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Abstract

The angular asymmetry dependence in the positive pion emission in the reaction $p+p \rightarrow d+\pi^+$ has been measured on a polarized proton beam at the energies: 536, 616 and 654 MeV. The direct evidence that the d-state of mesons is present in the reaction $p+p \rightarrow d+\pi^+$ has been obtained. The results of the experiment is agree with the assumption that the amplitudes of the S and d transitions are considerably less than that of the transition $^1D_2 \rightarrow {}^3S_1 P_2$ The limiting values of some partial cross sections have been estimated.

I. Introduction

The measurements of the total cross sections of the reaction

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

at the proton energy from 460 up to 660 MeV [1], as well as the data for higher energies obtained from the experiments on the observation of the inverse reaction $\pi^+ + d \rightarrow p + p$ at the positive pion energies 174 - 307 MeV [2] made it possible to draw a conclusion about the resonance character of these two mutually inverse processes which is due to the strong interaction between the positive pion and the proton in the p-state with the total moment I = 3/2.

The angular distributions of positive pions in reaction (1) the proton energies 460-660 MeV were explained by assuming that the positive pion emission occurs mainly in the p-state[1]. However, on the basis of only these experiments it is impossible to draw quite definite conclusions about the relation between different amplitudes and, particularly, to clear up the question about the intensity of the transitions in reaction (1) with the positive pion emission in the d-state.

The experiments on the observation of different polarization effects may yield more complete information about the relation between the amplitudes of different transitions. Reaction (1) on a polarized proton beam was studied at the energy of 314 MeV[3] where the observed asymmetry was due to the interference between the S and p-states. Analogous experiments were conducted at the energy of 415 MeV[4] The values of the asymmetry obtained in the last case at two different angles were interpreted by the authors[4] only as a possible indication of the presence of the d-wave effect.

It is known that the process of a positive pion scattering on a proton in the d-state may occur with small probability at the positive pion energy ~ 150 MeV and becomes appreciable only at the energy ~ 300 MeV[5] where $\delta_{33} \simeq 10^{\circ}$, and $\delta_{35} \simeq -10^{\circ}$. In some papers, e.g. in[6], the data about the role of the d-wave in the positive pion scattering on protons have been considered as a basis for neglecting the d-state of a pion and analysing both the differential cross section and the polarization effects in reaction (1), only the S and p-states being taken into account.

However, the known analogy between the resonance properties of process (1) and the resonance in meson-nucleon scattering which is correct in general features may be in fact essentially different in details. This difference may be caused by the participation of the second nucleon in process (1). It has been shown in the phenomenological theory of positive and negative pion production in p-p collisions that in the reactions $p+p \rightarrow \pi^{+}+n+p$ and $p+p \rightarrow \pi^{o}+p+p$ at the proton energy from 400 MeV up to 900 MeV the mechanism of P-state production of the resonance meson-nucleon sub-system in $^{2}P_{3/2}$ state with respect to the second nucleon is observed with sufficiently great probability. The probability of P-state production mechanism in reaction (1) was found to be rather small value. The consequence of the P-state production in reaction (1) will be the positive pion emission in the d, as well as in the s-state. Thus, the additional moment of momentum carried away by the second nucleon not associated with the pion may lead to the appearance of the d-state in the meson-nucleon sub-system.

In the present paper there was obtained the direct evidence for the presence of the d-state of a positive pion in reaction (1) at the proton energies: 536, 616 and 654 MeV. It follows from the obtained results as well as from [4] that the effect of the d-state becomes appreciable at the energy $E_p \sim$ 400 MeV. The data on the polarized beam do not make it possible to determine all the S-matrix elements of process (1) since for the solution of this problem it is necessary to measure other polarization effects too. However, if some assumptions about the relation of the transition amplitudes in reaction (1) are made, then on the basis of the obtained results one may indicate the minimum values of the probability of pion emission in the S and d-states.

Experimental Procedure

The experiments were conducted with a polarized proton beam obtained in the scattering of the 673 MeV unpolarized proton beam extracted from the synchrocyclotron chamber on the carbon nuclei. The polarized protons scattered "to the right" at the angle of $6^{\circ}20$ with respect to the direction of the primary beam (fig. I) were separated by two collimators so that the beam would be directed to the centre of the deviating magnet with the diameter of the poles 100 cm. The shims of special form [8] were placed in the gap 13 cm high between the polar pieces of the magnet along the beam trajectory. They created the inhomogeneous magnetic field equivalent by its action to a field of a system of two quadrupole lenses. The calculation value of the focal length of the lenses was 2,5 meters. The use of such a focusing method made it possible to increase the intensity of the polarized proton beam in the place of hydrogen target position as much as three times.

