MEASUREMENT OF THE POLARIZATION OF DEUTERONS IN THE REACTION $p + p \rightarrow d + \pi^+$ AT PROTON ENERGIES OF 670 Mev

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The spin polarization of deuterons from the reaction $p + p \rightarrow d + \pi^+$ was measured for proton energies of 670 Mev at three angles, 121°, 140° 30′, and 162°, in the center-of-mass system. The nonresonance p transition $^1S_0 \rightarrow {}^3S_1p_0$ was found. The contribution of this transition to the total cross section is about 1%. The measured angular dependence of the spin polarization does not contradict the assumption that the transition amplitudes from the initial two-proton states $^3F_2$ and $^3F_3$ are equal to zero.

1. INTRODUCTION

THE investigation of the polarization states of deuterons in the reactions

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

is an integral part of the group of experiments connected with the elementary process of the formation of mesons in nucleon-nucleon collisions. In Tripp's experiment[1] the deuteron polarization was measured for proton energies of 340 Mev. His results made it possible to complete the determination of the phenomenological parameters that characterize reaction (1) in the Rosenfeld[2] and also the Gell-Mann and Watson[3] schemes. It was shown that the "resonance" transition $^1D_2 \rightarrow {}^3S_1p_2$ is dominant in this energy region, in comparison with the "nonresonance" transition $^1S_0 \rightarrow {}^3S_1p_0$. Besides this the Tripp experiment was able to give the ratio between the phase shifts for elastic p-p scattering in the $^1S_0$, $^1D_2$, and $^3P_1$ states and the complex phases of the transition amplitudes in reaction (1). The calculation of this ratio, as is well known, reduces the ambiguity in choosing from a group of phase shifts for 310-Mev p-p scattering.[4]

The results of reaction (1) studied in a polarized proton beam at energies of 536, 616, and 654 Mev[5] established that, beginning at proton energies of 450 Mev, the emission of particles in reaction (1) is observed, not only in s and p states, but also in d states. The results of these experiments and also of experiments with unpolarized beams[6,7] are consistent with the assumption that the d-transition amplitudes for $^3F_2 \rightarrow {}^3S_1d_2$ and $^3F_3 \rightarrow {}^3S_1d_3$ are equal to zero.

The purpose of the present experiment, besides obtaining supplementary information on reaction (1), was to examine the foregoing assumption and also to improve the estimates of partial cross sections for the examined process at proton energies of 670 Mev.

2. EXPERIMENTAL SETUP

In measuring the deuteron polarization state in reaction (1) we used the approximation method developed by Tripp[1] allowing us to determine the spin polarization of the deuteron.

It is well known that in the general case the polarization state of the deuteron beam is given by the average values of the following spin tensors[8]

$$T_{00} = 1, \quad T_{11} = -(\sqrt{3}/2)(S_x + iS_y), \quad T_{10} = \sqrt{3/2}\,S_z;$$
$$T_{22} = (\sqrt{3}/2)(S_x + iS_y)^2,$$
$$T_{21} = -(\sqrt{3}/2)[(S_x + iS_y)S_z + S_z(S_x + iS_y)],$$
$$T_{20} = \sqrt{1/2}\,(3S_z^2 - 2). \quad (2)$$

For a fully unpolarized deuteron beam, the average values of all the spin tensors, with the exception of $\langle T_{00} \rangle$, go to zero. If the deuterons are scattered by some nucleus, then a deuteron polarization is produced. The angular distribution of the polarized deuterons from the second target is given by the relation

$$I = I_0[1 + \alpha + e\cos\Phi + B\cos 2\Phi], \quad (3)$$

where Φ is the azimuthal angle, determined by the relation $\mathbf{n}_1 \cdot \mathbf{n}_2 = n_1 n_2 \cos\Phi$, $\mathbf{n}$ is the normal to the scattering plane, and I_0 is the differential scattering cross section for unpolarized deuterons on the second target. As in the proton case, the deuteron spin after the first scattering lies along the vector $\mathbf{n}_1$, so that

$$\langle S_x \rangle = \langle S_z \rangle = 0, \quad \langle T_{11} \rangle = -i \frac{\sqrt{3}}{2} \langle S_y \rangle.$$

