π^+ – Meson Energy Spectrum for $pp \to np\pi^+$ Reaction at 556 and 657 MEV

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The π^+ spectrum for the reaction $pp \to np\pi^+$ was studied at bombarding energies of 556 and 657 mev. By magnetic analysis at an angle of 24° to the proton beam. The ratio of the differential cross section at 45° (measured in the center-of-mass system) for the two energies proved to be $(d\sigma^*/d\omega^*)_{657} : (d\sigma^*/d\omega^*)_{556} = 2.2:1$. For both bombardment energies, approximately 80% of the available energy is spent in the formation of the π^+ – meson in a single elementary act. A comparison of the measured spectrum with the energy distribution corresponding to the statistical weights of the final states computed under the assumption that the meson is formed directly indicated that in the low energy part of the spectrum the matrix element associated with the initial and final state for the reaction varies linearly with meson momentum and has approximately the same value at identical momenta for both bombarding energies.

1. INTRODUCTION

ALL the present experimental results dealing with p-on-p collisions indicate that the basic inelastic process in the energy range of 560 – 660 mev is the production of π^+ – mesons by the reaction $pp \to np\pi^+$.

The total cross section for this reaction can be obtained from the total pp interaction cross section at 560 and 660 mev[1], $(34.0 \pm 0.5) \times 10^{-27}$ cm^2 and $(41.4 \pm 0.6) \times 10^{-27}$ cm^2, respectively, by subtracting the total cross sections for elastic scattering[2], $pp \to d\pi^+$ reaction[3] and $pp \to pp\pi^0$ reaction[4]. The results of this subtraction are listed in the Table together with the total cross sections of the listed processes. It appears that the total cross section for $pp \to np\pi^+$ is somewhat higher at 660 mev, a consequence of the omission of the contribution due to the formation of two π – mesons in a single pp collision. The $pp \to np\pi^+$ reaction, for which the final state is specified by the interaction of two nucleons and a nucleon and π^+ – meson, should be characterized by an energy spectrum for both mesons and nucleons. The existing data on the spectrum of mesons produced in p-on-p collisions are known only for bombarding energies of 340 mev[5], 380 mev[6] and 440 mev[7]. The data (see cited references) were obtained by passing the mesons through a filter and identifying the remaining mesons in a nuclear emulsion through $\pi^+ \to \mu^+$ decay. This method is applicable only for low energies and can give only approximate information about the form of the meson spectrum. In addition, considerable time must be spent in gathering necessary statistical material.

TABLE

Process	Total cross section in units of 10^{-25} cm^2	
	560 mev	660 mev
$pp \to pp$	25,2±0,8	24,7±1,0
$pp \to np\pi^+$	5,0±1,0	10,2±1,2
$pp \to d\pi^+$	2,6±0,2	3,1±0,2
$pp \to pp\pi^0$	1,2±0,3	3,4±0,4

In the present study, the π^+ – meson spectrum for proton energies of 556 and 657 mev has been studied by means of a magnetic analyzer. The same method was used to study the parallel problem of the secondary proton spectrum produced in the reactions $pp \to np\pi^+$ and $pp \to pp\pi^0$. The results of this experiment are presented in another paper (see following article).

2. EXPERIMENTAL PROCEDURE

The location of the magnetic spectrometer and concrete shield relative to the proton beam of the 6 – meter synchrocyclotron (of the Institute for Nuclear Problems of the Academy of Sciences, USSR) is indicated in Fig. 1. The proton beam was brought out by perturbing the radial motion of the

