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SOME FEATURES OF THE PROCESS OF CHARGED π-MESON PRODUCTION ON CARBON BY 670 Mev PROTONS

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The energy spectra of π^+ and π^- mesons from p + C collisions are measured at an angle of 56° to the proton beam, using a magnetic spectrometer designed especially for such types of measurements. The spectra of both π^+ and π^- mesons each had a maximum in the region ~ 110 Mev and could still be measured up to ~ 400 Mev. Smearing out of the spectrum on the high-energy side is thought to result from production of π mesons inside the nucleus on correlated groups of nucleons which have large relative momenta. The differential cross sections for π^+ and π^- production were $(5.1 \pm 0.8) \times 10^{-27}$ and $(1.0 \pm 0.2) \times 10^{-27}$ cm^2/sterad. The angular distributions of π^+ and π^- mesons were nearly isotropic in the c.m. system of the colliding nucleons. The measured ratio of π^+ to π^- yields was not in agreement with that predicted by the simple model in which π mesons are produced only via excitation of the nucleon to a $T = J = 3/2$ intermediate state, and indicates that inelastic collisions in the $T = 0$ state contribute substantially.

1. INTRODUCTION

In a preceding article[1] we described measurements of the energy spectra of π^+ and π^- mesons produced by 660-Mev protons on beryllium and carbon. For both elements the π^+ spectrum, observed at an angle of 24° relative to the proton beam, showed a strong maximum in the region of energies in the center of mass system of the two colliding nucleons (c.m.s.) corresponding to the maximum of the total cross section for the scattering of π mesons by nucleons. This situation can be viewed as an indication that the production of π mesons at this energy in nucleon-nucleon collisions inside the nucleus is mainly determined by the presence of resonance interaction between the π meson and one of the nucleons in a state of angular momentum $J = 3/2$ and isotopic spin $T = 3/2$ ($P_{3/2,3/2}$-state). However, for both elements the measured ratio of π^+ to π^- production turned out to be markedly lower than the ratio calculated under the assumption that the interaction of the nucleon with the nucleus can be reduced to a series of collisions of nucleon pairs, in which the production of π mesons proceeds only via the intermediate $P_{3/2,3/2}$-state.[2]

For a more detailed explanation of the character of the process of π-meson production by protons on complex nuclei, it is essential, first, to make a quantitative estimate of how the form of the energy spectra and π^+ to π^- ratio change with angle. Second, it is necessary to note the influence of the process of π-meson production in collisions of the incident proton with compact groups of strongly-interacting nucleons on the form of the spectra near to the upper energy limits. Such a process appears possible, if one takes account of the fact that collisions of protons with quasi-deuteron groups in the nuclei occur fairly often.[3]

The experiments described in this article were carried out on the six-meter synchrocyclotron of the Joint Institute for Nuclear Research with the

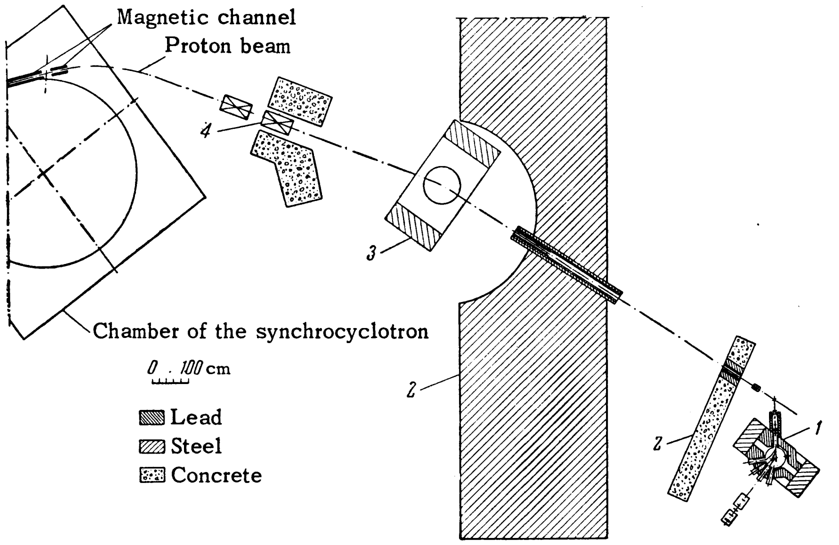

FIG. 1. Placement of the spectrometer (1), shielding wall (2), deflecting magnet (3), and focusing lens (4), shown relative to the synchrocyclotron chamber.