From (3) it is evident that an experiment on the double scattering of deuterons is characterized by three functions in the polar angle θ (not counting I_0):

1) the change in the differential scattering cross section, given by $\alpha = \langle T_{20} \rangle_1 \langle T_{20} \rangle_2$;

2) the azimuthal asymmetry term $\sim \cos \Phi$ with the coefficient $e = 2[-\langle T_{21} \rangle_1 \langle T_{21} \rangle_2 + i \langle T_{11} \rangle_1 i \langle T_{11} \rangle_2]$;

3) the other azimuthal asymmetry term, $\sim \cos 2\Phi$, with the coefficient

$$B = 2 \langle T_{22} \rangle_1 \langle T_{22} \rangle_2.$$

The investigation of the dual scattering of deuterons by carbon nuclei was carried out for energies from 94 to 157 Mev.[9] Here only one of the three possible effects showed up, the azimuthal asymmetry $\sim \cos \Phi$. The quadrupole deuteron polarization components $\langle T_{20} \rangle$ and $\langle T_{22} \rangle$ turned out to be equal to zero within the limits of experimental error. This result materially limits the possibilities of observing the deuteron quadrupole polarization, which also appear in other processes, in particular in reaction (1). The coefficient e is determined by both the vector and the tensor character of the deuteron polarization, but the calculations of Stapp[10] show that $\langle T_{21} \rangle$ from carbon is about zero at the same time as $\langle T_{20} \rangle$ and $\langle T_{22} \rangle$, or more exactly, $\langle T_{21} \rangle < 0.15 \langle T_{11} \rangle$.

Thus, if we take $\langle T_{21} \rangle = 0$, the double scattering of deuterons from carbon is described by the relation

$$I = I_0 [1 + 2i \langle T_{11} \rangle_1 i \langle T_{11} \rangle_2 \cos \Phi]. \quad (4)$$

If s, p, and d states of the emitted particles are taken into account in reaction (1), the deuteron vector polarization from an unpolarized beam of protons is described by the form[11]

$$i \langle T_{11} \rangle_{d\pi^+} = \frac{{}^1/_4 \sqrt{{}^3/_2} \sin \theta^* \cos \theta^* e^{i\varphi} (\nu_0 + \nu_2 \cos^2 \theta^*)}{\gamma_0 + \gamma_2 \cos^2 \theta^*}, \quad (5)$$

where θ^* and φ are the angles of emission of the deuterons in the center-of-mass system. The denominator of this expression is equal to the cross section for (1) for an unpolarized proton beam. The coefficients ν_0 and ν_2 are expressed in the following way by amplitudes of the transitions considered:

