INVESTIGATION OF THE $p + p \rightarrow d + \pi^+$ REACTION WITH A POLARIZED PROTON BEAM

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The angular dependence of the asymmetry in π^+ mesons emitted in the $p + p \rightarrow \pi^+ + d$ reaction was measured for a polarized proton beam of energies 536, 616 and 654 Mev. A direct demonstration of the presence of d-state mesons in the reaction $p + p \rightarrow \pi^+ + d$ is obtained. The experimental results are consistent with the assumption that the amplitudes of s- and d-transitions are substantially less than the transition amplitude ${}^1D_1 \rightarrow {}^3S_2\, p_2$. Estimates of limiting values for some of the partial cross sections are given.

1. INTRODUCTION

MEASUREMENTS of total cross sections for the reaction

$$p + p \rightarrow \pi^+ + d \qquad (1)$$

for proton energies from 460 to 660 Mev,[1] and also data for higher energies obtained from experiments on the inverse reaction $\pi^+ + d \rightarrow p + p$ for π^+-energies of 174 — 307 Mev,[2] made it possible to draw conclusions about the resonance character of these two mutually inverse processes coming from the strong interaction of the π meson and proton in p-states with total angular momentum $J = 3/2$.

The angular distributions of the π^+ mesons in reaction (1) for proton energies from 460 to 660 Mev have been explained up to now by starting from the assumption that emission of the π^+ meson proceeds mainly in the p-state.[1] However, on the basis of only these experiments one cannot draw completely definite conclusions about the ratios of different amplitudes and, in particular, it is impossible to answer the question of the intensity of transitions in reaction (1) with emission of the π^+ meson in a d-state. More complete information on the ratios of amplitudes of different transitions can be obtained from experiments involving observation of various polarization effects. The reaction (1) was studied using a polarized 314-Mev proton beam in the work of reference 3, where the asymmetry observed came from interference between s- and p-states. Analogous experiments were also carried out at 415 Mev.[4] Values of the asymmetry obtained at two different angles in the latter case were interpreted by the authors of reference 4 only as a possible indication of the presence of d-wave effects.

It is well known that the probability of scattering of a d-state meson by a proton is very small at π^+ energies ~ 150 Mev and becomes noticeable only for energies $\sim$ 300 Mev,[5] where $\delta_{33} \approx 10°$ and $\delta_{35} \approx -10°$. In several articles, for example in reference 6, preliminary data on the role of d-waves in the scattering of π^+ mesons by protons were considered to give a basis for neglecting d-state π mesons and analyzing both the differential cross section and the polarization effects in reaction (1), taking only s- and p-states into account. However, the well known analogy between the resonance character of process (1) and the resonance in meson-nucleon scattering, correct in general features, may not hold in detail. A difference might be caused by the second nucleon in process (1). In the phenomenological theory of processes of π-production in p-p collisions,[7] it was shown that, in reactions $p + p \rightarrow \pi^+ + n + p$ and $p + p \rightarrow \pi^0 + p + p$ for proton energies from 400 to 900 Mev, there is rather a high probability of the mechanism of the subsystem of a meson and nucleon in a ${}^2P_{3/2}$ state going off in a P state relative to the second nucleon. The probability of the mechanism of P emission in reaction (1) turned out to be very small. As a consequence of P emission in reaction (1), the π^+ meson is emitted in s- and also d-states. Thus, the additional angular momentum carried away by the second nucleon, not bound with the π meson, can lead to the occurrence of d-states for the π^+ meson in reaction (1), while they are absent in the meson-nucleon subsystem.

In the present work we obtained a direct demonstration of the presence of d-state mesons in reaction (1) for proton energies of 536, 616 and 654 Mev. From the results obtained, and also on the basis of reference 4, one can conclude that the effect of d-states becomes observable, starting with energies $E_p \sim 400$ Mev. Data from polarized beams are not sufficient to determine all elements of the S-matrix for process (1), since other polarization effects must also be measured to solve this problem. However, if one makes several assumptions about relative sizes of the transition amplitudes in reaction (1), then, on the basis of the results obtained, one can indicate minimum probabilities of emission of π-mesons in s- and d-states.

