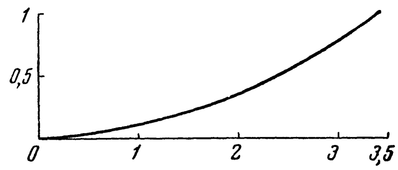

FIG. 7. Dependence of optimum angle on accelerator parameter $\varkappa^2 \nu^2$ ($n_1 + n_2 = 0$) for injector located between sectors. The ordinates are $(2R/\varkappa\nu\rho_0)\,\gamma_{\mathrm{opt.}}$ The abscissa is $\varkappa^2 \nu^2$.

accelerators. By means of this method one can easily compare the focusing of different types of accelerators and solve the problems associated with the achievement of maximum efficiency of injection.

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Interaction of 230–250 mev Negative π-Mesons with Carbon and Lead Nuclei

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The interaction of 230–250 mev negative pions with carbon and lead nuclei was investigated by the method of the Wilson chamber in a magnetic field. The total and differential cross sections for both elastic and inelastic scattering were determined, as well as the total cross section for all the inelastic scattering processes. Within the experimental errors, the elastic scattering is in agreement with the diffraction pattern of an opaque nucleus. The energy spectrum of the scattered pions shows that the major part of the inelastic scattering between 60° and 180° is due to the collisions of the incoming pions with single nucleons in the nucleus.

THE most complete data on the different interaction processes of pions with complex nuclei have been obtained in experiments with thick layer photo-emulsions and Wilson chambers. Most data correspond to an energy range from 30 to 150 mev; there have been only a few experiments done for nuclei in emulsion[1–3] at higher energies, and a single experiment for the helium nucleus[4] at higher energy.

The present work has been carried out on the synchrocyclotron of the Institute of Nuclear Problems of the USSR Academy of Sciences. The interaction of 230–250 mev pions with carbon and lead nuclei was investigated by the method of a Wilson chamber in a magnetic field.

EXPERIMENTAL ARRANGEMENT AND METHOD OF PROCESSING THE PHOTOGRAPHS*

The experimental arrangement is shown schematically on Fig. 1. The source of negative pions was a graphite target placed inside the accelerator in the circulating beam of 670 mev protons. The 230–250 mev pions ejected from the target in the forward direction were directed by a four meter collimator and by a deflecting magnet on the Wilson chamber; the Wilson chamber had a diameter of 400 mm and was placed behind a concrete

*A detailed description of the experimental arrangement is given in Ref. 5.

shield.** The sample plate was placed in the center of the chamber, at an angle of 90° with the incoming pion beam. In the case of graphite, the thickness of the plate was 4.29 gm/cm^2, in the case of lead it was 4.6 gm/cm^2.

The chamber was placed in the 10^4 uniform magmetic field produced by the electromagnet-solenoid. The amount of non-uniform field did not exceed 3%. The chamber was synchronized with the acclerator in the so-called "single-burst" state. During the working cycle of the chamber, which lasted for 1.5 min, the accelerator emitted only a single burst at the moment when the widening was concluded in the chamber. The magnetic field was increased to its nominal value only forthe time necessary for the action ofthe chamber.

The photograph ofthe tracks was taken by a stereocamara from a distance of 1,000 mm on a negative panchromatic film of 800–1,000 GOST units. The stereocamera had a base of 120 mm and a diameter of 24 mm. The photographs were processed on a reprojector and a stereocomparator designed for the stereocamera used.

