to 180°. The experimental spectrum is marked with a solid line, the calculated spectrum by a dashed line.

The indicated pion spectrum has an average energy $E_{\text{exp}} = 64 \pm 3$ mev and a half-width

$$\Delta E_{\text{exp}} = \left(\Sigma\left(\overline{E} - E_i\right)^2 k_i / \Sigma k_i\right)^{1/2} = 30.9 \pm 3 \text{ mev}.$$

Here k_i is the statistical weight defined above. The angular distribution of pions scattered inelastically on nuclei is shown in Fig. 3.

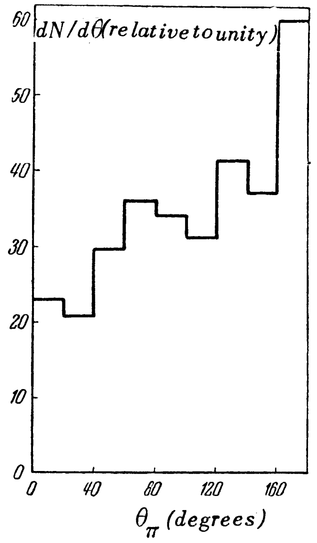

FIG. 3. Angular distribution of pions scattered on emulsion nuclei.

2. CALCULATION OF THE INELASTIC SCATTERING OF 160 MEV NEGATIVE PIONS ON EMULSION NUCLEI

A calculation of the inelastic scattering of pions on nuclei according to the model of individual meson-nucleon collisions can be carried out only under specific assumptions about a set of innacurately known characteristics of the interaction of pions with nuclear nucleons. In particular such characteristics refer to: 1) the angular and energy dependences of the cross sections for meson- nucleon collisions in the nucleus; 2) the parameters of the energy distribution of the nucleons in the nucleus; 3) the average interaction potential of pions with the nucleus.

In order to estimate the effect of the specified parameters of the interaction of pions with the nucleus upon the results of the calculation of the inelastic scattering of 160 mev negative pions on nuclei, a preliminary calculation was performed: the angular and energy spectra of pions that had undergone a single collision with the moving nucleons in the nucleus were computed under different assumptions on the characteristics of the meson-nucleon collisions in the nucleus. The Pauli principle, which forbids collisions in which a nucleon with an energy $E_N \leq 20$ mev or $E_N \leq 30$ mev (depending upon the assumed distribution of nucleons within the nucleus) is formed, was taken into account in the calculation. The results of this calculation are shown in Figs. 4 and 5 and in Table 1.

A comparison is shown in Fig. 4 of the calculated distributions of pions that have undergone a single collision with a nuclear nucleon for the cases of interaction of the pions with a neutron and a proton. Since the scattering cross sections of pions on protons and neutrons have different angular and energy dependences, it follows from Fig. 4 that the results of the calculation of the scattering of 160 mev pions on moving nucleons is not particularly sensitive to the characteristics of the cross sections of the interaction of the pion with nuclear nucleons.

In Fig. 5 there are shown the energy and angular spectra of pions scattered on nuclear neutrons and protons under the assumption that the nuclear nucleons have the momentum distribution of a degenerate Fermi gas with maximum energies $E_N^{\max} = 30$ mev and $E_N^{\max} = 20$ mev. From Fig. 5 it is seen that the spectra of pions scattered by nucleons are also insensitive to the details of the energy distribution of nucleons within the nucleus.

In the present work it has also been shown that the angular and energy spectra of pions scattered on nuclear nucleons remain insensitive to the assumed characteristics of meson-nucleon collisions in the nucleus even for lower pion energies ($E_\pi = 70$ mev).

The average potential V of the interaction of the pion with the nucleus is related to the change of energy of pions as they cross the boundary of the nucleus. The average energies of pions that have escaped from the nucleus after a single collision with a nuclear nucleon are given in Table 1 for the cases $V = 0$ and $V = -30$ mev. The energy of the incident mesons was taken as $E_\pi = 160$ mev.

