ENERGY SPECTRA OF Π^+ MESONS IN THE $pp \rightarrow np\Pi^+$ REACTION AT 556 AND 657 MEV

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Summary

π^+ spectra of the $pp \rightarrow np\,\pi^+$ reaction were measured by magnetic analysis at an angle of 24° to the proton beam, at collision energies of 556 and 657 Mev. Upon leaving the magnetic spectrometer, the mesons were registered with a scintillating counter telescope. For the angle of 45°, the ratio of the differential cross-sections of the reaction $pp \rightarrow np\,\pi^+$ in the centre-of-mass system for the two energies is :

$$\left(\frac{d\sigma^*}{d\omega^*}\right)_{657} : \left(\frac{d\sigma^*}{d\omega^*}\right)_{556} = 2.2 : 1 .$$

At both collision energies, for the production of π^+ mesons in one elementary act of reaction $pp \rightarrow np\,\pi^+$, an average of about 80 per cent of available energy is consumed. A comparison of the measured spectra with energy distributions corresponding to the statistical weights of the final state, calculated on the supposition that the meson production occurs directly, showed that in the low-energy part of the π^+ spectra, the matrix element connecting the initial and final states of reaction $pp \rightarrow np\,\pi^+$ rises linearly with the meson momentum and for equal momentum values, has about the same value for both collision energies.

I. Introduction

All available experimental results concerning p-p collisions show that in the region of energies of 560 to 660 Mev, the main inelastic process is the π^+ meson production in the reaction $pp \rightarrow \pi^+ np$.

The value of the total cross-section of this reaction at 560 and 660 Mev can be estimated by subtracting from the total cross-sections of the (p-p) interaction, equal to $(34.0 \pm 0.5) \cdot 10^{-27}$ cm^2 and $(41.4 \pm 0.6) \cdot 10^{-27}$ cm^2 respectively [1], the sum of total cross-sections of the elastic p-p scattering [2] and reactions $pp \rightarrow \pi^+ d$ [3] and $pp \rightarrow \pi^\circ pp$ [4]. The results of such evaluations, together with the total cross-sections of the reactions named, are presented in Table I. Evidently the value of the total cross-section of reaction $pp \rightarrow \pi^+ np$ at 660 Mev thus attained is somewhat too large, because the contribution of the production processes of two mesons in a single p-p collision has been neglected.

TABLE I

Process	Total cross-section in 10^{-27} cm^2	
	560 Mev	660 Mev
$pp \rightarrow pp$	25.2 ± 0.8	24.7 ± 1.0
$pp \rightarrow np\,\pi^+$	5.0 ± 1.0	10.2 ± 1.2
$pp \rightarrow d\pi^+$	2.6 ± 0.2	3.1 ± 0.2
$pp \rightarrow pp\,\pi^\circ$	1.2 ± 0.3	3.4 ± 0.4

The peculiarities of the reaction $pp \rightarrow \pi^+ np$, determined by the interaction of two nucleons, as well as a nucleon and a π^+ meson in the final state, must be reflected in the character of both the meson and nucleon energy spectra. Data on spectra of mesons produced in (p-p) collisions exist only for protons with energies of 340 [5], 380 [6], and 440 [7] Mev. In all the papers listed the meson energy was determined by the range in filters with subsequent registration in nuclear photoplates of the $\pi^+ \rightarrow \mu^+$ decays of stopped mesons. This method, evidently, is applicable only in the region of low energies, and can furnish only tentative information on the form of the meson spectra, quite apart from the fact that it demands considerable time for collecting the necessary statistical material.

In this work π^+ meson spectra with proton energies of 556 and 657 Mev were investigated by the method of magnetic analysis. Simultaneously the same method was used also for investigating spectra of secondary protons emitted in the reactions $pp \rightarrow \pi^+ np$ and $pp \rightarrow \pi^0 pp$. The results of the latter experiments will be published in another paper.