object of clarifying the features indicated above of charged π-meson production on carbon by 670-Mev protons.

2. EXPERIMENTAL SETUP

The energy spectra of π^+ and π^- mesons were measured with a magnetic spectrometer. Its placement relative to the vacuum chamber of the synchrocyclotron and concrete shielding is shown in Fig. 1. The extracted proton beam was focused by two quadrupole lenses, deflected through 12° by a magnet, and then led through a 2-cm diameter steel collimator, placed in a four-meter shielding wall of reinforced concrete, and directed towards the spectrometer. The intensity of the beam was controlled by an ionization chamber (He at a pressure of 0.5 atmos). At the position of the target, the mean proton energy in the beam was 670 ± 5 Mev, and the intensity of the current in the beam (cross section ~ 7 cm²) was ~ 3×10^8 protons/cm³ sec.

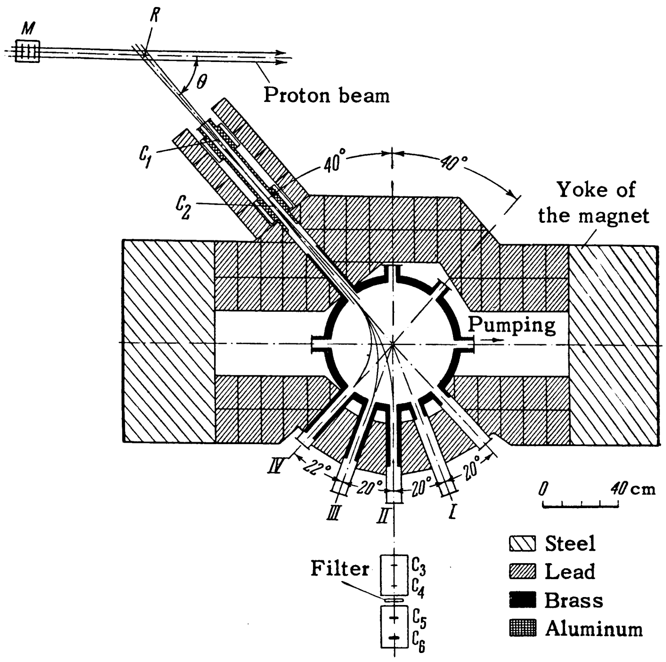

FIG. 2. Diagram of the spectrometer: M – monitor, R – target, C_1 to C_6 – scintillators.

The basic piece of experimental apparatus was an analyzing magnet which weighed 28 tons and had circular pole tips of diameter 60 cm and a gap of 6 cm. The maximum magnetic field was 20,000 oersteds. The field strength H in the gap was measured to an accuracy of 0.2% by nuclear absorption. An electronic stabilizer held the given magnetic field strength constant within 0.2%. The supply to the magnet was such that the field through the coils could be reversed, making it possible to analyze particles of either polarity. A vacuum chamber of diameter 60 cm was mounted between the poles of the magnet. In the brass rim of this chamber were ten radial openings with soldered brass tubes. The ends of the tubes were covered with copper foil 40 μ thick.