In the computing ofthe total flux of impinging pions, only such tracks were taken into account a) which intersected the plate at a point not less than 10 mm away from its edges, b) which entered the plate at an angle of 90 ± 10°, and c) which were bright enough to enable one to measure them on a projector and on the stereocomparator. All the tracks chosen according to the above criteria were subjected to the following measurements: measurement of the magnetic curvature, and measurement of the height-with respect to a small rod in the plate- and of the coordinates of the point in the plate where a nuclear interaction took place. In the case of nuclear interactions, the curvatures and the emission angles of the scattered

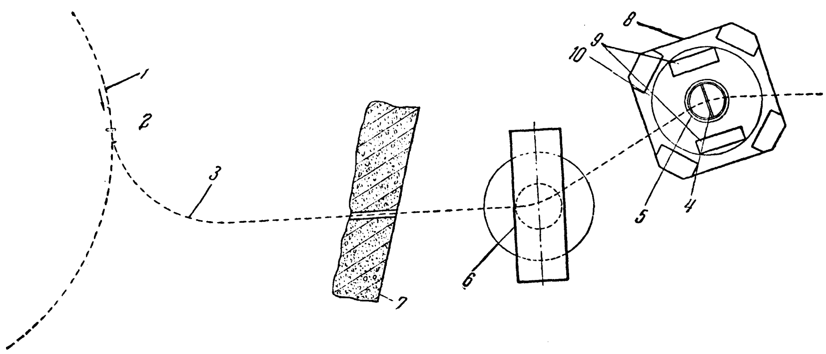

FIG. 1. Experimental arrangement: *1*—circulating proton beam; *2*—target; *3*—π^-—meson beam; *4*—target; *5*—Wilson chamber; *6*—deflecting magnet; *7*—shield; *8*—magnet.sollenoid; *9*—scintillators; *10*—sollenoid coil.

pions and secondary particles were also measured. The average error in the angular measurements was 1–2°. The error in the measurement of the radius of curvature of the incoming pions (taking into account the curvature due to multiple Coulomb scattering of the particles in the chamber gas and to the motion of the gas) was of 6–7%. The usual classification of nuclear interactions was used: star (stop), elastic scattering, inelastic scattering and radiative absorption (exchange scattering). The cases of elastic and inelastic scattering were differentiated according to the magnitude of the energy release: if the energy release in the scattering was less than 45 mev, the scattering was considered elastic; if the energy release in the scattering was greater or equal to 45 mev. the scattering was considered inelastic. The magnitude of this limiting release was determined by the average error in the determination of the meson energy difference before and after scattering.

Geometry corrections were made on all the measurements of elastic and inelastic scattering. The scanning of the photoplates, the measurements of the tracks and the identification of the nuclear interaction events were performed independently by two observers. The value of the total flux of particles impinging on the plate was obtained by taking the average of the results ofthe two independent calculations. In the calculation of the cross sections, the errors on the determination of the total meson flux and on the differentiation between cases of elastic and inelastic scattering were taken into account, in addition to the statistical deviations.

**The number of μ-mesons and electrons mixed to the beam was 12.5 ± 3% of the total number of particles.

EXPERIMENTAL RESULTS

During the exposure time of the camera to the negative pion beam, a total of 6,000 photographs were taken; they recorded 760 events of pion interaction with carbon and 629 events of interaction with lead. A few examples of nuclear interactions are given in Figs. 2 and 3.

FIG. 2. Elastic scattering of the π^--meson: a–incident π^--meson, b–scattered π^--meson; 2–star: c–incident π^--meson, d–proton

FIG. 3. Inelastic scattering of the π-meson: a–incident π^--meson; b–scattered π^--meson.

The analysis of these data gives, for carbon and lead nuclei, a) the total and differential cross sections for elastic scattering at angles between 10 and 180° ; b) the total and differential cross sections for inelastic scattering; c) the total cross section for all the inelastic interaction processes. All the measured cross sections for carbon nuclei refer to the energy of 230 ± 30 mev; for lead nuclei– to the energy of 250 ± 30 mev.

A. ELASTIC SCATTERING

Under the conditions of the present experiment, the elastic scattering of pions by C and Pb nuclei at small angles is determined mainly by the multiple and single Coulomb scattering; it is only for angles greater than 10–15° that the scattering has practically a nuclear character. The total elastic scattering of pions by C and Pb nuclei measured in the indicated angular interval (from 10 to 180°) is given in Tabel I.

