In conclusion, the author expresses his thanks to Prof. A. P. Komar for his continuing interest in this work and for a number of valuable comments.

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ENERGY SPECTRUM AND ANGULAR DISTRIBUTION OF π^+ MESONS PRODUCED ON CARBON BY 660-Mev PROTONS

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The energy spectrum of π^+ mesons produced by 660-Mev protons on carbon was measured at five angles from 19°30′ to 65°. The absolute cross-sections $d\sigma_+/d\Omega$ were also measured. In the c.m.s. of the two colliding nucleons, the mean π^+ meson energy was found to be independent of the angle of emission, and equal to 100 Mev. Conclusions are drawn concerning the angular distribution of π^+ mesons; the total cross-section for their production on carbon by 660-Mev protons has been found to be $(46.7 \pm 5.1) \times 10^{-27}$ cm^2. The probability of π^+-meson production in p—p collisions in the carbon nucleus is half the analogous probability for free p—p collisions.

1. INTRODUCTION

THE production of charged π mesons on carbon by 660-Mev protons was investigated for various angles of observation in several experiments.[1-4] Meshcheriakov et al. measured the relative energy spectrum of π^+ and π^- mesons at 24°.[1] Energy spectra and absolute yields of π^+ mesons[2] and π^- mesons[3] were studied at 45°. Analogous information on mesons of both signs was obtained for 90° as well.

In the present work, we have studied the energy

spectra and the absolute yield of positive π mesons produced by 660-Mev protons on carbon at 19°30′, 29°, 38°, 56°, and 65° in the laboratory system. All measurements were carried out on the external proton beam of the synchrocyclotron of the Joint Institute for Nuclear Research, Laboratory of Nuclear Problems, using a π-meson spectrometer described earlier.[5]

TABLE I

19°30′		29°		38°		56°		65°	
Meson energy, Mev	$\frac{d^2\sigma_+}{d\Omega\, dE}\cdot 10^{28}$, cm² sterad⁻¹ Mev⁻¹	Meson energy, Mev	$\frac{d^2\sigma_+}{d\Omega\, dE}\cdot 10^{28}$, cm² sterad⁻¹ Mev⁻¹	Meson energy, Mev	$\frac{d^2\sigma_+}{d\Omega\, dE}\cdot 10^{28}$, cm² sterad⁻¹ Mev⁻¹	Meson energy, Mev	$\frac{d^2\sigma_+}{d\Omega\, dE}\cdot 10^{28}$, cm² sterad⁻¹ Mev⁻¹	Meson energy, Mev	$\frac{d^2\sigma_+}{d\Omega\, dE}\cdot 10^{28}$, cm² sterad⁻¹ Mev⁻¹
102	2,97±0.38	80	2.45±0.72	80	2.44±0.26	75	2.79±0.24	44	1.68±0.32
129	3.61±0.39	105	2.31±0.55	104	2.58±0.27	88	3.05±0.33	60	2.36±0.19
161	4.21±0.47	135	3.81±0.65	128	3.06±0.27	100	3.16±0.17	87	2.62±0.28
188	4.16±0.39	160	3.78±0.53	152	3.13±0.25	116	2.77±0.18	111	1.81±0.15
225	4.68±0.42	187	4.10±0.54	172	3.17±0.26	130	2.34±0.14	142	1.78±0.13
261	4.04±0.42	212	4.04±0.64	192	2.75±0.33	149	2.19±0.19	161	1.19±0.10
283	4.14±0.41	235	4.70±0.51	212	2.65±0.31	172	1.86±0.23	178	1.14±0.11
300	4.66±0.42	262	4.37±0.49	231	2.42±0.23	192	1.38±0.07	190	0.78±0.10
317	3.15±0.37	283	3.43±0.41	253	2.11±0.20	212	1.05±0.08	206	0.75±0.10
328	2.86±0.45	299	2.51±0.28	269	1.95±0.15	236	0.74±0.14	245	0.43±0.07
341	2.10±0.28	324	1.90±0.39	275	1.70±0.16	251	0.51±0.13	268	0.38±0.07
356	2.31±0.25	—	—	295	1.59±0.18	263	0.55±0.12	—	—
—	—			313	1.11±0.17	278	0.56±0.11		

