INTERACTION OF NEGATIVE Π MESONS WITH COMPLEX NUCLEI IN THE ENERGY RANGE 140-400 MEV

Review of experiments performed on the six-metre synchrocyclotron

A. E. IGNATENKO

Institute of Nuclear Problems, USSR.

Introduction

The greater part of the experimental data on the interaction of π mesons with nuclei obtained on accelerators refers to energy range 30-150 Mev. With the extraction of sufficiently intense collimated beams of π mesons from the synchrocyclotron of the Institute of Nuclear Problems of the USSR Academy of Sciences the study of these processes has been extended to the energy range 150-400 Mev. In the following we set forth the main results of these investigations, as performed using various experimental techniques during 1954-1955.

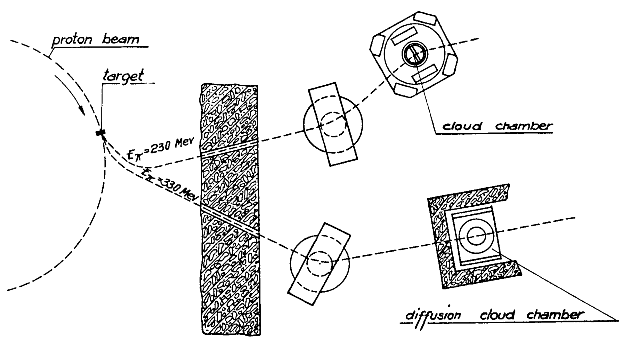

Fig. 1b. Experimental arrangement.

1. Experimental results

a) *Experiments with scintillation counters*

A. E. Ignatenko, A. I. Mukhin, E. B. Ozerov and B. Pontekorvo measured the total cross-sections of interaction of π mesons with Be, C, and O nuclei and the cross-sections of inelastic collisions of π mesons with B, C, Cu and Pb nuclei in the energy range 140-400 Mev[1,2]. The cross-sections were determined from the attenuation of the meson beam in passing through the scatterer. The scheme of the experiment is shown in fig. 1a. The mesons were obtained by bombarding a carbon target in the synchrocyclotron vacuum chamber with 670 Mev protons. After passing through the collimator set up in the yoke of the synchrocyclotron magnet the mesons entered the room containing the experimental apparatus ("meson laboratory"). Here the π mesons were deflected by an auxiliary magnet through an angle of 30° and were registered by scintillation counters.

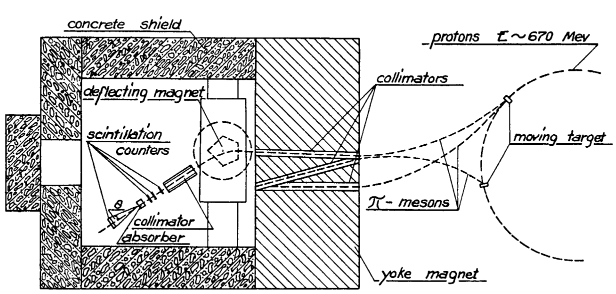

Fig. 1a. Experimental arrangement.

The cross-sections for Be, C and O for all energy values were measured with the distance between the center of the scatterer and the last counters equal to 35 cm., which corresponded to a mean angle of registration θ of the last detector of about 8°. The measurements of the cross-sections for Cu and Pb were carried out at an angle θ of about 25°. In the case of Be and C the experiments were carried out in addition at $\theta = 40°$. All these experiments were also performed under conditions of identical geometry for all values of the energy.

The cross-sections for oxygen were found from the entire set of measurements of the meson beam attenuation upon passage through paraffin, carbon and water scatterers. The results of the measurements are given in columns 1-8 of Table I. The values of the cross-sections in columns 2-8 have been corrected for : 1) contamination by μ mesons, 2) incidental coincidences and 3) counting losses of the registering apparatus. The errors given in columns 2-8 include both statistical errors and the indeterminate factors in these corrections.

TABLE I

Energy of π⁻-mesons (Mev)	Measured attenuation cross-sections (10^{-27} cm²)							Total cross-sections-σ_t (10^{-27} cm²)			Inelastic cross-sections-σ_{in} (10^{-27} cm²)			
	geometry θ∼8°			geometry θ∼25°		geometry θ∼40°								
	Be	C	O	Cu	Pb	Be	C	Be	C	O	Be	C	Cu	Pb
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
140±7	540±31	610±30	760±31			300±17		560±32	638±31	792±32	273±20			
184±7	562±23	623±23	783±32					583±24	654±24	827±34				
197±7	570±25	619±20	776±31					594±26	661±21	826±33				
216±7		624±19	699±23	999±42	2244±95	257±11	327±13		666±20	753±25	275±21	350±24	1048±67	2356±152
226±7		557±21	680±25						614±23	739±27				
240±7	495±19							526±20						
256±7		499±22	615±28	976±44	2250±93		297±15		547±24	683±31		326±31	1054±84	2430±183
290±7		448±18	564±22	850±41	2142±90		245±13		502±20	640±25		269±26	918 ±76	2313±175
335±7		380±16	468±20						469±19	557±24				
350±7	318±18					137±9	150±12	368±21			150±16	166±21		
363±7		344±19	427±8						440±11	523±10				
393±7		307±11	394±11						411±14	498±14				

The total cross-sections were obtained from the "measured" cross-sections given in columns 2-4 of Table I. Corrections were made only for mesons elastically scattered at angles less than 8°. These corrections were computed for all energy values by the theory of diffraction scattering for an "opaque" nucleus. The total cross-sections σ_t thus obtained are given in columns 9-11 of Table I.

The cross-sections for inelastic scattering were obtained from the data of columns 5-9, Table I. The following corrections were made:

a) for mesons inelastically scattered within an angle θ° and for secondary charged particles which could be registered in the last detector; these corrections were made by utilizing the results of investigations to be discussed later on;

b) for mesons elastically scattered at angles greater than θ°; the correction was made only for Be for the meson energy of 140 Mev where it was important; in all the other cases it was small enough to be neglected.