The measuring apparatus was protected from the background created by the primary beam and by the scattered particles by means of the concrete wall 4 meters thick and by means of the lead blocks which were placed on the path of the primary beam after it passes the carbon target and in the space between the magnet yoke and poles.

In order to increase the density of the unpolarized proton beam at the carbon target the focusing quadrupole lenses with the aperture of 40 mm have been used. When the current in the windings of these lenses was optimum the density of the polarized beam increased 1.7 times.

The experimental arrangement consisted of a liquid hydrogen target [9], of the detecting scintillation counters, of a single counter for determining the profile of the beam in the measurements, as well as of an ionization chamber which was placed behind the hydrogen target.

The target and the counters were adjusted with respect to the axis of the 4-meter collimator. The position of this axis was fixed with the help of a polyamide filament 0.2 mm in diameter. The target container for the liquid hydrogen was aligned with the axial line of the target with the accuracy of $\pm$ 0.3 mm and was fixed in place with stopscrews. The alignment of the target and the collimator was checked just before each run with the accuracy of some fractions of a millimeter. Misalignment of the target was corrected if it exceeded 0.4 - 0.5 mm.

The absence of the hidden asymmetry in the apparatus was proved by the experiments with a unpolarized proton beam by detecting the processes $p + p \rightarrow d + \pi^+$ with the other experimental conditions unchanged. The value of the asymmetry at the angle $\theta_{lab.} = 20^\circ$ which is the most unfavourable as for the appearance of the hidden asymmetry was found to be $\varepsilon_o = -(2,4 \pm 1,9)\%$ Besides these control measurements those of asymmetry in the elastic (p-p)-scattering on the polarized proton beam were made at the angle $\theta_{lab.} = 41^o$ to which $\varepsilon_{pp}(41^o) = 0$ corresponds. The measured value of the asymmetry was found to be $\varepsilon_{pp}(41^o) = -(0,5 \pm 0,9)\%$.

Both the control measurements and the main experiments were conducted at the values of the magnetic intensity of the diviatiating magnet corresponding to the maximum of the polarized beam intensity. In order to exclude the drift effect in the magnitude of the proton deviating angle the provision was made for controlling the position and the profile of the polarized proton beam in the measurements. Such a control was achieved by using a movable scintillation counter situated behind the hydrogen target (fig. 1). The counter consisted of a narrow tolane crystal (diphenylacetylene) of the dimensions 1 x 40 x 40 mm with its narrow edge facing the baam. The currect from the photomultiplier tube of this counter was detected by the potentiometer EPPB-51. The position of the center of the beam was determined with the accuracy of $\approx$ 1 mm from the curve on the ribbon with calibration marks. This corresponded to the relative drift of the value of the current in the magnet winding of $\simeq$ 0.5%, or to a misalignment of the beam and the collimator $\simeq$ 0.05%.

The degree of the proton beam polarization was determined in a usual manner by means of double acattering on carbon

nuclei at the angle of $6^{\circ}20'$. It was found to be $P_1 = (44,0 \pm 2,4)\%$
As a verifiction of the quantity P , the ε asymmetry of elastic (p-p)-scattering at the angle of 30° in the lab. system has been measured the magnitude of which was found in paper [10] on the polarized beam with the degree of polarization $P_2 = (58 \pm 3)\%$ For the used beam the value $\varepsilon_{pp}(30^{\circ}) = (11,9 \pm 0,6)\%$ has been obtained whereas the value of the asymmetry [10] recalculated for $P_1 = 44\%$ must have been equal to $\varepsilon = 12,0\%$

The energy of the polarized beam and the spread in energy were determined by measuring the range curves with a telescope consisting of several scintillation counters the last of which was in anticoincidence with the previous one. In fig. 2 two range curves are given: curve I - on the unpolarized proton beam of energy 670 MeV and of spread in energy $\Delta E = \pm 5$ MeV, curve 2 - on the polarized beam with the mean energy E = 616 MeV whereas the spread in energy $\Delta E = \pm 7$ MeV. When calculating the proton energy by the magnitude of the slowing down absorber there were used the computed values of the correction coefficient taking into account the effect of multiple proton scattering in copper [11].