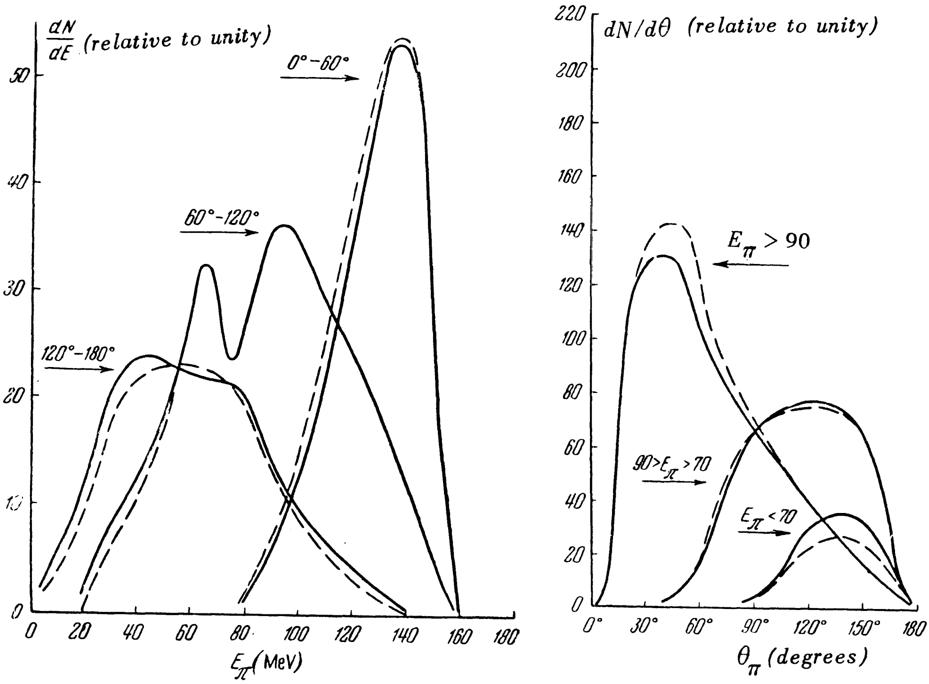

FIG. 4. Comparison of the angular and energy spectra of pions that have undergone a single collision with the nuclear nucleons in the reactions: 1 — (dashed curve) $\pi^- + p \to \pi^- + p$; 2 — (solid curve) $\pi^- + n \to \pi^- + n$. The momentum distribution of the nucleons in the nucleus is that of a degenerate Fermi gas with a maximum energy $E_{max} = 30$ mev.

From Table 1 it is evident that the results of the calculation of inelastic scattering of pions on nuclei are sensitive to the average potential of interaction of the pion with the nucleus. This permits a sufficiently effective determination of the magnitude V by comparing experimental data on inelastic scattering of pions on nuclei with the results of calculation. The insensitiveness of the angular and energy spectra of pions scattered on nuclear nucleons to other inaccurately known parameters of the meson-nucleon collisions in the nucleus makes the problem of determining the magnitude of V sufficiently definite.

TABLE 1

Average energies of pions that have escaped from the nucleus after a single collision with a nucleon of the nucleus.

ϑ_π	0–60°	60–120°	120–180°
$V = 0$	133	105	87
$V = -30$ MeV	128	89	61

The inelastic scattering of 160 mev negative pions by nuclei was calculated by the Monte Carlo method. In the calculation it was assumed that: a) the characteristics of the interaction of pions with nuclear nucleons do not differ from those for free nucleons; b) the momentum distribution of nucleons in the nucleus is that of degenerate Fermi gas with a maximum energy $E_N^{\max} = -30$ mev; c) the quantity V for 160 mev negative pions is taken equal to –30 mev, i.e., in entering the nucleus, a 160 mev π^- meson increases its energy by 30 mev; d) the calculation takes into account the Pauli principle, which forbids collisions in which a nucleon would be formed with an energy $\leq$ 30 mev.

It was shown above that for the case of the pion-nucleus interaction, the results of calculation are not sensitive to assumptions a) and b). Effects associated with a change in V and also with a change in certain other parameters of the interaction of pions with nuclei will be considered later.

