Pion Production in Zero Isotopic Spin Nuclei

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The energy spectra and differential cross section for the production of π^+ and π^- mesons in deuterium and of π^- mesons in carbon by 600-Mev protons were measured at 45°. Comparison of the data on the production of charged and neutral pions confirms the correctness for deuterium and carbon of the relation $d\sigma^+ + d\sigma^- = 2d\sigma^0$ which follows from the hypothesis of isotopic invariance for zero isotopic spin nuclei.

1. INTRODUCTION

THE HYPOTHESIS OF isotopic invariance leads to a number of relations among the cross sections of various interactions between nucleons and pions, nucleons, or nuclei. The experimental testing of these relations can provide valuable information concerning the accuracy with which this hypothesis is satisfied.

For pion production in nucleon-nucleon collisions the following relations exist among the total cross sections:[1-3]

$$\sigma(pn \to nn\pi^+) = \sigma(pn \to pp\pi^-), \tag{1}$$

$$\sigma(pp \to d\pi^+) = 2\sigma(pn \to d\pi^0), \tag{2}$$

$$\sigma(pp \to pn\pi^+) + 2\sigma(pn \to nn\pi^+) = 2[\sigma(pp \to pp\pi^0) + \sigma(pn \to pn\pi^0)]. \tag{3}$$

Relations (1) and (2) have been verified experimentally with 400-Mev nucleons.[4,5] Relation (1) has also been confirmed with neutrons at about 600 Mev (Ref. 6).

When pions are produced in collisions between nucleons and zero isotopic spin nuclei (H^2, He^4, C^{12}, N^{14}, *etc.*) we have the relation

$$\sigma^+ + \sigma^- = 2\sigma^0, \tag{4}$$

where σ^+, σ^- and σ^0 are the total or differential cross sections for π^+, π^- and π^0 production. This relation has thus far not been checked experimentally.

Prokoshkin and Tiapkin[7] recently measured the cross section for neutral pion production by 660-Mev protons on a few nuclei including deuterium and carbon. It thus became possible to check (4) for two isotopic spin zero nuclei by measuring the cross sections for π^+ and π^- production on these nuclei by 660-Mev protons. We have previously[8] obtained the π^+ production cross section in carbon at 45° by protons with this energy. In the present work we have measured the energy spectra and differential cross sections of the production of π^+ and π^- mesons in deuterium and of π mesons in carbon at the same angle. In this way the results of Prokoshkin and Tiapkin have been supplemented to provide the necessary information for the comparison of relation (4) with experiment.

2. EXPERIMENTAL METHOD

We worked with an external proton beam from the synchrocyclotron of the Joint Institute for Nuclear Research. The experimental method and a description of the apparatus are contained in our earlier papers.[8,9]

Pion production in deuterium was determined by the difference of counts from LiD and Li targets. Both targets were solid plates 1 cm thick. The carbon target was of special construction.[8]

It was shown[9] that the electron background in our apparatus could not exceed 2 to 3% of the total π^+ count. Since the π^- yield is considerably smaller than the π^+ yield it was necessary in the present work to estimate the electron background more accurately than previously.

The relative number of electrons was determined in two ways. In the first method, as previously, the number of registered electrons was taken to be the difference between counts from the paraffin and carbon targets when the direction of the magnetic field was such that negative particles were recorded. The electron count obtained in this manner clearly represented π^0 production in hydrogen nuclei in the paraffin target. To determine the electron background for a carbon target the count was multiplied by the ratio of the gamma-ray yields of carbon and hydrogen that was obtained at 33° in the laboratory system, which was close to our angle.[10] We have assumed that this ratio varies very little with energy since from the experiments on π^0 production it follows that the gamma-ray spectra are approximately the same for hydrogen and carbon.[11] The second method was a direct determination of the electron background, for which purpose a lead filter was placed close to the carbon target in the path of the particles before their entrance into the strong magnetic field. In the presence of the filter the counter telescope recorded almost no electrons so that the number of electrons could be determined from the counts with and without the filter.