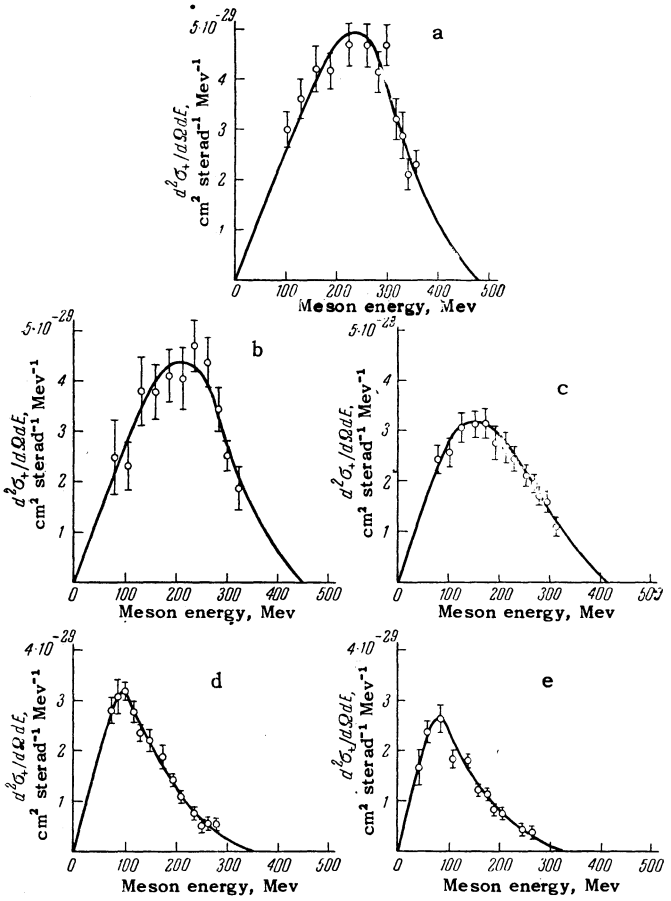

FIG. 1. Energy spectrum of π^+ mesons produced by 660-Mev protons on carbon at a – 19° 30′, b – 29°, c – 38°, d – 56°, and e – 65° in the laboratory frame.

2. RESULTS

The results of measurements of the differential cross-sections $d^2\sigma_+/d\Omega dE$ at various angles of observation are given in Table I. The errors given in the table represent the statistical errors of the measurements. The energy spectra of π^+ mesons based on the date of Table I are shown in Fig. 1. The curves are drawn to obtain best fit with experimental points. Our experimental data are insufficient to determine the shape of the spectrum in the low energy region, in view of the high energy threshold for π mesons detection in the spectrometer. In that region, the curves have been drawn under the assumption that the spectrum is almost linear near the origin of the coordinate system. This was shown experimentally[1] for carbon at 24°, and also in the study of the yield of π mesons with energies up to 40 Mev on emulsion nuclei.[6] It has been assumed that the cut-off in the high-energy region occurs at the π^+ meson energy, calculated from kinematic considerations under the assumption that the energy of nucleons in the nucleus is

TABLE II

Angle of observation, laboratory system	16°30′	29°	38°	45°	56°	65°
$d\sigma_+/d\Omega$ в $cm^2\ sterad^{-1} \times 10^{-27}$	12.34±1.44	10.22±0.78	7.13±0.43	6.77±0.62	4.62±0.28	3.70±0.57
$d\sigma^*_+/d\Omega^*$ в $cm^2\ sterad^{-1} \times 10^{-27}$	3.61±0.42	3.54±0.27	2.90±0.17	3.27±0.30	2.96±0.18	3.01±0.46
Mean energy $\bar{E}^*$ in c.m.s., Mev	101	103	102	103	101	106
Mean angle of emission in c.m.s., $\bar{\nu}^*$	36°	53°	67°	77°	93°	103°

of the order of 25 Mev. Extrapolation of the experimental curves in Fig. 1 into the high-energy region is, at all angles, in satisfactory agreement with the calculated maximum energy of π^+ mesons.