The cross-sections obtained σ_{in} are given in columns 12-15, Table I. The indicated errors in the cross-sections also take into account the indeterminate factors involved in the introduction of the above corrections.

b) *Experiments carried out by means of a Wilson cloud chamber in a magnetic field*

V. P. Dzhelepov, V. G. Ivanov, M. S. Kozodaev, V. T. Osipenko, N. I. Petrov and V. A. Rusakov investigated the interaction of π mesons with carbon and lead nuclei at the energies of 230 ± 30 and 250 ± 30 Mev, respectively [3]. The scheme of the experiment is shown in fig. 1b. Mesons obtained by bombarding a carbon target with protons of

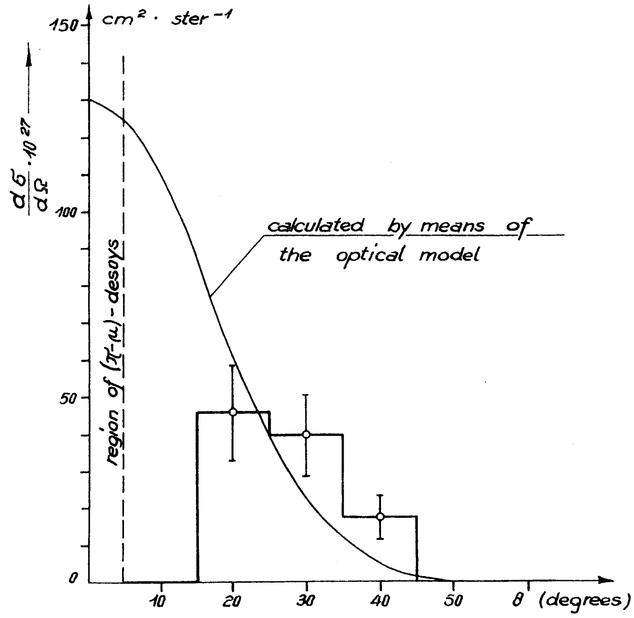

Fig. 2a. Angular distribution of elastically scattered π− mesons in helium.

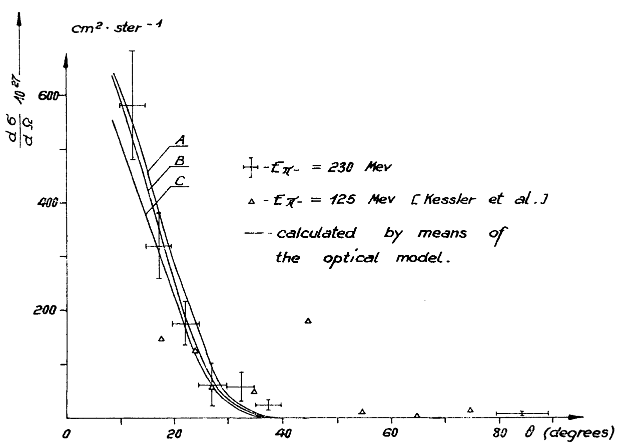

Fig. 2b. Angular distribution of elastically scattered π− mesons in carbon.

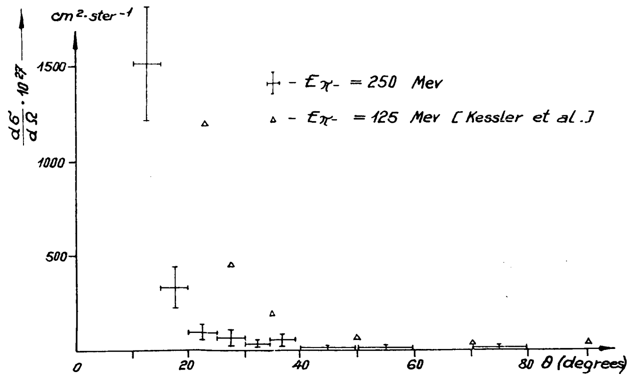

Fig. 2c. Angular distribution of elastically scattered π− mesons in lead.

the energy about 670 Mev entered a room separated from the synchrocyclotron by a four-metre concrete shield. Here an auxiliary magnet directed the π mesons into a 40 cm. cloud chamber in a magnetic field.

In the experiment the synchrocyclotron was operated in a one-impulse regime synchronously with the cloud chamber. During the exposure of the chamber to the meson beam, 6000 stereoscopic photographs were obtained showing 760 cases of interaction with carbon and 629 cases of interaction with lead. The generally accepted classification of nuclear interactions was used: stop, star, elastic scattering, charge exchange and inelastic scattering. Cases of scattering with energy losses less than 45 Mev were classified as elastic scattering. Charge exchanges were difficult to observe in the conditions of the given experiment, so practically all these cases were registered as stars and stops.

The results of the measurements are shown in figs. 2b, 2c, 3a, 3b, 4a, 4b and in Tables II a and II b.

The data for the cross-sections of the different processes are collected in Table II a; figs. 2b and 2c present the results for elastic scattering; figs. 3a, 3b, 4a and 4b show the results for inelastic scattering.

c) *Experiments performed with a diffusion chamber*

M. S. Kozodaev, R. M. Sulaiev, A. I. Filippov and I. A. Shcherbakov studied the interaction of π^- mesons of

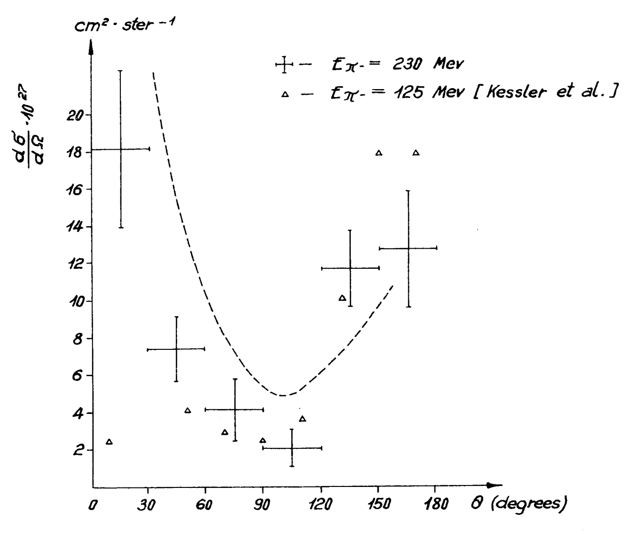

Fig. 3a. Angular distribution of inelastically scattered π− mesons in carbon; the dotted curve is the angular distribution of π− mesons scattered by protons.

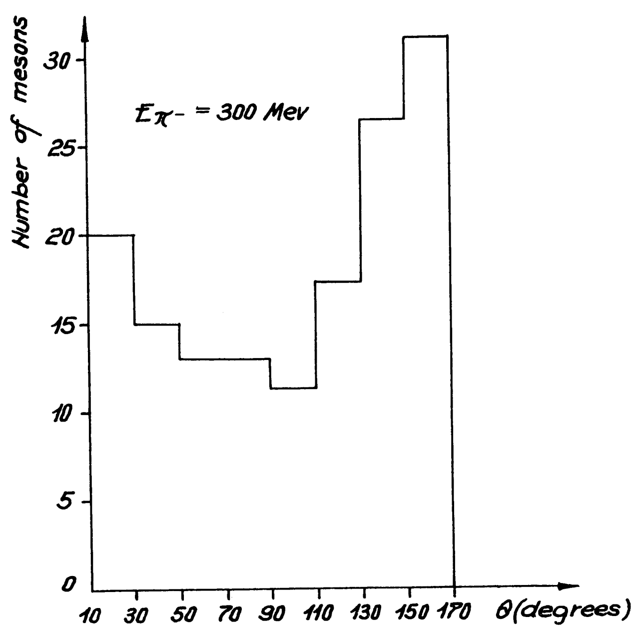

Fig. 3b. Angular distribution of inelastically scattered π− mesons in emulsion.