Other characteristics of the polarized beam at three energies are given in Table I.

The detection of secondary particles from the reaction $p + p \rightarrow d + \pi^{+}$ was achieved by two conjugate telescopes of scintillation counters in coincidence. The radiotechnical circuit was stable enough due to the use in the telescopes [12] of the coincidence circuits, having negative values of the selection coefficients. The three counter telescope detected positive pions.

T a b l e I.

Energy of the polarized beam, MeV	536	616	654
Intensity $\frac{\text{Protons}}{\text{cm}^2 \text{ sec}}$	$0,9\cdot10^5$	$5.5\cdot10^5$	$2,8\cdot10^5$
Thickness of the carbon scatterer , g/cm^2	22,9	22,9	7,3
Thickness of the carbon absorber on the way of the primary beam, g/cm^2.	34,2	was not used.	

The deuteron telescope consisted of five counters. The first three counters were in coincidence, while the last two were connected in anticoincidence with the first three. A slowing down copper absorber was placed between the second and the third counters. The thickness of it corresponded to the minimum deuteron range from reaction (1) at the conjugate angle. The range interval was given by the absorber placed between counters 3 and 4. At such a position of the absorbers the telesopce detected the dauterons of a definite energy, whereas the counting efficiency of the reactions $p+p \to \pi^{+}+n+p$ and $p+p \to \pi^{0}+p+p$ considerably decreased. The measurement of the contribution from these reactions as well as of accidental coincidences between the telescopes was made under the conditions when the thickness of the slowing absorber placed between counters 2 and 3 increased so that process (1) was not recorded. The magnitude of the background did not exceed 10% of the process under investigation $p+p \rightarrow d+\pi^+$ The angular resolution of the telescope at the angle $\theta_{lab}=20^\circ$ $\theta_{c.m.s.}35^\circ$ was $\pm 1,9^\circ$ ($\pm 3,5^\circ$ in c.m.s.) while at the angle $\theta_{lab}=96^\circ$ ($\theta_{c.m.s.}=130^\circ$)$\pm 2,5^\circ$($\pm 2^\circ$in c.m.s.).

Results and their Discussion

As is knwon [6] the differential cross section of the reaction $p+p \rightarrow d+\pi^+$ on the polarized proton beam is of the form:

$$K^2 \frac{d\sigma}{d\Omega}(\theta,\varphi) = (\gamma_0 + \gamma_2 \cos^2\theta + \gamma_4 \cos^4\theta) +$$

$$+ P\sin\theta\cos\varphi(\lambda_0 + \lambda_1\cos\theta + \lambda_2\cos^2\theta + \lambda_3\cos^3\theta), \qquad (2)$$

where P is the degree of the beam polarization, whereas the coefficients γ and λ 13) are determined by the elements of the S-matrix of process (1). In our case the positive pion emission "to the right" corresponds to the aximutal angle $\varphi=\pi$ while the polarization vector $\vec{P}$ is directed "down". [14,15].

In the experiments performed "the right vs left" asymmetry $\varepsilon = \frac{R-L}{R+L}$ was measured at the angles of positive pion emission from 35° up to 130°.

The results of the measurement of ε at three energies are given in Fig. 3. When analyzing the obtained experimental data the magnitude

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

was introduced, where P is the degree of polarization. The normalization factor ($\frac{\sigma_t}{4\pi}$) serves to make the analysis of the magnitude of asymmetry of reaction (1) in the wide energy interval more convenient.

The differential cross section ($\frac{d\sigma}{d\Omega}$) on the unpolarized proton beam as well as the total cross sections σ_t for the reaction $p + p \to d + \pi$, the values of which were used when calculating Λ have been obtained by averaging the results of the papers |1,2;16| and were assumed to be the following

1) $E_p = 654\, Mev$ $\quad \frac{d\sigma}{d\Omega} \sim 0{,}27 + \cos^2\theta$ $\quad \sigma_t = 3{,}1 \cdot 10^{-27} cm^2$

2) $E_p = 616\, Mev$ $\quad \frac{d\sigma}{d\Omega} \sim 0{,}22 + \cos^2\theta$ $\quad \sigma_t = 3{,}14 \cdot 10^{-27} cm^2$

3) $E_p = 536\, Mev$ $\quad \frac{d\sigma}{d\Omega} \sim 0{,}24 + \cos^2\theta$ $\quad \sigma_t = 2{,}42 \cdot 10^{-27} cm^2$