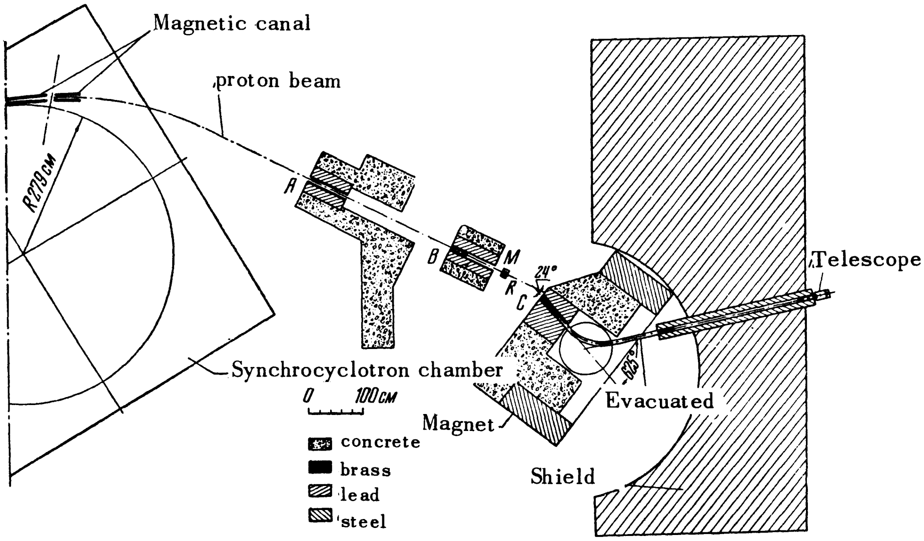

FIG. 1. Experimental layout.

accelerated protons in their final orbit by means of a local nonhomogeneous magnetic field of the synchrocyclotron[8]. At the target location the proton flux was about 2×10^9 protons/cm^2 sec. The mean proton energy proved to be 660 mev[9] and was measured by using the Cerenkov radiation of the beam. The mean dispersion in the primary beam was not greater than ±5 mev.

An electromagnet with a circular pole piece 100 cm in diameter was used in the spectrometer. The maximum attainable magnetic field for an air gap of 10 cm was 19,000 oersteds. In order to compute the trajectory of a particle in the spectrometer one must include the leakage of the field. The field was held constant to 0.2% by means of an electron stabilizer. The field strength was measured to an accuracy of 0.2% by an instrument which utilized the proton nuclear resonance method.

The mesons which emerge at an angle of 24° to the proton beam pass in a vacuum through a slitted wedge-shaped collimator C and have an angular spread of ±1° in the magnetic field. The angle of deflection in the field was selected so that the particles were focused in a horizontal plane at the detector which was located behind a thick (3.6 meter) steel-concrete cyclotron shield. For an angular deflection of 62.5°, the radius of curvature for the average trajectory was 96.5 cm. A telescope, composed of three scintillation counters, served as the detector of the particles emerging from the spectrometer. For the range of energies studied the detector efficiency was independent of energy and was close to 100%. The second crystal of the telescope with a cross section 2.5 cm × 2.5 cm acted as the exit slit for the spectrometer. The particles leaving the spectrometer were identified by their momentum and range. Thus, slow protons with the same momentum as π-mesons are separated from the latter by means of a 2 cm thick copper filter inserted in front of the third counter in the telescope.

The proton beam falls on a hydrogen target R after passing through the collimators A and B and the monitor M which is a thin-walled ionization chamber filled with helium. In the first series of measurements the target was made of a glass dewar (with an overall wall thickness of 0.5 grams/cm^2) filled with liquid hydrogen. The effect of the liquid state was studied by utilizing the difference in measurements obtained with the dewar filled with liquid and then with gaseous hydrogen. In these measurements the background level which is produced by the scattered radiation from the synchrocyclotron amounted to about 10% for the low energy portion of the spectrum and decreased to 1% as the meson energy approached 300 mev. The mean proton energy at the center of the hydrogen target in measurements with the maximum attainable proton energy was equal to 657 mev. To reduce this mean energy to 556 mev a carbon filter, 42.7 grams/cm^2 thick, was inserted in collimator A.

The use of a collimator to define the meson beam for the spectrometer may introduce distortions into the form of the spectrum through the scattering and slowing-down action of the collimator walls. Since this effect depends upon the dimensions of the target which, in this case, acts as the entrance slit for the spectrometer, a second series of measurements were made with a polyethylene target 5 mm wide by 25 mm high having a thickness of 1.0 gram/cm^2. The effect of the carbon was subtracted out by measurements on a pure carbon target. The two series of measurements gave results which were identical within the errors of measurement (±5%). This fact, together with the agreement of the measured and calculated width of the line which is produced by π^+ – mesons from the reaction $pp \to d\pi^+$, indicates the absence of any gross distortions of the meson spectrum. Further definite proof that the spectrometer with the slitted collimator preserves, in all cases, the correct form of the meson distribution was demonstrated by experiments which measured the form of the diffracted proton peak produced by scattering in carbon. In these experiments it was found that the constant disturbance produced by protons being scattered and slowed down in the walls of the entrance collimator amounted to no more than 2% of the peak signal produced by the diffraction scattered protons.