Using channels I, II, III, and IV of the spectrometer, shown in Fig. 2, π mesons with energies up to 500 Mev could be analyzed. As the charged particles pass through the channels II, III, and IV, they are focused in the horizontal plane by the homogeneous magnetic field of the spectrometer. In the experiments described, the distance from the center of the target to the edge of the poles was 144 cm. The calculated distances from the edge of the poles to the focal surface for channels II, III and IV are given in Table I, together with other spectrometer characteristics. In calculating the parameters of the spectrometer, the drop off of the field at the edge and the stray field in the gap of the magnet were taken into account. Values for

TABLE I

Channel	I	II	III	IV
Angle of deflection	20°	40°	60°	82°
Radius of curvature ρ of the mean trajectory in cm	200	97	61	42
Distance from the edge of the pole to the focal surface in cm		926	82	19

the radii of curvature of the mean trajectories were found by measurements with a thin current-carrying wire and also by calibration measurements of the position of the peaks corresponding to protons from elastic p-p scattering and π^+ mesons from the reaction $p + p \rightarrow d + \pi^+$.

The entrance telescope, consisting of the two scintillation counters C_1 and C_2 connected for two-fold coincidence, selected π mesons from the beam produced in the target. The scintillators of the counters C_1 and C_2 were placed in a branch tube connected to the chamber of the spectrometer. Particles going through the spectrometer were registered by an exit telescope composed of four scintillation counters C_3, C_4, C_5 and C_6, connected pairwise (C_3C_4, C_5C_6) for two-fold coincidence. Pulses from the two-fold coincidences were, in turn, included in a secondary two-fold coincidence circuit. In the experiments, two-fold coincidences in the entrance telescope, four-fold coincidences in the exit telescope, and six-fold coincidences in the pulses from all counters could be registered. The background of random coincidences was measured by introducing a delay line, to shift the coincidence pulse from counters C_5C_6. Standard electronic circuitry was employed for amplification, discrimination, and for the coincidence circuits. The resolving times of the coincidence schemes are given in Table II, along with the widths and heights of the scintillators, ground tolan crystals about 2.5 mm thick. The scintillators defined the dimensions of the beam traversing the spectrometer so that particles in the path did not touch the walls of the apparatus at any point. This excluded any possibility of distortion of the form of the spectrum because of scattering or slowing down of the particles. The scintillators were joined to photomultipliers of type FEU-19M. To collect the light more effectively, the scintillators were surrounded by reflectors made of aluminum foil. The photoelectric multiplier was shielded from scattered magnetic fields by multi-layer screens of soft iron. Before the measurements were begun, it was established that the counting equipment worked on a plateau of ~ 100 v with respect to the voltage of the photoelectric multipliers. The scintillation-counting efficiency was close to 100% in the entire range of π-meson energies studied.

In view of the high intensity of the beam in the experimental area, it was necessary to surround the entrance telescope and chamber of the spectrometer by a thick lead shield, as shown in Fig. 2. To shield the counting apparatus from the protons scattered off the end of the collimator which defined the beam, a supplementary reinforced-concrete wall, which was one meter thick and had an opening of diameter 5 cm through which the focused beam from the target passed was placed in front of the spectrometer.

Depending on the purpose of the experiment, the exit telescope was placed in one of the guiding grooves cut, coaxial with channels I to IV, in a duraluminum plate securely attached to the magnet. The analyzing magnet, together with the vacuum chamber, shielding and the equipment on which the target was fastened, could be rotated on a platform which, in turn, could be moved along a rail perpendicular to the proton beam. In this way the angle of observation of the secondary particles could be varied between 15 and 175° relative to the primary beam.

The system described here, comprising two telescopes and an analyzing magnet between them, was especially well suited for the counting of particles in a narrow range of momenta. Under the conditions of the present experiment, such particles were secondary protons, π mesons, μ mesons, and electrons. The relative content of these particles in the beam with given momentum was determined by range measurements in copper, for which copper filters were introduced just in front of the scintillator C_5.