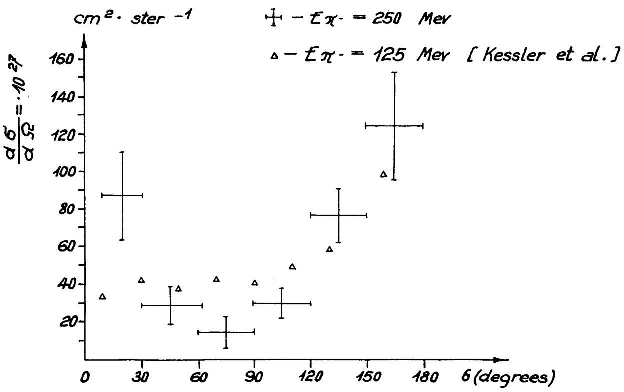

Fig. 3c. Angular distribution of inelastically scattered π^- mesons in lead.

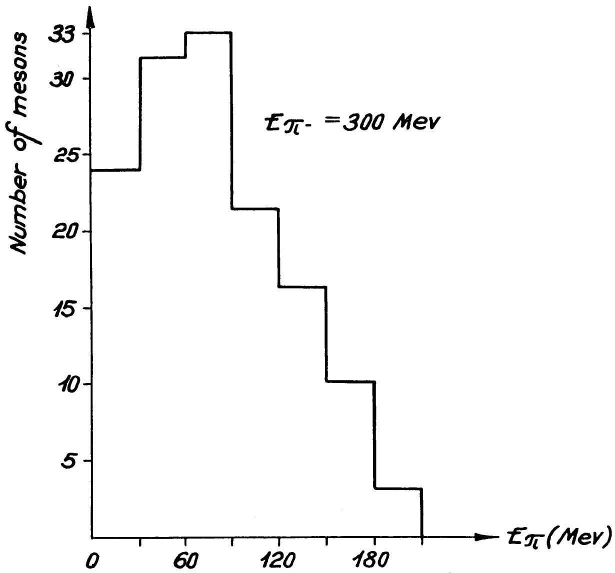

Fig. 4b. Energy distribution of inelastically scattered π^- mesons in emulsion.

energy 330 $\pm$ 6 Mev with helium nuclei [4]. A diffusion chamber 270 mm. in diameter filled with helium under a pressure of 14 atmospheres was placed in a meson beam beyond a four-metre concrete shield (see fig. 1b). During the experiments the accelerator was operated in an 8-second period impulse regime synchronously with the diffusion chamber.

The results of the experiments are based on an analysis of 97 cases of interaction registered by scanning about 13,000 photographs. Due to the absence of a magnetic field in the chamber it was impossible in all cases to carry out a complete analysis of the interaction processes. Nevertheless, the clean conditions of observation and the comparatively small number of possible processes made it possible with a good degree of certainty to distinguish several groups of processes, as well as a number of separate reactions by the angular relations, by ionizations and also, occasionally, by the ranges of the particles in the gas. The results of the experiments are shown in figs. 2a and 5, and in Tables II b and II d.

Table II b contains the values of the cross-sections for the different processes. The figures in parentheses indicate the number of corresponding cases of interaction. Table II gives the average differential cross-sections of inelastic scattering in the laboratory system for three angular intervals. For the reaction $\pi^- + He^4 \rightarrow \pi^- + n + He^3$ it proved possible to obtain the momentum distribution of He^3 nuclei. This distribution is shown in fig. 5. The angular distribution of He^3 nuclei proved to be almost isotropic. Fig. 2a represents the angular distribution of the elastic scattering of π^- mesons on helium in the center of mass system.

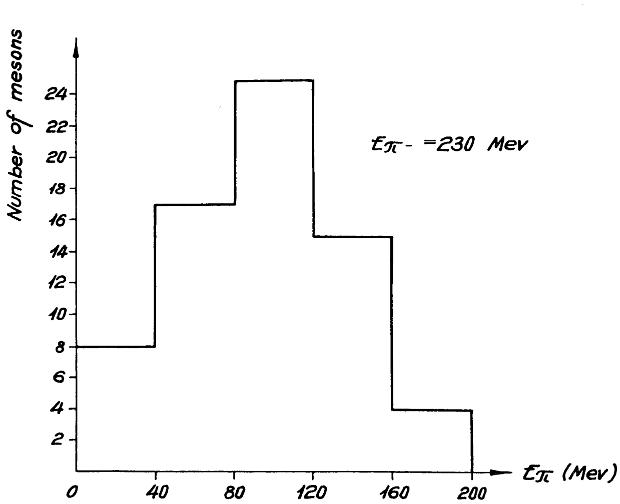

Fig. 4a. Energy distribution of inelastically scattered π^- mesons in carbon.

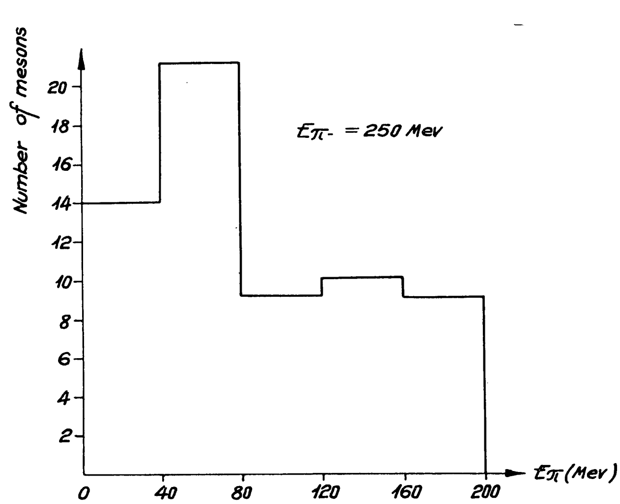

Fig. 4c. Energy distribution of inelastically scattered π^- mesons in lead.