$$\begin{aligned}
\nu_0 = {} & \tfrac{3}{4} \sqrt{5} \, |c_{p_0}| \, |c_{p_2}| \sin (c_{p_0}, c_{p_2}) \\
& + |c_{d_1}| \Big\{ \tfrac{3}{2} \sqrt{\tfrac{5}{2}} \, |c_{d_2}| \sin (c_{d_1}, c_{d_2}) - \tfrac{\sqrt{15}}{2} |c_{d_3}| \sin (c_{d_1}, c_{d_3}) \Big\} \\
& + |c_{d_4}| \Big\{ \tfrac{25}{8} \sqrt{\tfrac{21}{2}} \, |c_{d_1}| \sin (c_{d_1}, c_{d_4}) - \tfrac{3}{8} \sqrt{\tfrac{105}{2}} \, |c_{d_2}| \sin (c_{d_2}, c_{d_4}) \\
& - \tfrac{3}{8} \sqrt{35} \, |c_{d_3}| \sin (c_{d_3}, c_{d_4}) \Big\} + |c_s| \Big\{ \tfrac{9}{4} |c_{d_1}| \sin (c_s, c_{d_1}) \\
& + \tfrac{3}{4} \sqrt{5} \, |c_{d_2}| \sin (c_s, c_{d_2}) - \tfrac{1}{2} \sqrt{\tfrac{15}{2}} \, |c_{d_3}| \sin (c_s, c_{d_3}) \\
& + \sqrt{21} \, |c_{d_4}| \sin (c_s, c_{d_4}) \Big\}, \\
\nu_2 = {} & \tfrac{15}{2} \sqrt{7} \, |c_{d_4}| \Big\{ -3 \sqrt{\tfrac{3}{2}} \, |c_{d_1}| \sin (c_{d_1}, c_{d_4}) \\
& - \sqrt{\tfrac{15}{2}} \, |c_{d_2}| \sin (c_{d_2}, c_{d_4}) + \sqrt{5} \, |c_{d_3}| \sin (c_{d_3}, c_{d_4}) \Big\}. \quad (6)
\end{aligned}$$

From (5) it is evident that, in contradistinction to Tripp's experiments, carried out only for one angle ($\theta_d^* = 115$ c.m.s.), the measurements for 670-Mev protons must be done at several angles so that the values of the coefficients ν_0 and ν_2 can be separately determined.

Since we had no data on deuteron scattering from carbon at all the necessary energies, the conditions of the experiment had to be chosen such that the energies of the deuterons from reaction (1) did not go significantly beyond the limits of the investigated energy interval. This requirement was fulfilled for deuteron emission angles greater than 90° in the center-of-mass system.

3. CONDITIONS OF THE EXPERIMENT

The experiment was carried out on a beam of protons with an average energy of 670 Mev and a total intensity of about 5×10^{10} protons/sec. The experimental scheme is shown in Fig. 1. The proton beam emerging from the accelerator was deflected magnetically, focused by quadrupole lenses, and directed onto the first target, in which the reaction $p + p \rightarrow d + \pi^+$ took place. The deuterons and the other secondary particles formed by the interaction of the protons in the primary target were segregated with two collimators and directed toward the center of the deflecting electromagnet, in which the charged particles underwent magnetic analysis. For the choice of the angle and direction of the deflecting in the magnetic field, we used the results of other experiments done under analogous conditions.[12] The deuterons and the other secondary particles were focused by shims set for momenta $p = 900$ Mev/c and finally were picked out by the collimator in the shielding wall. The secondary target was placed in the laboratory space directly behind the wall. The whole alignment was checked before each run. The ac-

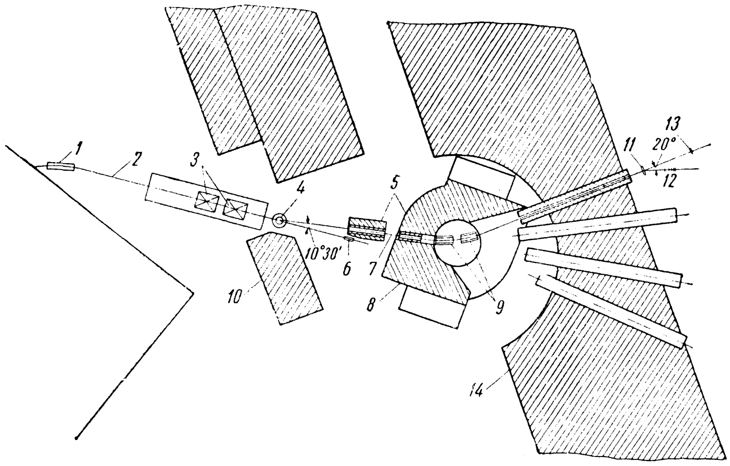

FIG. 1. Experimental setup: 1 – deflectors, 2 – unpolarized proton beam, 3 – 80 mm magnetic lenses, 4 – liquid hydrogen target, 5 – lead shielding, 6 – monitor, 7 – trajectory of particles with momenta 900 Mev/c, 8 – deflecting electromagnet, 9 – focusing shims, 10 – concrete shielding, 11 – carbon target, 12 – deuteron telescope, 13 – removable counter, 14 – shielding wall.

curacy of the alignment was ±1 mm.

