INELASTIC SCATTERING AND ABSORPTION OF (195 ± 15)-Mev POSITIVE PIONS BY CARBON AND LITHIUM NUCLEI

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Submitted to JETP editor May 13, 1959

J. Exptl. Theoret. Phys. (U.S.S.R.) **37**, 957-965 (October, 1959)

The inelastic scattering and absorption of (195 ± 15) Mev π^+ mesons with carbon and lithium nuclei were investigated using the method of the Wilson cloud chamber in a magnetic field. The total and differential cross sections for inelastic scattering and the summed total cross section for charge exchange scattering and pion absorption were determined. A comparison of the experimental data obtained with the results of the cascade calculation in the carbon nucleus was made, and it was shown that the inelastic scattering of mesons is satisfactorily described on the basis of the pair collision hypothesis. It was established that only two nucleons in the nucleus take part actively in the absorption of (195 ± 15) - Mev pions; here the probability of meson capture by n, p pairs is 2 or 3 times greater than that of capture by pairs of like nucleons.

THE experimental data relating to the inelastic scattering of pions with complex nuclei is in satisfactory agreement with the pair interaction model developed in the papers of Serber and Goldberger.[1,2] Of special interest from the point of view of verifying this model are the processes of inelastic scattering of incident pions in their first interaction with the nucleons in the nucleus (called afterward the primary processes of inelastic scattering) in which the scattered pion and the recoil nucleon leave the nucleus without further collisions. However, as a result of the fact that the majority of the experiments previously carried out studied the interaction of negative pions with heavy nuclei, the experimental material on the primary inelastic scattering processes is very scanty.

In the present work with positive pions, thanks to the use of the light nuclei carbon and lithium as targets, such processes of the interaction were detected with a measurable probability, so that the values of the cross sections and angular distributions for them could be determined. Besides this, observations of the positive pion capture processes in which fast nucleons formed left the nucleons without undergoing collisions made it possible to construct a picture of the absorption of fast pions by light nuclei.

The experimental data obtained were compared with the results of a cascade calculated for the carbon nucleus which included 560 separate trials.* In that calculation the carbon nucleus was considered as a degenerate Fermi gas of nucleons with a maximum kinetic energy E = 25 Mev contained in a square well potential 34 Mev deep; the well radius was 3.2×10^{-13} cm. Pion absorption was treated on the basis of a quasi-deuteron model, where the coefficient connecting the pion capture cross section by n, p pairs in the nucleus and by free deuterons was chosen such that the calculated inelastic scattering cross section was equal to the experimental cross section. The value of this coefficient was 5. The initial energy of the pions in the cascade calculation was taken as 230 Mev, applicable to the data in the work of V. P. Dzhelepov et al.[3] with negative pions.*

The work was carried out on the synchrocyclotron of the Joint Institute for Nuclear Research by bombarding carbon and lithium targets set in a Wilson cloud chamber with (195 ± 15) - Mev positive pions. The experimental procedure has been described in a separate communication,[4] in which data are given on the inelastic scattering of positive pions by the same nuclei.

RESULTS OF THE EXPERIMENT

In the bombardment of the chamber by the pion beam 693 acts of an inelastic interaction with carbon and 508 with lithium were detected. The meas-

*The cascade calculation for the carbon nucleus was carried out by Yu. A. Budagov, V. G. Ivanov, and N. I. Petrov.

*Although the calculated data refer to an initial meson energy of 230 Mev, the majority of them are reasonable for 195-Mev mesons. In some cases, where unavoidable, the calculated data are related to the 195 Mev initial energy.

TABLE I

Nucleus	Sign of pion	Energy, Mev	Total cross sections, 10^{-27} cm^2		
			Inelastic scattering	Stars and stoppings	All inelastic processes
C	+	195	122±13	203±22	325±26
Li	+	195	62±9	164±16	226±18

ured total cross sections are given in Table I.

The inelastic scattering data refer to the angular interval 10 — 180°. The measurement errors include only the statistical deviation and the errors in separating the elastic and inelastic scattering.