The range of pions between two collisions with nuclear nucleons and also the scattering by this or that angle in collisions with nuclear nucleons was determined in each separate case by the Monte Carlo method.

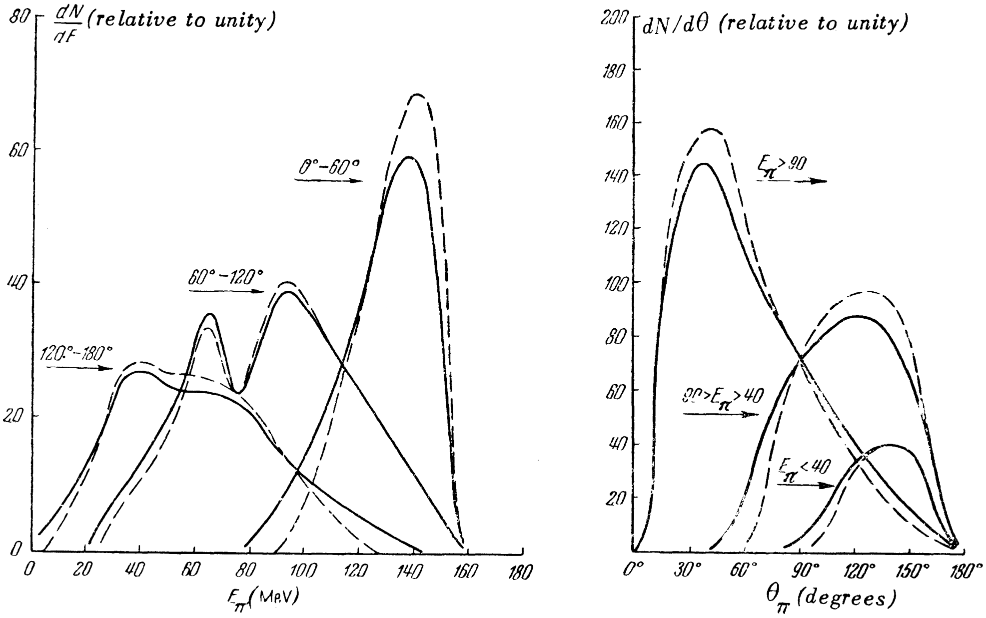

FIG. 5. Energy and angular spectra of pions that have undergone a single collision with the nuclear nucleons, for different momentum distributions of the nucleons in the nucleus. The ratio of the number of neutrons and protons corresponds to that of a nucleus with $A \sim 100$. The solid curves are for a Fermi distribution with $E_{\max} = 30$ mev, the dashed curves for $E_{\max} = 20$ mev.

A. Range of Pion in Nucleus

The probability that a pion of given energy has a range R in the nucleus is

$$p(R) = \bar{\sigma}\rho e^{-\bar{\sigma}\rho R}, \tag{1}$$

where $\bar{\sigma}$ is the cross section of the pion-nucleon interaction averaged over the motion of the nucleons and over the ratio of the number of protons and neutrons in the nucleus, and ρ is the density of nucleons in the nucleus. In the present work it was assumed that the nucleon density is the same on the periphery and in the center of the nucleus. Actually the nucleon density in the center of the nucleus, it seems, is larger than on the periphery, which introduces certain changes into the calculated results. These changes will be discussed below.

In the computation of the pion range according to formula (1), the cross sections of the interaction of the pion with nuclear nucleons were replaced by the total cross sections of the interaction of free particles, i.e., the absorption of pions in the nucleus was neglected. The absorption of pions in the nucleus will be discussed in detail in Section D.

Average cross sections of the interaction of negative pions with protons and neutrons of the nucleus were computed by the method described above and are presented in Table 2.

According to the principle of isotopic invariance, the total cross sections of the interaction of neutral pions with nucleons can be written as

$$\sigma(\pi^0 + N) = {}^1/_2\,[\sigma(\pi^- + n) + \sigma(\pi^- + p)]. \tag{2}$$

TABLE 2

Average cross sections of the interaction of pions with nuclear nucleons.