The measured angular distribution for elastic scattering is shown in Fig. 4. For the carbon nuclei, the graph also shows a plot of the angular distribution computed for the optical model with a uniform distribution of the nuclear matter inside a

TABLE I.

Total cross section (in units of $10^{-27}cm^2$)

Element	Elastic scattering at $\theta > 10^\circ$	Inelastic scattering $\Delta E \geq 45$ mev	Stars and Stops	Total inelastic interaction cross section	Geometric cross section
C	200 ± 32	90 ± 15	217 ± 26	307 ± 37	325
Pb	329 ± 53	555 ± 83	1600 ± 160	2153 ± 194	2150

sphere of radius $R = 1.4 A^{1/3} \times 10^{13} = 3.2 \times 10^{-13}$ cm and with the following values of the coefficient K of pion absorption in the matter and of the real part of the potential:

Curve	K (in units of 10^{-13} cm)	V (in mev)
A	∞	0
B	0.79	+32*
C	0.79	0

In the cases B and C, the value of the absorption coefficient is determined (as in Ref. 6) from the value of the total cross section for 230 mev pion interaction with free neutrons and protons, according to the formula $K = 1/2\,(\sigma_{\pi,p} + \sigma_{\pi,n})\,A/4/3\,\pi R^3$, where R is the radius of the carbon nucleus. The comparison of the experimental and theoretical distribution shows that the inelastic scattering of 230 mev pions by carbon nuclei is described satisfactorily by the optical model. However, the experimental cross sections are determined with a large error and the shape of the angular distribution for a large pion absorption in the nucleus depends only weakly on the magnitude of the real part of the complex potential, and the experimental data fit the diffraction scattering by an opaque nucleus as well as the elastic scattering described by the curves B and C.

The total cross section at the angles $\theta > 10^\circ$ is equal to 219×10^{-27} cm^2 and to 193×10^{-27} cm^2 for the cases B and C, respectively. The total inelastic cross section is 300×10^{-27} cm^2 in these cases.

As Table I shows, the experimental total cross sections are in agreement with the total cross sections computed for the optical model. It can be concluded that, for an absorption coefficient $K = 0.79 \times 10^{13}$ cm^{-1}, the real part of the complex potential is bound by the limits 0 and 30–40 mev.

B. INELASTIC SCATTERING

The experimental data on inelastic scattering are obtained in the entire interval of scattering angles, excluding the range from 0 to 10° for lead, in which region the inelastic scattering cases cannot be identified reliably because of the large number of single electrons. The total experimental cross sections for inelastic scattering are listed in Tabel I, and the angular distributions of inelastic scattering are plotted on Fig. 5. The anisotropy of the scattering with a prevailing forward and backward peaking is a characteristic property of these angular distributions; the same is also observed in the scattering of pions by free nucleons at the same energy.

The authors of a series of papers[1-4, 7-11] conclude (from the measured energy release in inelastic scattering, and from the investigations of the energetic dependence of the total cross section for pion nucleus interaction)–that the interaction of pions with complex nuclei is a result of their quasi-elastic scattering by single nucleons in the nucleus. The data from the present work confirm this conclusion.

As Fig. 6 shows, the mean energy loss of pions in inelastic scatterings by carbon and lead nuclei are 135 and 150 mev respectively, which is 60% of the original pion energy. Such large values for the energy transferred in inelastic scattering cannot be explained on the basis of a mechanism where pions transfer energy to several nucleons in a single collision event. Another experimental fact– the equality of the mean energy of pions scattered inelastically by carbon and lead nuclei, which nuclei

*This value is equal to the one computed[6] from the scattering amplitudes in the forward direction of 230 mev pions by free nucleons.

differ in size—forces the assumption that the observed inelastic scattering is, apparently, the result of a small number of pion collisions with single nucleons in the nucleus. This assumption is confirmed by the existence of a correlation between the scattering angle and the energy release, in the scattering angle range between 60 and 180°.