The intensity of the proton beam was controlled by an ionization chamber whose current was provided by the δ electrons produced from the walls and electrodes by the action of the proton beam.

4. COUNTING APPARATUS

The telescope which recorded the deuterons elastically scattered by carbon nuclei consisted of five scintillation counters arranged as in the block diagram, Fig. 2. Counters 1, 2, and 4 registered on coincidences, counter 5 on anticoincidences. Pulses from the spectrometric counter 3, which had to act on the amplitude discriminator, passed through a high-speed filter circuit.[13] The pulse from the coincidence circuit acted as a "deciding" signal. If there was no "deciding" signal, the pulses from the spectrometric counter suppressed themselves. The "deciding" signal, destroying the "suppression" signal from the first anticoincidence circuit to the second, let the pulse from the spectrometric counter get to the amplitude discrimanator. After discrimination, pulses were formed by a Kipp oscillator and then impinged on a scaler circuit through a phase inverter and cathode follower. Simultaneously with this, pulses from the coincidence circuit went to another scaler.

5. RESULTS AND EVALUATION

The asymmetry values for the scattering of polarized deuterons, formed on carbon nuclei in the reaction $p + p \rightarrow d + \pi^+$, were measured at angles of 5°30′, 10°22′, and 12°47′. The emission of deuterons at these angles in the laboratory system corresponds to deuteron emission angles of 162°, 140°30′, and 121° in the center-of-mass system.

Figure 3 shows the results of the measurements of the quantity $i\langle T_{11}\rangle_{d\pi^+}$ for the three calculated angles. To determine $i\langle T_{11}\rangle_{d\pi^+}$ from the observed asymmetry e, we used the relation between the scattering asymmetry of deuterons from the second target and the average values of the spin

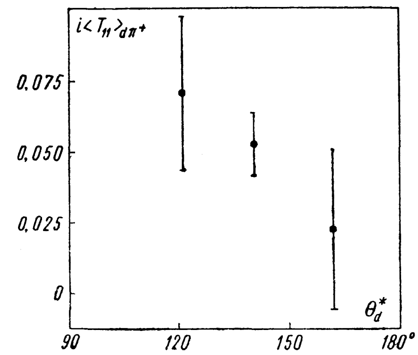

FIG. 3. Measured values of $i\langle T_{11}\rangle_{d\pi^+}$.

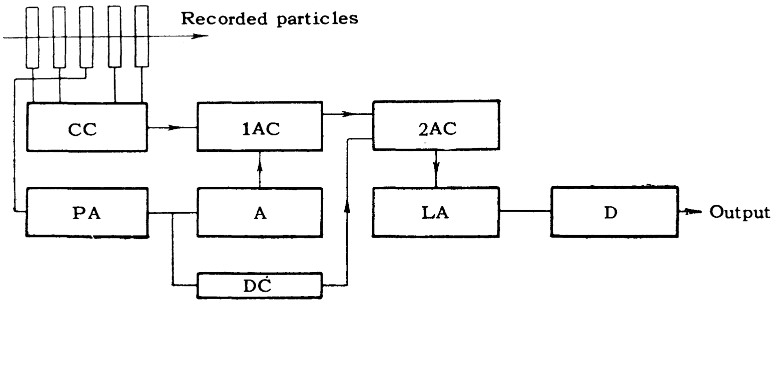

FIG. 2. Block diagram of the counter and discriminator arrangement: CC – coincidence circuit, 1AC – first anticoincidence circuit, 2AC – second anticoincidence circuit, PA – preamplifier, A – amplifier, LA – linear amplifier, D – discriminator, DC – delay circuit, 5 – anticoincidence counter, 3 – spectrometric counter.