The centre-of-mass values of Λ as a function of θ are given in fig. 4 for the proton energies: 654 MeV, 6I6 MeV, 536 MeV. In the absence of d-transitions the quantity Λ at a given value of the energy must be constant. The presence of strong angular dependence $\Lambda(\theta)$ as can be seen from the graphs, serves as direct proof of d-states of the positive pion in reaction (1) at all three values of the energy. The experimental values of $\Lambda(\theta)$ were approximated by the expressions

$$\Lambda = \frac{1}{\gamma_0 + \frac{1}{3}\gamma_2} (\lambda_0 + \lambda_1 \cos\theta + \lambda_2 \cos^2\theta)$$

using the method of orthogonal polinomials [17]. The values of the coefficients λ and the erros were the following:

T a b l e 2.

E_p Mev	$\frac{\lambda_0}{\gamma_0+\frac{1}{3}\gamma_2}$	$\frac{\lambda_1}{\gamma_0+\frac{1}{3}\gamma_2}$	$\frac{\lambda_2}{\gamma_0+\frac{1}{3}\gamma_2}$	$\frac{\delta\lambda_0\,\delta\lambda_1}{(\gamma_0+\frac{1}{3}\gamma_2)^2}$	$\frac{\delta\lambda_0\,\delta\lambda_2}{(\gamma_0+\frac{1}{3}\gamma_2)^2}$	$\frac{\delta\lambda_1\,\delta\lambda_2}{(\gamma_0+\frac{1}{3}\gamma_2)^2}$
654	0,18 ± 0,03	0,20 ± 0,06	1,05 ± 0,10	$-2,2\cdot10^{-4}$	$-14,0\cdot10^{-4}$	$-15,0\cdot10^{-4}$
616	0,09 ± 0,03	0,05 ± 0,08	1,06 ± 0,11	$-7,0\cdot10^{-4}$	$-5,5\cdot10^{-4}$	$-6,0\cdot10^{-4}$
536	-0,003 ± 0,04	0,15 ± 0,12	0,87 ± 0,20	$-1,1\cdot10^{-3}$	$-3,4\cdot10^{-3}$	$-7,7\cdot10^{-3}$

The real values of the coefficient λ_3 could not be determined from the obtained experimental data. In order to determine this coefficient it was necessary to make rather difficult measurements of the asymmetry at the angles θ_π close to 0° and 180° where the asymmetry effect disappears due to the dependence $\sim \sin^2\theta$. The coefficients are determined with the smallest error when only three terms of the series are taken, hence the expansion can be cut off on the term $\sim \cos^2\theta$. The problem of the real values of the coefficient λ_3 should be considered together with the problem of determining the coefficient γ_4 in the angular distribution on the unpolarized beam. Both the first and the second coefficients are determined by the expressions quadratic with respect to the amplitudes of the d-transitions which, as is shown below, are sufficiently small.

The variation of the energy dependence of Λ found out in this investigation may be followed in the region of smaller energies if one makes use of experimental results at the energies 415 MeV [4] and 314 MeV [3]. In the notations used here the results of these two investigations may be presented as follows.

Table 3.

E_p Mev	$\frac{\lambda_0}{\gamma_0+\frac{1}{3}\gamma_2}$	$\frac{\lambda_2}{\gamma_0+\frac{1}{3}\gamma_2}$	$\frac{\delta\lambda_0\,\delta\lambda_2}{(\gamma_0+\frac{1}{3}\gamma_2)^2}$
415	-0,34 ± 0,05	0,43 ± 0,28	$-6,2 \cdot 10^{-3}$
314	-0,22 ± 0,03	-	-

As is seen from Fig. 4 at the proton energy $E_p \sim 500$ MeV the change in the sign of the asymmetry is observed. The values of the coefficients:

$$\frac{\lambda_0}{\gamma_0+\frac{1}{3}\gamma_2}, \quad \frac{\lambda_1}{\gamma_0+\frac{1}{3}\gamma_2}, \quad \frac{\lambda_2}{\gamma_0+\frac{1}{3}\gamma_2}$$

are given in Fig. 5 as functions of the pion momentum in the c.m.s. expressed in the units $m_\pi c$. At zero energy only the S-state of the meson may occur and all the coefficients must disappear. At small values of the positive pion momentum the coefficient $\frac{\lambda_0}{\gamma_0+\frac{1}{3}\gamma_2}$, being negative, increases with the positive pion momentum increase, reaches the extremel value, then falls off to zero at $E_p \sim 530$ MeV after which it increases again, but this time with the positive values. When