Inelastic scattering. In Figs. 1 and 2 are given the experimental angular distributions of inelastic scattering for both nuclei and also the calculated distribution for carbon nuclei and the angular distribution for the elastic scattering of 200 Mev positive pions from free protons;[5] here the two last distributions were normalized to the value of the experimental total cross section for inelastic scattering by a carbon nucleus. Comparing these figures we see that on going over from free to bound nucleons a change takes place in the form of the angular distribution, included in the increase of the scattering cross section in the angular region near 180°. The general character of this change is correctly shown by the calculated distribution. The calculation also shows that the effect of the increase of the backward scattering cross section should become weaker in direct proportion to the growth of the energy (as long as the range of the mesons in the nuclear substance increases). This conclusion is strengthened by the experimental data for 250 — 270 Mev positive pions,[6] according to which the inelastic scattering distribution for carbon differs little from the corresponding elastic scattering from free nucleons. It must be noted, however, that there is no rigorous quantitative correspondence between the experimental and the calculated angular distributions: in comparison with experiment the calculation underestimates the value of the cross sections in the large-

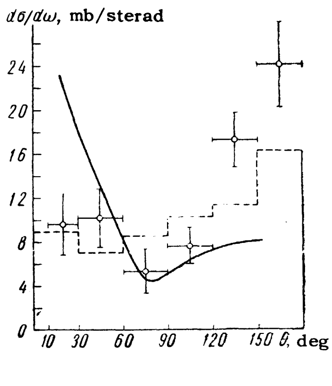

FIG. 1. Angular distribution of inelastic scattering of mesons on carbon nuclei. The dotted line shows the calculated angular distribution for inelastic scattering of positive pions with initial energy E_0 = 230 Mev on carbon nuclei; the solid line shows the angular distribution for the elastic scattering of positive pions with energy E = 200 Mev from free protons.

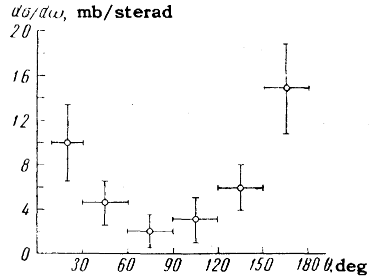

FIG. 2. Angular distribution for positive pion inelastic scattering from lithium nuclei.

and small-angle scattering regions. This circumstance can be looked at as an indication of the difference between the angular distributions for pion scattering from free and bound nucleons, which, according to the work of Watson and Zemach,[7] can depend on the influence of the potential that describes the interaction of particles with atomic nuclei in the framework of the optical model on the pion-nucleon collision in the nucleus.

The calculated and observed energy distributions of the mesons inelastically scattered in the angular intervals 0 — 60° and 120 — 180° are shown in Figs 3 and 4. Since the average energies (see Table II) of the scattered particles for carbon and

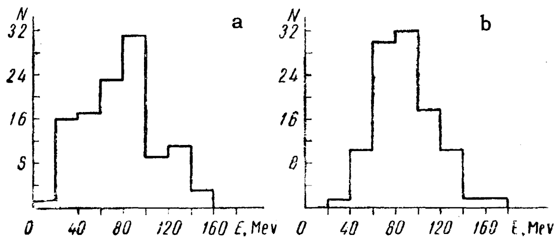

FIG. 3. Energy spectrum of positive pions inelastically scattered in the angular interval $\Delta\theta$ = 120–180°. a – total experimental spectrum. b – calculated spectrum for E_0 = 230 Mev mesons.

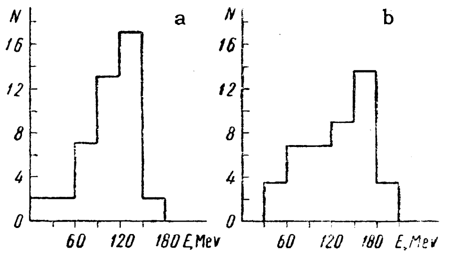

FIG. 4. Energy spectrum of positive pions inelastically scattered in the angular interval $\Delta\theta$ = 0–60°. a – total experimental spectrum. b – calculated spectrum for E_0 = 230 Mev mesons.