tensors in the following approximate form:

$$e = 2i\langle T_{11}\rangle_{d\pi^+} \cdot i\langle T_{11}\rangle_{dC}. \quad (7)$$

Since the quantity $i\langle T_{11}\rangle_{dC}$ at the angle $\theta_d^{lab} = 20°$ is equal to 0.50 for energies from 125 to 156 Mev,[9] $i\langle T_{11}\rangle = e$. Analyzing the experimental data we effected the transition to the function

$$N(\theta_d^*) = \nu_0 + \nu_2 \cos^2\theta_d^*$$
$$= i\langle T_{11}(\theta_d^*)\rangle_{d\pi^+} \frac{\gamma_0 + \gamma_2\cos^2\theta_d^*}{{}^1/_4\sqrt{{}^3/_2}\sin\theta_d^*\cos\theta_d^* e^{i\varphi}}, \quad (8)$$

where (θ_d^*, φ) are the c.m. deuteron emission angles. Under the conditions of all three runs, $\varphi = 0°$. We used average values[5] for the values of γ_0 and γ_2. The values of $N(\theta_d^*)$ are given in Fig. 4.

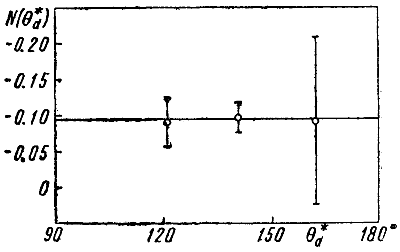

FIG. 4. Measured values of $N(\theta_d^*)$. Solid line – approximating function of the form: $-0.095-0.002\cos^2\theta_d^*$.

The coefficients ν_0 and ν_2 were determined by the method of orthogonal polynomials for a system of weighted points[14] and were equal to

$$\nu_0 = -(9.5\pm 2.6)\cdot 10^{-2}, \qquad \nu_2 = -(0.2\pm 3.6)\cdot 10^{-2}, \quad (9)$$

where the correlated error $\delta\nu_0\delta\nu_2 = -6.7\times 10^{-4}$. The choice of a solution with two coefficients of expansion was made on the basis both of the χ^2 criterion and of the insignificant[14] difference in the estimates of S_1^2 and S_{22}^2.

Since $\nu_2 \approx 0$, it follows from (6) that either $|c_{d_4}| = 0$ or

$$-3\sqrt{\tfrac{3}{2}}|c_{d_1}|\sin(c_{d_1}, c_{d_4}) - \sqrt{\tfrac{15}{2}}|c_{d_2}|\sin(c_{d_2}, c_{d_4}) + \sqrt{5}|c_{d_3}|\sin(c_{d_3}, c_{d_4}) = 0.$$

For direct conclusions about the d-transition amplitudes, these two possible relations alone are not enough. However, the observed value of ν_2 is consistent with the assumption that the transition probabilities ${}^3F_2 \to {}^3S_1d_2$ and ${}^3F_3 \to {}^3S_1d_3$ are equal to zero and that these transitions can be completely neglected. This assumption corresponds to the first assumption above, $|c_{d_4}| = 0$.

Knowledge of the coefficient ν_0 lets us set up a quantitative relation with the amplitudes c_{p_0} and c_{p_2} if we suppose that the basic transition in the reaction $p + p \to d + \pi^+$ is ${}^1D_2 \to {}^3S_1p_2$ and that the amplitudes of all the rest of the transitions are significantly less in absolute value. In this case all the terms except the first in the expression for ν_0 can be dropped, and then

$$\nu_0 = \tfrac{3}{4}\sqrt{5}\,|c_{p_0}|\,|c_{p_2}|\sin(c_{p_0}, c_{p_2}). \quad (10)$$

