CHARGED PION PRODUCTION BY 660 MEV PROTONS ON BERYLLIUM AND CARBON

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(presented by M. G. Meshcheriakov)

Summary

Energy spectra of positive and negative π mesons (emitted in p+Be and p+C collisions at an angle of 24° to a 660 Mev proton beam) were measured by means of magnetic analysis. Spectra of π^+ mesons have pronounced maxima at an energy near 210 Mev in the laboratory system. The number of π^- mesons changes insignificantly in the range from 60 to 250 Mev.

The probability of π^+ production in collisions of protons with protons bound in Be and C nuclei is found to be three times less than that in free proton-proton interactions.

The maximum in the spectrum of π^+ mesons is near 100 Mev in the c.m.s. The ratio of π^+ and π^- meson yields for Be and C in the whole spectrum range was determined.

The ratios of the total yields of π^+ and π^- mesons for these elements are respectively 5.3 ± 0.6 and $7.0 + 0.8$.

1. *Introduction*

The present report describes the investigation of energy spectra of positive and negative π mesons produced under bombardment of beryllium and carbon by protons, the energy of which was sufficient to make one of the colliding nucleons in a nucleon-nucleon collision pass into an excited state with an angular momentum $^3/_2$ and isotopic spin $^3/_2$ (the $P_{3/2, 3/2}$ state), but not high enough to make the process of double π meson production in single collisions take place to a noticeable degree.

2. *Experimental technique*

In order to investigate the energy distribution of π mesons, a magnetic spectrometer was used. The π mesons emitted at the angle of 24° to the proton beam, after having passed through the spectrometer, were recorded by a telescope of three scintillation counters. Information on the proton beam and magnetic spectrometer is given in [1]. A method of determining μ meson and electron contamination in the π meson beam at the exit of the spectrometer is also given there. The influence of π meson absorption in the target as well as in the crystals and filters was estimated on the basis of information on total cross-sections of nuclear interaction of π mesons [2–5]. The values of the corresponding corrections for beryllium and carbon targets, the thickness of which was chosen so that the energy losses of 660 Mev protons in each of them would amount to 3.7 Mev, ranged from 3% at the lower spectrum boundary to 6.6% at the energy of 200 Mev, and then fell again to 3.5% at the energy of 420 Mev.

In computing the correction for π meson decay in flight, it was assumed that the lifetime of π mesons is $(2.54 \pm 0.11) \times 10^{-8}$ sec.[6,7]

3. π *meson energy spectra*

The π^+ and π^- meson energy distributions obtained both for beryllium and carbon are shown in figs. 1 and 2. The errors given there include both statistical errors of measurements and all that was uncertain in determining corrections for π meson decay in flight and for μ meson and electron contamination. The spectra were normalized in relative units according to the area of the π^+ meson peak in the reaction $pp \to d\pi^+$ [8].

The principal properties of the measured spectra are as follows:

a) The upper limits of the π^+ meson spectra for Be as well as for C are located at noticeably higher energies than those of the π^- meson spectra.

b) For both elements the average π^+ meson energy equals about 215 Mev, and the average π^- meson energy about 180 Mev.

c) Both π^+ meson spectra have pronounced maxima at the energy of about 210 Mev, while the number of π^- mesons in the spectra of both elements varies insignificantly in the energy interval from 60 to 250 Mev.

d) In the π^+ meson spectra there is some disturbance of smooth change in the number of mesons in the region of 140-200 Mev energy, that is in the same range where the