TABLE II a

Cross-sections found experimentally for carbon and lead (10^{-27} cm^2)

	π-meson energy(Mev)	Elastic scattering $\theta > 10^\circ$	Inelastic scattering $\Delta E > 45$Mev	Stars and stops	Total interaction	$\pi(1.4\cdot 10^{-13}A^{1/3})^2$
C	230	200±31	90±15	217±21	307±37	325
Pb	250	329±53	555±83	1598±160	2153±194	2150

TABLE II b

Cross-sections found experimentally for helium (10^{-27} cm^2)

Total interaction σ_t	Elastic scattering $\theta > 5^\circ$ σ_e	Inelastic interaction σ_c	Absorption and charge-exchange scattering $\sigma_a + \sigma_{ex}$	Inelastic scattering without charge exchange σ_i	Reaction $\pi^- + He^4 \to \pi^- + n + He^3$ σ_n	Absorption by a pair of protons $\sigma_{a/pp/}$	Production of π mesons σ_π
150±15 (97)	51±9 (33)	99±12 (64)	31±7 (20)	65±10 (42)	33±7 (21)	3±2 (2)	3±2 (2)

TABLE II c

Comparison of energy losses suffered by emerging mesons

	Energy of π mesons (Mev)	Angular interval (degrees)	Ratio calculated to observed energy loss $\gamma = \frac{E_\pi^\circ - E_c}{E_\pi^\circ - E_0}$	Number of events
C	230	0-60 60-120 120-180	23 77 99	20 14 35
Pb	250	0-60 60-120 120-180	22 85 87	16 10 28
	500*	0-60 60-120 120-180	61 63 69	37 42 33

* M. Blau and M. Caulton [18]

TABLE II d

Differential cross-sections of inelastically scattered π mesons in helium (10^{-27} cm^2 $ster^{-1}$)

$\left\|\frac{\Delta\sigma}{\Delta\Omega}\right\|_{0^\circ-60^\circ}$	$\left\|\frac{\Delta\sigma}{\Delta\Omega}\right\|_{60^\circ-120^\circ}$	$\left\|\frac{\Delta\sigma}{\Delta\Omega}\right\|_{120^\circ-180^\circ}$
7,9 ± 2,0	2,5 ± 0,8	4,5 ± 1,5

TABLE II e

Total cross-sections of helium for 60-330 Mev pions

Energy of pions (Mev)	60	105	330
σ_t ($10^{-27}cm^2$)	89 ± 18	207 ± 24	150 ± 15

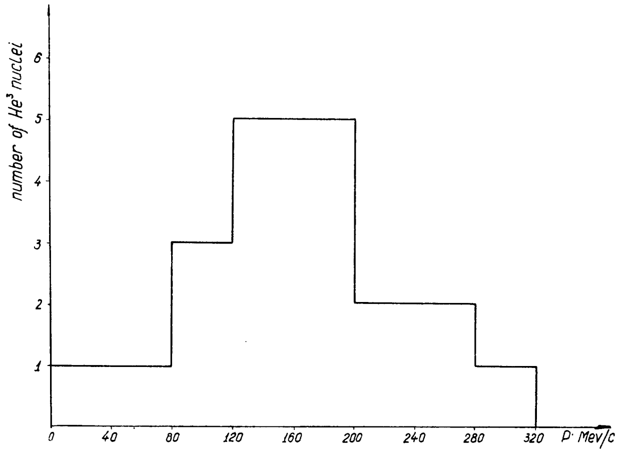

Fig. 5. Momentum distribution of He^3 nuclei emitted in the reaction $\pi^- + He^4 \rightarrow \pi^- + n + He^3$.

d) *Experiments utilizing the method of photographic plates*

N. A. Mitin and E. L. Grigoriev studied the angular and energy distributions of inelastic scattering of π^- mesons with an energy of 300 $\pm$ 4 Mev on photoemulsion nuclei [5]. Electron-sensitive photographic plates with a layer of emulsion 400 μ thick were irradiated in the "meson laboratory" (see fig. 1a). The plates were scanned under the microscope at a magnification of 630 $\times$. Those nuclear interactions of π mesons were counted in which one or more charged particles were generated and left black traces in the emulsion. The charged particles emerging from the emulsion were identified and their energy determined by the combined application of multiple scattering and grain density measurements. The identification of mesons among the particles that stopped in the emulsion was done visually, and their energies were determined from the residual ranges. For the measurement of multiple scattering those tracks were selected, the lengths of which in the emulsion were not less than 2000 μ. All the measurements were limited to the angular interval 10-170°. The distorsion of the emulsion was small and introduced no noticeable errors in the results of the multiple scattering measurements. The statistical errors in the measurement of the energy comprised on the average 15%.

Upon scanning 20 cm² of photoemulsion, the authors detected 4900 cases of interaction of π mesons with nuclei. Among them were found 122 cases of inelastic scattering, in which the traces of π mesons satisfied the above-mentioned selection rules, and 24 cases in which the scattered mesons possessed energies in the range 0-12 Mev and stopped in the emulsion. Of this last group of slow mesons only 16 cases were utilized in plotting the spectrum of inelastically scattered π mesons.

The energy distribution of the inelastically scattered π mesons is depicted in fig. 4b; their angular distribution is shown in fig. 3b.

V. V. Krivitzki and A. A. Reut investigated the formation of π^+ mesons on carbon by π^- mesons with an energy of 308 $\pm$ 12 Mev [6]. The carbon target (a graphite cylinder 60 mm. in diameter and 40 mm. high) was placed in a π^- meson beam directly at the collimator exit in the "meson laboratory" (see fig. 1a)). The π^+ mesons emerging at an angle of 90° to the π^- meson beam were caught on a photographic plate with a layer of emulsion 280 μ thick, which registered only non-relativistic particles. The photographic plates were attached to aluminium wedges.

The number of π^+ mesons formed was determined from the number of π-μ disintegrations. Only those π-μ disintegrations were counted, in which the track of the μ meson did not emerge from the emulsion; otherwise the disintegration was considered doubtful.

The intensity of the incident beam of π^- mesons was determined by means of electron-sensitive photographic plates placed inside the collimator.

The plates were scanned under the microscope with a magnification of 300$\times$. On an area of 300 cm² of photoemulsion 16 π-μ disintegrations and 5 doubtful cases were found. The geometry of the experiment was such that the greatest number of observed π-μ disintegrations corresponded to an energy of the resultant π^- mesons of 30-50 Mev.

As a result of the experiments the differential cross-section of π^+ meson production of the energy of 40 Mev at an angle of 90° to the beam of the π^- mesons was determined. It turned out to be equal to $d^2\sigma/d\omega dE = (2.6 \pm 1.3) \times 10^{-30}$ cm²/sterad $\times$ Mev.

2. Discussion of the results

a) *Total cross-sections and cross-sections for inelastic collisions*

The data of the measurements given in columns 9-15 of Table I show that in the energy interval 140-250 Mev, the total cross-sections σ_t and the cross-sections of inelastic

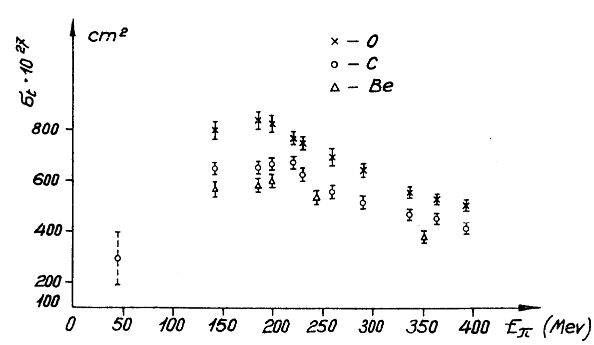

Fig 6a. The total cross-sections of beryllium, carbon and oxygen for 140-400 Mev π mesons.