2. EXPERIMENTAL ARRANGEMENT

The experiments were carried out with a polarized proton beam, obtained in scattering the internal beam of unpolarized protons of energy 673 Mev from nuclei of carbon introduced into the synchrotron chamber. Polarized protons scattered "to the right" through 6°20′ with respect to the direction of the initial beam (Fig. 1) were selected by two collimators so that the beam was directed towards the center of the deflecting magnet, the diameter of the poles of which was 100 cm. Special forms of shims[8] were set along the trajectory of the beam in the gap, equal to 13 cm, between the pole tips of this magnet. These created a region of inhomogeneous magnetic field, equivalent in its action to a system of two quadrupole lenses. The calculated value of the focal length of the lens was 2.5 m. Use of such a method of focusing made it possible to increase the intensity of the beam of polarized protons by a factor of three at the position of the hydrogen target.

The measuring apparatus was shielded from the background created by the primary beam and the scattered particles by a concrete wall of thickness 4 m, and also by lead blocks, placed in the path of the initial beam behind the carbon target and in the space between the yoke and poles of the magnet. In order to give a higher intensity of beam of unpolarized protons at the position of the carbon target, focusing quadrupole lenses with aperture 40 mm were used. At optimal values of the current in the windings of these lenses, the intensity of the polarized beam increased by a factor of 1.7.

The experimental arrangement consisted of a liquid hydrogen target,[9] scintillation counters for registering, a counter for determining the beam profile in the process of measurement, and also an ionization chamber placed past the hydrogen target.

The target and counters were accurately positioned relative to the axis of the 4-meter collimator. The establishment of this axis was carried out using a polyamide filament of diameter 0.2 mm. The target container of liquid hydrogen was positioned relative to the axis line of the target to an accuracy of 0.3 mm and was secured by screws. Control of the alignment of the axis line of the counter and axis of the collimator was carried out immediately before each experiment, and could be obtained to an accuracy of several parts of a millimeter. The adjustment of the target was not destroyed if they did not exceed 0.4 or 0.5 mm.

The absence of hidden asymmetry in the apparatus was demonstrated in experiments with the unpolarized proton beam by counting the $p + p \rightarrow \pi^+ + d$ processes without changing anything else in the experiment. The value of the asymmetry at angle $\theta_{lab} = 20°$, which would be most unfavorable with respect to hidden asymmetry, turned out to be equal to $\epsilon_0 = -2.4 \pm 1.9\%$. Besides these control measurements, measurement of the asymmetry in elastic p-p scattering with a polarized proton beam were carried out for angle $\theta_{lab} = 41°$, which corresponds to $\epsilon_{pp}(41°) = 0$. The measured value of the asymmetry turned out to be $\epsilon_{pp}(41°) = -0.5 \pm 0.9\%$.

Both the control experiments and the main ones were carried out for strengths of the magnetic field of the deflecting magnet corresponding to the maximum intensity of the polarized beam. In order to exclude drift effects in the angle of deflection of the protons, the possibility of a control on the position and profile of the beam during the course of measurements was considered. Such a control was carried out, using a movable scintillation counter placed before the hydrogen target (Fig. 1). The counter consisted of a narrow crystal of tolane (diphenyl acetylene) of dimensions $1 \times 40 \times 40$ mm, with its narrow edge turned to the beam. The current from the photomultiplier of this apparatus was registered by a potentiometer of type EPPV-51. The position of the center of the target was determined to an accuracy of ~ 1 mm by the pulse height on the tape. This corresponded to a relative drift of the current in the magnet windings of $\sim 0.5\%$, or a lack of alignment of the beam in the collimator of $\sim 0.05\%$.