The electron background was not measured for other targets; it was computed instead through multiplication of the result for the carbon target by the ratio of the gamma-ray yields of a given target and the carbon target. For this purpose we used the relative cross sections of gamma-ray production in different nuclei by 660-Mev protons at 33° in the laboratory system.[10]

For π^- energies beginning at 150 Mev the electron background was found to be insignificant. For example, for a carbon target and 160-Mev π^- mesons the electron background is 5% of the recorded negative particles. At lower π^- energies the electron background increases until it reaches 30% at 80 Mev. The values obtained for the electron background were taken into consideration in calculating the true number of pions produced in the targets.

3. RESULTS

Table 1 shows the π^+ and π^- energy spectra produced by 660-Mev protons on deuterium and carbon at 45°. The ion energies are given together with the corresponding differential cross sections $d^2\sigma^{\pm}/d\Omega dE$ in the laboratory system calculated for a single nucleus. Figures 1 and 2 are the spectra of π^+ and π^- production plotted from the data in Table 1.

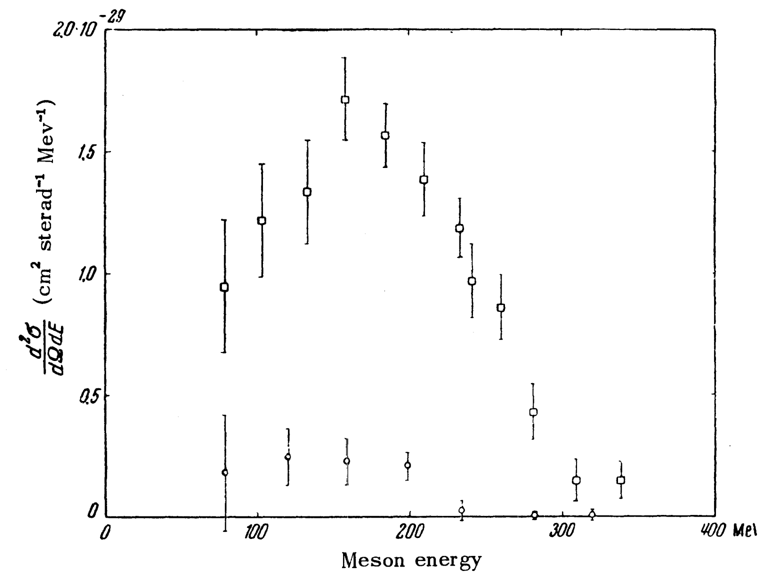

FIG. 1. Meson spectrum from deuterium: □—π^+ mesons; ○—π^- mesons

The results of integrating the spectra, that is, the differential cross sections $d\sigma^+/d\Omega$ and $d\sigma^-/d\Omega$ for π^+ and π^- production are given in Table 2. The result for π^+ mesons from carbon was taken from an earlier paper.[8] The table contains the calculated ratios $d\sigma^+/d\sigma^-$ of π^+ and π^- yields. The ratios obtained for the π^+ and π^- yields from deuterium and carbon are in good agreement with the results of other investigators who measured the relative π^+ and π^- yields at the same porton energy and at similar angles. At 24° Mescheriakov *et al.*[12] obtained $d\sigma_C^+/d\sigma_C^- = 7 \pm 0.8$ for carbon. At 90° Sidorov obtained $d\sigma_C^+/d\sigma_C^- = 5 \pm 0.7$ for carbon[6] and $d\sigma_d^+/d\sigma_d^- \approx 8$ for deuterium.[13]

4. DISCUSSION OF RESULTS

For the purpose of testing relation (4) in its differential form

$$d\sigma^+ + d\sigma^- = 2d\sigma^0 \qquad (5)$$

TABLE I.