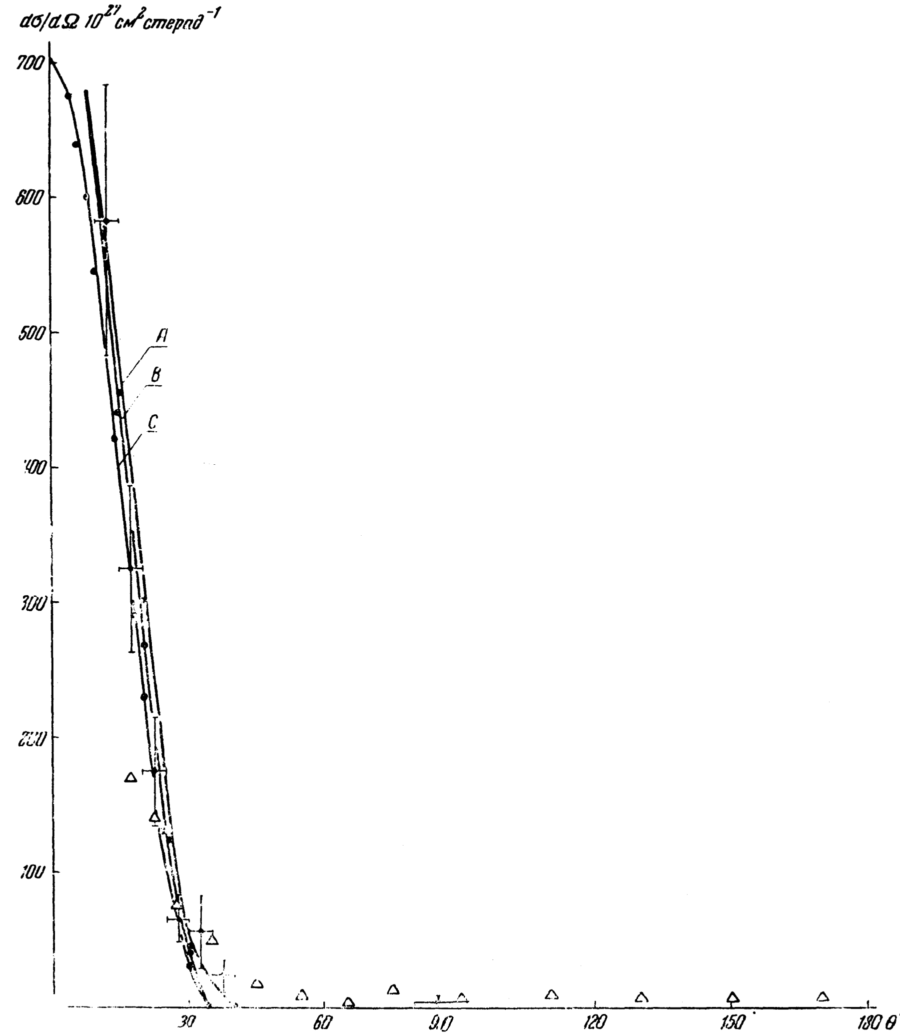

FIG. 4a. Angular distribution of the cross section for π^--meson elastic scattering by carbon nuclei; Δ—elastic scattering of 125 mev π^--mesons according to Ref. 2.

Table II shows the ratio of the calculated energy release (for a single pion scattering by a free nucleon, averaged over three angular intervals) to the observed energy release. It can be seen from the Table that, in the cases of carbon and lead, these ratios for the angular intervals of 120—180° and 60—120° are close to unity and are 3 to 4 times larger than the corresponding ratio for the angular interval of 0 to 60°. Such a large difference cannot be explained by the experimental errors and by the unsufficient statistics of the number of cases of pion inelastic scatterings used in the determination of these ratios. On the other hand, the mentioned ratios could not have been substantially overestimated because, in their calculation, the relatively small contribution of such scattering cases in which the slowly scattering mesons were stopped in the plate due to ionization were not taken into account.*

*It was found in Ref. 3—which reports on the interaction of 210 mev pions with nuclei in emulsion—that the relative number of scattered pions with energies between 0 and 40 mev is 6%.