Since the value of $|c_{p_2}|$ under the same assumption is equal to 0.56, if we use the data of Meshcheryakov and Neganov[6] on the total cross sections we get

$$c_{p_0}\sin(c_{p_0}, c_{p_2}) = -0.102.$$

From the angular distribution data used in the estimate of the coefficients γ_0 and γ_2, we find

$$c_{p_0}\cos(c_{p_0}, c_{p_2}) = 0.0465.$$

This approximation of the last quantity may have to be corrected slightly if we estimate the probability of an s-state of the particles in the reaction $p + p \to d + \pi^+$ (${}^3P_1 \to {}^3S_1s_1$ transition), using the results of the phenomenological analysis of Gell-Mann and Watson[3] and extrapolating these data to 670 Mev. This estimate of the s-state contribution to the total cross section of the reaction gives a result of about 8%, and this is evidently not an underestimate. Neganov's data[15] on the magnitude of the s-state matrix element corresponding to this contribution (equal to 4% of the total cross section) agree with our result. Consequently, we get

$$c_{p_0}\cos(c_{p_0}, c_{p_2}) = 0.074 \pm 0.04,$$
$$c_{p_0}\sin(c_{p_0}, c_{p_2}) = -0.102 \pm 0.027,$$
$$|c_{p_0}| = 0.126 \pm 0.032, \qquad \angle(c_{p_0}, c_{p_2}) = -54°. \quad (11)$$

Figure 5 shows the plane of the complex variable c_p and the value found for the amplitude $c_{p_0}^{670}$. For comparison, the amplitude $c_{p_2}^{670}$ and also the ampli-

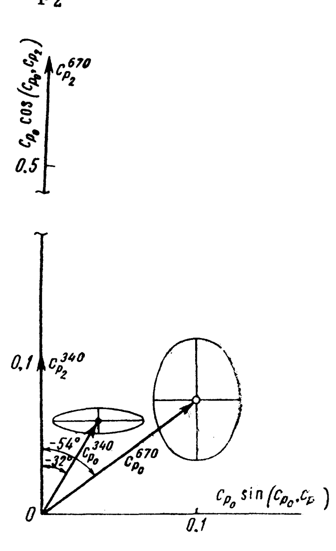

FIG. 5. Transition amplitudes c_{p_0} and c_{p_2} in the complex c_p plane: ● – according to reference 1, ○ – present work.

tudes c_{p_0} and c_{p_2} for a proton energy of 340 Mev are shown:[1]

$$c_{p_0}\cos(c_{p_0}, c_{p_2}) = 0.061 \pm 0.008,$$

$$c_{p_0}\sin(c_{p_0}, c_{p_2}) = -0.0383 \pm 0.0296, \quad |c_{p_0}| = 0.072,$$

$$|c_{p_2}| = 0.102, \quad \angle(c_{p_0}, c_{p_2}) = -32^\circ. \qquad (12)$$

Using these data, we determine the contribution of the nonresonance transition $^1S_0 \rightarrow {}^3S_1p_0$ to the total cross section for the reaction $p + p \rightarrow d + \pi^+$ at 670 Mev, or

$$\sigma(^1S_0 \rightarrow {}^3S_1p_0)/\sigma_t \approx \sigma(^1S_0 \rightarrow {}^3S_1p_0)/\sigma(^1D_2 \rightarrow {}^3S_1p_2)$$

$$= |c_{p_0}|^2/5|c_{p_2}|^2 = \left(1.0 {}^{+0.6}_{-0.45}\right)\cdot 10^{-2}.$$

6. NOTE ON THE APPROXIMATION METHOD OF MEASURING THE DEUTERON VECTOR POLARIZATION

As mentioned above, the basis of the approximation method of measuring the deuteron spin polarization is the vanishing of the spin tensor $\langle T_{21}(20^\circ)\rangle_{dC}$ for double scattering of about 150 Mev deuterons from carbon nuclei. However, experimentally this is not yet proved, so that it is necessary to indicate those possible deviations of this quantity from zero, which would not materially distort the results obtained here.