These difficulties can be avoided for sufficiently high meson energies if the discrimination of the meson beam is performed upon its entrance into the spectrometer by a system of high speed counters in coincidence with the detector which then registers the mesons which pass through the spectrometer. At the present, such a method is in use in our laboratory and was used in the measurement of the π^+ – meson spectrum.

Corrections which allow for the presence of an admixture of μ^+ – mesons and positrons in the π^+ – meson beam as well as for the absorption and decay of the π^+ – mesons during flight must be applied to the measurements. The contamination of μ^+ – meson and positrons in the emergent beam was determined by measuring the absorption of particles in a copper filter. For these measurements a fourth counter, 10 cm in diameter, with a liquid scintillator was put in coincidence with the telescope which consisted of three counters (diphenyl acetylene scintillator) with dimensions 3 × 3, 2.5 × 2.5 and 4.5 × 4.5 cm. In front of the fourth counter copper filters were inserted. The spectrum was not measured below 60 mev because of the difficulty in determining the admixture of μ^+ – mesons and positrons.

To include the corrections which are necessary because of the decay of the π^+ – meson during flight, a mean lifetime of $(2.54 \pm 0.11) \times 10^{-8}$ sec[10] was adopted. With the known cross sections for π^+ – meson interaction with nuclei one can determine the probability of absorption in the first two scintillators, in the copper filter and in the liquid hydrogen and dewar walls or in the polyethylene and carbon targets. Corrections were also introduced which allow for the small distortion in the spectrum because of changes in the meson energy through losses in the targets. Distortions produced by accidental coincidences and miscounts in the registering apparatus were negligibly small. The errors indicated in the graphs which represent the measured spectra included all uncertainties introduced with the corrections enumerated above in addition to the statistical errors of measurement.

In practice, the relative momentum spectrum of the mesons was determined by changing the strength of the magnetic field. Calibration of the spectrometer was accomplished by the location of the peak of the line from the $pp \to d\pi^+$ reaction. In the measurements with a bombarding energy of 657 mev, the spectrometer resolving power was about 3.5% for mesons with an energy of 300 mev. In this case the most essential factors which produce an increase in the half-width of the peak are: a) nonmonochromatic primary proton energy; b) finite dispersion of the spectrometer; c) angular spread of the mesons, selection by the collimator and, in a much smaller degree, multiple scattering in the target; d) energy spread of the protons and mesons because of the finite target thickness. The total energy spread of the mesons amounted to about ±5 mev.

3. EXPERIMENTAL RESULTS

Measurements at 657 mev. The resultant π^+ spectrum for equal energy intervals is represented in Fig. 2 and shows a distinct peak near 304 mev, produced by mesons from the $pp \to d\pi^+$ reaction. The half-width of the peak (width at half maximum) is about 10 mev, which agrees with the calculated value. The continuous spectrum produced by the $pp \to np\pi^+$ reaction borders the peak quite closely. If one considers the kinematics of the reactions $pp \to d\pi^+$ and $pp \to np\pi^+$ one can show that for the conditions of this experiment the upper boundary of the continuous π^+ spectrum should lie 2.9 mev below the peak. The resolving power of the spectrometer was not sufficient to see this separation.