TABLE II.

Element	π-meson energy mev	Angular interval, in degrees	Ratio of calculated to observed energy releases	Number of scattering events
C	230	0—60	23	20
		60—120	77	14
		120—180	99	35
Pb	250	0—60	22	16
		60—120	85	10
		120—180	87	28
Emulsion nuclei	500	0—60	61*	37
		60—120	63	42
		120—180	—	—

*The data for the emulsion nuclei is taken from Ref. 1.

The mean free path of pions with a mean energy of 230–250 mev for interaction with nuclear matter being of 1.2×10^{-13} cm, the nucleons mostly responsible for the inelastic scattering of pions are in the surface layer of the nucleus. This conclusion is confirmed by the proportionality between the experimental inelastic scattering total cross sections and the geometrical nuclear cross secrions (cf. Table I, columns 3 and 6, and Table III).

TABLE III.

Element	Meson energy mev	Ratio of total inelastic scattering cross section to geometric cross section, in %
C	230	30
Emulsion nuclei	250	26
	210	25—31*

*The data is taken from Ref. 3

It should be noted that this agreement between the cross sections for C and Pb nuclei improves if one computes the data relative to the scattering angles interval between 60 and 180°. It is easy to understand that such a picture for the inelastic scattering of pions by complex nuclei will be observed only for the energy range for which the pion mean free path for the second collision inside the nucleus is considerably larger than the mean free path for the first collision, i.e, for the energy range corresponding to the position of the maximum of the curve of the cross section of pions by free nucleons vs. energy. Indeed, (see Table II), the ratios of calculated to measured energy releases for all three angular intervals are already equal. when pions have an energy of 500 mev.

The observed angular distribution of inelastically scattered pions are apparently conditioned by two facts: the shape of the angular distribution of pions scattered by free nucleons and by the character of the absorption process of pions by the nuclear matter. In particular, it follows from the experimental data that about 70–75% of the pions scattered in the backward hemisphere in the first collision are absorbed by the nuclear nucleons. The absorption probability will apparently rise with the distance between the collision point and the nuclear surface. As it has been shown[8], this distance increases on the average, as the trajectory of the scattered pions deflects form the backward direction. Therefore, the observed decrease of the cross section in the angular interval between 180 and 90° can be explained qualitatively by the following two reasons: decrease of the pion scattering by nucleons as the scattering angle is changed from 180 to 90° and increase of the pion absorption effect after the first collision, for this scattering angle range.

C. TOTAL CROSS SECTION FOR INELASTIC INTERACTION PROCESSES

The main process of 230–250 mev inelastic interaction with complex nuclei is the absorption process, which finally leads to star formation (and stops). For carbon nuclei, the ratio between the number of stars and the number of stops (corrected for ionization absorption of protons in the plate) is one to one. If one assumes that the observed stops correspond to events of pion absorption by (p–n) pairs and if one takes into consideration that the number of stops decreases because of nucleon cascades from pion-nucleon collisions prior to the absorption and from pion capture, than one can conclude that the mentioned ratio is not in disagreement with the assumption that such a mechanism is predominantly responsible for pion absorption by nuclear matter at 230–250 mev, as well as at lower energies. The total cross sections for all inelastic interaction processes of pions with C and Pb nuclei (cf. Table I) are, within