Meson energy in Mev	$\frac{d^2\sigma^+}{d\Omega dE}\times 10^{29}\frac{cm^2}{\text{sterad-Mev}}$	Meson energy in Mev	$\frac{d^2\sigma^-}{d\Omega dE}\times 10^{30}\frac{cm^2}{\text{sterad-Mev}}$
	Deuterium		Deuterium
79	0.95±0.27	79	1.80±2.36
104	1.22±0.23	120	2.46±1.16
134	1.34±0.21	159	2.26±0.95
159	1.72±0.17	199	2.07±0.59
186	1.57±0.13	234	0.25±0.36
211	1.39±0.15	282	0.04±0.20
234	1.19±0.12	320	0.05±0.15
242	0.97±0.15		
261	0.86±0.13		
282	0.43±0.11		Carbon
310	0.15±0.09		
339	0.15±0.07	79	3.89±1.26
		120	5.79±0.70
		159	5.06±0.50
		199	3.81±0.30
		234	2.58±0.19
		282	1.18±0.10
		320	0.63±0.08

TABLE II.

Element	$d\sigma^+/d\Omega\times 10^{27}\frac{cm^2}{\text{sterad}}$	$d\sigma^-/d\Omega\times 10^{27}\frac{cm^2}{\text{sterad}}$	$d\sigma^+/d\sigma^-$
Deuterium	3.06±0.34	0.38±0.12	8.1±2.7
Carbon	6.77±0.62	1.00±0.13	6.8±1.1

we shall now combine the results obtained at 45° for deuterium and carbon with the data of Prokoshkin and Tiapkin on π^0 production.[7] Their work shows that the π^0 mesons produced by 660-Mev protons on deuterons are isotropically distributed in the center-of-mass system (c.m.s.) of the two colliding particles. Twice the value of the cross section in this system is $2d\sigma_d^0/d\Omega = (1.73 \pm 0.21)\times 10^{-27}$ cm² sterad⁻¹. Our data converted to the same system of coordinates give $d\sigma_d^+/d\Omega + d\sigma_d^-/d\Omega = (1.66 \pm 0.17) \times 10^{-27}$ cm² sterad⁻¹. A similar comparison for carbon in the laboratory system gives $2d\sigma_C^0/d\Omega = (7.20 \pm 0.70)\times 10^{-27}$ cm² sterad⁻¹ and $d\sigma_C^+/d\Omega + d\sigma_C^-/d\Omega = (7.77 \pm 0.63)\times 10^{-27}$ cm² sterad⁻¹. Thus (5) is satisfied within the limits of experimental error for both deuterium and carbon.

At the same time it can be shown that the results of similar experiments[7,8,14] on π production in non-zero isotopic spin nuclei do not satisfy $d\sigma^+ + d\sigma^- = 2d\sigma^0$. Examples are provided by Li^7 and Be^9 with isotopic spin ½ in the ground state. For charged pions we have[8,14] $d\sigma_{Li}^+/d\Omega = (4.24 \pm 0.32)\times 10^{-27}$ cm² sterad⁻¹, $d\sigma_{Li}^-/d\Omega = (0.93 \pm 0.4)\times 10^{-27}$ cm² sterad⁻¹, $d\sigma_{Be}^+/d\Omega = (4.91 \pm 0.45)\times 10^{-27}$ cm² sterad⁻¹ and $d\sigma_{Be}^-/d\Omega = (1.00 \pm 0.15)\times 10^{-27}$ cm² sterad⁻¹. Thus the sum $d\sigma^+/d\Omega + d\sigma^-/d\Omega$ is $(5.17 \pm 0.35)\times 10^{-27}$ cm² sterad⁻¹ for Li and $(5.91 \pm 0.47)\times 10^{-27}$ cm² sterad⁻¹ for Be, whereas[7] $2d\sigma_{Li}^0/d\Omega = (6.6 \pm 0.6)\times 10^{-27}$ cm² sterad⁻¹ and $2d\sigma_{Be}^0/d\Omega = (6.8 \pm 0.6)\times 10^{-27}$ cm² sterad⁻¹. It must be mentioned that results for the cross sections $d\sigma_{Li}^{\pm}/d\Omega$ were obtained with specimens of natural lithium,[8,14] but this fact cannot seriously affect the comparison since there is only a relatively small amount of Li^6 in natural lithium.