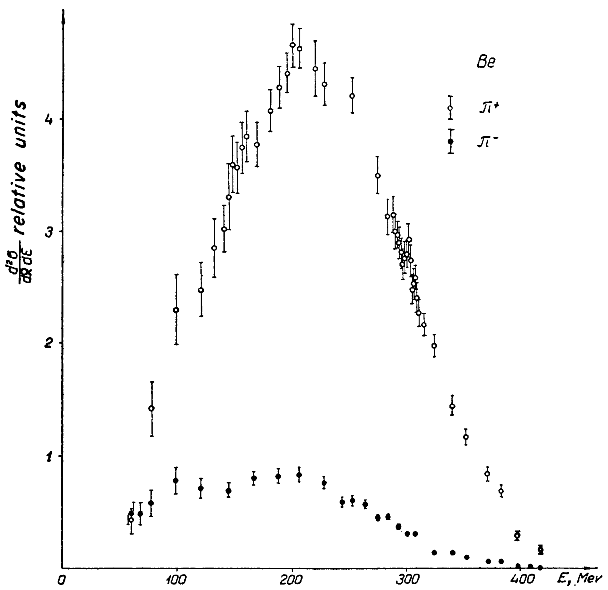

Fig. 1. Energy distribution of $\pi+$ and $\pi-$ mesons from Be at 24° in the l.s.

cross-section of the π^+ meson-proton interaction reaches its maximum. This circumstance leads to the assumption that the cause of this disturbance lies in the interaction of π^+ mesons with nucleons of the initial nuclei.

Special attention was paid to the measurements of π^+ spectra in the interval $250 < E_\pi < 350$ Mev in which a peak was observed corresponding to π^+ mesons originating from the reaction $pp \rightarrow d\pi^+$. If it were possible to find this peak in our experiments also, it could mean that in the Be and C nuclei the protons spend a considerable time on the surface, away from the region of strong interaction with other nucleons. In this case the protons must have a small spread in momentum. As seen in figs. 1 and 2, the obtained results give no indication of the existence of deviations exceeding experimental errors, from a monotonous decrease of the π^+ meson number in the spectra in the whole energy interval.

4. *Comparison of π meson yields with free and bound protons*

By means of integration of spectra over the energy, the values of the π^+ and π^- meson yields at the angle of 24° were determined. The yield for one nucleus of the target is given in Table 1. The total yield of π^+ mesons from the reactions $pp \rightarrow np\pi^+$ and $pp \rightarrow d\pi^+$ on free protons, found under the same conditions, is also given. The π^+ meson yield from a p-p collision is taken as a unit.

TABLE I

Element	y^+	y^-
H	1.0	—
Be	1.4	0.26
C	1.7	0.24

According to the charge independence hypothesis, the total cross sections $\sigma(pn \rightarrow nn\pi^+)$ and $\sigma(np \rightarrow pp\pi^-)$ must be equal, and the π^+ meson yield at the angle θ in the first reaction in the c.m.s. must equal the π^- meson yield at the angle $180° - \theta$ in the second reaction. At an energy near 660 Mev

$$\sigma (pp \rightarrow d\pi^+) = (3.1 \pm 0.2) \times 10^{-27}\ \text{cm}^2\ ^{(8)},$$
$$\sigma (pp \rightarrow np\pi^+) = (10.2 \pm 1.8) \times 10^{-27}\ \text{cm}^2\ ^{(1)},$$
$$\sigma (pp \rightarrow pp\pi^0) = (3.4 \pm 0.4) \times 10^{-27}\ \text{cm}^2\ ^{(9)},$$
$$\sigma (pn \rightarrow pn\pi^0) = (7.8 \pm 1.6) \times 10^{-27}\ \text{cm}^2\ ^{(10)}.$$

From the relation

$$\tfrac{1}{2} [\sigma (pp \rightarrow d\pi^+) + \sigma (pp \rightarrow np\pi^+)] = \\ = \sigma (pp \rightarrow pp\pi^0) + \sigma (pn \rightarrow pn\pi^0) - \sigma (pn \rightarrow nn\pi^+),$$

it follows that

$$\sigma (pn \rightarrow nn\pi^+) = \sigma (np \rightarrow pp\pi^-) = (4.6 \pm 1.8) \times 10^{-27}\ \text{cm}^2.$$

Having in mind the values of these cross sections, we may make the approximate assumption, that in the energy range under consideration, the π^+ meson production inside the nuclei takes place mostly in p-p collisions.