The degree of polarization of the proton beam was determined by the usual method of double scattering on carbon nuclei at an angle of 6°20′ and turned out to be equal to $P_1 = 44 \pm 2.4\%$. As a control on the quantity P_1, the asymmetry ϵ in elastic p-p scattering was measured at 30° in the

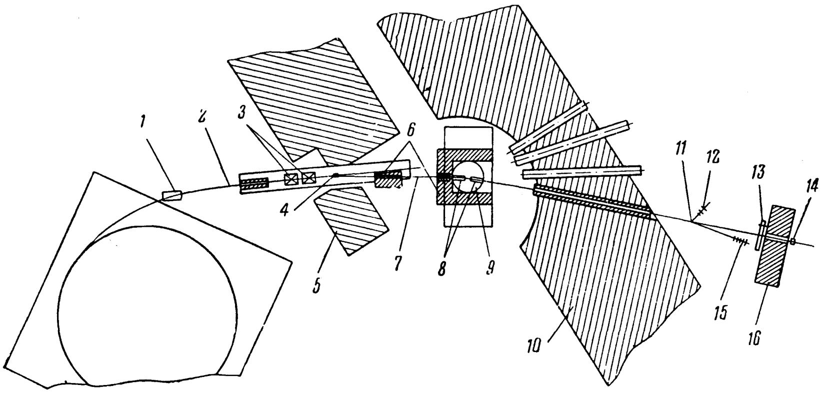

FIG. 1. Scheme of the Experiment. 1 – deflecting mouthpiece, 2 – unpolarized proton beam, 3 – magnetic quadrupole lenses of 40 mm, 4 – carbon scatterer, 5 – concrete shielding, 6 – lead shielding, 7 – polarized proton beam, 8 – focusing shim, 9 – deflecting magnet, 10 – shielding wall, 11 – target with liquid hydrogen, 12 – meson telescope, 13 – movable counter, 14 – ionization chamber, 15 – deuteron telescope, 16 – concrete shielding.

laboratory system. Its value was found in the work of reference 10 with a polarized beam of degree $P_1 = 58 \pm 3\%$. For the beam used, the value $\epsilon_{pp}(30°) = 11.9 \pm 0.6\%$ was found, whereas the value of the asymmetry[10] calculated from $P_1 = 44\%$ should be equal to $\epsilon = 12.0\%$.

The energy of the polarized beam and its spread in energy were determined by range measurements using a telescope of several scintillation counters, the last of which was connected in anti-coincidence with the first. In Fig. 2 we give two range curves:

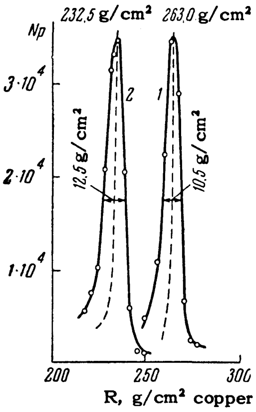

FIG. 2. Range curves in copper. 1 – unpolarized beam of protons, $E_p = 670$ Mev; 2 – polarized beam of protons, $E_p = 616$ Mev.

curve 1 with the unpolarized beam of protons of energy $E_p = 670$ Mev and spread $\Delta E = \pm 5$ Mev; curve 2 with the polarized beam, the mean energy of which turned out to be equal to $E_p = 616$ Mev, and spread $\Delta E = \pm 7$ Mev. In calculating the proton energy from the filters used in slowing down, the effect of multiple scattering in copper was taken into account.*

The remaining characteristics of the polarized beam are given in Table I for three values of the energy. Secondary particles from the reaction $p + p \rightarrow \pi^+ + d$ were counted by two conjugate telescopes of scintillation counters, connected in coincidence. The electronic scheme had the necessary stability, owing to the use of negative coefficients of selection in the telescopes of the coincidence scheme.[11] A telescope consisting of three counters counted the π^+ mesons.