The value which we obtained for the ratio $d\sigma^+/d\sigma^-$ in the case of deuterium will now be compared with theoretical result of Lapidus,[15] who evaluated the ratio for the pion energy range in which the pion-nucleon interaction involves predominantly states with isotopic spin 3/2. His result for the ratio of the differential cross sections is $d\sigma_d^+/d\sigma_d^- = 11$. The fact that this value is close to the experimental result $d\sigma_d^+/d\sigma_d^- = 8.1 \pm 2.7$ indicates that in our case during the production of charged pions from $p-d$ collisions most of the final states of the pion-nucleon subsystem actually possess isotopic spin $T_{\pi N} = 3/2$ and a smaller fraction have $T_{\pi N} = 1/2$.

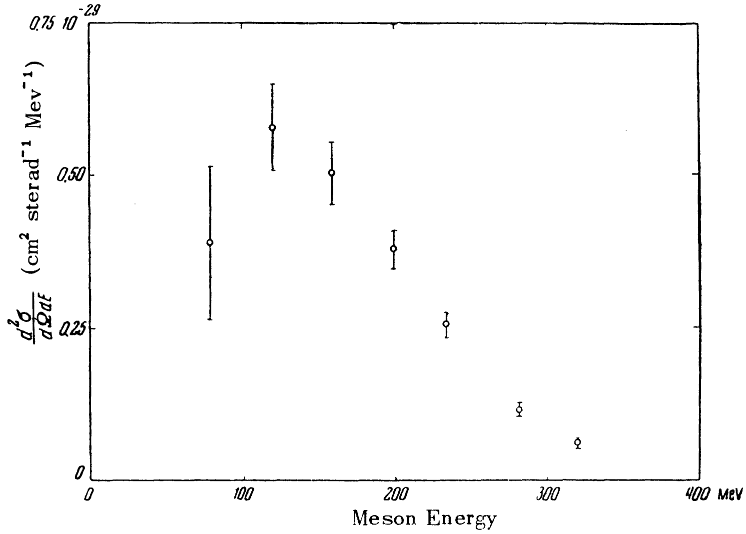

FIG. 2. π^- spectrum from carbon.

In π^+ production from $p-d$ collisions the reaction $pd \to H^3\pi^+$ is possible; this has been investigated with 340-Mev protons.[16] When the angle of ejection of the pions is 45° and the proton energy is 660 Mev the pion energy in the $pd \to H^3\pi^-$ reaction must be 343 Mev. Fig. 1 shows that relatively few π^+ mesons are in the spectral vicinity of 340 Mev. Thus in the total process of π^+ production from $p-d$ collisions at 45° the $pd \to H^3\pi^+$ reaction evidently plays only a small part.

Fig. 1 shows that the spectra of π^+ and π^- production from $p-d$ collisions differ markedly at high energies where the π^- yield falls off much more rapidly than that of the π^- mesons. A possible explanation of this result is the fact that since π^- mesons are produced in $p-d$ collisions through the reaction $pd \to ppp\pi^-$ the presence of three protons in the final state must be forbidden by the Pauli principle at relatively low proton beam energies. In connection with this explanation it is interesting to compare the probabilities of the reactions $pd \to ppp\pi^-$ and $pn \to pp\pi^-$, *i.e.*, the production of π^- mesons on the neutrons of deuterons and on free neutrons. The pion production cross section must clearly be smaller in the first case than in the second if there is partial forbiddenness of the first reaction.