If we now refer the values Y^+ for Be and C to one proton in the target nucleus, it will appear that the probability for π^+ meson production in p-p collisions inside the nucleus is approximately 3 times less than that for free protons.

Such a considerable decrease of the probability of meson production on bound protons is caused to some degree

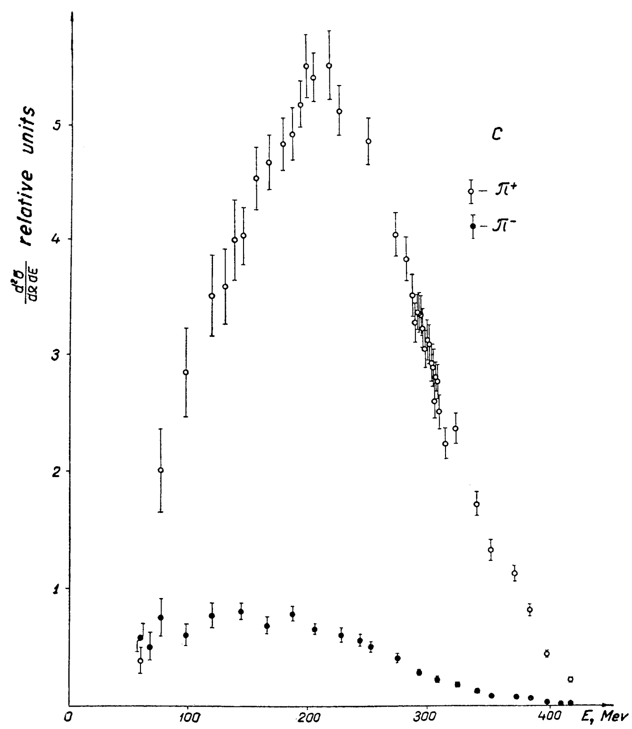

Fig. 2. Energy distribution of $\pi+$ and $\pi-$ mesons from C at 24° in the l.s.

by the absorption of mesons in the initial nuclei, and also by slowing down and scattering of the incident protons in the nuclear matter.

Thus, nucleons situated on the surface of the nucleus play the greatest role in meson production. The binding of nucleons in the nuclei might be an additional factor which decreases the probability of meson production inside the nuclei even at high energies.

5. *Analysis of the π meson energy spectra*

On the assumption that the π meson production on complex nuclei takes place in an interaction of the incident proton with one of the bound nucleons and that the scattering of π mesons in the initial nuclei is insignificant, the produced spectra were transformed into c.m.s. of two nucleons. In this system the kinetic energy of two nucleons equals 305 Mev, when one of them has the energy of 660 Mev in the laboratory system. The values of $d^2\sigma/d\omega dE$ in the c.m.s. were found by using the invariance of the expression $1/p\ d^2\sigma/d\omega dE$, where p is the π meson momentum.

The obtained spectra of π^+ and π^- mesons, with indications of the angles at which the π mesons of the stated energy were emitted *, are shown in figs. 3 and 4.

It is seen that the energy interval 50-200 Mev corresponds to the angular region between 48° and 42°. The average total energy of π^+ mesons for both elements proved to be