TABLE II

Counter	Dimensions of the scintillator, cm	Resolution time of the coincidence circuit, sec		
C_1	1.3×3.1	$3\cdot10^{-8}$		$7\cdot10^{-8}$
C_2	1.2×3.1			
C_3	3.6×3.6	$3\cdot10^{-8}$	$5\cdot10^{-8}$	
C_4	2.0×4.0			
C_5	6.0×6.0	$3\cdot10^{-8}$		
C_6	6.0×6.0			

3. EXPERIMENTAL PROCEDURE AND ANALYSIS OF RESULTS

In these experiments the energy spectra of positive and negative mesons from $p + C$ collisions were observed at an angle of 56° relative to the initial beam; this corresponded to emission of π

TABLE III

Energy of the mesons, Mev	$\frac{d^2\sigma^+}{d\omega dE}$, 10^{-29} $\frac{\text{cm}^2}{\text{sterad Mev}}$	$\frac{d^2\sigma^-}{d\omega dE}$, 10^{-29} $\frac{\text{cm}^2}{\text{sterad Mev}}$	$\left(\frac{d^2\sigma^+}{d\omega dE}\right)/\left(\frac{d^2\sigma^-}{d\omega dE}\right)$
30	1.08±0.10	0.23±0.02	4.72±0.64
47	1.66±0.09		
68	2.28±0.13	0.54±0.03	4.22±0.34
85	2.92±0.13		
109	3.08±0.08	0.59±0.02	5.23±0.27
130	2.96±0.07		
154	2.66±0.05	0.51±0.02	5.18±0.27
186	2.12±0.06		
203	1.56±0.06	0.27±0.02	5.86±0.51
226	1.06±0.05		
250	0.58±0.06	0.09±0.01	6.44±0.87
247	0.33±0.05		
300	0.18±0.02	0.022±0.006	8.13±2.43
324	0.080±0.016	0.009±0.004	8.64±4.35
348	0.068±0.009	0.003±0.004	
370	0.052±0.031	0.012±0.005	
394	0.008±0.014		

mesons at approximately 90° in the c.m.s. of the colliding nucleons. The main part of the measurements were carried out with a graphite target of height 3 cm, width 2 cm, and thickness 1.53 g/cm^2. The target impurities did not exceed 0.01% by weight. The target was so placed that the normal to its surface coincided with the axis of the telescope C_1C_2. The energy of the incident protons in the center of the target was 669 Mev. The angular divergence of the analyzed beam constituted $\sim \pm 1°$ in the horizontal plane. The exit telescope was so placed at the end of channel II that the distance from the edge of the pole to the scintillator C_4, which acted as an exit slit, was 75 cm. Under these conditions, the momentum interval selected by the scintillators of the spectrometer was constant over the whole range of momenta studied, and comprised $\Delta p \approx 0.05\,p$.

The experiments reduced to measurements, as a function of the magnetic field, of the following quantities: (a) the rate of counting of the six-fold coincidences between pulses from counters $C_1 - C_6$ with the target in the beam and without it; (b) the rate of counting of six-fold random coincidences with the target in the beam and with a delay line to shift the coincident pulse from the pair of counters C_5C_6 by 3.2×10^{-7} sec. When the range of secondary protons present in the analyzed beam became equal to the thickness of the first five scintillators, a copper filter was placed between scintillators C_5 and C_6. Its thickness was sufficient to stop secondary protons. The measurements were carried out so that the momentum intervals corresponding to the various thicknesses of filters employed overlapped; this made it possible to estimate directly the magnitude of correction needed to account for absorption of π mesons in the filter. In addition, this correction was also calculated from known data on the nuclear-interaction cross sections of π^+ and π^- mesons. In this way, corrections were introduced for absorption of π mesons in the target and in the scintillators, and also for the change in energy loss with changing energy of the π mesons. The loss of π mesons in the beam by multiple scattering in the target and in the first scintillators was found to have a negligible effect on the spread of the energy interval studied, and, therefore, no corresponding correction was introduced.