II. Experimental procedure

The arrangement of the magnetic spectrometer and concrete shield in relation to the proton beam of the six meter synchrocyclotron of the Institute of Nuclear Problems of the USSR Academy of Sciences is shown in fig. 1. The beam is ejected by the method of exciting radial oscillations of the protons on the final orbits under the influence of local inhomogeneities of the synchrocyclotron magnetic field [8]. At the position of the target, the proton flux density was about 2.10^9 protons per cm^2 per sec. The average proton energy, found by measuring the emission angle of the Čerenkov radiation, was 660 Mev [9]. The average proton energy spread in the initial beam did not exceed $\pm$ 5 Mev.

In the spectrometer, an electromagnet with circular pole pieces, 100 cm. in diameter, was used. The maximum magnetic field intensity with an air gap of 10 cm. could reach 19,000 oersteds. In calculating the particle path in the spectrometer, the fringing fields were taken into account. The magnetic field intensity was kept constant to an accuracy of 0.2 per cent with an electronic stabilizer. The magnetic field intensity was measured to an accuracy of 0.2 per cent with an apparatus based on the utilization of nuclear proton resonance absorption.

The mesons, emitted at an angle of 24° to the proton beam, passed in vacuum through a slotted wedge-shaped collimator C with a divergence angle of $\pm$ 1° in the magnetic field, in which the particle deflection angle was so chosen that the particles focused in the horizontal plane at the position of the detector behind a 3.6 meter reinforced concrete synchrocyclotron shield. At a deflection angle of 62.5°, the radius of curvature of an average path was 96.5 cm. A telescope composed of three scintillation counters served as the particle detector at the spectrometer exit. The efficiency of the detector during the spectral investigations did not depend on the energy and was close to 100 per cent. The function of the spectrometer exit slit was performed by a second crystal in the telescope, with a cross-section of 2.5×2.5 cm^2. The particles were identified on leaving the spectrometer by their momentum and range. Thus, slow protons with the same momentum as π mesons were separated from the latter by a two-centimeter copper filter set up before the third counter in the telescope.

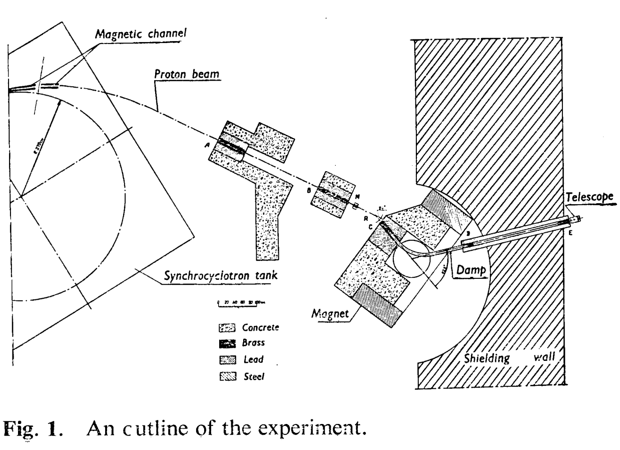

Fig. 1. An outline of the experiment.

The proton beam, passing through collimators A and B and monitor M, a helium-filled, thin-walled ionisation chamber, reached the hydrogen target R. In the first series of experiments, a Dewar flask was employed as the target, filled with liquid hydrogen, and with a total wall thickness of 0.5 gm. per cm^2. The effect of the liquid hydrogen was calculated by the difference in measurements of Dewar flasks with liquid and with gaseous hydrogen. In these measurements, the value of the background, determined by the diffused radiation from the synchrocyclotron, was about 10 per cent for the low-energy part of the spectrum and decreased to 1 per cent with the increase of meson energy to 300 Mev. The mean proton energy in the centre of the hydrogen target, measured at the maximum attainable proton energies for these experiments, was 657 Mev. In order to reduce the proton energy to 556 Mev, a hydrogen filter 42.7 gm. per cm^2 thick was placed in the path of the beam in collimator A.