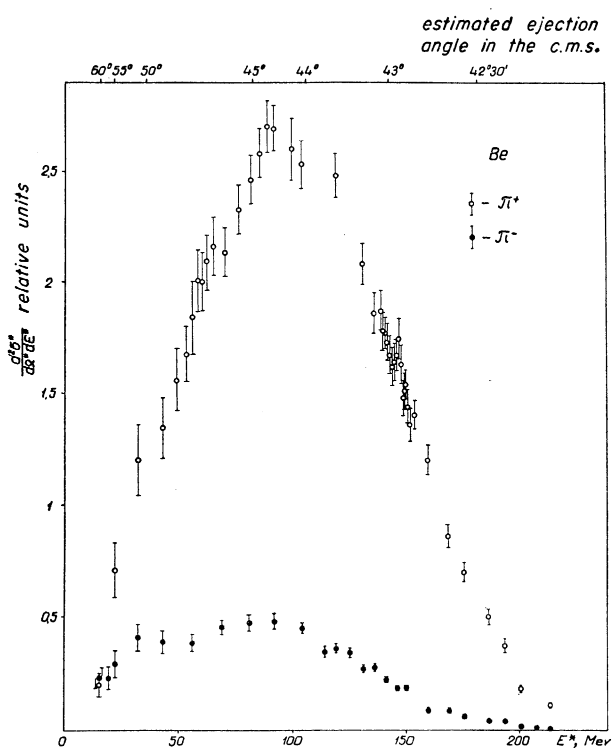

Fig. 3. Energy distribution of $\pi^\pm$ mesons from Be in the c.m.s.

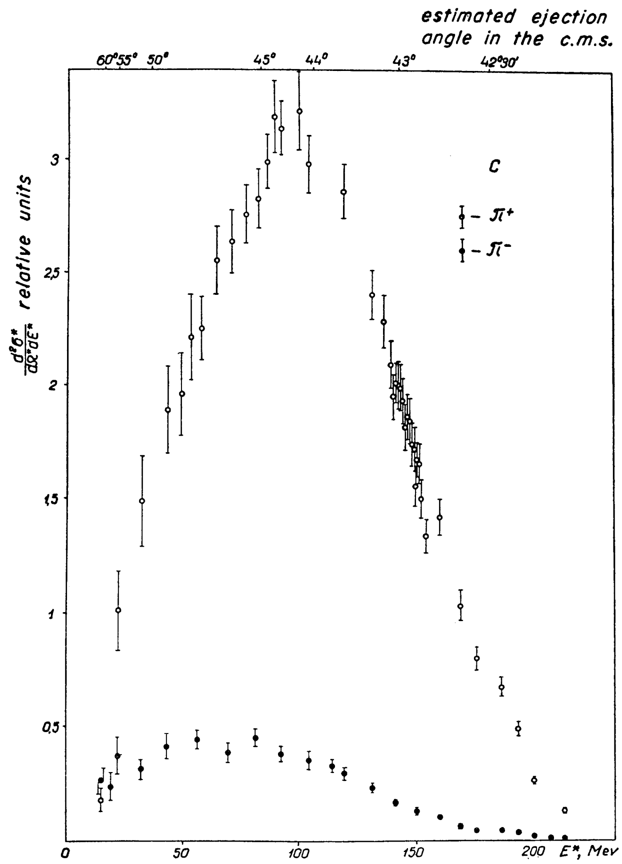

Fig. 4. Energy distribution of $\pi^\pm$ mesons from C in the c.m.s.

242 Mev, which nearly coincides with the value found under the same conditions for free p-p collisions [1], the average total energy of π^- mesons in both cases being 225 Mev.

From these figures it follows that in one act of π meson production an average of about 75 % of the available energy in the c.m.s. is spent.

Both π^+ meson spectra show a maximum near 100 Mev. If we add to this the most probable value of the π^+ meson energy in the c.m.s. the nucleon recoil energy and the π meson rest energy, the most probable value of the total energy at π meson emission will be about 260 Mev.

The obtained value of the total energy is only a little less than the resonance energy of the excited $P_{3/2,3/2}$ state.

It is interesting to compare the π meson spectra obtained in the present investigation with those measured at much higher energies.

According to [11], the maximum of the spectrum of the π^+ mesons produced on beryllium by 2300 Mev protons and recorded at an angle of 32° to the initial beam, is located near 130 Mev. It is also known that at an energy of 1720 Mev in π^+ and π^- meson spectra originating from

* The values of these angles are estimated, since the calculations disregarded the nucleon motion in the nucleus.