E_{π} в MeV	30	50	70	90	110	130	150	170	190
$\bar{\sigma}(\pi^- + n)\cdot 10^{27}$ см^2	7,9	19,5	37,2	66,0	98,8	135,1	139,8	168,6	164,1
$\bar{\sigma}(\pi^- + p)\cdot 10^{27}$ см^2	8,3	13,3	18,7	27	37.4	48,9	56,0	58.0	55,9

This relationship obviously holds also for the averaged cross sections.

B. Calculation of the Scattering of Pions on Nuclear Nucleons

In order to determine the energy and scattering angle of a pion after collision with a nuclear nucleon it was necessary in each individual case to transform into the center-of-mass system of the two colliding particles, then to determine the scattering angle by the Monte Carlo method, and finally to find the corresponding scattering angle and the energy in the laboratory system. (The method of this calculation has been described in Ref. 28). In place of the cross sections for the pion-nucleon interaction we took cross sections obtained from the unique system of phase shifts that best fit the experimental results[29].

In calculating the collision of a pion with nuclear nucleons the fact was also taken into account that a collision of a pion and a nucleon is less probable when the directions of motion of both particles coincide as compared with the case when the particles move toward one another. The corresponding change of cross section can be described in the following form:

$$\sigma = \sigma_0\left(1 - \frac{v_N \cos\alpha}{v_\pi}\right). \tag{3}$$

Here v_N and v_π are the velocities of the nucleon and the pion, and α is the angle between the directions of motion of the nucleon and the pion.

C. Effects Associated with the Change of Potential during Passage of the Pion across the Boundary of the Nucleus

Because the average potential V of the pion-nucleus interaction is different from zero, the pion changes its energy by an amount V, and also the direction of its motion as it passes through the boundary of the nucleus. If the angle of incidence of the pion upon the boundary of the nucleus is sufficiently large, reflection of the particle back into the nucleus may take place. But an exact account of the effect of reflection does not appear feasible since the dependence of the quantity V on the energy can be determined only approximately.

TABLE 3

Average energies of pions going backward ($\theta \geq 90^\circ$) in mev.

Number of collisions	Without reflection	With reflection
1	92.4±3,6	96.1±4.4
2	74,2±3.8	81.7±4.7
3	55,2±4.7	60.1±7,8
4	54.3±2.5	58,1±5.9

Therefore two limiting cases are discussed in the present article: 1) reflection of pions back into the nucleus does not occur on the boundary of the nucleus; 2) reflection on the boundary of the nucleus can take place for pions of any energy under the assumption that $V = -30$ mev.

Average energies of charged pions that have escaped from an emulsion nucleus after one, two, and so forth collisions with nuclear nucleons have been calculated by the Monte Carlo method and are given in Table 3; the absorption of pions in the nucleus was not taken into account.

It is evident from Table 3 that the effect of reflection of pions into the nucleons in crossing the boundary of the nucleus does not change the average energies of inelastically scattered pions substantially.

D. Absorption of Pions in the Nucleus

From experiment it is known that at a pion energy of about 200 mev the number of inelastically scattered charged pions constitutes approximately 30 percent of the number of all interactions of pions with emulsion nuclei (excluding diffraction scattering)[15]. From this it follows that pions are efficiently absorbed by nuclei. Since the mechanism of pion absorption in the nucleus is unknown, an exact calculation of this process does not appear to be possible.

One of the possible models for the absorption of pions in the nucleus can be constructed on the basis of employing the results on capture of pions in deuterium: $\pi^+ + d \rightarrow 2p$. According to this model it is assumed that the cross section of the capture of the pion in a nucleus is proportional to the capture cross section in deuterium:

$$\sigma_{\text{nucleus}} = \gamma\sigma(d), \qquad (4)$$

where the coefficient γ takes into account the probability of the formation of quasi-deuteron states in the nucleus and the Pauli exclusion of certain final states of nucleons in the nucleus. Various authors[16,18,19] estimate that $\gamma \approx 4$. In the calculation of absorption according to this model, the capture of a pion on some part or other of its trajectory in the nucleus is determined by the Monte Carlo method.