In calculating the correction for the decay of the π mesons in flight, their mean life time was taken to be $(2.55 \pm 0.11) \times 10^{-8}$ sec. Corrections for the presence of μ-mesons and electrons in the analyzed beam of π mesons of both signs were found, as already noted at the end of Sec. 2, by painstaking measurements of the range curves in copper at various energies. To minimize the possible effect of vertical defocusing in the scattered magnetic field, the analyzed beam was made of relatively small height in these experiments and the particles were made to enter and leave at right angles to the edge of the field. Comparison of the counting rate for π mesons at various field strengths and for a different height of analyzed beam showed that the distortion of the form of the spectrum due to the variation of vertical defocusing with field strength was within the limits of the statistical errors of the measurements.

Introduction of the corrections listed above into the number of registered six-fold coincidences per monitor count gave the relative yield $Q(p)$ of π mesons emitted with momentum in the interval $p - \frac{1}{2}\Delta p$ to $p + \frac{1}{2}\Delta p$. The differential cross section per unit momentum of the meson, $d^2\sigma/d\omega\, dp$, was connected with $Q(p)$ by the usual relation

$$d^2\sigma / d\omega dp = Q(p) / nN\Delta\omega\Delta p \sim Q(p) / nN\Delta\omega H\rho,$$

where n is the number of carbon nuclei per cm^2

of target surface, N is the current of primary protons incident on the target per unit monitor count, and $\Delta\omega$ is the solid angle subtended by the scintillators at the center of the target.

The transformation from momentum distribution to energy distribution was carried out by the formula

$$d^2\sigma / d\omega\, dp = v d^2\sigma / d\omega\, dE,$$

where v is the velocity of the π meson.

In view of the impossibility of defining accurately the quantity $\Delta\omega$, the absolute values of $d^2\sigma/d\omega\, dE$ were evaluated by normalizing the area under the π-meson spectrum, using the differential cross section for elastic p-p scattering. This operation reduced to comparing the areas lying under the π-meson spectrum and under the proton peak in p-p scattering, measured by the polyethylene-carbon difference method under the same conditions as the π-meson spectrum. The π-meson curves giving $d^2\sigma/d\omega\, dp$ as a function of p were extrapolated linearly from the lowest experimental point to the origin of coordinates. The differential cross section for elastic p-p scattering for 670 Mev and 56° (60° in the c.m.s. of the colliding protons) was taken to be the same as for 657 Mev, i.e., equal to $(6.70 \pm 0.26) \times 10^{-27}\, cm^2/sterad$ $[(3.41 \pm 0.13) \times 10^{-27}\, cm^2/sterad$ in the c.m.s.].[4]

4. RESULTS OF THE EXPERIMENTS AND DISCUSSION

The values of $d^2\sigma^+/d\omega\, dE$ and $d^2\sigma^-/d\omega\, dE$, in the laboratory system, are given in Table III together with the statistical errors of measurements. The spectra of the π^+ and π^- mesons, constructed from the data in Table III, are shown in Fig. 3. There the upper parts of both spectra are shown separately, with the ordinate enlarged ten-fold compared with the remaining parts of the spectra. It can be seen that the spectra of π mesons of both signs have maxima in the region ~ 110 Mev. The mean energy of the π^+ mesons is ~ 136 Mev, that of the π^- mesons ~ 126 Mev. If, neglecting the motion of the nucleons inside the nucleus, we transform the spectra to the c.m.s. under the assumption that π mesons are produced by collision of the protons with individual nucleons inside the nucleus, then it turns out that in this system: (a) the mean energy of the π^+ mesons is 108 Mev, and thus does not differ appreciably from the value found previously at 24° ($\sim 45°$ in the c.m.s.); (b) the mean energy of the π^- mesons is 102 Mev, which is ~ 17 Mev larger than the value found at $\sim 45°$; (c) the energy interval from 30 to 200 Mev, which includes