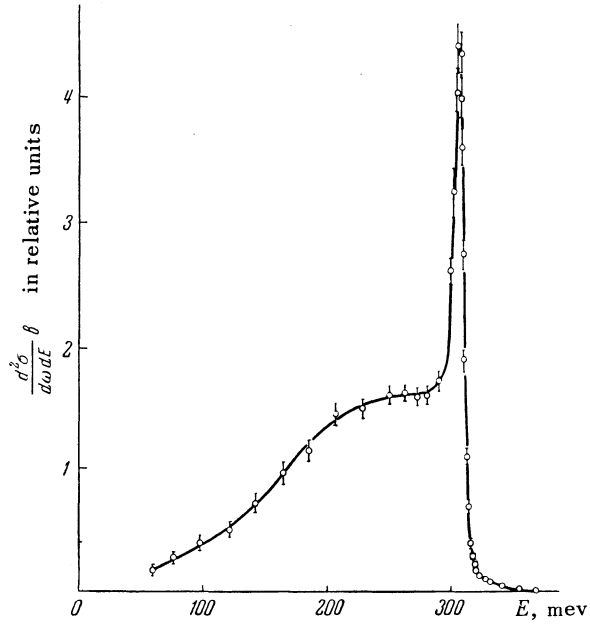

FIG. 2. The energy spectrum of π^+ – mesons for the reaction $pp \to np\pi^+$ at an angle of 24° in the laboratory system. Bombarding energy is 657 mev.

From the form of the continuous spectrum one can definitely conclude that at 657 mev there appears, together with a strong dispersion in meson energy, a clearly indicated tendency for the emission of mesons with energies near the upper limit. The average meson energy for the continuous spectrum is 220 mev.

The value of the differential cross section $d\sigma/d\omega\,(pp \to np\pi^+)$ for the formation of mesons with energies greater than 60 mev at an angle of 24° can be determined from the ratio of the area under the continuous spectrum to the area under the peak and the known cross section for the reaction $pp \to d\pi^+$ [3]. In this fashion it was found that $d\sigma/d\omega\,(pp \to np\pi^+)_{24^\circ} \cong 4.7 \times 10^{-27}$ cm²/steradian with $d\sigma/d\omega\,(pp \to d\pi^+)_{24^\circ} = 0.95 \pm 0.05 \times 10^{-27}$ cm²/steradian. It is clear that such an evaluation of the magnitude of $d\sigma/d\omega\,(pp \to np\pi^+)_{24^\circ}$ is very approximate in view of the uncertain structure of the line on the low energy side.

The invariant expression $(1/p)\,d^2\sigma/d\omega dE$, where p is the π – meson momentum in the system of coordinates in which $d^2\sigma/d\omega dE$ is measured, was used to transform the measured meson spectrum into the center-of-mass system. As is seen from Fig. 3, the spectrum obtained at an angle of 24° to the beam in the laboratory system corresponds to the spectrum for angles from 60° to 43° in the center-of-mass system. The limits of the continuous spectrum fall at 15 and 148 mev. The average meson energy for this spectrum is 110 mev whereas the energy available from the collision of the protons amounts to 305 mev. Consequently, in the formation of a π^+ – meson in a single elementary act, 83% of the available energy is spent on the average. About 90% of the mesons are emitted with energies from 50 to 148 mev within the angles 43° to 48°. Hence, in the first approximation one can assume that the measured spectrum represents, basically, the energy distribution of mesons emitted at an angle of 45° in the center-of-mass system. The corresponding differential cross section $d\sigma^*/d\omega^*\,(pp \to np\pi^+)_{45^\circ}$ is about 1.4×10^{-27} cm²/steradian.

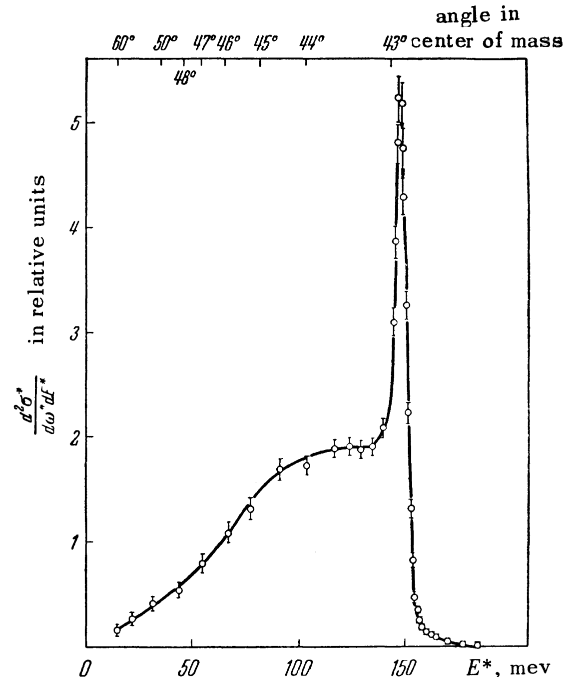

FIG. 3. The energy spectrum of π^+ – mesons in the center-of-mass system from the reaction $pp \to np\pi^+$ at 657 mev.