TABLE I

Energy of the polarized beam Mev	536	616	654
Intensity, protons/cm² sec	$0.9 \cdot 10^5$	$5.5 \cdot 10^5$	$2.8 \cdot 10^5$
Thickness of the carbon scatterer, g/cm²	22.9	22.9	7.3
Thickness of the carbon absorber in the path of the initial beam, g/cm²	34.2	Not used	

The deuteron telescope consisted of five counters. The first three counters were connected in coincidence, and the last two in anti-coincidence with the first three. Between the second and third counters, there was a copper filter, the thickness of which corresponded to the minimum range of deuterons from reaction (1) at the conjugate angle. The interval of ranges was given by the filter placed between counters 3 and 4. With filters in this position, the telescope counted deuterons of a definite energy, and the counting efficiency for $p + p \rightarrow \pi^+ + n + p$ and $p + p \rightarrow \pi^0 + p + p$ reactions was substantially lowered by this. The measuring of the contributions from these reactions, and also of the random coincidences between telescopes was carried out with a filter of somewhat increased thickness between counters 2 and 3, so that the process (1) was not registered. The magnitude of the background was less than 10% of the considered process $p + p \rightarrow \pi^+ + d$. The angular resolution of the telescope for angle $\theta_\pi^{\rm lab} = 20°$ $(\theta_\pi^{\rm c.m.s.} = 35°)$ was $\pm 1.9°$ ($\pm 3°$ in c.m.s.), and at angle $\theta_\pi^{\rm lab} = 96°$ $(\vartheta_\pi^{\rm c.m.s.} = 130°)$ was $\pm 2.5°$ ($\pm 2°$ in c.m.s.).

3. RESULTS AND DISCUSSION

It is known[6] that the differential cross section for the reaction $p + p \rightarrow \pi^+ + d$ with a polarized beam of protons has the form

*The values of the coefficients were calculated by V. P. Zrelov.

$$k^2 d\sigma(\theta, \varphi)/d\Omega = (\gamma_0 + \gamma_2 \cos^2\theta + \gamma_4 \cos^4\theta) + P \sin\theta \cos\varphi (\lambda_0 + \lambda_1 \cos\theta + \lambda_2 \cos^2\theta + \lambda_3 \cos^3\theta), \quad (2)$$

where P is the degree of polarization of the beam, and the coefficients γ and λ[12] define elements of the S-matrix of process (1). In our case, emission of a π^+ meson to the right corresponded to azimuthal angle $\varphi = \pi$, and the polarization vector **P** pointed downwards.[13,14]

In the experiments carried out, the right-left asymmetry $\epsilon = (R - L)/(R + L)$ was measured at π^+-emission angles from 35° to 130°.

Results of the measurements of ϵ for three values of the energy are shown in Fig. 3. In the analysis of the experimental data obtained, we introduced the quantity

$$\Lambda = \frac{4\pi\varepsilon}{P \sin\theta\, \sigma_t} \left(\frac{d\sigma}{d\Omega}\right)_{\text{unpol}}. \quad (3)$$

The normalization factor $(\sigma/4\pi)$ is convenient for the analysis of the asymmetry in reaction (1) over a wide range of energies.

The differential cross sections $(d\sigma/d\Omega)$unpol. with an unpolarized proton beam, and also the total cross section σ_t for the reaction $p + p \rightarrow \pi^+ + d$, used in calculating Λ, were obtained by averaging the results of references 1, 2, and 15 and were taken to be the following:

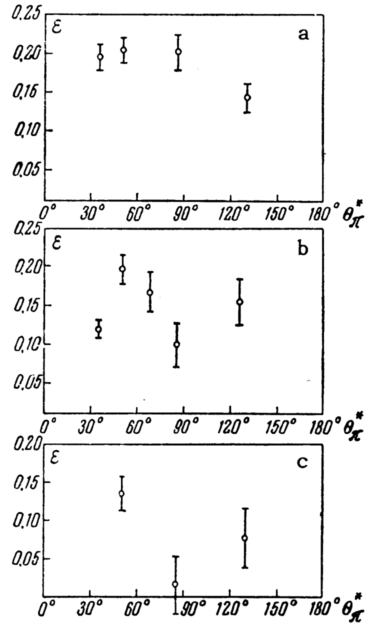

FIG. 3. Measurements of the asymmetry ε in the reaction $p + p \rightarrow d + \pi^+$ with polarized proton beams. a) E_p = 654 Mev; b) E_p = 616 Mev; c) E_p = 536 Mev.

