SOVIET PHYSICS JETP VOLUME 4, NUMBER 3 APRIL, 1957

Production of Positive π-Mesons in Hydrogen by 660 MEV Protons

A. G. MESHKOVSKII, IU. S. PLIGIN, IA. IA. SHALAMOV AND V. A. SHEBANOV

(Submitted to JETP editor May 25, 1956)
J. Exptl. Theoret. Phys. (U.S.S.R.) 31, 560-564 (October, 1956)

With observation angles of 29° and 46° relative to a proton beam there were obtained energy spectra for the production of charged π-mesons in the process $p + p \rightarrow \pi^+$. Differential cross sections were measured for the angles of 29°, 46° and 65° in the laboratory system.

IT is known that the production of positive mesons takes place by means of two reactions

$$p + p \rightarrow \pi^+ + d, \tag{1}$$

$$p + p \rightarrow \pi^+ + p + n. \tag{2}$$

The total cross section for meson production by the process $p + p \rightarrow \pi^+$, that is, the sum of cross sections of the reactions (1) and (2) was investigated previously for various observational angles with proton energies in the range 340-440 mev[1-4]. Reaction (1) was studied with proton energies of 460-660 mev[5,6].

The present research, carried out with the synchrocyclotron of the Institute for Nuclear Problems of the USSR Academy of Sciences, investigated the energy spectra of mesons produced by 660 mev protons in reactions (1) and (2), without separating the two reactions, with angles of 29°, 46° and 65° with respect to the beam.

1. METHOD OF MEASUREMENT AND DESCRIPTION OF THE SET-UP

The method of magnetic analysis was used to record the π-mesons and to determine their energies. The schematic layout of the apparatus is shown in Fig. 1. The beam of 660 mev protons passed through collimators K_1 and K_2 and struck target *M*. On leaving the collimator K_2 the beam had a rectangular cross section 1×3 cm for the 29° measurements and 2×3 cm for the 46° and 65° angles. The proton beam intensity was measured by means of the ionization chambers I_1 and I_2, which were calibrated with a Faraday cylinder. The magnetic field, perpendicular to the plane of the drawing, was produced in the gap between two pole pieces of special shape, the cross section of which is shown in the Figure (section *AB*).

The π-mesons produced in the target at an angle α to the beam were deflected by the magnetic field and were recorded in a telescope of four scintillation counters *I-IV*, consisting of stilbene crystals *1-4* and photomultipliers *1a-4a* of the FEU-19 type. Special precautions were taken to avoid the influence of the magnetic field on the photomultipliers of the scintillation counters. To do this the photomultipliers were placed in many-layered nonmagnetic screens of "Armco" iron and permalloy and removed from the strong magnetic field region. The photocathodes of the photomultipliers *1a* amd *2a* were connected to the crystals by plexiglass light pipes *1b* and *2b* each 80 cm long. The thickness of the crystals *1* and *2* (1.5 cm each) were selected so as to ensure a sufficient magnitude of light impulses in the crystal from the recorded mesons by comparison with the impulses produced in the plexiglass light pipes by the passage of the particles.

The target *M* was located 20 cm from the edge of the magnetic pole pieces. At the same distance from the other edge crystal *2* was located. The aluminum filter *5* was placed between crystals *2* and *4*. The thickness of the filter was chosen so that the protons having the same impulse as the recorded mesons would not get through the filter and would not be counted by the telescope.

The counters *III* and *IV* were in the general nonmagnetic screen. The independence of the number of coincidences *1234* on the voltage of counters *I-IV* (the voltage plateau of the counters) was checked periodically. The scintillation counter impulses entered the cathode followers and after passing through coaxial cables of 200 Ω wave impedance came into wide band amplifiers and from there to a coincidence circuit with a resolving time of 2×10^{-8} sec.

The effect of π-meson production on hydrogen was determined by the difference paraffin-carbon. The paraffin target was a parallelopiped of thickness $d = 0.5$ cm (Fig. 1). The dispersion angle of the recorded π-mesons was approximately ±1°.