Measurements at 556 mev. The measured spectrum is given in Fig. 4. The peak, which corresponds to mesons from the reaction $pp \to d\pi^+$, falls at 227 mev. Because of the energy dispersion in the proton beam after passing through a filter 42.7 grams/cm^2 thick, the peak is more washed out than in the preceding measurements. As is evident the continuous π^+ spectrum is distorted in the high energy range. The average meson energy is 165 mev. The estimated differential cross section $d\sigma/d\omega(pp \to np\pi^+)_{24°}$ is 1.5×10^{-27} cm^2/steradian, whereas $d\sigma/d\omega(pp \to d\pi^+)_{24°} = (0.7 \pm 0.07) \times 10^{-27}$ cm^2/steradian.

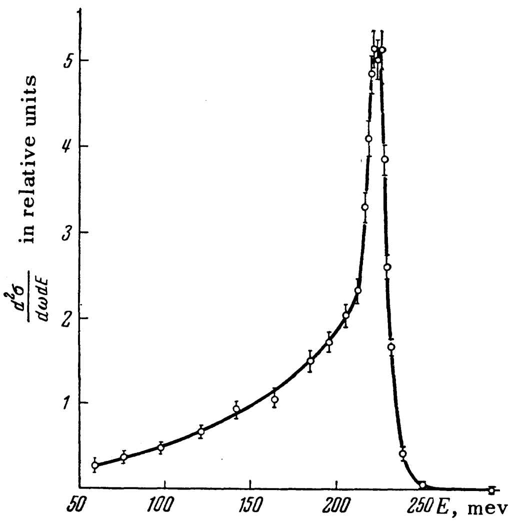

FIG. 4. Energy spectrum of π^+—mesons from the reaction $pp \to np\pi^+$ at 24° (in the laboratory system) to the beam of 556 mev protons.

The transformation to the center-of-mass system is shown in Fig. 5. It is apparent that, under the conditions of this experiment, the observed mesons are emitted from 42° to 57°, i.e., approximately in the same direction as at 657 mev. The average meson energy in this spectrum equals 82 mev, whereas the available energy is 260 mev. Hence, for a bombarding energy of 556 mev the formation of a meson in a single elementary act requires on the average about 85 % of the available energy. About 90% of the mesons with energies from 40 mev to the upper limit of 112 mev are emitted within 47° to 42°. This permits one to consider the measured spectrum as approximately representing the energy spectrum of mesons emitted at 45°. Evaluation of the absolute differential cross section indicates that $d\sigma^*/d\omega^*, pp \to \pi^+)_{45°} \simeq 0.6 \times 10^{-27}$ cm^2/steradian.

Comparison of the values of $d\sigma^*/d\omega^*(pp \to np\pi^+)$ obtained in this experiment indicates a factor 2.2 increase in the cross section when the energy is increased from 556 to 657 mev. The total cross section for this reaction also increases by the same factor for the indicated energy interval (compare Table). If this result is confirmed by further precise measurements, it will mean that the angular distribution of mesons from the $pp \to np\pi^+$ reaction changes slowly from 556 to 657 mev.

4. DISCUSSION OF RESULTS

Knowledge of the behavior of the matrix element for the formation of mesons as a function of meson momentum will permit a comparison of the measured π^+ spectrum with the energy distribution predicted by the statistical weights of the final states. For this purpose one must evaluate the dependence of $[(d^2\sigma^*/d\omega^* dq)/\rho_\epsilon(q)]^{1/2}$ on the meson momentum. Here $d^2\sigma^*/d\omega^* dq$ is the differential cross section for the formation of π^+—meson in the center-of-mass system; $\rho_\epsilon(q)$ is the density of final states under the condition that the meson is emitted with a momentum between q and $q + dq$, where ϵ is the total energy of the two colliding nucleons. For the assumption that the formation of the meson occurs directly, without the participation of any intermediate state, the density of final states is given by (compare M. I. Podgoretskii and I. L. Rozental'[11])

$$\rho_\varepsilon(q) \sim \frac{B^{1/2}}{(A^2-q^2)^2}\left\{\left(1-\frac{4A^2}{A^2-q^2}\right)\right.$$

$$\left. \times\ B + 6A^2[A^2-(q^2+2M^2)]\right\}q^2,$$

where $A = \epsilon - \sqrt{q^2+\mu^2}$, $B = (q^2 + 2M^2 - A^2)^2 - 4M^4$, $\epsilon = \sqrt{2M(E+2M)}$, E is the kinetic energy of the incident proton and M and μ are the rest energies of the nucleon and π—meson ($c = 1$).