1) $E_p = 654$ **Mev**, $d\sigma/d\Omega \sim 0.27 + \cos^2\theta$; $\sigma_t = 3.1 \cdot 10^{-27}$ cm^2;
2) $E_p = 616$ **Mev**, $d\sigma/d\Omega \sim 0.22 + \cos^2\theta$; $\sigma_t = 3.14 \cdot 10^{-27}$ cm^2;
3) $E_p = 536$ **Mev**, $d\sigma/d\Omega \sim 0.24 + \cos^2\theta$; $\sigma_t = 2.42 \cdot 10^{-27}$ cm^2.

Values of Λ as a function of θ_π in the c.m.s. are given in Fig. 4 for proton energies of 654, 616, 536 Mev. In the absence of d-transitions, the values of Λ for a given energy should be constant. The fact that a strong angular dependence of $\Lambda(\theta_\pi)$ was observed in the experiment, as can be seen by the graphs, is a direct demonstration of d-state π^+ mesons in reaction (1) for all three energies. The experimental values of $\Lambda(\theta_\pi)$ were approximated by the expressions

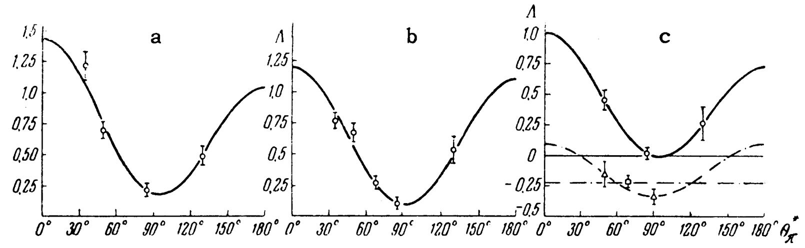

FIG. 4. Curves of $\Lambda(\theta_\pi)$: a) E_p = 654 Mev; b) E_p = 616 Mev; c) circles – date of this work, E_p = 536 Mev; triangles data from reference 4, E_p = 415 Mev; squares – data from reference 3, E_p = 314 Mev.

$$\Lambda = (\lambda_0 + \lambda_1 \cos\theta + \lambda_2 \cos^2\theta) / (\gamma_0 + {}^1/_3 \gamma_2)$$

using the method of orthogonal polynomials.[16] Values of the coefficients λ_i and errors are given in Table II.

TABLE II

E_p, Mev	$\dfrac{\lambda_0}{\gamma_0 + \frac{1}{3}\gamma_2}$	$\dfrac{\lambda_1}{\gamma_0 + \frac{1}{3}\gamma_2}$	$\dfrac{\lambda_2}{\gamma_0 + \frac{1}{3}\gamma_2}$	$\dfrac{\delta\lambda_0\delta\lambda_1}{\left(\gamma_0 + \frac{1}{3}\gamma_2\right)^2}$	$\dfrac{\delta\lambda_0\delta\lambda_2}{\left(\gamma_0 + \frac{1}{3}\gamma_2\right)^2}$	$\dfrac{\delta\lambda_1\delta\lambda_2}{\left(\gamma_0 + \frac{1}{3}\gamma_2\right)^2}$
654	0.18 ± 0.03	0.20 ± 0.06	1.05 ± 0.10	$-2.2 \cdot 10^{-4}$	$-14 \cdot 10^{-4}$	$-15.0 \cdot 10^{-4}$
616	0.09 ± 0.03	0.05 ± 0.08	1.06 ± 0.11	$-7 \cdot 10^{-4}$	$-5.5 \cdot 10^{-4}$	$-6 \cdot 10^{-4}$
536	-0.003 ± 0.04	0.15 ± 0.12	0.87 ± 0.20	$-1.1 \cdot 10^{-3}$	$-3.4 \cdot 10^{-3}$	$-7.7 \cdot 10^{-3}$