TABLE II

Nucleus	Initial energy and meson sign	Average energy, Mev			
		$\Delta\theta = 0-60°$		$\Delta\theta = 120-180°$	
		Experiment	Calculation	Experiment	Calculation
C	195 (+)	107	—	74	84
Li	195 (+)	104	—	78	—
C[3]	230 (—)	107	128	88	94

lithium practically coincide, the sum of the data has been used in constructing the histogram.

As can be seen from Figs 3 and 4 and Table II, there is satisfactory agreement between the distributions and the corresponding values of the average energy. This testifies that energy exchange from the incident pions to the nucleons in the nucleus proceeds essentially via quasi-elastic collisions with individual nuclei. Our data on the acts of the primary inelastic scattering of positive pions constitute further and more descriptive proof of this energy-exchange mechanism. Altogether 44 primary inelastic scattering acts were observed, out of which 25 were from carbon and 19 from lithium. As a criterion for selection we used the requirement that the sum of the energies of the scattered pion and of the recoil proton was not more than 30 — 35 Mev smaller than the energy of the incident pion. In Figs 5, 6, and 7 the distributions of the indicated interaction events (corrected for efficiency of observation) are given by meson scattering angle, by angle of separation, and by the difference in azimuthal angle of the scattered pion and the recoil proton. The corresponding calculated distributions are also given. The average values of the noncoplanarity of the angles, observed and calculated, are respectively 15° and 13°. The agreement between the calculation and the experimental data is satisfactory, considering the poor statistics. This shows that the collision of a pion with a nucleon in the nucleus proceeds in approximately the same way as with a free but moving nucleon. On this basis one finds, in particular, an explanation of the fact that the curve of the angular distribution for the selected primary inelastic scattering processes drops faster, beginning at a scattering angle of 180°, than the corresponding curve for the entire inelastic scattering. In fact, together with the decrease of the scattering angle, the energy given to the proton and correspondingly the length of its path in the nuclear substance decreases. This fact leads to a fall in the probability of the emission of a proton from the nucleus without collision, and so to a corresponding decrease in the cross section for primary inelastic scattering processes accompanied by the emission of energetic protons. However, even here, as for the entire inelastic scattering, the experimental scattering cross sections diverge significantly from those calculated in the angular region close to 180° (see Fig. 5). The indicated discrepancy is lessened if the calculated distributions are corrected for the influence of the optical potential, using the results of reference 7.

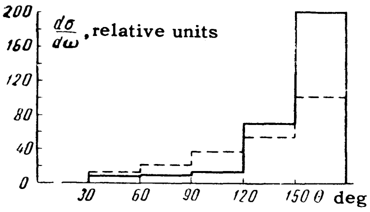

FIG. 5. Angular distribution of pions of primary quasi-elastic scattering processes. The calculated distribution is shown dotted.

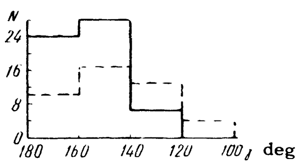

FIG. 6. Distribution of primary quasi-elastic scattering processes by angle of separation of the scattered pion and the recoil proton. The calculated distribution is shown dotted.

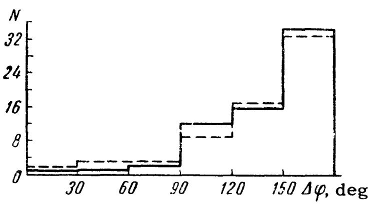

FIG. 7. Distribution of primary quasi-elastic scattering processes by difference of azimuthal angle between the scattered pion and the recoil proton. The calculated distribution is shown dotted.

Table III shows the values of the calculated and experimental probabilities* for the selected events of primary inelastic scattering in relation to the total number of inelastic interactions and also in relation to the total number of inelastic scatterings. The satisfactory agreement between the experimental and calculated probabilities indicates not only that the hypothesis of quasi-inelastic collisions is useful but also that the scattering cross sections for pions with bound nucleons do not differ greatly from the scattering cross sections for these particles with free nucleons. In this connection it is interesting to compare the data on inelastic scattering from carbon for positive and

*The calculated probabilities are corrected for the stoppings of recoil protons in the target.