The transformation from the energy representation to momentum representation was performed with the use of the relation

$$d^2\sigma^*/d\omega^*\,dq = \beta^*\,d^2\sigma^*/d\omega^*\,dE^*,$$

where β^* is the velocity of the π—meson in the center-of-mass system. If absolute values from the independent measurements at 556 and 657 mev bombardment energies, which were determined by us with an accuracy of 20% are used for $d^2\sigma^*/d\omega^* dE^*$ then the values derived for $[(d^2\sigma^*/$

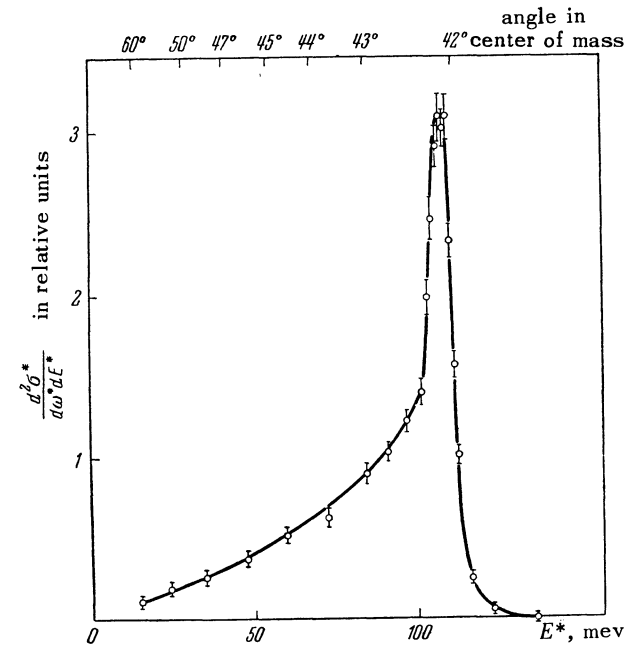

FIG. 5. Energy spectrum in the center-of-mass of π^+ — mesons from the reaction $pp \to np\pi^+$ at 556 mev bombarding energy.

$d\omega^* dq)/\rho_\epsilon(q)]^{1/2}$ should represent the actual relation between the values of the matrix element for the indicated energies.

Figure 6 represents the results of the calculations. It is necessary to note two most essential characteristics of the results: a) the obtained values for $[(d^2\sigma^*/d\omega^* dq)/\rho_\epsilon(q)]^{1/2}$ are found to be approximately identical for the same value of q within the region of momentum overlap and b) the low energy part of the π^+ spectrum does not follow the statistical distribution. As is evident, the matrix element varies like a linear function of the momentum in the range from 60 to 160 mev/c for both 556 and 657 mev energies. For the latter bombardment energy the linear behavior for the matrix element continues up to 200 mev/c. The behavior at higher momenta was impossible to study because of the inability of accurately separating the spectrum at the upper limit into line and continuum. The resultant information regarding the dependence of the matrix element on the momentum would have been more reliable if spectra were obtained at other angles in the laboratory system.

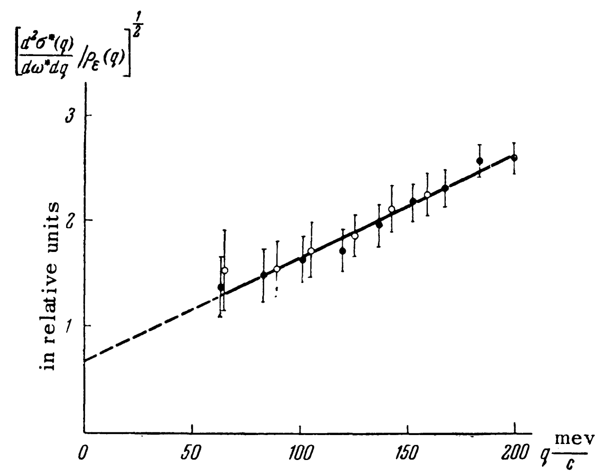

FIG. 6. Dependence of $[(d^2\sigma^*(q)/d\omega^* dq)/\rho_\epsilon(q)]^{1/2}$ on meson momentum in the center-of-mass system. O — E_p = 556 mev, O — E_p = 657 mev.