When using the collimator to define the meson beam at the spectrometer entrance, it is necessary to consider the possibility of some spectrum deformation, caused by the slowing down and the scattering of mesons in the walls of the collimator. Since the influence of these effects depends on the target dimensions acting as the spectrometer entrance slit, in the second series of experiments the spectrum of π^+ mesons of the p-p collisions was found by a polyethylene-carbon difference from the target, 5 mm. wide and 25 mm. high. Polyethylene targets with a surface density of 1.0 gm. per cm^2 were used. The results of both series of experiments proved to be the same, within the limits of observation errors ($\sim 5\%$). This fact, as well as the coincidence of the observed line width for the π^+ mesons of the $pp \rightarrow \pi^+ d$ reaction with the computed value, shows the absence of coarse deformations of the meson spectrum. A more definite proof that the spectrometer with a slit entrance collimator in general shows the energy distribution of mesons correctly, was furnished by the results of experiments in which measurements were made of the shape of the proton peak after diffraction scattering on carbon nuclei. In these experiments it was found that the level of disturbances caused by the stopping and diffusion of protons in the collimator walls was no more than 2 per cent of the peak height of the proton diffraction scattering.

With sufficiently large π^+ meson energies, these difficulties may to a great degree be avoided by defining the meson beam at the spectrometer entrance by a system of high speed counters, connected in coincidence with the detector for registration of the mesons passing through the spectrometer. At the present time, the π^+ meson spectra are measured in our laboratory by this method.

The admixture of μ^+ mesons and positrons in the π^+ meson beam at the spectrometer exit was determined by measurement of the particle absorption curves in copper filters. In these measurements, a counter with a liquid scintillator, 10 cm. in diameter, with copper filters placed before it, is added to a telescope composed of three scintillation counters with dimensions of 3×3 , 2.5×2.5, and 4.5×4.5 cm. Spectra were not measured below 60 Mev because of the difficulties in determining the μ^+ meson and positron admixture.

In determining the correction for the π^+ meson disintegration in flight, their average life-time was taken as $(2.54 \pm 0.11) \cdot 10^{-8}$ sec.[10]. From the known data on the π^+ meson nuclear interaction cross-sections, the fraction of π^+ mesons absorbed in the first two scintillators, the 2 cm. copper filter, the liquid hydrogen, and in the walls of the Dewar flask was determined; and in the second series of experiments it was determined in the polyethylene and carbon targets. Corrections were also introduced considering insignificant distortions of the shape of the spectrum due to changes in the π^+ meson energy loss in the target along the spectrum. Distortions due to random coincidences and errors in the registering apparatus were negligible. Included in the errors shown on the diagrams of observations of the π^+ meson spectra, are, besides statistical errors, also all the uncertainties due to the introduction of the corrections cited above.

The spectrometer was calibrated at the position of the peak corresponding to the mesons of the reaction $pp \rightarrow d\,\pi^+$. In experiments with 657 Mev protons, the spectrometer resolution power for mesons of 300 Mev energy was about 3.5 per cent. The significant factors broadening the meson peak are :

(*a*) the energy heterogeneity of the proton beam,

(*b*) the finite value of the spectrometer dispersion,

(*c*) the spread in angle of mesons selected by the collimator, and to a far lesser extent, the multiple scattering of mesons in the target,

(*d*) the proton and meson spread in energy, due to the finite thickness of the target.

The complete meson energy spread was about $\pm$ 5 Mev.

III. Results of the experiment

1. Measurements at 657 Mev

The π^+ spectrum obtained at equal energy intervals, shown in fig. 2, has a pronounced peak at the upper limit,