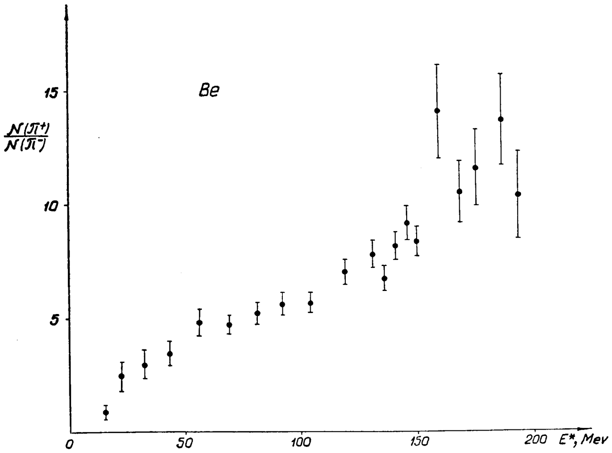

Fig. 5. Dependence of the ratio of $\pi+$ and $\pi-$ meson yields for Be upon the pion energy in the c.m.s.

the reaction $np \rightarrow np\pi^+\pi^-$, the average energy values are respectively 112 and 120 Mev[12].

These facts show that with the increase in energy from 660 to 2300 Mev, the position of the maximum in the π^+ meson spectrum is changed insignificantly, remaining always near the resonance energy of the $P_{3/2,3/2}$ state. From these facts, one may assume that the same specific mechanism of π meson production acts in the whole energy range under consideration.

It may be concluded that in the energy range of 600-1000 Mev this mechanism consists in exciting one, and at higher energies both colliding nucleons, into an intermediate state, from which the nucleons, almost like free particles, decay by emitting π mesons.

Such an assumption was used in [12] to explain the preferred formation of two π mesons in one elementary event at the energy 1720 Mev and of the angular distribution of particles.

The causes of the sharp difference in the spectral form of positive and negative mesons deserve special discussion. Supposing that nucleon collisions inside the nuclei have the same properties as free nucleons with respect to their interaction in the final nucleon system and to the isotopic spin conservation, and the preferred π meson emission in the p-state, the difference mentioned above of the positive and negative meson spectra may be qualitatively explained if we assume that the reactions $pp \rightarrow n p\pi^+$ and $pn \rightarrow pp\pi^-$ correspond in general to different final states of the two-nucleon system and that the form of the π meson spectrum must be sensitive to the nature of the interaction in these final states.

6. *The ratio* $\frac{N(\pi^+)}{N(\pi^-)}$

Using the measured values of $\frac{d^2\sigma}{d\omega\, dE'}$ the energy dependence of the ratio of π^+ and π^- meson yield was determined. For both elements, as seen in figs. 5 and 6, $\frac{N(\pi^+)}{N(\pi^-)} \leqslant 1$ at the energy $E \approx 15$ Mev. In the range of 160-180 Mev the ratio $\frac{N(\pi^+)}{N(\pi^-)}$ reaches its maximum value which is 14 for Be and 17.7 for C.

For the same elements the ratios of the integral π^+ and π^- meson yields is equal respectively to 5.3 ± 0.6 and 7.0 ± 0.8.

According to [13], the ratio of integral π^+ and π^- meson yields is 5.0 ± 0.7 at an angle of 90° in the laboratory system for collisions at the energy of 600 Mev.

A large excess of the π^+ meson yield over that of the π^- mesons is caused by the fact that the incident nucleon is a proton, and also by the relatively low probability of π meson production in the state of the two-nucleon system with zero isotopic spin.