TABLE III

Nucleus	Probability, %			
	In relation to the inelastic scattering cross section		In relation to the cross section for inelastic interactions	
	Experiment	Calculation	Experiment	Calculation
C	16	21	5,5	7,5
Li	25	—	7	—

TABLE IV

Nucleus	Energy in Mev and meson sign	N_1	N_2	Ratio N_2/N_1, %	
				Calculation	Experiment
C	230 (—)	64	10	16	23
C	195 (+)	91	50	55	50

negative pions. A comparison of the quantity (N_2) of inelastic scattering processes accompanied by the emission of a recoil proton from the target relative to the total inelastic scatterings (N_1) for the scattering angle interval 120 — 180° is given in Table IV.*

Considering that the calculated ratio changes little in going from 230 Mev to 195 Mev, we see that there is good agreement between the data for positive and negative pions. This fact also confirms the qualitative agreement between the experimental and calculated data obtained by Fry and Takeda[8,9] for the primary quasi-elastic scattering of 220-Mev pions by photoemulsion nuclei. For additional confirmation we can point out the agreement between the calculated and experimental cross sections for exchange scattering. The calculated exchange scattering cross section for carbon nuclei is (15 ± 3)%, and the experimental cross section for the same reaction, found for the elements contained in freon,[10] is (10 ± 3)% for a wide range of energies. To these numbers can be added the experimental estimate of the contribution of the exchange scattering of 125-Mev negative pions by carbon nuclei, obtained by Kessler and Lederman.[11] The data on the average number of pion collisions in the nucleus also testify to the usefulness of the hypothesis that the pion scattering cross sections for free and bound nucleons are not greatly different from each other. According to the calculation, the average number of pion collisions in a carbon nucleus is 1.5. This means that more than half of the inelastically scattered pions undergo only one collision in the nucleus. An estimate of the relative contribution of single scattering in the angular interval 120 — 180°, made for primary scattering acts (in which energy balance holds), is 60%. This obviously agrees with the calculated estimate and, in particular, strengthens the conclusion stated in reference 3 that the inelastic scattering of 230-Mev negative pions from carbon nuclei in the angular interval 120 — 180° proceeds predominantly as the result of single collisions of incident pions with nucleons in the nucleus. To end this section we indicate that the value of the momenta of the residual nuclei formed in the primary inelastic scattering of pions (determined for each process as the difference between the vectors of the initial momenta and of the total momentum of the scattered pion and the recoil proton) are included in the limits 0 to 400 Mev/c and are predominantly directed into the forward hemisphere. It must also be noted that, among all the primary inelastic scattering acts for pions from carbon and lithium nuclei, only one was found which could be interpreted as the direct knocking out of a deuteron by an incident pion.

Absorption of Pions. In investigating the mechanism of the absorption of pions in the low energy region from 0 to 60 Mev, it was found that small complexes of nucleons inside the nucleus, consisting mainly of one neutron and one proton, take part in the act of absorption. For example, according to the data of Byfield, Kessler, and Lederman[12] and Tenney and Tinlot,[13] 60 — 70% of the total absorption is contributed by the capture of pions by n, p pairs in the nucleus. Lately two papers[6,10] appeared in which the process of pion absorption was studied for the energy region 80 to 300 Mev; however, contradictory results were obtained for

*The geometry of the experiment is the same for both cases, and the number of inelastic scattering processes is therefore given without corrections for efficiency of observation.

TABLE V

Reaction	Pion energy	Number of protons, $\Delta\theta$ = 0–60°			Number of protons, $\Delta\theta$ = 120–180°		
		Total	With measured energy	$E>100$ Mev	Total	With measured energy	$E>100$ Mev
$\pi^+ + C$	195	365	213	67	96	63	3
$\pi^+ + Li$	195	254	180	48	40	27	5
$\pi^- + C$	230	71	54	17	11	8	5

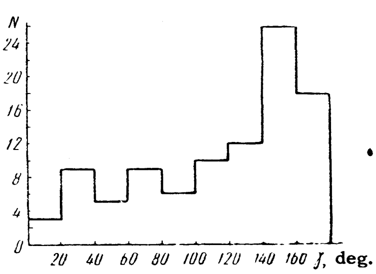

FIG. 8. Distribution of two-pronged stars by emission angle of the protons, for carbon nuclei.