Results of integration of the spectra over the curves, i.e., the cross-sections $d\sigma_+/d\Omega$, are given in Table II. The value of $d\sigma_+/d\Omega$ for 45°, measured earlier,[2] is also given in the table. Both statistical and systematic errors, the latter ranging for the various angles, from 5 to 10% were taken into account in the integration.

It is known from experiments on the production of π mesons by protons and neutrons of various energies, that in collisions between nucleons and complex nuclei π mesons are produced essentially on single nucleons of the nucleus and not on the nucleus as a whole. In connection with the above fact, it is of interest to transform the obtained spectra into the c.m.s. of two colliding nucleons. Results of integration of the spectra in the c.m.s., i.e. the values of the cross-section $d\sigma^*_+/d^*\Omega$, as well as the average π^+-meson energy in the c.m.s. for each spectrum and the mean angle of emission $\bar{\vartheta}^*$, are given in Table II. The values of $\bar{\vartheta}^*$ represent a rough estimate, since the motion of the nucleus was neglected in their calculation.

The dependence of the cross section $d\sigma^*_+/d\Omega^*$ on the angle of emission ϑ^* in the c.m.s., based on the data of Table II, is shown in Fig. 2. The curve is drawn for best fit with the experimental points. Assuming that this experimental curve represents the angular distribution of π^+ mesons in the interval 36 to 103° in the c.m.s., we have calculated the cross-section σ^*_+ for π^+-meson production in that region. We found $\sigma^*_+(36\text{ to }103°) = (20.5 \pm 0.8) \times 10^{-27}\ cm^2$.

3. SHAPE OF THE SPECTRUM AND MEAN POSITIVE π-MESON ENERGY

As the result of transformation of the π^+ meson spectra into the c.m.s., we find that a maximum is attained at $E^* = 100$ Mev for $\bar{\vartheta}^* = 36°$. For $\bar{\vartheta}^* = 93°$ and $\bar{\vartheta}^* = 103°$, the maxima in the c.m.s. are located between 70 and 75 Mev. The maxima of the remaining spectra are contained between 70 and 100 Mev, a shift of the position of the maximum in the c.m.s. towards higher energies being observed for smaller angles, indicating that the shape of the spectrum depends on the angle. A similar variation of the spectrum with the angle was observed earlier for free p — p collisions in the reaction $pp \rightarrow pn\pi^+$.[5,7] It is possible that the effect exists in production of π^+ mesons on bound protons as well.

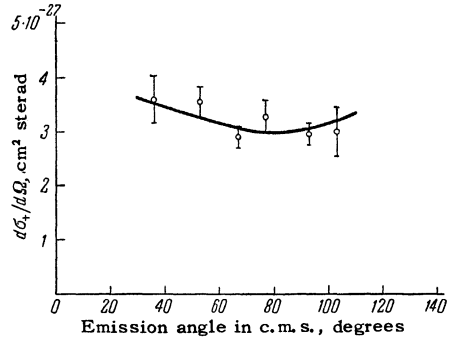

FIG. 2. Dependence of the differential cross section for the production of π^+ mesons on carbon on the angle of emission in the c.m.s.