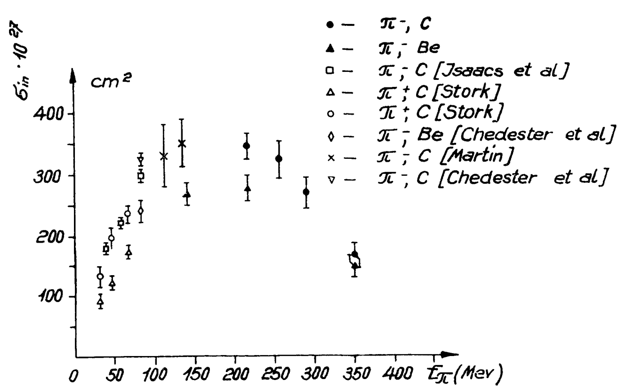

Fig. 6b. The inelastic cross-sections of beryllium and carbon for 30-350 Mev pions.

collisions σ_{in} depend on the energy slightly, while at energies greater than 250 Mev they decrease fairly rapidly. It can be seen from the data of columns 12-15, Table I and column 6, Table II a that the cross-sections σ_{in} obtained by different methods are in good agreement within the limits of experimental error.

Fig. 6a shows the energy dependence of the total cross-sections σ_t for Be, C and O, as well as the total cross-section for carbon, obtained [7] at the energy of 48 Mev. Figs. 6b, 6c and 6d represent the energy dependence of the cross-sections σ_{in}. These figures also give the value of the cross-sections σ_{in} measured [8-11] by the method of scintillation counters for energies less than 140 Mev. The values of the cross-sections σ_{in} in these figures are given after correction for the Coulomb interaction. Table II e gives the total cross-section for helium obtained at the energy of 330 Mev at the Institute of Nuclear Problems of the USSR Academy of Sciences and at energies of 60 and 105 Mev in the work[12].

As appears from fig. 6 and Table II e, the energy dependence of the cross-section σ_t and σ_{in} for nuclei in the 30-400 Mev interval resembles in its general outlines the

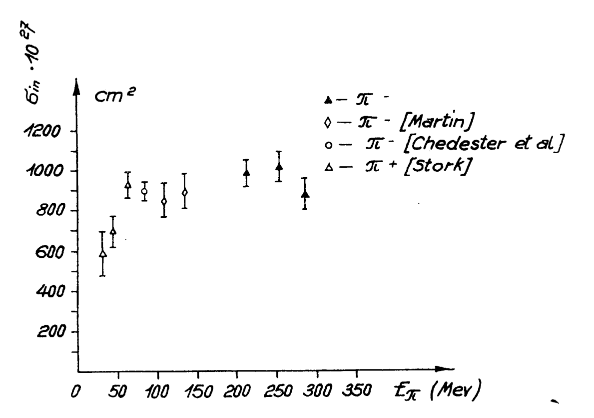

Fig. 6c. The inelastic cross-sections of copper for 30-350 Mev pions.

energy dependence of the total cross-sections of π mesons scattering on hydrogen and deuterium. In the energy range 100-250 Mev the cross-sections depend weakly on the energy, while at energies greater than 250 Mev the cross-sections decrease comparatively rapidly. The cross-sections also fall off rapidly at energies less than 100 Mev. σ_t and σ_{in} pass through a maximum in the energy range (about 190 Mev), in which the cross-sections of π meson scattering on hydrogen and deuterium reach their maximum values.

In the study of the phenomena taking place in nuclei struck by mesons, great interest attaches to the mean range λ of the mesons in the nuclear matter. In order to obtain information on the energy dependence of the range $\lambda = f(E)$ an analysis was made of the results of the σ_{in} measurements on the basis of the optical model. For a radius of the nuclei $R = 1.42 \times 10^{-13} A^{1/3}$cm. the expression

$$\sigma_{in} = \pi R^2 \left\{ 1 - \frac{1}{2}\left[1 - \left(1 + \frac{2R}{\lambda} \right) e^{-\frac{2R}{\lambda}} \right] \left(\frac{\lambda}{R} \right)^2 \right\}$$

yields values of λ, which satisfy the measured magnitudes of σ_{in} for Be and C at every energy. The values of λ obtained are shown in fig. 7. The same figure also gives the values of λ found in a number of works cited in [13] for energies less than 140 Mev.

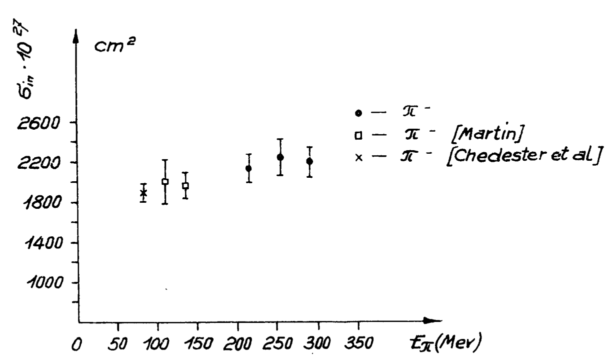

Fig. 6d. The inelastic cross-sections of lead for 85-350 Mev pions.

If it is assumed that the π mesons interact in the nucleus with the individual nucleons, then the values of the ranges can be computed on the basis of the data on the cross-sections of π mesons interaction with free nucleons from the expression

$$\lambda' = 1/\rho_p \alpha \sigma_t (\pi^-,p) + \rho_n \beta \sigma_t (\pi^-,n),$$

where ρ_p and ρ_n are the densities of protons and neutrons in the nucleus respectively, σ_t (π^-, p) and σ_t (π^-,n) — the total cross-sections of π^- mesons interaction with free protons and neutrons, α and β — coefficients less than unity introduced to account for the Pauli principle.

In computing the magnitude of λ' for carbon in the energy range 30-350 Mev it was assumed that $\alpha = \beta = 1$,

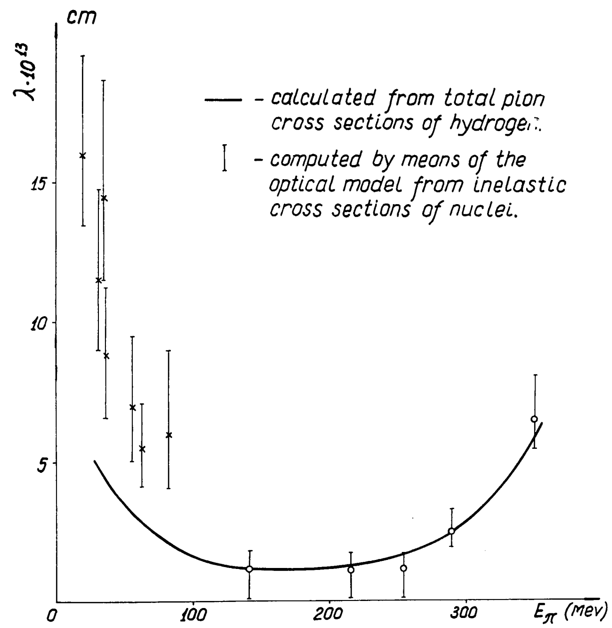

Fig. 7. The mean free path for the interaction of pions in nuclear matter.