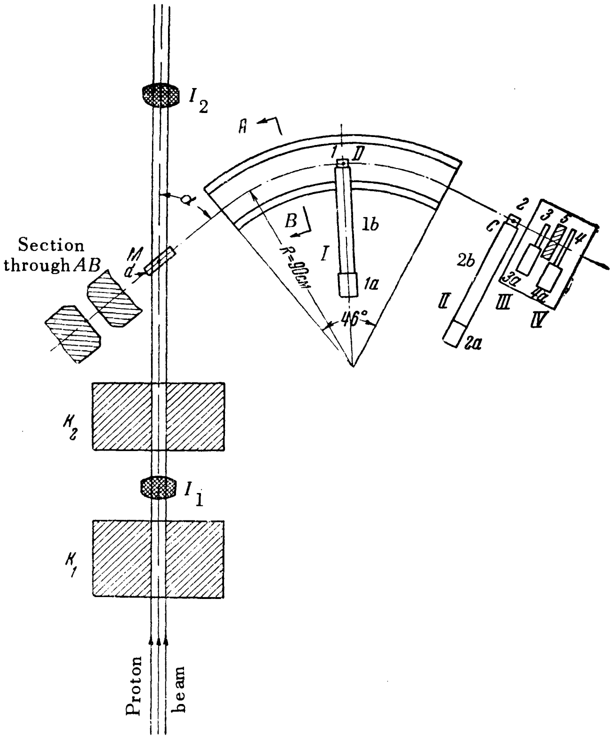

FIG. 1. Schematic layout of the apparatus

The magnitude of the magnetic field in the gap varied during the experiments from 5000 to 17000 oersteds, which ensured the recording of mesons in the impulse range of 130 to 450 mev/*c*. The topography of the magnetic field along the curve *MDC* was measured with a fluxmeter with varying values of current in the magnet winding. The fluxmeter was calibrated in a magnetic field, the value of which was measured by the method of nuclear resonance.

The topography of the magnetic field investigated by this means and the meson trajectories determined by the orientation of the target and counters served as a basis for the computing of the impulse distribution of mesons recorded by our system (resolution curves). During the computation the multiple Coulomb scattering of π-mesons by the matter in the system as well as the ionization energy losses in the target and crystal *1* were taken into account. The mean square angle of dispersion was calculated by the usual formula. From the resolution curves obtained the mean values of meson impulses and effective solid angles were determined for the mesons recorded by the system. One of these resolutions curves for the case of an average impulse of 396 mev/*c* is shown in Fig. 2.

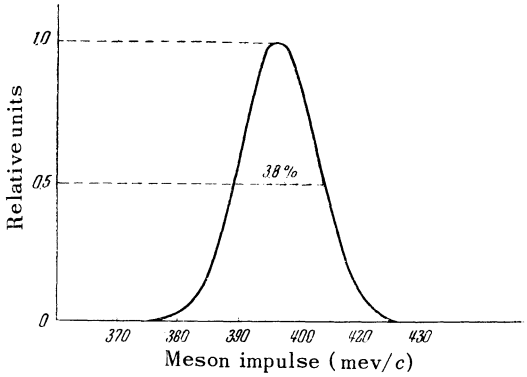

FIG. 2. The resolution curve.

The curve half-width constitutes 3.8%. The resolution worsens in the region of smaller impulses, reaching 10% for an impulse of 150 mev/*c*.

The indicated computations were made by G. M. Adel'son according to the Monte Carlo method with the electronic computer of I. S. Brook in the Institute of Energetics of the USSR Academy of Science. The calculations comprised 10^9 operations.

2. CONTROL EXPERIMENTS AND CORRECTIONS

In making the measurements it was important to be sure that the described system did not record electrons originating from the conversion of photocurrents during decay of the π^0-mesons produced in the targets. To evaluate the possible addition of electrons, control experiments were carried out in which the number of particles were measured entering the telescope with a magnetic field of opposite direction to that for recording only negative π-mesons and electrons. In doing this the carbon and paraffin targets had the same cascade length in the direction of the motion of recorded π-mesons. Experiments showed that the number of particles recorded with the paraffin target did not differ within the limits of statistical accuracy from the number counted by the system with the carbon target. It was therefore concluded that the possible electron background produced by the $p + p \to \pi^0$ process could not exceed 2-3%. This value was not taken into account in subsequent calculations.

The number of recorded mesons was corrected for the nuclear absorption of mesons by the system's matter and decay in flight. In calculating the correction for the nuclear absorption the interaction cross section was taken to be equal to the geometrical cross section of the nucleus for all elements except hydrogen, for which the dependence of the cross section on the energy of π-mesons was taken

TABLE II

The angle of mesons ejection in the laboratory system, degrees	Production cross sections of mesons in reactions (1) and (2) in $cm^2 sterad^{-1}$, calculated for 1 nucleon	
	In the laboratory system	In the center-of-mass system
29	$(3.01 \pm 0.24) \cdot 10^{-27}$	$(1.07 \pm 0.08) \cdot 10^{-27}$
46	$(2.12 \pm 0.14) \cdot 10^{-27}$	$(1.06 \pm 0.07) \cdot 10^{-27}$
65	$(1.20 \pm 0.12) \cdot 10^{-27}$	$(0.99 \pm 0.10) \cdot 10^{-27}$