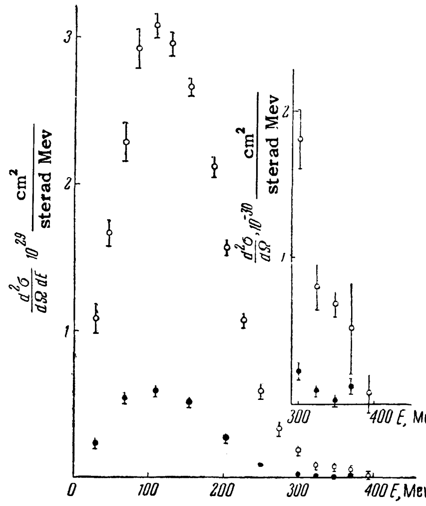

FIG. 3. Energy spectra of π^+ and π^- mesons from p + C collisions at an angle of 56° to the beam of 670- Mev protons. ○ – π^+ mesons, ● – π^- mesons.

about 90% of the π mesons, corresponds in the c.m.s. to emission angles between 110 and 88°. In this angular interval, the yields of π^+ and π^- mesons from the reactions $pn \rightarrow \pi^+ + 2n$ and $pn \rightarrow \pi^- + 2p$ should be roughly the same, because of charge invariance. From the values obtained for the mean energies of π^+ and π^- mesons, it follows that in a single act of production of a π meson, emitted at an angle of 56° to the beam, about 80% of the available energy is used up on the average.

Putting these data together with results of analogous measurements of Yuan and Lindenbaum,[5] it is seen that upon increasing the energy of the incident protons from 670 to 1000 and 2300 Mev (in the last case paired production of π mesons is dominant), the maximum of the π^+-meson spectrum is hardly shifted in the direction of higher energies. Over the whole region of energies and angles studied, the position of the maximum in the π^+ spectra closely corresponds to the resonance energy of the $P_{3/2,3/2}$-state. This is convincing proof that the interaction of the π meson with the nucleon in the $T = J = 3/2$ state plays the essential role in the production of a large part of the π^+ mesons in nucleon-nucleon collisions.

A characteristic feature of the observed π^+ and π^- spectra is the presence of a long 'tail' on the high energy side. It can be seen from Fig. 3 that the spectra of π mesons of both signs persist almost up to 400 Mev. It can not be excluded that the spectra stretch even further, right up to the maximum possible energy (470 Mev) corresponding to the reaction $p + C^{12} \rightarrow \pi^+ + C^{13}$. However, observations at such high energies would require the expenditure of a great deal of time, since even at 390 Mev the number of random coincidences comprises about 90% of the number of six-fold coincidences. Judging from the fact that at energies above the maximum possible, the number of six-fold coincidences was equal to the number of random coincidences, within the limits of statistical error, it should be considered that the excess in the number of six-fold coincidences over the background of random coincidences (observed with the carbon target in the region of energies above 320 Mev) really indicates the presence of π mesons of high energy. This is also supported by the fact that in analogous measurements of the π^+-spectrum due to p-p collisions in a liquid hydrogen target, no increase in the number of six-fold coincidences over the background of random coincidences was observed to the right of the peak corresponding to the π^+ mesons from the reaction $p + p \rightarrow d + \pi^+$.