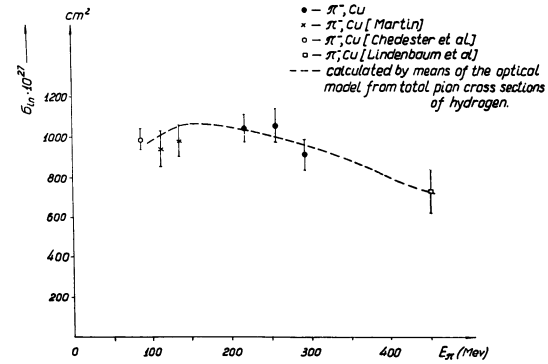

Fig. 8b. The inelastic cross-sections of copper for 80-450 Mev π^- mesons.

In view of the principle of charge symmetry the quantities σ_t (π^-, n) were replaced by the quantities σ_t (π^+,p). The results of the computations of λ' are represented as a continuous line in fig. 7.

As can be seen from fig. 7, there is good agreement between the values of λ and λ' at energies greater than 140 Mev, where we are more justified in neglecting the effect of the Pauli principle. This fact indicates immediately that the initial assumption is correct, that is, that π mesons interact in the nucleus, in the main, with the individual nucleons.

The above conclusion can be extended, if we compare the functions $\sigma_t = f(E)$ and $\sigma_{in} = f(E)$ obtained experimentally for C, Cu and Pb with the functions $\sigma_{el} = f(E)$ and $\sigma_{in} = f(E)$, computed [14] on the basis of the optical model for the energy range 100 Mev to 2.5 Bev. This comparison is especially interesting in view of the fact that in computing the energy dependence of the elastic scattering cross-section $\sigma_{el} = f(E)$, values of the real part of the amplitude in the forward hemisphere found on the basis of the causality conditions from the data on the total cross-sections of mesons scattering on protons were utilized. In fig. 8a the dotted line represents the energy dependence of the cross-section $\sigma_t = f(E)$ for carbon, obtained by summing the computed relations $\sigma_{in} = f(E)$ and $\sigma_{el} = f(E)$. As can be seen, there is good agreement between the computed and the measured energy dependences.

It is evident from figs. 8b and 8c, where the measured cross-sections σ_{in} for Cu and Pb are compared with the computed values, that the computed cross-sections for these nuclei also agree with the experimental values within the limits of experimental error.

Thus, an analysis of the results of the energy dependence from the investigation of the cross-sections allows us to conclude that the optical model with parameters computed on the assumption that mesons interact with individual nucleons in the nucleus, satisfactorily describes the energy dependence of the cross-sections σ_t and σ_{in} for Be, C, Cu and Pb in the energy range 140-450 Mev.

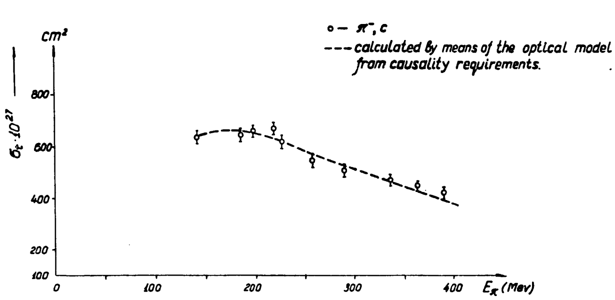

Fig. 8a. The total cross-sections of carbon for 140-400 Mev π^- mesons.

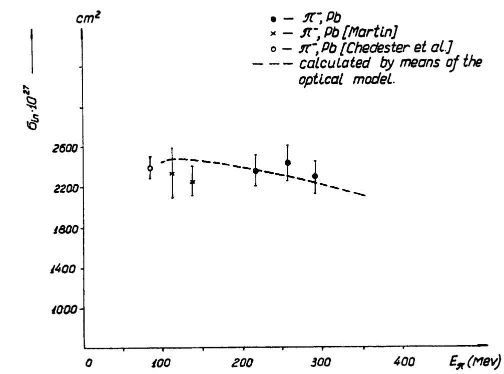

Fig. 8c. The inelastic cross-sections of lead for 80-350 Mev π^- mesons.

From the values of the cross-sections σ_t and σ_{in} at an energy $\sim$ 190 Mev, where the real part of the potential of π mesons interaction with a nucleus, computed on the basis of the causality condition [14,15] passes through the zero value, one can obtain information on the dimensions of the nuclei. The values of the cross-sections σ_t for Be, C, O and of the cross-sections σ_{in} for Be, C, Cu and Pb in this energy range coincide with the quantities $2\pi R^2$ and πR^2, respectively, if the radius of the nucleus is taken equal to $R = 1.42 \times 10^{-13} A^{1/3}$ cm.

b) *Inelastic scattering*

More direct information on the mechanism of interaction of a π meson with a nucleus can be obtained from an analysis of inelastic scattering processes. This refers in the first place to the experiments with helium. Among the 42 cases of inelastic scattering of π^- mesons of an energy exceeding 330 Mev on helium there were three cases in which the relation between the scattering angle of the π meson and the angle of emission of one of the recoil particles closely approached the angular relation in the elastic scattering of π mesons on free protons. The reaction $\pi^- + He^4 \rightarrow \pi^- + n + He^3$ and the above-mentioned three cases can be regarded as the result of the quasi-elastic scattering of π mesons on neutrons and protons, respectively. The direct observation of cases of quasi-elastic scattering offers the most immediate support of the mechanism of one-nucleon interaction, in some of the cases at any rate.

Important conclusions pertaining to the nature of the interaction of π mesons with matter can also be drawn from a consideration of the angular and energy distributions of the inelastic scattering of mesons on various nuclei.

As can be seen from fig. 4, the characteristic feature of the energy distributions is the large energy loss of the π mesons. Thus, in the case of π meson inelastic scattering of the 300 Mev energy by nuclei in the photo-emulsion, the mean energy in the spectrum amounts to about 80 Mev. The mean energy with which a meson emerges from carbon and lead nuclei is equal to about 90 Mev.

The large losses observed cannot be explained by single collisions of the π mesons with the nucleons of the nucleus. Indeed, the greatest energy which a π meson of, say, 300 Mev can transit to a free nucleon equals 200 Mev. However, collisions with maximum energy transfer should be relatively rare. It is, therefore, natural to assume that the meson loses its energy in the nucleus in a number of successive collisions.

A characteristic feature of the angular distributions, as appears from fig. 3 and Table II d, is their anisotropy, the forward and backward scattering being predominant. Figs. 3a and 3b show for comparison the angular distributions of inelastic scattering of π^- mesons of the energy of 125 Mev on C and Pb nuclei, also obtained [16] by the cloud-chamber method. As can be seen from these figures the character of the angular distributions radically changes as the energy varies from 125 to 230-250 Mev.