It is also possible to assume that each collision of pions with nuclear nucleons is accompanied by the absorption of one and the same fraction α of the pions. The magnitude of α is chosen so that the total number of charged pions coming out of the nucleus under consideration of absorption is equal to the experimental value. In considering the absorption according to this model, the energy spectra of pions coming out of the nucleus after the first, second and so forth collision remain unchanged; only the relative number of pions, that have undergone several collisions up to their escape from the nucleus, decreases.

It is to be noted that under the assumption of the meson-nucleon picture of the interaction of the pion with the nucleus the "deuteron" model of pion absorption seems to be more justified. The assumptions about the nature of pion absorption in the nucleus, made according to the second model, cannot claim any rigorous theoretical basis. The results thus obtained appear to be rejected ones and, as follows from Table IV show only that the energy spectra of pions scattered inelastically by the nucleus are not sensitive to the assumptions about the nature of pion absorption in the nucleus.

In Table IV are given the calculated values of the average energies of pions scattered on emulsion nuclei into the angular interval 90° to 180° for the case of absorption according to the "deuteron" model (I) and for the case of equally probable absorption of pions in every collision (II).

TABLE 4

Average energies of pions in mev with absorption taken into account ($\theta_\pi \geq 90°$).

	With reflection	Without reflection
I	93,2±3,6	88,7±3,0
II	87,2±3,2	84,5±2,7

3. COMPARISON OF THE RESULTS OF THE CALCULATIONS OF INELASTIC SCATTERING OF PIONS BY NUCLEI WITH EXPERIMENTAL DATA

The results of the calculation were obtained on the basis of statistics in 517 cases of interaction of 160 mev negative pions with emulsion nuclei. As the photographic emulsion consists of heavy ($A \sim 100$) and light ($A \sim 14$) nuclei, the calculation includes a computation of the corresponding characteristics for both types of nuclei. From Table 4 it follows that the calculated value of the average energy of the spectrum of pions escaping backward ($\theta \geq 90°$) is given by $(\bar{E}_\pi)_{\text{calc}} = 88 \pm 5$ mev. The quoted error includes the statistical error and a possible spread of values in taking account of reflection and absorption according to the various models. This value of $(\bar{E}_\pi)_{\text{calc}}$ is obtained under the assumption that 160 mev negative pions increase their energy by 30 mev as they enter the nucleus, i.e., $V = -30$ mev. This value of V agrees with the results of experiments on elastic scattering of pions on nuclei (see Table 5). But the exact value of V remains unknown. In the present work, it was shown that a change of the quantity V by 30 mev leads to a change of the average energy of pions scattered backward ($\theta \geq 90°$) by an amount $\Delta E = 7$ mev. Thus, in spite of the inaccurate knowledge of the quantity V at $E_\pi = 160$ mev, the value of $(\bar{E}_\pi)_{\text{calc}}$ obtained appears to be sufficiently definite. The indicated value of $(\bar{E}_\pi)_{\text{calc}}$ applies to the energy spectrum of pions in the nucleus. Upon leaving the nucleus, the pions decrease their energy by the magnitude of the average potential of the pion-nucleus interaction, i.e., by $-V$. Thus by comparing the experimentally found value, $(\bar{E}_\pi)_{\text{exp}} = 64$

± 2.5 mev, of the average energy of pions scattered backward and the magnitude of the calculated energy, $(\bar{E}_{\pi})_{\text{calc}}$, of pions in the nucleus, it is possible to determine the quantity V for negative pions with an energy $E_{\pi} = 160$ mev as

$$V = (\bar{E}_{\pi})_{\text{exp}} - (\bar{E}_{\pi})_{\text{calc}} = -(24 \pm 6) \text{ mev} .$$

The minus sign implies that the meson-nucleon forces at $E_{\pi} = 160$ mev are attractive. The absolute value of V is found to be in good agreement with the magnitudes of the average potential of the pion-nucleus interaction obtained in experiments on the elastic scattering of pions on nuclei. The results of these experiments are given in Table 5.

TABLE 5

Values of V obtained from experiments on the elastic scattering of pions on nuclei.