In order for a π meson to be emitted, in a proton-proton collision, with energy 400 Mev at an angle of 56° to the beam of 669-Mev protons, the nucleon in the nucleus must move towards the incident proton with a momentum of at least* ~ 350 Mev/c, which exceeds by more than ~ 100 Mev/c the upper limit of the momentum corresponding to a degenerate Fermi gas of noninteracting nucleons. The separate nucleons in the nucleus possess high momenta because of the presence of strong, short-acting interactions between pairs of nucleons which lead to the appearance of compact two-nucleon groups[6,7] that last for only a short time. Observation of deuterons knocked out of light nuclei by 675-Mev protons[3] shows that the incoming protons sometimes undergo elastic collisions with such compact two-nucleon groups inside the nucleus. The substantial smearing out of the π-meson spectra on the high energy side means that collisions inside the nucleus between the incident protons and groups of nucleons having large relative momenta sometimes also gives rise to π meson production. Since this observation comes only from the high-energy parts of the spectra, of the π-mesons produced on compact groups of nucleons, it is hard to estimate quantitatively the contribution of this process to the total yield of the π mesons. However, it is clear that the dominant process is that of production of π mesons in the collision of the incident protons with individual nucleons. It should be noted that, owing to the Pauli principle, emission of π mesons with energies close to the maximum possible should be strongly suppressed in collisions of nucleons with compact groups of nucleons. In the case of production of π mesons by protons on two-nucleon groups, the Pauli principle should have a greater effect in processes such as $p + pp \rightarrow \pi^0 + 3p$, $p + np \rightarrow \pi^- + 3p$, $p + nn \rightarrow \pi^+ + 3n$ than in processes of the type $p + pp \rightarrow \pi^+ + n + 2p$, $p + pp \rightarrow \pi^+ + p + 2n$, etc.

Integration of $d^2\sigma/d\omega\, dE$ over the energy yields the following values for the differential cross sections for the production of π mesons at angle of 56° to the proton beam in p + C collisions:

$$d\sigma^+/d\omega = (5.1 \pm 0.8)\cdot 10^{-27}\ \text{cm}^2/\text{sterad};$$
$$d\sigma^-/d\omega = (1.0 \pm 0.2)\cdot 10^{-27}\ \text{cm}^2/\text{sterad}.$$

The indicated errors include both the statistical errors and all uncertainties arising in determining the absolute value of $d^2\sigma/d\omega\, dE$. Corresponding values of $d\sigma/d\omega$ for π^+ and π^- mesons in the c.m.s. are $(3.3 \pm 0.7) \times 10^{-27}$ and $(0.65 \pm 0.12) \times 10^{-27}$ cm^2/sterad. From this, the differential cross section for production of π^+ mesons on one proton in the carbon atom turns out to be $\sim 0.5 \times 10^{-27}$ cm^2/sterad, whereas the differential cross section for production of π^+ mesons under the same conditions in free p-p collisions is $(0.65 \pm 0.10) \times 10^{-27}$ cm^2/sterad.

Together with measuring the spectra at 56°, we also determined the absolute values of $d^2\sigma/d\omega\, dE$ for the π-meson spectra measured earlier[1,8] at 24°. These were emitted in the bombardment of hydrogen, beryllium, and carbon by protons of roughly the same energy. It was found that at $\sim 45°$ in the c.m.s., the differential cross sections for production of π^+ and π^- mesons on carbon were $(3.6 \pm 1.0) \times 10^{-27}$ and $(0.52 \pm 0.13) \times 10^{-27}$ cm^2/sterad respectively. In this case the differential cross section for production of π^+ mesons on a single proton in the carbon nucleus has again a value $\sim 0.5 \times 10^{-27}$ cm^2/sterad, whereas in free p-p collisions this is $\sim 1.4 \times 10^{-27}$ cm^2.

Thus, from the results of absolute measurements of yields of charged π mesons from p + C collisions at 24° and 56° to the proton beam, one can assert the following: (1) The differential cross section for production of π^+ and π^- mesons does not depend strongly on the angle in the c.m.s. (2) When the angle is reduced from $\sim 90°$ to $\sim 45°$, the ratio of differential cross sections for production of π^+ mesons in p-p collisions inside the carbon

*This value of the minimum momentum of a nucleon in the nucleus was obtained by considering the $p + p \rightarrow d + \pi^+$ reaction under the assumption that, in all, 30 Mev went into tearing the nucleon away, exciting the final nucleus, and into the recoil. For this, the Fermi energy of the nucleon $E \approx 24$ Mev corresponds to a maximum π-meson energy of ~ 310 Mev.