All the features of the angular distributions also speak in favour of the one-nucleon interaction mechanism. Indeed, for π mesons of an energy of 230-300 Mev, in view of the small range λ of mesons in the nuclear matter (see fig. 7), the first collisions will take place in the main on the surface of the nucleus. In this case the conditions for the emergence of the mesons from the nucleus in the direction of the incident meson and in the opposite direction will be essentially different: in "backward" scattering the mesons leave the nucleus in the majority of cases without having undergone collisions, whereas in "forward" scattering additional collisions are possible. As a result of this phenomenon, due to the weak coupling of the surface nucleons, the angular distribution of the "backward" scattered π mesons should retain, in the main, the same features as the angular distribution of scattering of π^- mesons on neutrons. This last statement will become clear if we take into consideration, in the first place, the well-known inequality existing between the cross-sections of elastic scattering $\sigma(\pi^+p, \pi^+p) \gg \sigma(\pi^-p, \pi^-p)$ for this energy range, and in the second place, the equality of the cross-sections $\sigma(\pi^-n, \pi^-n) = \sigma(\pi^+p, \pi^+p)$, which follows from the hypothesis of charge symmetry.

As for the angular distribution in the region of small angles, the scattering and subsequent absorption of mesons should lead to a decrease in the number of π mesons emitted in this angular range in comparison with the scattering of π^+ mesons on free protons. It is quite evident that this effect will be greater, the heavier the nucleus. Fig. 3 presents for comparison the angular distribution of π^+ mesons scattered on hydrogen at the energy of 250 Mev [17]. As can be seen from this figure, from figs. 3, 3b and Table II, the angular distribution of inelastic scattering also testifies in favour of the multiple scattering of π^- mesons in the nucleus.

The above considerations are supplemented by data obtained from the study of the relations between the scattering angle and the energy loss of π mesons. Table II b gives the values averaged over three angular intervals of the energy loss ratio computed on the assumption that the π meson is scattered on one nucleon of the nucleus to the energy loss observed in the experiment with carbon and lead. For comparison the same table presents similar data, obtained [18] for photoemulsion nuclei for an energy of the 500 Mev π^- mesons.

It can be concluded from these data that in the angular range 60°-180° inelastic scattering is primarily due to single collisions of π mesons with surface nucleons of the nucleus: the scattered π mesons which fell into the range of angles 0°-60° had undergone several collisions in the nucleus. No correlation between energy loss and scattering angle is observed for π^- mesons of the energy of 500 Mev, either. This is evidently due to the fact that at such energies, due to the large magnitude of λ (see fig. 7), the first collisions of the mesons occur inside the nucleus, and therefore throughout the whole angular range inelastic scattering takes place as a result of several collisions.

A consideration of the ratio of the number of quasi-elastic collisions on neutrons and on protons in helium also testifies in favour of successive collisions. Indeed, the ratio of the cross-sections of quasi-elastic scattering on neutrons and protons (σ_n/π_p) should be equal to or exceed the ratio of the cross-section of π^+ mesons scattering to the cross-section of π^- mesons elastic scattering on free protons ($\sigma_{\pi}{}^+/\sigma_{\pi}{}^-$). For an energy of the π mesons of 330 Mev the ratio ($\sigma_n{}^+/\sigma_{\pi}{}^-$) equals about 5. Only cases of quasi-elastic scattering on neutrons which are not accompanied by plural processes (the reaction $\pi^- + He^4 \rightarrow \pi^- + n + He^3$) can be identified unambiguously. As for quasi-elastic scattering on protons, only some of the cases can be identified. If we neglect the part of plural processes in the scattering of π mesons on α patricles, then all cases of inelastic scattering (excepting the reaction with the formation of He^3) can be taken for cases of quasi-elastic scattering on protons. The ratio σ_n/σ_p is then equal to unity. The evident disagreement with the ratio $\sigma_n{}^+/\sigma_{\pi}{}^-$ makes us assume, that among the cases regarded as quasi-elastic scattering on protons the greater part must be either the result of interaction with complexes of nucleons, or the result of plural scattering processes. In the light of the discussion of [$\lambda = f(E)$] in paragraph *a*), the first assumption seems hardly probable. It remains to assume, therefore, that in approximately 40% of all cases of inelastic scattering we have to deal with plural processes, and among them processes of plural scattering of π mesons.

From a comparison of the results for helium of the present experiments and those performed at the energies of 60 and 105 Mev [12] we can obtain information on how the interaction of π mesons with nuclei varies with energy. Thus, for example, the contribution of absorption to the total cross-section of interaction decreases from 30% at an energy of 105 Mev to 6% at 330 Mev*. The importance of absorption declines due to the increasing importance of inelastic scattering.

c) *Elastic scattering*

A peculiarity of the angular distribution elastic scattering of π meson at an energy of 230 Mev on carbon nuclei and at an energy of 250 Mev on lead nuclei (see fig. 2) is the predominance of forward scattering. It should also be observed that in both cases scattering has not been detected at angles exceeding 90°.

Figs. 2b and 2c show for comparison the angular distribution of elastic scattering of π^- mesons on C and Pb nuclei, also obtained by the cloud-chamber method at an energy of 125 Mev [16]. As appears from fig. 2, as the energy varies from 125 to 240 Mev, elastic scattering occurs in a region of noticeably smaller angles.

Fig. 2b shows the angular distribution of elastic scattering of π^- mesons at an energy of 230 Mev on carbon nuclei, computed on the basis of the optical model. The radius of the nucleus was taken to be equal to $R = 1.4 \times 10^{-13} A^{1/3}$ cm. The following values of the meson absorption coefficient K in the nuclear matter and of the real part of the potential V_1 were taken: *a)* $K = \infty$ $V_1 = 0$; *b)* $K = 0.79 \times 10^{13}$ cm^{-1}; $V_1 = 30$ Mev and *c)* $K = 0.79 \times 10^{13}$ cm^{-1}, $V_1 = 0$. The value of V_1 taken in case *b)* coincides with the value computed in [14]. For the cases *b)* and *c)* the values of K were found from the total cross-sections of π meson interaction with hydrogen.

It is evident from fig. 2b that the elastic scattering of π^- mesons on carbon nuclei at an energy of 230 Mev is satisfactorily described by the optical model. However, due to the fact that the experimental errors are large and the form of the angular distribution depends on V_1 slightly when there is strong absorption of mesons in the nucleus, the experimental data are equally well satisfied both by diffraction scattering on an opaque nucleus and by the elastic scattering described by curves *b* and *c*. The computed total cross-sections of elastic scattering at angles greater than 10° for cases *b)* and *c)* are equal, respectively, to 220×10^{-27} cm^2 and 190×10^{-27} cm^2. If we compare these figures with the experimental values given in Table II a, then we can assert that within the limits of experimental errors the measured cross-sections coincide with the computed values. On the basis of this agreement we can draw the conclusion that at $K = 0.79 \times 10^{13}$ cm^{-1} the real part of the complex potential lies within the limits 0-30 Mev.