In the energy region with which we are concerned there is no direct experimental information regarding the $pn \to pp\pi^-$ reaction, but the magnitude of $d\sigma(pn \to pp\pi^-)/d\Omega$ can be estimated by utilizing relation (3), which for the differential cross sections becomes[17]

$$d\sigma(pp \to pn\pi^+) + d\sigma(pn \to nn\pi^+) + d\sigma(pn \to pp\pi^-) = 2\left[d\sigma(pp \to pp\pi^0) + d\sigma(pn \to pn\pi^0)\right]. \quad (6)$$

In this relation the cross section of the $pn \to nn\pi^+$ reaction can be expressed in terms of the $pn \to pp\pi^-$ cross section by means of the equality

$$\left.\frac{d\sigma(pn \to nn\pi^+)}{d\Omega}\right|_{\vartheta} = \left.\frac{d\sigma(pn \to pp\pi^-)}{d\Omega}\right|_{180^\circ-\vartheta}, \quad (7)$$

where the angle ϑ is in the c.m.s. Furthermore, since the 45° laboratory angle at which we performed our measurements is close to 90° in the c.m.s. we can quite accurately replace (7) with the equality $d\sigma(pn \to nn\pi^+) = d\sigma(pn \to pp\pi^-)$. Inserting this in (6) and utilizing available data[9,10] concerning the differential cross sections of the reactions $pp \to pp\pi^+$, $pp \to pp\pi^0$ and $pn \to pn\pi^0$ we obtain $d\sigma(pn \to pp\pi^-)/d\Omega = (0.32 \pm 0.10) \times 10^{-27}$ cm² sterad⁻¹, whereas our experimental result in the c.m.s. is $d\sigma_d^-/d\Omega = (0.18 \pm 0.06) \times 10^{-27}$ cm² sterad^{-1}. Thus the probability of π^- production on the neutron of a deuteron is actually smaller than the probability on a free neutron, although the large experimental errors do not at present permit us to obtain a reliable quantitative result.

We now make a similar comparison of π^+ production on deuteron nucleons and on free nucleons. The present work gives the result $d\sigma_d^+/d\Omega = (1.48 \pm 0.16) \times 10^{-27}$ cm² sterad^{-1} in the c.m.s. of the two colliding nucleons. We also have[9]

$d\sigma_d^+/d\Omega = d\sigma(pp \to \pi^+)/d\Omega = (1.06 \pm 0.07) \times 10^{-27}$ cm^2 $sterad^{-1}$ and, as mentioned previously, $d\sigma_n^+/d\Omega = d\sigma(pn \to pp\pi^-)/d\Omega = (0.32 \pm 0.10) \times 10^{-27}$ cm^2 $sterad^{-1}$. Hence $d\sigma_p^+/d\Omega + d\sigma_n^+/d\Omega = (1.38 \pm 0.12) \times 10^{-27}$ cm^2 $sterad^{-1}$, which is very close to the value of $d\sigma_d^+/d\Omega$. Thus π^+ production on deuteron nucleons possesses approximately the same probability as on free nucleons, which differs from the observed results for π^- production. This can be associated with the absen ce among the different $pd \to \pi^+ \ldots$ reactions of a $pd \to ppp\pi^-$ type reaction, which, as mentioned earlier, is partly forbidden.

The difference in shape between the π^+ and π^- spectra at high energies, which we observed in the case of deuterium, may also have a second cause besides the Pauli principle with respect to the $pd \to ppp\pi^-$ reaction. B. L. Ioffe has pointed out to us that π production at relatively high energies must involve the excitation of nucleons with relatively high kinetic energies, *i.e.*, nucleons of the beam, whereas at low π energies the excitation of target nucleons can also be involved. Since in $p-d$ experiments π^- mesons are produced only on target neutrons there must be a reduction of the π^- yield at high energies. This effect should of course be observed for other comples nuclei besides deuterium under proton bombardment. Confirmation is obtained in experiments on carbon which also show a difference of the π^+ and π^- spectra at high energies, as can be seen by comparing the spectrum in Fig. 2 with the π^+ spectrum obtained previously.[8] A similar distinction was detected earlier and subjected to thorough experimental investigation for beryllium and carbon by Meshcheriakov *et al.*[12]

In conclusion we wish to express our deep appreciation to Academician A. I. Alikhanov for his continued interest, and also to Iu. D. Prokoshkin, A. A. Tiapkin and L. L. Lapidus for fruitful discussions and communication of their results before publication.

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