It follows from Table I that the mean π^+-meson energy $\bar{E}^*$ in the c.m.s. hardly varies with the angle of emission and amounts to 100 Mev. The same value of mean π^+-meson energy has been obtained earlier for Be and C at 24° in the laboratory system.[1] Most remarkable is the fact that the position of the maximum and the value of the mean energy change very little at higher proton energies. This result follows from comparison of the present results and those of other experiments carried out at 660 Mev[1] with the data of Yuan and Lindenbaum,[8] who have found for Be that, at an energy of 1 Bev, the π^+-meson spectrum attains a maximum at 100 Mev for an angle of observation of 32° in c.m.s. A further energy increase to 2.3

Bev causes the maximum to shift only 30 Mev. This weak dependence of π-meson energy on the proton energy can be explained[8] by the predominant role of the isobaric $P_{-3/2\,-3/2}$ state in the π-meson production.

4. ANGULAR DISTRIBUTION OF π^+ MESONS AND CALCULATION OF THE TOTAL CROSS-SECTION

It follows from Fig. 2 that the cross-section $d\sigma^*_+/d\Omega^*$ does not vary greatly with the angle between 36° and 103°. An analogous result has been obtained for neutral π mesons produced on carbon by 660-Mev protons.[9] It follows that the π^0-meson yield in the c.m.s. varies very slowly with the angle in the interval 0° to 100°. A marked increase in the π^0 yield is observed with a further increase in angle. The π^0-meson production cross section for 180° is twice that for 0° in the c.m.s. This increase can be explained by simple qualitative considerations which follow from the optical model of the nucleus and which are connected with the absorption of protons traversing the nucleus. An analogous increase of the cross section for large angles can be observed for charged π mesons.

Prokoshkin[9] calculated the angular distribution of π^0 mesons produced by protons on carbon, using the optical model, and assuming an isotropic angular distribution of π^0 mesons in the c.m.s. in proton-nucleon collisions. The calculated curve is in good agreement with the experimental data. To calculate an analogous curve for π^+ production, it is necessary to know the angular distribution of π^+ mesons in elementary collisions. Experimental data concerning this problem are, at present, inconsistent[7,10] but, most probably, the angular distribution of π^+ mesons in p—p collisions at 660 Mev does not differ appreciably from isotropic.[5] Taking the above into account, one could expect that the angular distribution of π^+ mesons produced by protons on carbon should not differ appreciably from the angular distribution of π^0 mesons.

The similarity between the angular distributions of π^+ and π^0 mesons, expected in view of the above considerations, permits us to find the total cross-section for the production of π^+ mesons on carbon by 660-Mev protons, from the data of the present work. The fraction of the total production cross section of neutral π mesons contributed by the angle interval from 36° to 103° in the c.m.s. can be calculated from experimental data,[9] and amounts to 45%. Assuming that the angular distribution of π^+ mesons is similar to that of π^0 mesons, we obtain from σ_+(36° to 103°) $= 20.5 \times 10^{-27}\,\mathrm{cm}^2$, measured in the present experiment (Sec. 2), a value $\sigma_+ = 45.5 \times 10^{-27}\,\mathrm{cm}^2$ for the total cross-section for the production of π^+ mesons on carbon.

5. PRODUCTION OF π MESONS ON CARBON AND THE PRINCIPLE OF ISOTOPIC INVARIANCE

The cross-section obtained in Sec. 4 can also be estimated from the principle of isotopic invariance. It should be noted that the isotopic spin of C^{12} is zero. The principle of isotopic invariance leads to the following relation for the production of π mesons in collisions between nucleons and nuclei of zero isotopic spin:

$$\sigma_+ + \sigma_- = 2\sigma_0, \tag{1}$$

where σ_+, σ_-, and σ_0 are the total or the differential production cross-sections for π^+, π^-, and π^0 mesons respectively.[11] Equation (1) was tested experimentally for deuterons and carbon, in π meson production by protons, at 45° in the laboratory system.[3]

Data on the cross sections for production of negative and neutral π mesons on carbon are necessary for a comparison of the results of the present work with Eq. (1). The results for π^0 mesons are known for a wide angle interval.[9] The yield of π mesons can be estimated from the ratio $d\sigma_+/d\sigma_-$ for carbon, given by several authors.