Reliable values of the coefficient λ_3 could not be determined from the experimental data. In order to determine this coefficient it would be necessary to carry out very difficult measurements of the asymmetry at angles θ_π close to 0° to 180°, where the effect of the asymmetry vanishes, owing to the approximate proportionality to $\sin\theta_\pi$. The smallest errors in the coefficients were obtained for three terms in the expansion, making it possible to break off the expansion with the $\cos^2\theta_\pi$ term. The question of actual values of the coefficient λ_3 should be considered together with that of the determination of the coefficient γ_4 in the angular distribution with an unpolarized beam, since both are determined by expressions quadratic in the amplitude for d-state transtions which, as will be shown below, are rather small.

The variation of the dependence of $\Lambda(\theta_\pi)$ observed in the present work with transition from one energy to another, can be followed to the region of still smaller values if one uses results of experiment carried out at 415 Mev (reference 4) and 314 Mev.[3] The results of these experiments are given in Table III in the notation employed here.

TABLE III

E_p, Mev	$\dfrac{\lambda_0}{\left(\gamma_0+\frac{1}{3}\gamma_2\right)}$	$\dfrac{\lambda_2}{\left(\gamma_0+\frac{1}{3}\gamma_2\right)}$	$\dfrac{\delta\lambda_0\delta\lambda_2}{\left(\gamma_0+\frac{1}{3}\gamma_2\right)^2}$
415	-0.34 ± 0.05	0.43 ± 0.28	$-6.2\cdot10^{-3}$
314	-0.22 ± 0.03	—	—

As can be seen from Fig. 4, the sign of the asymmetry changes for proton energies $E_p \sim 500$ Mev. Values of the coefficients

$$\lambda_0/(\gamma_0+{}^1\!/_3\gamma_2),\ \lambda_1/(\gamma_0+{}^1\!/_3\gamma_2),\ \lambda_2/(\gamma_0+{}^1\!/_3\gamma_2)$$

are given in Fig. 5 as a function of π-meson momentum in the c.m.s., expressed in units of $m_\pi c$. At zero energy there can be only s-state mesons, and all coefficients should go to zero. For small values of the momentum of the π^+ meson, the coefficient $\lambda_0(\gamma_0+{}^1\!/_3\gamma_2)$, which is negative, increases with the momentum of the π^+ meson, reaches an extreme value, then decreases and, going through zero at $E_p \sim 530$ Mev, again grows, but not with a positive sign. When η is small, the change in $\lambda_0(\gamma_0+{}^1\!/_3\gamma_2)$ is connected with the growth of the effect of the P-wave with respect to the S-amplitude. For large values of η, the p-d interference is added to the s-p interference. It seems that the effects of these two interferences are comparable, beginning with the proton energy for which the coefficient $\lambda_0/(\gamma_0+{}^1\!/_3\gamma_2)$ goes through the extreme value. Verification of this follows from the fact that the coefficient $\lambda_2(\gamma_0+{}^1\!/_3\gamma_2)$, coming from interference between p- and d-states, becomes observable at energies $E_p \sim 400$ Mev.