nucleus to that in collisions of free protons drops from ~ 0.8 to ~ 0.3. This is caused both by the reabsorption of π mesons in the initial nuclei, the influence of which increases with decreasing angle, and by the difference in the angular distributions of the π mesons produced by protons on free protons and on those bound in a nucleus. In the former case, according to Neganov and Savchenko,[9] the angular distribution of π^+ mesons in the reaction $p + p \rightarrow \pi^+ + n + p$ has the form $0.66 + \cos^2 \vartheta$. Under the assumption that the emission of charged π mesons in $p + C$ collisions is isotropic over the entire range of angles, the total cross sections for production of π^+ and π^- mesons would be estimated to be $\sim 44 \times 10^{-27}\,\text{cm}^2$ and $\sim 7 \times 10^{-27}\,\text{cm}^2$, respectively. From this, on account of charge independence, one has the relation $\sigma^+ + \sigma^- = 2\sigma^0$ between the cross sections for the production of positive, negative, and neutral π mesons on nuclei with isotopic spin zero. For $p + C$ collisions at 670 Mev, this gives $\sigma^0 \approx 25 \times 10^{-27}\,\text{cm}^2$, which agrees well with the value $(28 \pm 3) \times 10^{-27}\,\text{cm}^2$ obtained at roughly the same energy by observing γ-rays from the decay of π^0 mesons.[10]

As can be seen from Table III, the values of the ratio $(d^2\sigma^+/d\omega\,dE)/(d^2\sigma^-/d\omega\,dE)$ increase slowly with energy, namely, from ~ 4.7 for 30 Mev to ~ 8 for 300 Mev. This result differs markedly from that obtained at 24°, where the same ratio grew from ~ 1 to ~ 15 over the energy interval 30 to 300 Mev. For 56°, the ratio of integrated yields $(d\sigma^+/d\omega)/(d\sigma^-/d\omega)$ was 5.2 ± 0.7. Approximately the same value should be obtained for the ratio σ^+/σ^- of the total cross sections for the production of π^+ and π^- mesons in hydrogen, if the conclusion about the weak dependence of $d\sigma^+/d\omega$ and $d\sigma^-/d\omega$ on angle is correct. In fact, at 24° the ratio $(d\sigma^+/d\omega)/(d\sigma^-/d\omega)$ constitutes 7.0 ± 0.8.

If it is assumed that single production of π mesons in nucleon-nucleon collisions proceeds only through the excitation of one of the colliding nucleons into an intermediate resonant $P_{3/2,3/2}$-state, then, according to the calculation of Peaslee,[2] the ratio σ^+/σ^- should be 11 in the case of protons bombarding a nucleus containing equal numbers of protons and neutrons. The sharp disagreement between this number and experiment means, first, that in collisions of protons with bound nucleons nonresonant production of π mesons in the p-n system in the state $T = 0$ proceeds together with resonant production of π mesons in p-p and p-n systems with states of $T = 1$. In order to satisfy the observed value of the ratio $(d\sigma^+/d\omega)/(d\sigma^-/d\omega)$, it is necessary to assume that production of π^- mesons in the p-n system proceeds equally in states with $T = 1$ and $T = 0$.* Peaslee's disregard of the interference between different states of the two-nucleon system, which participate in the process of production of π mesons, could evidently also lead to an erroneous value of σ^+/σ^-. This argument was recently used by Mandelstam[12] to explain the marked difference between the theoretical and experimental values of the ratio σ^+/σ^0 for p-p collisions at 660 Mev. Finally, it should also be considered that the production of π^+ mesons inside the nucleus could be partly suppressed as a result of de-excitation of the $P_{3/2,3/2}$-state without emission of a π meson in collision of the excited nucleon with one of the neighboring nucleons.[13,14]

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*In connection with this, it should be noted that in the data of Kazarinov and Simonov,[11] the total cross section for inelastic scattering at 590 Mev, in the $T = 0$ state of the two-nucleon system, is $(9.3 \pm 3.7) \times 10^{-27}\,\text{cm}^2$.