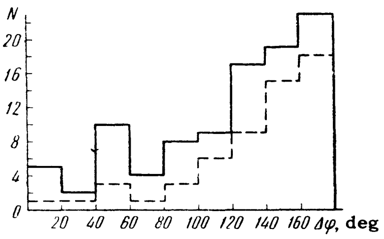

FIG. 9. Distribution of two-pronged stars by the difference of the proton azimuthal angles for carbon nuclei. The distribution for stars with $\gamma > 120°$ is shown dotted.

the mechanism of the capture reaction. In particular, to explain the observed distribution of stars by number of prongs, reference 6 draws on the hypothesis that the nucleus as a whole took part in the capture of 250 – 270 Mev pions in carbon.

In the present experiment 432 stars were detected in carbon and 344 stars in lithium.* As a basis for analysis of these data we determined the relative cross sections for the capture of positive pions by pairs of like and unlike nucleons and also found the relative contribution to the absorption by these particles in the first interaction with the nucleons in the nucleus. Table V shows the numbers of fast protons in the scattering angle interval 0 – 60° and 120 – 180°, including the formerly unpublished data from the experiments with negative pions.

It is evident from this table that a sharp anisotropy is seen in the angular distribution of fast protons, which is hard to explain from the point of view of the many-nucleon mechanism of pion absorption. A direct qualitative estimate of the contribution of pion capture by n, p pairs in the nucleus does not agree either with the supposition of the predominant role of the many-nucleon absorption mechanism.

When a positive pion is captured by a proton and neutron, producing fast protons scattered at an angle close to 180°, the difference of their azimuthal angles is also close to 180°, but the angle of noncoplanarity lies in a relatively narrow angular interval about 0°. In Figs. 8 and 9 are given the distributions of the protons by scattering angle and by the difference in their azimuthal angles for 97 two-pronged stars observed in carbon.* They show that among all the stars there are a considerable number (called by us, from here on, primary) both of whose protons leave the nucleus without experiencing collisions with other nucleons. It can also be seen from the distributions that the contribution of primary stars begins at the angle of emission $\gamma > 120°$ and at the azimuthal difference $\Delta\varphi > 120°$, where the average value of the angle of noncoplanarity is 12°. (A calculation taking account of the intranuclear motion of nucleon pairs gives identical regions of the distribution for the angles indicated.) To determine the true quantity of primary stars in the distribution of Fig. 9, all the stars with $\Delta\varphi \leq 120°$ can be looked at as a background of nonprimary stars which have to be subtracted from the number of two-pronged stars with $\Delta\varphi > 120°$. If the indicated selection rule for primary stars (one of whose prongs is included in the interval 120 – 180°)† is used and the calculated probability of counting primary stars, the correction for stars with prongs below the angle considered, and the contribution to the stars from the pion exchange scattering (equal to 32, 40, and 15%, respectively) are taken into account, we get that 65% of all the carbon stars and 44% of all the lithium ones depend on the absorption of pions by n, p pairs in the nucleus. The value of the cross section obtained for lithium nuclei is probably underestimated, since for them the exchange scattering contribution to the stars may be greater than for carbon nuclei because of the relative abundance of neutrons. Here, however, the possibility is not excluded that some decrease in the cross section for pion absorption by n, p pairs in lithium is connected with the increase of the relative contribu-

*For the analysis here all observed stars are used regardless of their distribution in the exposed region.

*The distribution is analogous for lithium nuclei.

†The emission angle interval 120–180° is excluded from the examination because the true proton spectrum is distorted there by ionization braking in the target.

tion of pion absorption by n, n pairs and by more complicated complexes of nucleons. The observation of one pion capture process by a deuteron and a neutron in lithium serves as an indication of the last situation.

We made an estimate of the contribution to meson absorption by pairs of identical nucleons by comparing the energy spectra of protons in stars formed by positive and negative pions in carbon.* The observed and calculated ratios for the number of fast protons in stars for negative pions and the analogous number for positive pions is given below for the emission angle interval 0 — 60°.