Let us compare for this purpose the average values of the spin tensors $\langle T_{11}\rangle$ and $\langle T_{21}\rangle$ in the reaction $p + p \rightarrow d + \pi^+$. Using explicit expressions,[11] we get

$$|\langle T_{11}\rangle|_{d\pi^+}/|\langle T_{21}\rangle|_{d\pi^+}$$

$$= \frac{1}{4}\sqrt{\frac{3}{2}}\sin\theta\cos\theta\,\nu_0 \Big/ \frac{1}{8}\sqrt{\frac{3}{2}}\sin\theta\cos\theta\,\rho_0 = 2\nu_0/\rho_0.$$

Further

$$\nu_0 = \frac{3}{4}\sqrt{5}\,|c_{p_2}|\,|c_{p_0}|\sin(c_{p_0}, c_{p_2});$$

$$\rho_0 = -5|c_{p_2}|^2 + \sqrt{\frac{5}{2}}\,|c_{p_2}|\,|c_{p_0}|\cos(c_{p_0}, c_{p_2}) \approx -5|c_{p_2}|^2,$$

$$|\langle T_{11}\rangle|_{d\pi^+}/|\langle T_{21}\rangle|_{d\pi^+} = 3|c_{p_0}|\sin(c_{p_0}, c_{p_2})/2\sqrt{5}\,|c_{p_2}|.$$

Since for 670 Mev $|c_{p_0}|\sin(c_{p_0}, c_{p_2}) \sim 0.1$, and $|c_{p_2}| = 0.56$, we have

$$|\langle T_{11}\rangle|_{d\pi^+}/|\langle T_{21}\rangle|_{d\pi^+} = 0.12.$$

Thus, owing to the very large value of $\langle T_{21}\rangle_{d\pi^+}$ the values of $\langle T_{21}\rangle_{dC}(20^\circ)$ must be contained within the limits

$$\langle T_{21}\rangle_{dC} \ll 0.12\langle T_{11}\rangle_{dC}.$$

If this condition is not fulfilled, it is necessary to introduce a correction into the analysis of the results obtained.

For Tripp's experiment at 340 Mev

$$|c_{p_0}|\sin(c_{p_0}, c_{p_2}) \sim 0.038, \quad |c_{p_2}| = 0.102,$$

$$|\langle T_{11}\rangle|_{d\pi^+}/|\langle T_{21}\rangle|_{d\pi^+} = 0.25.$$

At this energy the limits are somewhat widened:

$$\langle T_{21}\rangle_{dC} \ll 0.25\langle T_{11}\rangle_{dC}.$$

The assumption of the smallness of the quantity $\langle T_{21}\rangle_{dC}$ at $\theta_d^{lab} = 20^\circ$ requires an experimental examination, and this will provide a problem for future experiments.

7. CONCLUSIONS

1. The measured values of the spin polarization of deuterons in the reaction $p + p \rightarrow d + \pi^+$ together with the data on the angular distribution from this reaction on an unpolarized proton beam allow us to determine the amplitude for the transition $^1S_0 \rightarrow {}^3S_1p_0$. The contribution of this transition to the total cross section is equal to

$$\left(1.0 {}^{+0.6}_{-0.45}\right)\cdot 10^{-2}\sigma_{tot}(p + p \rightarrow d + \pi^+).$$

2. The transition amplitude $^1S_0 \rightarrow {}^3S_1p_0$ increases somewhat (~ 1.7) as the energy goes from 340 to 670 Mev, and its complex phase relative to the transition $^1D_2 \rightarrow {}^3S_1p_2$ changes roughly by 20°.

3. The measured angular dependence of the magnitude of the deuteron polarization does not contradict the assumption that the amplitudes of the transitions $^3F_2 \rightarrow {}^3S_1d_2$ and $^3F_3 \rightarrow {}^3S_1d_3$ are equal to zero.

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8