The results are collected below:

Observation angle in the lab. system	24°	45°	56°	90°
$d\sigma_+/d\sigma_-$	7.0±0.8[1]	6.8±1.1[3]	5.2±0.6[12]	5.0±0.7[4]

It can be seen that the ratio $d\sigma_+/d\sigma_-$ varies slowly with the angle and that the π^--meson yield is only 15 to 20% of the π^+-meson yield. Both facts make it possible to compare the experimental results with Eq. (1), in spite of insufficient data on π^--meson production.

On the basis of the above data, we shall assume that $\sigma^*_+/\sigma^*_- = 6 \pm 1$ between 37° and 103° in the c.m.s. Then, for the same angle interval, $\sigma^*_+ + \sigma^*_- = (7/6)\,\sigma^*_+ = (24.0 \pm 1.1) \times 10^{-27}\,\mathrm{cm}^2$ (using the value for σ^*_+(36° to 103°) given in Sec. 2). Using the data of reference 9, we obtain, for the same angle interval, $2\sigma^*_0 = (25.5 \pm 2.7) \times 10^{-27}\,\mathrm{cm}^2$. Relation (1) is therefore satisfied, as expected from the principle of isotopic invariance.

In view of the good agreement between the absolute measurements of the present work and the results obtained for π^0 mesons, Eq. (1) can be used to compute the total cross section. Assuming that

for total cross-sections we have $\sigma_- = \frac{1}{6}\sigma_+$, and taking into account that $\sigma_0 = (28 \pm 3) \times 10^{-27}\,\mathrm{cm}^2$,[9] Eq. (1) yields $\sigma_+ = (48.0 \pm 5.3) \times 10^{-27}\,\mathrm{cm}^2$. This result is in a good agreement with the value $\sigma_+ = 45.5 \times 10^{-27}\,\mathrm{cm}^2$ obtained in Sec. 4 from different considerations. From the two results we obtain $\sigma_+ = (46.7 \pm 5.1) \times 10^{-27}\,\mathrm{cm}^2$.

6. COMPARISON OF YIELDS OF π^+ MESONS PRODUCED ON FREE AND BOUND PROTONS

It is useful, for the understanding of processes that take place during the production of π mesons on complex nuclei, to estimate the relative probabilities of π-meson production on free and bound nucleons. We shall make such an estimate for positive π mesons produced on the protons of a carbon nucleus, using the results of the present experiment.

Let us write the total cross section for carbon in the form $\sigma_+ = \sigma^+_{p'} + \sigma^+_{n'}$, where $\sigma^+_{p'}$ and $\sigma^+_{n'}$ are the cross sections corresponding to π^+-meson production on the protons and on the neutrons of the carbon nucleus respectively. We shall note, furthermore, that the principle of charge symmetry requires that, for the production of π mesons on free neutrons, the cross-section for the $pn \to nn\pi^+$ reaction equal that for the $pn \to pp\pi^-$ reaction, i.e., $\sigma^+_n = \sigma^-_n$. We can assume, with an accuracy sufficient for our purposes, that an analogous relation holds for experiments with complex nuclei, i.e., that $\sigma^+_{n'} = \sigma^-_{n'}$. On the other hand, $\sigma^-_{n'}$ is the cross-section for the production of π^- mesons on carbon, i.e., equal to σ_-, since the production of π mesons on nuclei can occur in $p-n$ collisions only. We have, therefore, $\sigma_+ = \sigma^+_{p'} + \sigma^+_{n'} = \sigma^+_{p'} + \sigma^-_{n'} = \sigma^+_{p'} + \sigma_-$. Moreover, it has been shown in Sec. 5 that $\sigma_- \approx \frac{1}{6}\sigma_+$ and, consequently, $\sigma_+ = \sigma^+_{p'} + \frac{1}{6}\sigma_+$. Hence, using the value of σ_+ obtained in the present experiment, and relating the cross-section $\sigma^+_{p'}$ to one proton of the carbon nucleus, we find that the π^+-meson production cross section on a bound proton equals $(6.5 \pm 0.8) \times 10^{-27}\,\mathrm{cm}^2$. The value of the cross section for an analogous process on a free proton is $(13 \text{ to } 14) \times 10^{-27}\,\mathrm{cm}^2$.[5,7,10] We conclude, therefore, that the probability for π^+-meson production in $p-p$ collision in the carbon nucleus at 660 Mev is half the analogous probability for collisions of free protons. It should be noted that a similar halving of the probability has been observed in the production of π^0 mesons on carbon as well. This was found from the values of the cross sections $\sigma(pp \to \pi^0)$, $\sigma(pn \to \pi^0)$, and $\sigma(pC \to \pi^0)$, measured at 660 Mev.[9]