Energy of protons E, Mev	>70	>100	>120	>150
Experimental ratio, %	24	25	22	19
Calculated ratio for 100% absorption by n, p pairs, %	14	12	11	5
Calculated ratio for 70% absorption by n, p pairs and 30% absorption by pairs of identical nucleons, %	29	28	27	26

From this it is evident that pion absorption by pairs of identical nucleons takes place in carbon, but it takes place with a probability 2 — 3 times less than capture by pairs of unlike nucleons. It is obvious that the presence of a many-nucleon absorption mechanism exercises an influence on the size of this estimate especially in the case when the energy realized by the capture of the pion is divided very unevenly between the nucleons. However, if this mechanism were responsible for 30 — 40% of the whole absorption, a group of very fast, isolated protons would appear in the energy spectrum: at the same time, a difference between the energies of the fast particles from one- and two-pronged stars was not observed. Besides, for positive pions in the emission angle interval 120 — 180°, out of 65 protons whose momenta were measured, only two particles with energies greater than 120 Mev were found. Therefore, the contribution of the many-nucleon absorption mechanism is not great and so cannot markedly change the value of the estimate made.

An answer to the question about the relative contribution to the positive pion scattering by the first interaction with nucleons was obtained from the data on the measured total energies of the protons in the primary two-pronged stars. For example, for the carbon nucleus, out of 27 primary stars where the total momenta of both protons were measured, ten stars had a total energy of the protons as an average of 60 Mev less than the total energy of the incident pion. Keeping in mind that the emission of an n, p pair from a carbon nucleus necessarily takes up not less than 30 Mev, these facts must relate to the absorption of a pion in the first interaction. According to the calculation, the relative part of the absorption coming from the first interaction (in which one of the protons falls in the interval 120 — 180°) is 50%; the experimental ratio, 37%, is evidently in agreement with it. The same result is got by comparing the number of energetic protons in stars (by experiment and by calculation) for the interval 0 — 60°, applied to the identical number of stars. For example, the number of protons with energy E > 150 Mev, related for the greatest part to the first interaction, was observed to be 64 in the experiment, while calculated to be 80.

*For negative pions we used the data we got in 1956.

CONCLUSION

1. A comparison of the experimental data obtained with the results of a cascade calculation for the carbon nucleus shows that the inelastic scattering of (195 ± 15) -Mev positive pions from carbon is satisfactorily explained, within the limits of experimental error, by the hypothesis of pair collisions. This is expressed in the following:

a) the calculation gives correctly the general character of the change of the angular distribution of the elastic scattering of pions by free nucleons in the transition to the inelastic scattering of these particles by atomic nuclei;

b) the experimental energy distributions for inelastic scattering and the average values of the energy of inelastically scattered pions is in satisfactory agreement with the corresponding calculated data;

c) the relative cross sections for the primary inelastic scatterings accompanied by fast outgoing recoil protons is equal to the relative cross sections found in the calculations, within the limits of experimental error;

d) the kinematics for the experimentally observed processes of primary inelastic scattering (the angular distribution, and also the distribution by separation angle and difference of azimuthal angles of the scattered mesons and recoil protons) agree with the calculated kinematics for quasi-elastic pion scattering by moving nucleons.

2. A basic mechanism of the absorption of pions at 195 Mev is their capture by n, p pairs of nucleons. For carbon, this mechanism gives a contribution of 60 — 70%.

The contribution to the absorption cross section from meson capture by pairs of identical nucleons is $1/3$ to $1/2$ that from capture by pairs of unlike nucleons.

3. The proportion of captures of incident pions in the first interaction is not less than 35 — 40%

of the whole absorption.

The authors express their thanks to V. P. Dzhelepov for his constant interest in the work and his criticism of the results, to M. S. Kozodaev for his assistance in preparing the work, to A. M. Rozanova, I. M. Rudnevskaya, and P. I. Zhabin for their help in processing the exposures, to Yu. A. Budagov and G. P. Dolya for their help in making the nuclear cascade calculation, and to B. A. Nikol'skiĭ for acquainting us with a nomogram technique for the calculations. The authors also express their profound thanks to V. T. Osipenkov, who gave a great deal of assistance in the first part of the work.

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Translated by W. Ramsay
189