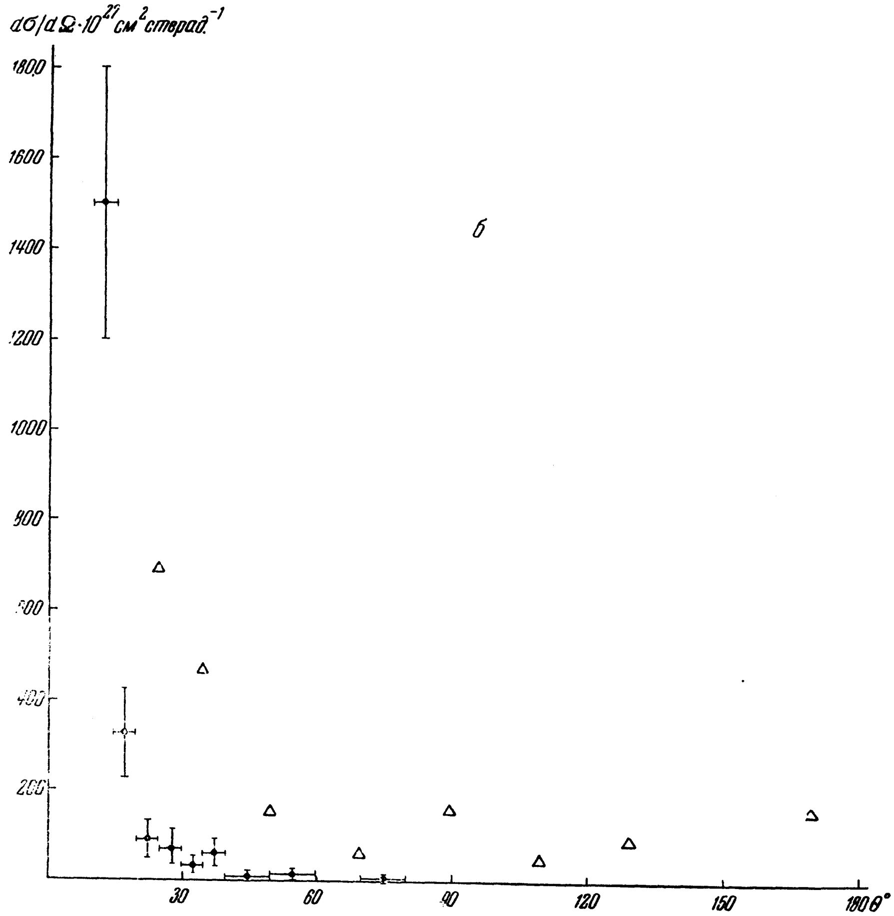

FIG. 4b. Angular distribution of the cross section for π^--meson elastic scattering by lead nuclei, Δ—elastic scattering of 225 mev π^--mesons according to Ref. 2.

experimental errors, equal to the geometrical nuclear cross sections and the cross sections[7] for 125 mev pions. This is in agreement with the data from Ref. 9 and 12; it is shown in these papers that the total cross section for inelastic interaction of pions with complex nuclei does not practically change with energy in the energy range from 100 to 240 mev.

CONCLUSION

The investigation of the different interaction processes of 230–250 mev negative pions with carbon and lead nuclei gave the following results:

1. The observed distributions and total elastic cross sections for pions at $\theta > 10°$ as well as the total inelastic interaction cross section can be described on the basis of an optical model for the interaction of pions with complex nuclei. For an absorption coefficient $K = 0.79 \times 10^{13}$ cm^{-1}, the real part of the complex potential is bound by the limits 0 and 30–40 mev.

2. The inelastic scattering in the scattering angle interval between 10 and 180° is mostly produced as a result of single collisions between the impinging pions with single nuclear nucleons. One can think that the situation can be taken advantage of in the future for the investigation of the momentum distribution of the nuclear nucleons.