To explain these facts, we shall make use of the theory of Ansel' m and Shekhter,[13] who have shown that the experimental data on the production of π mesons on complex nuclei by protons can be explained by means of a model, according to which the π mesons observed are produced only on the surface of the nucleus (according to a $A^{2/3}$ law), and that deviations are due to the absorption of protons in traversing the nucleus. Let us denote by σ' the total cross section for π-meson production on the nucleus in the absence of absorption, and by σ the actually-observed cross section. We then obtain[13]

$$\frac{\sigma'}{\sigma} = (\eta R)^2 \int_0^\pi \frac{d\sigma_+}{d\Omega}(\vartheta) \sin\vartheta\, d\vartheta \Big/ \int_0^\pi \frac{d\sigma_+}{d\Omega}(\vartheta)\, F(\eta R, \vartheta) \sin\vartheta\, d\vartheta. \tag{2}$$

where $d\sigma_+/d\Omega$ is the π^+-meson production cross section in free nucleonic collisions, η the proton absorption coefficient, R the radius of the nucleus, and F a function calculated in reference 13. The value of η and the dependence of $d\sigma_+/d\Omega$ on ϑ must be known if the computations are to be according to Eq. (2). The absorption coefficient η can be found from the expression

$$\frac{\sigma_a}{\pi R^2} = 1 - \frac{1 - (1 + 2\eta R)\exp\{-2\eta R\}}{2(\eta R)^2}, \tag{3}$$

which follows from the optical model of the nucleus.[14] The cross section σ_a for the inelastic interaction between protons and nuclei can be obtained from experimental data obtained at 650 Mev[15]. The dependence of $d\sigma_+/d\Omega$ on ϑ can be approximated by the expression $a + b\cos^2\vartheta$.[7,10] It is found that the result for σ'/σ depends very little on a and b so that their value is immaterial for the calculation.

Computation carried out according to Eq. (2) showed that $\sigma'/\sigma = 1.8$, which has to be considered as good agreement with the experimental value $\sigma'/\sigma \cong 2$. One can therefore attribute the 50% decrease in the probability for π^+-meson production in $p-p$ collisions in the carbon nucleus, compared with the analogous probability for free $p-p$ collisions, to the absorption of protons in the nuclear matter, assuming that the π^+ mesons observed are produced on the surface of the nucleus.

In conclusion, the authors wish to thank Iu. D. Prokoshkin for the discussion of results.

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ON THE EXISTENCE OF A TANGENTIAL VELOCITY DISCONTINUITY IN THE SUPERFLUID COMPONENT OF HELIUM NEAR A WALL

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The question of the development of a discontinuity in the velocity of the superfluid component of helium II moving relative to a solid wall is investigated experimentally. It has been assumed that the formation of such surface discontinuities requires the application of some minimal force, which is manifested in the form of a threshold shear stress. Apparatus has been constructed which permits the threshold shear stress to be determined with great accuracy. The measurements have shown that tangential discontinuities in the velocity of the superfluid component of helium II do not arise in the vicinity of a wall.

COMPARISON of the results of measurements on the viscosity η_n of the normal component of liquid helium II carried out by means of the oscillating disk method[1,2] on the one hand, and by the method of the uniformly rotating cylinder,[3] on the other, has revealed the existence of a considerable