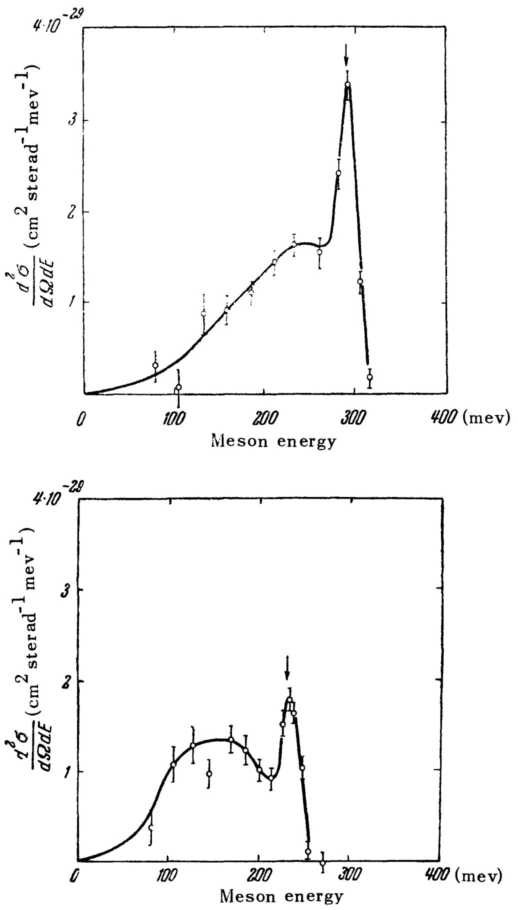

FIG. 3. Spectrum of π^+-mesons in the laboratory system from the reactions $p + p \rightarrow \pi^+ + p + n$ and $p + p \rightarrow \pi^+ + d$ with meson flight angles with respect to the proton beam: $a - 29°$, $b - 46°$.

into account[7]. In calculating the decay corrections, an evaluation of the possible effect on the telescope recording of the decay μ-mesons showed it to be negligibly small. The decay and nuclear absorption corrections are shown in Table I. The correction for multiple Coulomb scattering was automatically accounted for by the method of calculating impulse intervals and effective solid angles described in Sec. 1.

3. THE DATA

The spectra of mesons produced in hydrogen with observation angles of 29° and 46° are shown in Fig. 3. The ordinates represent differential cross section of meson production $d^2\sigma / d\Omega dE$ $cm^2/sterad^{-1}/mev^{-1}$, calculated for one nucleon; the abscissas, meson energies in mev. We do not reproduce the meson spectrum for the 65° angle because it was obtained when measurements were made with a different version of our apparatus in which the resolution of the system was not sufficiently good to determine the shape of the differential spectrum with adequate precision.

The meson spectra recalculated in the center-of-mass system for two colliding protons are shown in Fig. 4. Above the graphs are shown the values of the angles in the center-of-mass system, as a function of the meson energy.

The solid curves, shown in Figs. 3 and 4, are the best approximations to the experimental points. The figures show only the statistical errors of measurement. The systematic errors on the order of 5% are accounted for during the integration of the spectra, i.e., in calculating the cross sections $d\sigma / d\Omega$. The results of computations are shown in Table II. Included in this table also are the results of integrating the spectrum obtained with an observational angle of 65°.

4. DISCUSSION OF RESULTS

The energy of π-mesons recorded in our system was determined by the computation method indicated in Sec. 1. In accordance with this, the abscissa axis in Fig. 3 was calibrated. For reaction (1), proceeding with the formation of a deuteron, the energy of π-mesons can also be computed from