The more rapid increase of the number of π^+ — mesons with momentum in comparison to the statistical distribution can be explained by two factors: a) the emission of mesons in states with non-zero orbital momentum; b) the presence of an interaction between the nucleons in their final states which leads to the emission of mesons with predominantly high energies. The influence of this last factor will be that much weaker, the larger the energy carried away by the secondary proton or neutron. It can easily be shown that for the range of the meson momentum under consideration, 60 mev or more is shared by the secondary nucleons, principally as internal energy of motion of a two-nucleon system. With this circumstance in mind it is reasonable to expect that, in the region of low energies where $\hbar/q$ is greater than the characteristic distance R (the distance from the center of the colliding nucleons where meson formation occurs), the character of the change in $[(d^2\sigma^*/d\omega^* dq)/\rho_\epsilon(q)]^{1/2}$ will reflect fundamentally the dependence of the matrix element on the meson momentum. In Rosenfeld's review[7] of the experimental data dealing with meson formation in nucleon-nucleon collision one finds that $R \leq \frac{1}{2}\hbar/\mu c$*. To the degree to which $\hbar/q \gg \frac{1}{2}\hbar/\mu c$ is almost fulfilled for the entire analyzed π^+ spectral region, the linear dependence of the matrix element on the meson momentum will approximately mean that at the given bombarding energies the low energy mesons are emitted in a p-state relative to the two-nucleon system. If this conclusion is correct, then for those cases in which the isotopic spin of the final $(n-p)$ system is unity (i.e., processes where $T=1 \to T=1$) one may have the following transitions ${}^3P_0 \to {}^3P_1$, ${}^3P_1 \to {}^3P_0$, ${}^3P_1 \to {}^3P_1$, ${}^3P_1 \to {}^3P_2$, ${}^3P_2 \to {}^3P_1$, ${}^3P_2 \to {}^3P_2$, ${}^3F_2 \to {}^3P_1$, ${}^3F_2 \to {}^3P_2$, ${}^3F_3 \to {}^3P_2$. The intensity of these transitions can be strengthened because of meson-nucleon interaction in states with isotopic spin 3/2 and total momentum 3/2. As is apparent from the table, the contribution of the process $T=1 \to T=1$ to the total cross section for the reaction $pp \to np\pi^+$ is about 30%. For the case of $T=1 \to T=0$, the emission of a π-meson in the p-state is possible by transitions such as ${}^1D_2 \to {}^3S_1$, ${}^1S_0 \to {}^3S_1$, ${}^3P_0 \to {}^1P_1$, ${}^3P_1 \to {}^1P_1$, ${}^3P_2 \to {}^1P_1$, ${}^3F_2 \to {}^1P_1$.

We note that the linear dependence of $[(d^2\sigma^*/d\omega^* dq)/\rho_\epsilon(q)]^{1/2}$ on q which is represented equally well by the experimental points of both spectra does not extrapolate through the origin. This fact can be explained if one allows for the possibility of some emission of mesons in the s-state relative to the final two-nucleon system[13]. For the transition $T=1 \to T=1$, the s-state is permitted for the transitions ${}^3P_0 \to {}^1S_0$, ${}^1S_0 \to {}^3P_0$, and ${}^1D_2 \to {}^3P_2$; for $T=1 \to T=0$, ${}^3P_1 \to {}^3S_1$ is allowed.