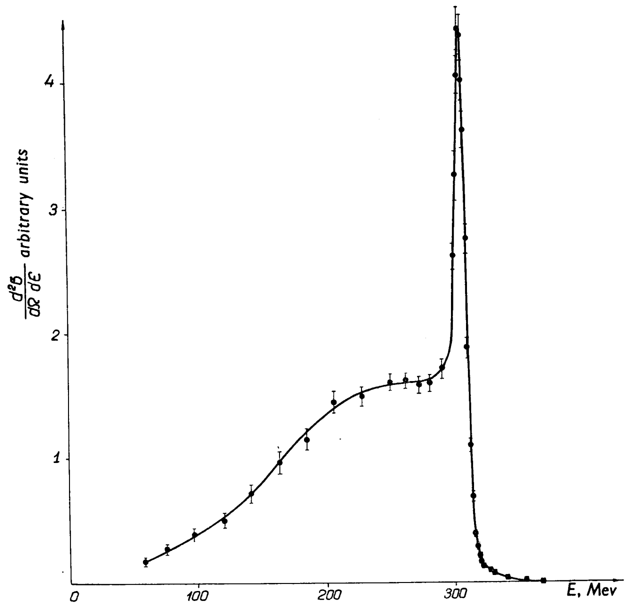

Fig. 2. Energy spectrum of π^+ mesons in the $pp \rightarrow np\pi^+$ reaction at an angle of 24° in the laboratory system at 657 Mev.

at 304 Mev, corresponding to the mesons of reaction $pp \rightarrow \pi^+ d$. The peak width at the half-height is about 10 Mev, which agrees with the computed value. The continuous meson spectrum of the reaction $pp \rightarrow \pi^+ np$ runs into the peak without a dip in between. From a consideration of the $pp \rightarrow \pi^+ d$ and $pp \rightarrow \pi^+ np$ reaction kinematics, it follows that under the conditions of this experiment, the upper boundary of the continuous π^+ spectrum should be shifted with respect to the peak position by 2.9 Mev towards the lower energies. The resolving power of the spectro meter was insufficient to note a gap of such size between the continuous spectrum and the peak.

From the appearance of the continuous spectrum, it may definitively be concluded that at 657 Mev, together with a strong spread in meson energies, there is a strong tendency for meson emission with energies close to the upper boundary. The mean meson energy in the continuous spectrum equals 220 Mev.

The value of the differential cross-section $d\sigma/d\omega$ $(pp \rightarrow \pi^+ np)$ of the meson production at energies above 60 Mev under 24°, can be evaluated by a comparison of the continuous spectrum and peak areas and using the known meson production cross-section of the $pp \rightarrow \pi^+ d$ reaction[3]. It was found that $d\sigma/d\omega\, (pp \rightarrow \pi^+ np)_{24^\circ} \approx 4.7 \cdot 10^{-27}$ cm^2 per sterad., while $d\sigma/d\omega\, (pp \rightarrow \pi^+ d)_{24^\circ} = (0.95 \pm 0.05) \cdot 10^{-27}$ cm^2 per sterad. It is clear that such an evaluation of $d\sigma/d\omega\, (pp \rightarrow \pi^+ np)_{24^\circ}$ is quite approximate because of the line shape inaccuracy at the lower energies.

The invariance of the expression $1/p\; d^2\sigma/d\omega\, dE$, where p is the π meson momentum in the same system in which the values of $d^2\sigma/d\omega\, dE$ are obtained, was used to transform the observed meson spectrum into the centre-of-mass system (c.m.s.). It was found that the spectrum of mesons ejected at angles of 60° to 43° in the c.m.s. corresponds to the energy spectrum measured at an angle of 24° to the beam. The boundaries of the continuous spectrum are located correspondingly at 15 and 148 Mev. The mean meson energy in this spectrum is 110 Mev, while the available energy of colliding protons is 305 Mev. Thus, an average of about 83 per cent of the available energy is used to produce the π^+ meson in a single elementary event. About 90 per cent of the mesons in the continuous spectrum are emitted at energies of 50 to 148 Mev in the angular interval between 43 and 48°. It may, therefore, be assumed in first approximation that the resulting spectrum represents mainly the meson energy distribution emitted towards 45° in the c.m.s. The corresponding differential cross-section $d\sigma^*/d\omega^*\,(pp \rightarrow \pi^+ np)_{45^\circ} \approx 1.4 \cdot 10^{-27}$ cm² per sterad.