An attempt [14] has been made to predict the value of the ratio $\frac{N(\pi^+)}{N(\pi^-)}$ on the basis of an assumption that the nucleon collision passes through two independent stages, excitation of one or both nucleons, and then an independent decay by π meson emission. When the energy is sufficient for excitation of only one nucleon, the ratio $\frac{N(\pi^+)}{N(\pi^-)}$ must be equal to 9 for p+Be collisions and 11 for p+C collisions, if only the π meson production takes place through the $P_{3/2,3/2}$ state. These predicted values of the ratio $\frac{N(\pi^+)}{N(\pi^-)}$

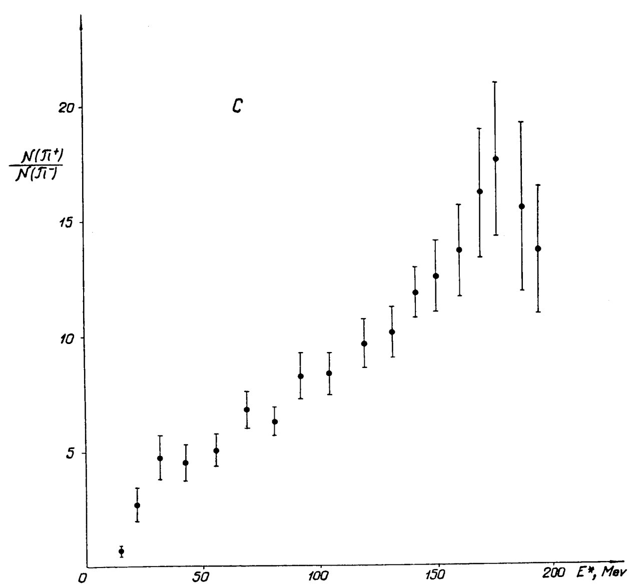

Fig. 6. Dependence of de ratio of $\pi+$ and $\pi-$ meson yields for C upon the pion energy in the c.m.s.

are noticeably higher than the corresponding experimental values.

Evidently this difference may be partly removed if we take into consideration the production in equal numbers of π^+ and π^- mesons in nucleon p-n collisions in the state with isotopic spin ½. Nevertheless, the initial assumption that the processes of nucleon excitation and of its decay are independent raises doubts, if only because the width of the excited $P_{3/2,3/2}$ state level is not much less than the energy of excitation [15].

7. *Conclusions*

In the present experiments the following facts were found concerning charged π meson production on nuclei of beryllium and carbon by 660 Mev protons:

1. The probability of the π^+ meson production referred to a proton of the target nuclei is reduced more than three times as compared to that in free p-p collisions.

It is possible that the reason for the small π^+ meson yields from complex nuclei even at high energies lies in nuclear binding of protons.

2. The spectra of positive and negative π mesons differ in form and in value of the mean meson energy. The relative softness and spread of the negative meson spectra leads to the assumption that in the reaction $pn \rightarrow pp\,\pi^-$ the interaction between nucleons is very weak in part of the final states.

3. On an average, in an elementary act of charged π meson production in a nucleon-nucleon interaction, nearly 75% of the available energy is consumed.

4. Perhaps the most unexpected fact in these experiments is that the maximum of the π^+ spectrum was found in the same energy region as in the investigations made with the Brookhaven proton accelerator at collision energies 1720 and 2300 Mev.

This result gives direct evidence in favour of the conclusion that both the single π^+ meson production in nucleon-nucleon collisions at the energy of 660 Mev and the double π meson production at the energies of 1720 and 2300 Mev are caused essentially by a strong meson-nucleon interaction in the intermediate $P_{3/2,3/2}$. state.

5. The ratio of negative and positive π meson yields increases with energies up to 160-180 Mev in the c.m.s. The ratio of integral yields of positive and negative π mesons is noticeably smaller than the values given by the theory using the assumption about the independent formation and decay of the intermediate $P_{3/2,3/2}$ state.

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DISCUSSION

M. M. Block asked what was the experimental evidence that $P_{3/2,3/2}$ states were involved even in π-pair formation at cosmotron energies.

M. G. Meshcheriakov gave the arguments put forward on p. 359 and 360. He added that it was possible that mesons interacted with the nucleons after they had been formed, and that this interaction might influence the shape of the energy spectrum.