Pion energy mev.	Sign of pion	Nucleus	V	Reference
48	+	C	$-(15 \pm 9)$	[30]
60	+—	He	$-(20 \pm 10)$	[31]
62	—	Photographic emulsion.	—20	[32]
62	+—	C	—18	[19]
80	+	Al	—20	[33]
80	—	Al	—30	[33]
105	+—	He	$-(18 \pm 14)$	[31]
125	—	C	—30	[34]

In Fig. 2 there is shown a comparison of the experimentally found spectrum of pions scattered on emulsion nuclei with the spectrum obtained in the present calculation, where it has been taken into account that the average potential of the interaction with the nucleus of the pions of the specified spectrum is given by $V = -24$ mev. The half-width of the energy spectrum shown in Fig. 2 was computed according to the formula

$$(\Delta E)_{\text{calc}} = \sqrt{\Sigma (E - E_i)^2 / (n - 1)} \qquad (5)$$

it turns out to be equal to $(\Delta E)_{\text{calc}} = 30.8 \pm 2.6$ mev. This value of $(\Delta E)_{\text{calc}}$ agrees well with the value $(\Delta E)_{\text{exp}} = 30.9 \pm 2.1$ mev found by experiment. The good agreement of the experimental and theoretical energy spectra of pions scattered on emulsion nuclei indicates that the assumed model satisfactorily describes the interaction of pions with the nucleus.

In calculating the forward ($\theta < 90°$) scattering, the change of density of nuclear nucleons from the center of the nucleus to the periphery has to be considered. A smaller nucleon density on the periphery of the nucleus must lead to an increase of pions coming out of the nucleus at angles $\theta < 90°$ as compared with the results obtained in the present calculation, where it was assumed that the nucleon density in the center and on the periphery of the nucleus is the same. In the performed calculation, the number of pions coming out of the nucleus at angles $\theta < 90°$ constitutes about 30 percent of the total number of pions scattered inelastically by the nucleus, whereas it was found by experiment that this number is about 40 percent.

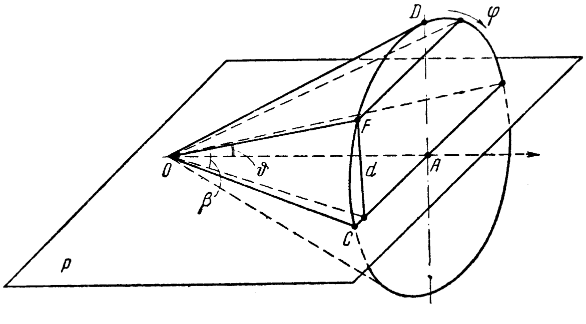

FIG. 6.

The calculation of the pion-nucleus interaction according to the model of individual collisions with nucleons of the nucleus for the case of varying nucleon density presents considerable difficulties and was not carried out in the present work. All the calculated results considered above apply to pions scattered backward ($\theta = 90°$ to $180°$), for which the effect of the variation of nucleon density with radius is not noticeable.

In conclusion the authors express gratitude to Professor I. I. Gurevich for a discussion of the results of the work, to Professor M. G. Meshcheriakov for the use of the synchrocyclotron of the Institute for Nuclear Physics of the Academy of Sciences of the USSR, to A. E. Ignatenko and A. I. Mukhin for aid in exposing the emulsion, to G. V. Kolganovii and A. A. Kondrashinii for help in the work, and to D. M. Samoilovich for developing the emulsion.

APPENDIX

In Fig. 6 there is drawn the cone of particles scattered into an angle θ relative to the direction *AO* of the incident particles. Obviously any azimuthal angle φ is equally probable. In the present case the direction of the primary beam lies in the plane *P* of the emulsion; therefore the dip angle β of a particle can be measured by the arc CF.

The probability that a particle has a dip angle $\beta \leq \beta_0$ is given by the ratio of the arc *CF* to the arc *CD*: $p = CF/CD$. Obviously p decreases with increasing θ.

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1 R. Serber, Phys. Rev. **72**, 1114 (1947).