2. *Measurements at 556 Mev*

The resulting spectrum is shown in fig. 3. The peak for mesons of the reaction $pp \rightarrow \pi^+ d$ is located at 227 Mev. Due to the increased proton energy spread after passing through a filter thickness of 42.7 g. per cm², the peak is wider than in the previous measurements. It is seen that the continuous π^+ spectrum is shifted into the region of high meson energies. In this spectrum the mean meson energy is 165 Mev. An estimated value of $1.5 \cdot 10^{-27}$ cm² per sterad. was obtained for the differential cross-section $d\sigma^*/d\omega^*\ (pp \rightarrow \pi^+ np)_{24^\circ}$, while $d\sigma/d\omega\,(pp \rightarrow \rightarrow \pi^+ d)_{24^\circ} = (0.7 \pm 0.07) \cdot 10^{-27}$ cm² per sterad.

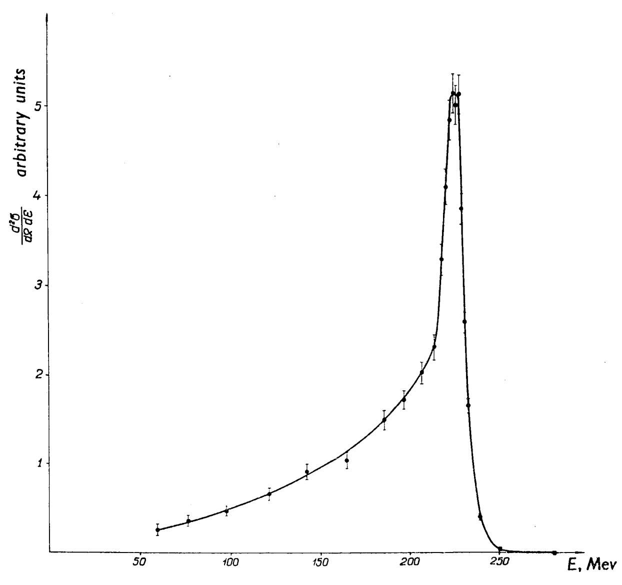

Fig. 3. Energy spectrum of π^+ mesons of the $pp \rightarrow np\pi^+$ reaction at an angle of 24° in the laboratory system at 556 Mev.

Under the conditions of this experiment we observed mesons which were emitted in the direction of 42° to 57° in the c.m.s., that is, in to about the same angular interval as for 657 Mev. The mean meson energy in this spectrum is 82 Mev, while the available energy is 260 Mev. From this it is seen that at a collision energy of 556 Mev, in one elementary meson production act, an average of about 85 per cent of the available energy is consumed. About 90 per cent of the mesons with an energy between 40 Mev and the upper limit at 112 Mev are emitted in the angular interval between 47° and 42°. For this reason we may assume that the measured spectrum represents approximately the energy distribution of mesons emitted in the direction of 45°. An evaluation of the absolute differential cross-section gives $d\sigma^*/d\omega^*\ (pp \rightarrow \pi^+ np)_{45^\circ} \approx 0.6 \cdot 10^{-27}$ cm² per sterad.

A comparison of the values of $d\sigma^*/d\omega^*\ (pp \rightarrow \pi^+ np)_{45^\circ}$ resulting from these experiments shows that when the energy rises from 556 to 657 Mev, the cross-section $d\sigma/d\omega\ (pp \rightarrow \pi^+ np)$ increases about 2.2 times. The total meson production cross-section in the investigated reaction, too, grows to the same extent in this proton energy interval. If this result is confirmed by more accurate measurements, it will mean that the meson angular distribution in the reaction $pp \rightarrow \pi^+ np$ undergoes a slight change as the energy grows from 556 to 657 Mev.

IV. Discussion

A comparison of measured π^+ spectra with energy distributions corresponding to the statistical weights of the final states can give information about the behaviour of the matrix element of the meson production in the reaction $pp \rightarrow np\,\pi^+$, as a function of meson momentum. For this it is necessary to express the dependence of the quantity $[(d^2\sigma^*/d\omega^* dq)/\rho_\varepsilon(q)]^{1/2}$ on the meson momentum. Here $d^2\sigma^*/d\omega^* dq$ is the differential cross-section for π^+ meson production in the centre-of-mass system, $\rho_\varepsilon(q)$ is the final state density, under the condition that the meson is emitted with a momentum between q and q + dq, when the total energy of two colliding nucleons is ε. On the assumption that in the investigated reaction the meson production takes place directly, without any intermediate states, the final state density is given by the formula (see [11]):