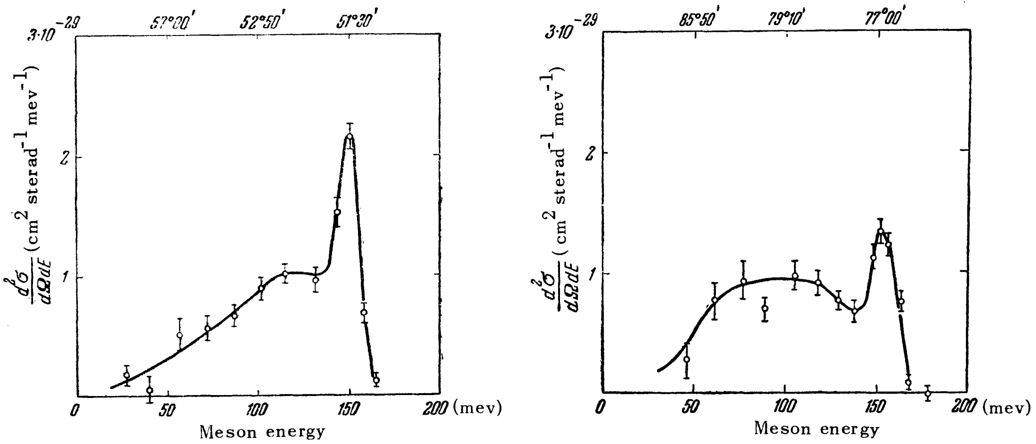

FIG. 4. The spectrum of π^+-mesons in the center-of-mass system from the reactions $p + p \to \pi^+ + p + n$ and $p + p \to \pi^+ + d$ with laboratory angles: $a - 29°$, $b - 46°$.

the conservation laws. The result of this calculation is shown by arrows in Fig. 3, the location of which agrees well (with a precision of 1-2%) with the peak position corresponding to reaction (1). Such a coincidence indicates the correctness of the calculations which serve as the basis of our methodology.

It follows from Table II that the meson production cross section $d\sigma / d\Omega$ in the reactions (1) and (2) recalculated in the center-of-mass system, remains constant (within experimental errors) for the three angles investigated by us, with the mean cross section value being $1.05 \times 10^{-27}/\text{cm}^2/\text{sterad}^{-1}$. If in accordance with this experimental fact one makes the assumption that the angular distribution of the mesons produced in the process $p + p \to \pi^+$ is nearly isotropic in the center-of-mass system, then the total cross section of charged meson production by 660 mev protons on protons turns out to be $\sigma(pp \to \pi^+) = 13.2 \times 10^{-27}$ cm^2. This quantity can also be evaluated if from the cross section for all the inelastic processes at this energy $\sigma pp = (16.7 \pm 1.2)\, 10^{-27}$ cm^2 [8] one subtracts the production cross section of neutral π-mesons. $\sigma(pp \to \pi^0) = (3.6 \pm 0.3) \times 10^{-27}\text{cm}^2$ [9]. As a result, we obtain $\sigma(pp \to \pi^+) = (13.1 \pm 1.2) \times 10^{-27}$ cm^2. The agreement of this value with our estimate and the observed independence of the differential cross section on the angle make the above-mentioned assumption quite probable, viz., the process $p + p \to \pi^+$ in the center-of-mass system is close to isotropic.

The contribution of reaction (1) to the total cross section of the process $p + p \to \pi^+$ can be evaluated by comparing out data with those of Meshcheriakov and Neganov[6] who studied reaction (1). Namely, for the observational angles of 29° and 46° the number of mesons from the reaction (1) constitutes 23.6 ± 2.6% and 10.8 ± 1.5% of all the mesons produced at the corresponding angle as a result of the $p + p \to \pi^+$ process.

The relatively small part of reaction (1) in the total process $p \to p \to \pi^+$ and the adequate energy resolution of our system allow an approximate judgment about the shape of the meson spectra produced by reaction (2). It follows from Fig. 4 that the maxima of these spectra are in the energy range 100-120 mev in the center-of-mass coordinate system.

In conclusion we express our thanks to A. I. Alikhanov for his continuous interest in the investigation and for valuable advice, to M. G. Meshcheriakov for the opportunity to carry out the current experiemnts and to G. M. Adel'son for making the computations. We also express thanks to the operating personnel of the synchrocyclotron of the Institute for Nuclear Problems of the USSR Academy of Sciences.

---

[1] Peterson, Iloff and Sherman, Phys. Rev. **84**, 372 (1951).

[2] Block, Passman and Havens, Phys. Rev. **88**, 1239 (1952).

[3] Passman, Block and Havens, Phys. Rev. **88**, 1247 (1952).

[4] A. H. Rosenfeld, Phys. Rev. **96**, 130 (1954).

[5] Meshcheriakov, Neganov, Bogachev and Sidorov, Dokl. Akad. Nauk SSSR **100**, 673 (1955).

[6] M. G. Meshcheriakov and B. S. Neganov, Dokl. Akad. Nauk SSSR **100**, 677 (1955).

[7] Ignatenko, Mukhin, Ozerov and Pontecorvo, J. Exptl. Theoret. Phys. (U.S.S.R.) **30**, 7 (1956); Soviet Phys. JETP **3**, 10 (1956).

[8] Dzhelepov, Moskalev, Starov, Golovin and Medved, Report at the All Union Conference on the Physics of High Energy Particles, May 1956.

[9] A. A. Tiapkin and Iu. D. Prokoshkin, *ibid.*

Translated by H. Kruglak
119