3. The pion absorption in the nuclear matter is

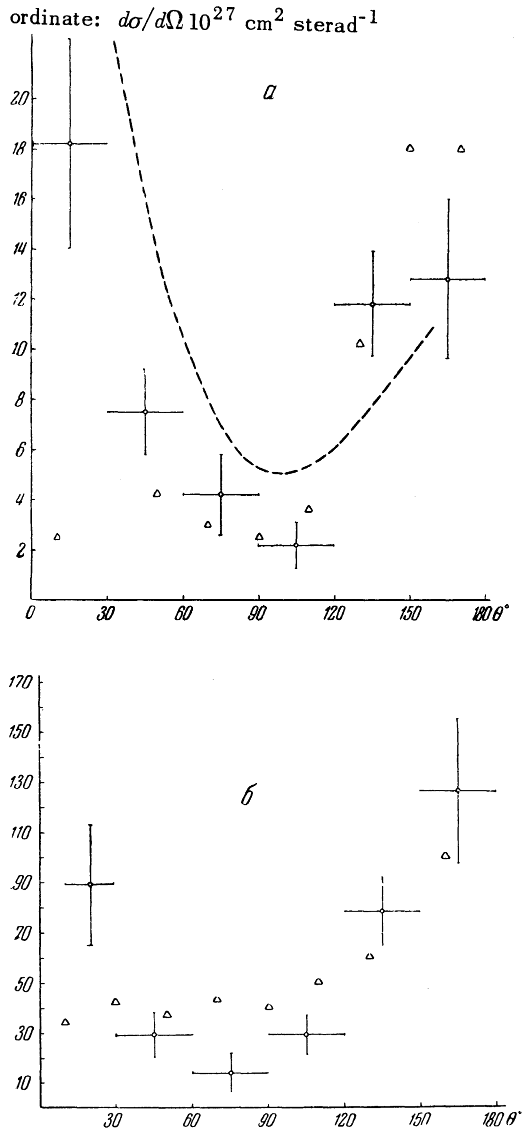

FIG. 5(a,b). π^-—meson inelastic scattering angular distribution: a—by carbon nuclei, b—by lead nuclei. Dotted line—angular distribution of the π^+—meson—proton elastic scattering at 240 mev; Δ—inelastic π^-—meson scattering at 125 mev.[2]

apparently primarily due to their capture by p—n pairs of nuclear nucleons (as in the case of lower energy).

5. The total pion cross sections for inelastic interaction processes are equal to the geometric cross sections.

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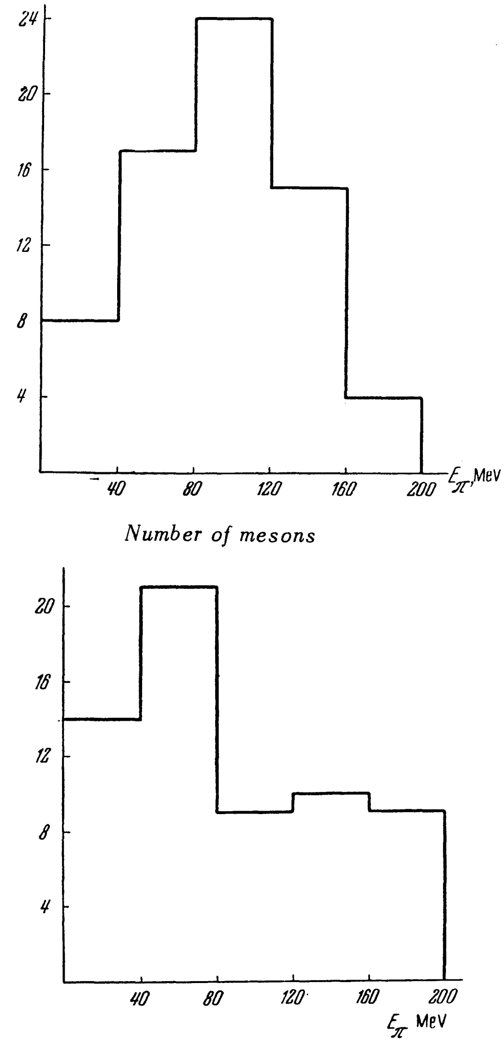

FIG. 6(a,b). π^-—meson inelastic scattering energy distribution: a—on carbon nuclei, E_{cp} = 95 mev; b—on lead nuclei, E_{cp} = 101 mev.