$$\rho_\varepsilon(q) \sim \frac{B^{1/2}}{(A^2 - q^2)^2} \left\{ \left(1 - \frac{4A^2}{A^2 - q^2}\right) B + 6A^2 [A^2 - (q^2 + 2M^2)] \right\} q^2,$$

where

$$A = \varepsilon - \sqrt{q^2 + \mu^2}, \quad B = (q^2 + 2M^2 - A^2)^2 - 4M^4,$$

$$\varepsilon = \sqrt{2M(E + 2M)}$$

E is the incident proton kinetic energy, M and μ are the nucleon and π meson rest energies (C = 1).

The transition from the energy distribution to the momentum distribution was made by using the relation

$$\frac{d^2\sigma^*}{d\omega^* dq} = \beta^* \frac{d^2\sigma^*}{d\omega^* dE^*},$$

where β^* – is the π^+ meson velocity in the c.m. system. Since absolute values were taken for $d^2\sigma^*/d\omega^* dE^*$, known thus far with an accuracy of 20 per cent from independent measurements made at collision energies of 556 and 657 Mev, the values obtained for $[(d^2\sigma^*/d\omega^* dq)/\rho_\varepsilon(q)]^{1/2}$ must represent the actual relation between the matrix element values for these energies.

The results of the corresponding calculations are shown in fig. 4. Two of the most significant peculiarities of these results must be noted. Firstly, the values found for $[(d^2\sigma^*/d\omega^* dq)/\rho_\varepsilon(q)]^{1/2}$ in the overlapping momenta intervals proved to be about the same for both spectra at one and the same value of q; secondly, the low-energy part of the π^+ spectra does not follow the statistical distribution. It may be seen that the matrix element is exactly the same at 556 Mev and at 657 Mev and increases approximately linearly with the momentum in an interval between 60 and 160 Mev/c. For the latter collision energy, the linear increase of the matrix element is found up to 200 Mev/c. We could not advance towards still higher momenta because of the impossibility of resolving the spectrum near the upper limit exactly into separate components corresponding to the peak and the continuous spectra. The information obtained concerning the matrix element dependence on the momentum would be more reliable if the π^+ meson spectra were measured at several angles in the laboratory system.

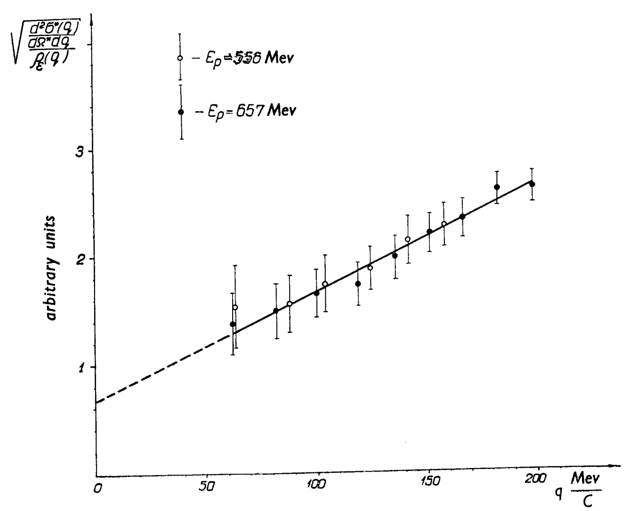

Fig. 4. Dependence of $\sqrt{\dfrac{\dfrac{d^2\sigma^*(q)}{d\Omega^* dq}}{\rho_\varepsilon(q)}}$ on meson momentum in the c.m.s. at 657 and 558 Mev.

A steeper increase in the number of π^+ mesons with momentum in the spectra measured, in comparison with the statistical distribution, could be determined by two factors,

(*a*) meson emission in states with non-zero orbital momentum, and

(*b*) interaction between the nucleons in the final state, due to which the mesons are emitted mostly with high energies.