2 G. F. Chew and G. C. Wick, Phys. Rev. **85**, 636 (1952).

3 J. Ashkin and G. C. Wick, Phys. Rev. **85**, 686 (1952).

4 M. L. Goldberger, Phys. Rev. **74**, 1269 (1948).

5 Bernardini, Booth and Lindenbaum, Phys. Rev. **85**, 826 (1952); Phys. Rev. **88**, 1017 (1952).

6 McManus, Sharp and Gellman, Phys. Rev. **93**, 924 (1954).

7 Lees, Morrison, Muirhead and Rosser, Phil. Mag. **44**, 304 (1953).

8 J. Combe, Nuovo cimento Suppl. **3**, No. 2, 182 (1956).

9 O. Chamberlain and E. Segrè, Phys. Rev. **87**, 81 (1952).

10 Cladis, Hess and Moyer, Phys. Rev. **87**, 425 (1952).

11 J. M. Wilcox and B. J. Moyer, Phys. Rev. **99**, 875 (1955).

12 Block, Passman and Havens, Phys. Rev. **88**, 1239 (1952).

13 H. Bradner and B. Rankin, Phys. Rev. **87**, 547, 553 (1952).

14 Bernardini, Booth and Lederman, Phys. Rev. **83**, 1075 (1951).

15 A. H. Morrish, Phys. Rev. **90**, 674 (1953).

16 G. Bernardini and F. Levy, Phys. Rev. **84**, 610 (1951).

17 Minguzzi, Puppi and Ranzi, Nuova cimento **11**, 697 (1954).

18 F. H. Tenney and J. Tinlot, Phys. Rev. **92**, 974 (1953).

19 Byfield, Kessler and Lederman, Phys. Rev. **86**, 17 (1952).

20 A. H. Morrish, Phil. Mag. **45**, 47 (1954).

21 G. Goldhaber and S. Goldhaber, Phys. Rev. **91**, 467 (1953).

22 J. O. Kessler and L. M. Lederman, Phys. Rev. **94**, 689 (1954); Lederman, Byfield and Kessler, Phys. Rev. **90**, 344 (1953).

23 Fay, Gottstein and Hain, Nuovo cimento Suppl. **11**, No. 2, 234 (1954).

24 H. Bradner et al., Phys. Rev. **77**, 462 (1950).

25 O. Heinz, Phys. Rev. **94**, 1728 (1954).

26 W. H. Barkas et al.; Phys. Rev. **102**, 583 (1956).

27 V. V. Alpers, R. I. Gerasimova et al.; Dokl. Akad. Nauk SSSR **105**, 236 (1955).

28 L. M. Barkov and B. A. Nikolskii, PTE 2 (1957)

29 deHoffman, Metropolis, Alei and Bethe, Phys. Rev. **95**, 1586 (1954); J. Orear et al., Phys. Rev. **96**, 174 (1954); J. Orear, Phys. Rev. **96**, 176 (1954).

30 A. M. Shapiro, Phys. Rev. **84**, 1063 (1951).

31 E. C. Fowler et al., Phys. Rev. **91**, 135 (1953).

32 A. Minguzzi, Nuovo comento **12**, 799 (1954).

33 Pevsner, Rainwater, Williams and Lindenbaum, Phys. Rev. **100**, 1419 (1955).

34 J. O. Kessler and L. M. Lederman, Phys. Rev. **94**, 689 (1954).

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Oscillations in a Fermi Liquid

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Different types of waves that can be propagated in a Fermi liquid, both at absolute zero and at non–zero temperatures, are investigated. Absorption of these waves is also considered.

THE present paper is devoted to the study of the propagation of waves in a Fermi liquid, and proceeds from the general theory of such liquids developed by the author.[1] These phenomena in a Fermi liquid should be distinguished by a large singularity, connected primarily with the impossibility of propagation in it of ordinary hydrodynamic sound waves at absolute zero. The latter circumstance is already evident from the fact that the path length, and therefore the viscosity of a Fermi liquid, tends to infinity for $T \to 0$, as a result of which the sound absorption coefficient increases without limit.

It is shown, however, that in a Fermi liquid at