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Interaction of 5–50 bev Cosmic Ray Particles with Be Nuclei. I

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Meson production by cosmic ray particles with energy 5–50 bev was investigated in a cloud chamber containing a 9.8 gm/cm^2 Be plate under conditions closely approximating nucleon-nucleon interaction. Eleven interactions involving formation of four or more secondary charged particles are analyzed in detail. The angular distribution of pions and nucleons in the center-of-mass system of the two colliding nucleons was obtained, as well as the energy distribution of the energy of the primary particle among the various secondary particles.

THE character of nucleon–nucleon interactions can be conveniently studied today up to energies ~ 5 bev[1] by means of artificially accelerated particles. For the study of the interaction at higher energies, we must make use of cosmic ray particles. Here, however, the situation is complicated by the low intensity of cosmic radiation and by indefiniteness in the energy determination. The low intensity does not permit us to obtain direct evidence on nucleon–nucleon interaction by irradiating hydrogen with cosmic ray particles. The analysis of large experimental material, obtained in the irradiation of nuclei of heavy atoms (photoplates) by cosmic rays, can give only indirect evidence on the nucleon–nucleon interactions of high energy.

1. APPARATUS

The purpose of our research was the investigation of meson generation by cosmic ray particles with energies in excess of 5 bev under conditions that are close to nucleon–nucleon collisions. We used a Wilson cloud chamber, which contained a plate of Be of thickness 9.8 gm/cm^2 (for 100 hours of the research, a graphite plate was used inside the chamber in place of the beryllium). The Wilson chamber, of diameter 30 cm and depth of irradiated region 8 cm, was placed in the magnetic field of an electromagnet of average magnetic field 8500 Oe. Control of the chamber was maintained by a system of counters located as shown in Fig. 1. Coincidence discharges were recorded in the counters of groups 1,2,3 (combined in parallel) and in any two counters of the groups 4 and 5 in the absence of discharges in the counters of group A. A lead filter was placed over the entire apparatus, to diminish the background of

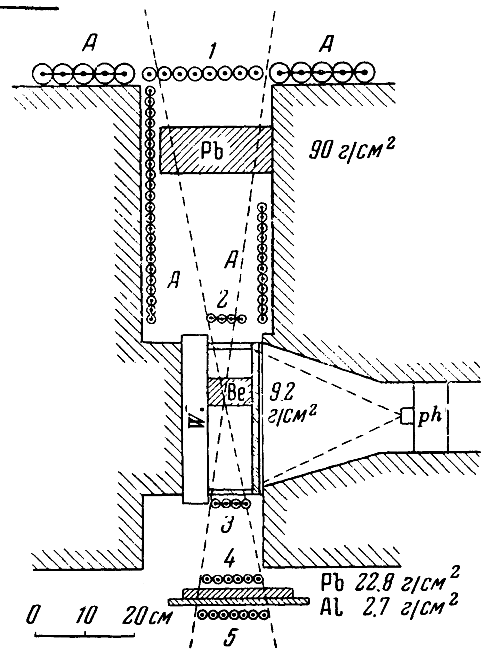

FIG. 1. Experimental scheme: *ph*—photographic apparatus; *W*—Wilson chamber.

the electron component. The work was carried out at an altitude of 3860 m above sea level (Pamir Scientific Station). The total research time with the apparatus, after deduction of the dead time of the chamber (2 min) was equal to 950 hours. In this time about 5300 photographs were obtained.

In 31 photographs there were electron–nuclear showers of four and more particles, formed in Be or C inside the chamber. Showers with a smaller number of particles (2,3 secondary particles) were ob-