The influence off the latter factor is the less, the greater the energy carried off by the secondary proton and neutron. It is easy to show that in the range of the investigated meson spectra at least 60 Mev goes to the secondary nucleons, mostly in the form of the energy of the internal movement of the nucleon system. Keeping this circumstance in mind, it is reasonable to expect that in the region of the lower energies, where $\hbar/q$ is greater than the characteristic distance from the nucleon collision centre R, on which the meson formation occurs, the character of the change in value of $[(d^2\sigma^*/d\omega^* dq)/\rho_\varepsilon(q)]^{1/2}$ will mainly reflect the dependence of the matrix element on the meson momentum. From the review by Rosenfeld [7] of experimental data on meson production processes in nucleon-nucleon collisions, it follows that $R \leqslant {}^1/_2 \cdot \hbar/Mc$.† Since this condition is observed almost throughout the whole range of the analysed π^+ spectra intervals, the linear matrix element dependence on the meson momentum may mean approximately that at the given collision energies in the reaction $pp \rightarrow \pi^+ np$, the mesons of the low-energy part of the spectrum are emitted mainly in the p state with respect to the two-nucleon system.

It should be noted that the straight line giving the dependance of $[(d^2\sigma^*/d\omega^* dq)/\rho_\varepsilon(q)]^{1/2}$ on q, which represents the experimental points of both spectra equally well, does not pass through the origin of coordinates. This fact can be explained by assuming that in meson emission in the p state with respect to the nucleon, there is the possibility of partial meson emission in the s state with respect to the final two-nucleon system [13].

In these experiments, especially at 657 Mev, the available energy was sufficient to excite one of the colliding protons in the ${}^3/_2$ angular moment state with an isotopic spin ${}^3/_2$ (the $P_{3/2,\ 3/2}$ state, the existence of which is indicated by experiments in nucleon scattering of π mesons). Therefore another attempt to explain the peculiarities of the investigated spectra can consist in assuming that the π^+ meson production in the reaction $pp \rightarrow \pi^+ np$ occurs by excitation

† The radius of the meson-nucleon interaction region appears to be of the same value [12].

of the intermediate nucleon $P_{3/2,3/2}$ state.† Such a model of the reaction of meson production in the nucleon-nucleon state, previously suggested by a number of authors [14–17], was utilised by Ia. A. Iappa [8] to calculate the form of the π^+ spectrum energy at the given collision energies. In these calculations it was assumed that:

(*a*) the formation and disintegration of the $P_{3/2,3/2}$ state take place independently of each other,

(*b*) the excitation probability of the $P_{3/2,3/2}$ state is expressed by the dispersion formula with parameters resulting from proton scattering of π^+ mesons [9],

(*c*) the separation of colliding particles in the c.m.s. takes place isotropically, as well as the disintegration of the excited nucleon in its own c.m.s.

As a result, it was found that the calculated spectra are closely similar in shape to the experimental ones. The mean energy in the calculated spectrum at 657 Mev was 112 Mev, while the experimental value was 110 Mev. The corresponding values for the mean energy at 557 Mev were 76 and 82 Mev.

The comparison given above shows that the assumption of the existence of an intermediate $P_{3/2,3/2}$ state in the reaction $pp \rightarrow \pi^+ np$ evidently does not contradict the experimental results. However, the resulting agreement should hardly be overestimated in view of the crudeness of the initial assumptions, and of the small difference in the shape of the π^+ spectra obtained using in calculations either the intermediate p state model or the model of the direct meson production. Obviously to solve the problem of the relative role of each of the investigated processes in the reaction $pp \rightarrow \pi^+ np$, it is necessary to include the intermediate $P_{3/2,3/2}$ state more rigorously in the theory of inelastic nucleon-nucleon collisions and to do further accurate experimental investigation of these collisions.

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† In experiments on the Birmingham proton accelerator at an energy of 650 Mev, an angular correlation between the proton and the π^+ meson in the reaction $pp \rightarrow \pi^+ np$ was observed (L. Riddiford, personal communication). This fact can mean that the π^+ meson production in the investigated reaction at least *partially takes place* through the compound state.