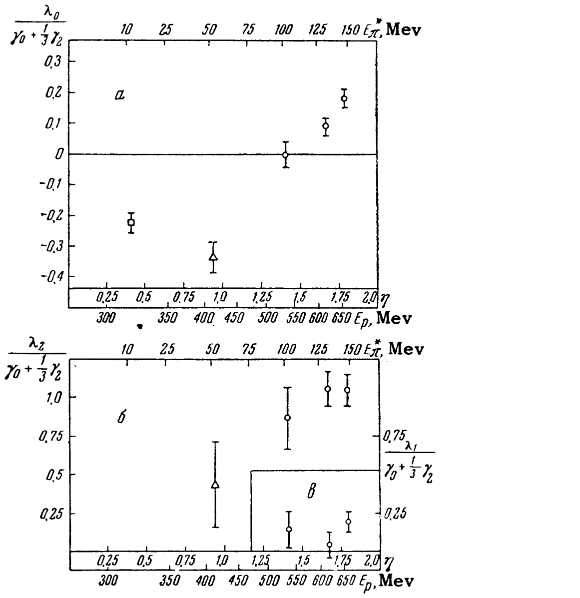

FIG. 5. Measured values of the coefficients: a) $\lambda_0/(\gamma_0+{}^1\!/_3\gamma_2)$, b) $\lambda_2/(\gamma_0+{}^1\!/_3\gamma_2)$, c) $\lambda_1(\gamma_0+{}^1\!/_3\gamma_2)$, circles – data of this work, squares – data from reference 3, triangles – data from reference 4.

The coefficient $\lambda_1(\gamma_0+{}^1\!/_3\gamma_2)$, connected with the effects of (s-d)- and (d-d)-interferences, turned out to be very small, and it was only observed with difficulty in our experiments.

All of these results can be simultaneously explained if the transition amplitude ${}^1D_2 \rightarrow ({}^3S_1 p)_2$ is taken to exceed the values of s- and d-amplitudes for $E_p \sim 600$ Mev. In this case, only s-p and p-d interferences would be observed, whereas s-d and d-d interferences would correspond to effects of second order.

The experiments carried out with a polarized proton beam add essential information about the reaction (1), but it is still not possible to evaluate all S-matrix elements connected with these reactions. However, using the smallness of s- and d-amplitudes, certain partial cross sections can be estimated. For this it is necessary to take account of the fact that d-transitions in reaction (1) are connected with a change in the orbital moment in the system of the two nucleons before and after the reaction, and also in the parity. This circumstance leads to a very small probability of d-transitions. The transitions ${}^3F_2 \rightarrow ({}^3S_1 d)_2$ and ${}^3F_3 \rightarrow ({}^3S_1 d)_3$, connected with a change in orbital momentum equal to $\Delta l = 3$ in the system of the two nucleons, should be especially impeded. This makes it possible to set the amplitudes of these transitions equal to zero, and, for limiting values of the partial cross sections, one obtains the values:

$$\sigma(^1S_0 \rightarrow {}^3S_1p_0) \geqslant 10^{-3} \cdot \sigma_t(pp \rightarrow d\pi^+);$$

$$\sigma(s + d) \geqslant 5.4 \cdot 10^{-2} \cdot \sigma_t(pp \rightarrow d\pi^+);$$

$$\sigma(^1D_2 \rightarrow {}^3S_1p_2) \leqslant 0.945 \cdot \sigma_t(pp \rightarrow d\pi^+).$$

4. CONCLUSIONS

1. Experiments measuring the asymmetry in the differential cross section of the $p + p \rightarrow d + \pi^+$ reaction with polarized proton beams at energies 536, 616, and 654 Mev demonstrate the presence of π^+-meson emission in d-states.

2. From analysis of the results of this experiment, and also of those of references 3 and 4, it follows that the effect of d-state π^+ mesons in experiments with polarized beams become observable, beginning with proton energy $E_p \sim 400$ Mev.

3. The results obtained are compatible with the assumption that the transition amplitudes for emission of π^+ mesons in s- and d-states are small in comparison with the amplitude for the transition $^1D_2 \rightarrow (^3S_1 p)_2$ over all of the region of energy studied.

4. Under the assumption that transitions from initial $^3F_2$- and $^3F_3$-states can be neglected, the following limiting values were obtained:

$$\sigma(^1S_0 \rightarrow {}^3S_1p_0) \geqslant 10^{-3} \cdot \sigma_t(pp \rightarrow d\pi^+);$$
$$\sigma(s + d) \geqslant 5.4 \cdot 10^{-2} \cdot \sigma_t(pp \rightarrow d\pi^+);$$
$$\sigma(^1D_2 \rightarrow {}^3S_1p_2) \leqslant 0.945 \cdot \sigma_t(pp \rightarrow d\pi^+).$$

5. The phenomenological theory of production of π mesons in p-p collisions of Mandelstam[7] agrees with the values obtained.

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