In the angular distribution of π^- meson elastic scattering on helium (see fig. 2a) attention is drawn by the fact that in the ranges 5-15° and 45-180° not a single case of elastic scattering was registered. It should be observed that elastic scattering events at small angles are difficult to identify due to the small range of the recoil α particles. It was therefore natural to assume that the absence of cases of elastic scattering in this range of angles may be due to incomplete scanning efficiency. In order that the differential cross-section of elastic scattering in the range 5-15° may remain at the level 50×10^{-27} cm^2 sterad. for the given statistical material, 5-6 cases should be observed in this range of angles. The twice-repeated careful scanning of 40% of the photographs did not yield a single additional case of elastic scattering, as compared with the first scanning. The small amount of statistical material does not permit us to judge the exact trend of the angular distribution. However, it is reasonable to assume that in the region of small angles the differential cross-sections of elastic scattering do not vary monotonically. Fig. 2a shows for comparison the angular distribution of π meson elastic scattering of the energy of 330 Mev on helium, as computed on the basis of the optical model with the following values of the parameters: $\lambda = 2.7 \times 10^{-13}$ cm.,

* The cross-section of π^- meson absorption by helium nuclei was estimated from the cross-section of absorption by a p-p pair σ_a (pp). It turned out to be equal to $\sigma_a (pp) = 9 \times 10^{-27}$ cm^2.

$V = 32$ Mev and $R = 1.4 \times 10^{-13} A^{1/3}$ cm. These values of the parameters were obtained from an analysis of the cross-sections of elastic and inelastic processes given in Table II d.

Comparison of this curve with the experimental points reveals a decided divergence in the region of small angles. If this circumstance is attributed to the interference of Coulomb and nuclear scatterings then it must be assumed that the real part of the potential of interaction of π mesons with the nucleus V_1 has a positive sign (repulsion). The assumption that $V_1 > 0$ for the meson energy of 330 Mev is also borne out by computations [14,15] of the dependence of V_1 on the energy, based on the causality condition.

d) *Formation of π^+ mesons by negative π mesons*

The two cases of meson formation observed in the experiments with helium have been identified with the generation of positive mesons. In this manner the cross-section of π^+ meson generation on helium by π^- mesons of the energy of 330 Mev turned out to be equal to $(3 \pm 2) \times 10^{-27}$ cm².

From the differential cross-section $d^2\sigma/d\omega dE$ given in § 1 we can estimate the total cross-section of π^+ mesons production on carbon.

Interaction of the differential cross-section over the spectrum computed [19] on the basis of perturbation theory gives for the cross-section of production of π^+ mesons by π^- mesons at an angle of 90° the value $d\sigma/d\omega = (2.1 \pm 1.1) \times 10^{-28}$ cm² × sterad.$^{-1}$. On the assumption that the angular distribution is isotropic, the total cross-section of π^+ meson production by π^- mesons of the energy of 308 Mev on carbon nuclei was found to be equal to $(2.6 \pm 1.3) \times 10^{-27}$ cm².

LIST OF REFERENCES

1. Ignatenko, A. E., Mukhin, A. I., Ozerov, E. B. and Pontekorvo, B. M. (Interaction of negative π mesons with beryllium, carbon, and oxygen nuclei in the energy interval from 140 to 400 Mev.) Doklady Akad. Nauk SSSR., *103*, p. 395-7, 1955.
2. Ignatenko, A. E., Mukhin, A. I., Ozerov, E. B. and Pontekorvo, B. M. RINP, 1955.
3. Dzhelepov, V.P. et al. RINP, 1955.
4. Kozodaev, M. S. et al. RINP, 1955.
5. Mitin, N.A. and Grigoriev, E. L. (Inelastic scattering of 300 Mev $\pi-$ mesons by complex nuclei.) Doklady Akad. Nauk SSSR, *103*, p. 210-22, 1955.
6. Krivitski, V. V. and Reut, A. A. RINP, 1955.
7. Shapiro, A. M. The interaction of π mesons with carbon nuclei. Phys. Rev., *84*, p. 1063-4, 1951.
8. Isaacs, P. J., Sachs, A. M. and Steinberger, J. Total cross-sections of 60 Mev mesons in hydrogen and deuterium. Phys. Rev., *85*, p. 803-5, 1952.
9. Chedester, C., Isaacs, P., Sachs, A. and Steinberger, J. Total cross-sections of π mesons on protons and several other nuclei. Phys. Rev., *82*, p. 958-9, 1951.
10. Martin, R. L. Nuclear cross-sections for negative pions of energy 113 and 137 Mev. Phys. Rev., *87*, p. 1052-60, 1952.
11. Stork, D. H. Interaction of pions complex nuclei. Phys. Rev., *93*, p. 868-80, 1954.
12. Fowler, E. C. et al. A diffusion cloud-chamber study of pion interactions in hydrogen and helium. Phys. Rev., *91*, p. 135-49, 1953.
13. Tenney, F. H. and Tinlot, J. Positive pi-meson interactions in beryllium. Phys. Rev., *92*, p. 974-7, 1953.
14. Sternheimer, R. M. Total cross-sections for scattering and absorption of pions by nuclei. Phys. Rev., *101*, p. 384-7, 1956.
15. Frank, R. M., Gammel, J. L. and Watson, K. M. Optical model potential for pion-nucleus scattering. Phys. Rev., *101*, p. 891-901, 1956.
16. Kessler, J. O. and Lederman, L. M. Interactions of negative pions in carbon and lead. Phys. Rev., *94*, p. 689-702, 1954.
17. Mukhin, A. I., Ozerov, E. B. and Pontekorvo, B. M. RINP, 1955.
18. Blau, M. and Caulton, M. Inelastic scattering of 500 Mev negative pions in emulsion nuclei. Phys. Rev., *96*, p. 150-60, 1954.
19. Lapidus, L. I. Dissertation, 1953. Institute of Nuclear problems.
20. Lindenbaum, S. J. and Yuan, L. C. L. The interaction cross-section of hydrogen and heavier elements for 450 Mev negative and 340 Mev positive pions. Phys. Rev., *92*, p. 1578-9, 1953.

DISCUSSION

G. Bernardini asked what kind of momentum distribution was used for the evaluation on a single nucleon model.

A. E. Ignatenko answered that the cross-section was assumed to be that of the sum of free nucleons, no momentum distribution was used.

L. M. Ledermann asked whether A. E. Ignatenko had calculated the sign of the potential as Watson's calculations indicate that the sign changes at 200 Mev.

A. E. Ignatenko said he had calculated the potential in the same way as G. N. Watson, and as the total cross-sections found in the experiment agree well with the calculations up to 100 Mev, it followed that his predictions about the dependence of potential on energy were correct.