In the present experiment sufficient energy was available (particularly at 657 mev) for the excitation of one of the colliding protons into the state with angular momentum 3/2 and isotopic spin 3/2 (the $P_{3/2,3/2}$ state whose existence is indicated in the scattering of π^+-mesons by nucleons). Consequently, (in another attempt to explain the peculiarity of the measured spectrum), the formation of the π^+-meson in the $pp \to np\pi^+$ reaction as occurring through the intermediate excited $P_{3/2,3/2}$ state of a nucleon can be considered*. Such a model for the formation of mesons in nucleon-nucleon collisions, which had been proposed earlier by a number of authors[14-17], was used by Iappa[18] to calculate the form of the π^+ energy spectrum for the present energies. In these calculations it was assumed that: a) the formation and decay of the $P_{3/2,3/2}$ state occur independent of one another; b) the probability of exciting the $P_{3/2,3/2}$ state is given by the dispersion formula with parameters obtained from π^+-meson-proton scattering[19]; c) the scattering of the colliding particles was isotropic in the center-of-mass system, as was also the decay of the excited nucleon. It was found that the calculated spectra were similar in form to the experimental. The mean calculated energy was 112 mev for the 657 mev case, whereas the experimental value was 110 mev. The corresponding value at 556 mev was 76 mev in comparison to the observed 82 mev.

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* This quantity also represents the radius of the region of meson-nucleon interaction[12].

* In experiments with the Birmingham proton accelerator, an angular correlation was found between the protons and the π^+-mesons for the $pp \to np\pi^+$ reaction at 650 mev (L. Riddiford, personal communication). This fact may indicate that the formation of π^+-mesons in the $pp \to np\pi^+$ reaction occurs at least partly through the intermediate state.

The above comparison indicates that the assumption of the existence of an intermediate $P_{3/2,3/2}$ state for the reaction $pp \rightarrow np\pi^+$ does not contradict the experimental results. However, the obtained agreement is hardly to be overrated in view of the rough initial assumptions and, as may be seen from the calculations, the slight difference in the form of the π^+ spectra obtained with this model (with the intermediate $P_{3/2,3/2}$ state) and with the model using the direct formation of a meson in the *p*-state. It is clear that, in order to resolve the question of the relative roles of the processes considered above in the $pp \rightarrow np\pi^+$ reaction, one needs more rigorous inclusion of the intermediate $P_{3/2,3/2}$ state in the theory of inelastic nucleon-nucleon collisions as well as further careful experimental studies of such collisions.

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[1] Dzhelepov, Moskalev and Medved', Dokl. Akad. Nauk SSSR **104**, 380 (1955).

[2] N. P. Bogachev, Dokl. Akad. Nauk SSSR **108**, No. 5 (1956).

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

[4] A. A. Tiapkin and Iu. D. Prokoshkin, Report (Otchet), Institute for Nuclear Problems, Academy of Sciences, USSR (1955).

[5] Cartwright, Richman, Whitehead and Wilcox, Phys. Rev. **91**, 677 (1953); V. Peterson, Phys. Rev. **79**, 407 (1950); Peterson, Iloff and Sherman, Phys. Rev. **84**, 372 (1951).

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

[7] A. Rosenfeld, Phys. Rev. **96**, 138 (1954).

[8] Dmitrievskii, Danilov, Denisov, Zaplitin, Katyshev, Kropin and Chestnoi, *Instrumentation and Experimental Technique* (in press).

[9] V. P. Zrelov, Report (Otchet), Institute for Nuclear Problems, Academy of Sciences, USSR (1954).

[10] Jakobson, Schulz and Steinberger, Phys. Rev. **81**, 894 (1951).

[11] M. I. Podgoretskii and I. L. Rozental', J. Exptl. Theoret. Phys. (U.S.S.R.) **27**, 129 (1954).

[12] J. Orear, Phys. Rev. **100**, 288 (1955).

[13] J. W. Mather and E. A. Martinelli, Phys. Rev. **92**, 780 (1953).

[14] F. Belinfanti, Phys. Rev. **92**, 145 (1953).

[15] D. Peaslee, Phys. Rev. **94**, 1085 (1954).

[16] R. Gatto, Nuovo Cimento **1**, 159 (1955).

[17] C. Belen'kii and A. Nikishov, J. Exptl. Theoret. Phys. (U.S.S.R.) **28**, 744 (1955); Soviet Phys. JETP **1**, 593 (1955).

[18] Iu. A. Iappa, Report (Otchet), Institute for Nuclear Problems, Academy of Sciences, USSR (1955).

[19] M. Gell-Mann and K. Watson, Ann. Rev. Nucl. Sci. **4**, 219 (1954).

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