η is small variation of $\frac{\lambda_0}{\gamma_0+\frac{1}{3}\gamma_2}$ is due to the increase in the effective amplitude of the P wave with respect to the s-amplitude. At great values of η (p-d)- interference is added to the (s-p)-interference. Apparently, the effects of these two inerferences are comparable beginning from the proton energy at which the coefficient $\frac{\lambda_2}{\gamma_0+\frac{1}{3}\gamma_2}$ passes through extremal value. It is confirmed by the fact that the coefficient $\frac{\lambda_2}{\gamma_0+\frac{1}{3}\gamma_2}$ which is due to the interference only between the P and d-states becomes observable at the energy $E_p \sim 400$ MeV. The coefficient $\frac{\lambda_1}{\gamma_0+\frac{1}{3}\gamma_2}$ associated with the effects of (S-d) and (d-d)-interference was found to be very small, and it was difficult to be noticed in our experiments.

All these results may be explained if one assumes that at $E_p \sim 600$ MeV the transition amplitude ${}^1D_2 \rightarrow {}^3S_1 P_2$ considerably exceeds the values of the S and d-amplitude. In this case only the (S-p) and (p-d) interferences will turn to be observable while the (S-d) and (d-d) -interferences will correspond to the second order effects.

The experiments performed with the polarized proton beam though contributed considerably to the information about reaction 1 do not make it still possible to find the values of all the S-matrix elements associated with this reaction. However, making use of the smallness of the S and d-amplitudes one may make some estimates of the partial cross sections. It is necessary to take into account that the d-transitions in reaction (1) are due to the change of the orbital moment in the two nucleon system before and after the reaction as well as to the change of parity. This circumstance leads to a very small probability of the d-transitions. The transitions $^3F_2 \rightarrow {}^3S_1 d_2$ and $^3F_3 \rightarrow {}^3S_1 d_3$ which are due to the change of the orbital moment in the two nucleon system equal to $\Delta\ell = 3$ should be especially difficult. This makes it possible to put the amplitudes of these transitions equal to zero and to obtain the values for the limiting extimates of the partial cross sections.

$$\sigma({}^1S_0 \rightarrow {}^3S_1 P_0) \geqslant 10^{-3}\, \sigma_t(pp \rightarrow d\pi^+);$$
$$\sigma(S + d) \geqslant 5{,}4 \cdot 10^{-2}\, \sigma_t(pp \rightarrow d\pi^+);$$
$$\sigma({}^1D_2 \rightarrow {}^3S_1 P_2) \leqslant 0{,}945 \cdot \sigma_t(pp \rightarrow d\pi^+).$$

4. Conclusions

1. Measurements of the asymmetry in the differential cross section of the reaction $p + p \rightarrow d + \pi^+$ on a polarized proton beam at the energies: 536, 616 and 654 MeV point out to the positive pion emission in the d-state.

2. It follows from the results of the given experiment as well as from [3,4] that the effect of the d-state of a positive pion in the experiments with the polarized beam becomes observable, begining with a proton energy $E_p \sim 400$ MeV.

3. The reaults obtained are consistent with the assumption that the transition amplitudes accompanied by the positive pion emission in the S- and d-states are small if com-

pared with the transition amplitude $^1D_2 \rightarrow {}^3S_1 P_2$ in all the energy region under investigation.

4. By assuming that the transitions from the initial $^3F_2$ and $^3F_3$ -states may be neglected the following limiting estimates are obtained: $\sigma(^1S_0 \rightarrow {}^3S_1 P_0) \geqslant 10^{-3}\sigma_t(pp \rightarrow d\pi^+)$;

$\sigma(s+d) \geqslant 5{,}4 \cdot 10^{-2}\sigma_t(pp \rightarrow d\pi^+)$; $\sigma(^1D_2 \rightarrow {}^3S_1 P_2) \leqslant 0{,}945\,\sigma_t(pp \rightarrow d\pi^+)$.

5. The phenomenological theory of pion production in (p-p) collisions suggested by S. Mandelstam [7] is in agreement with the obtained results.

In conclusion the authors express their gratitude to M.G. Meshcheryakov, B.S. Neganov and L.I. Lapidus for the discussion of the paper. They are grateful to N.P. Klepikov and S.N. Sokolov for help in treating the experimental data.

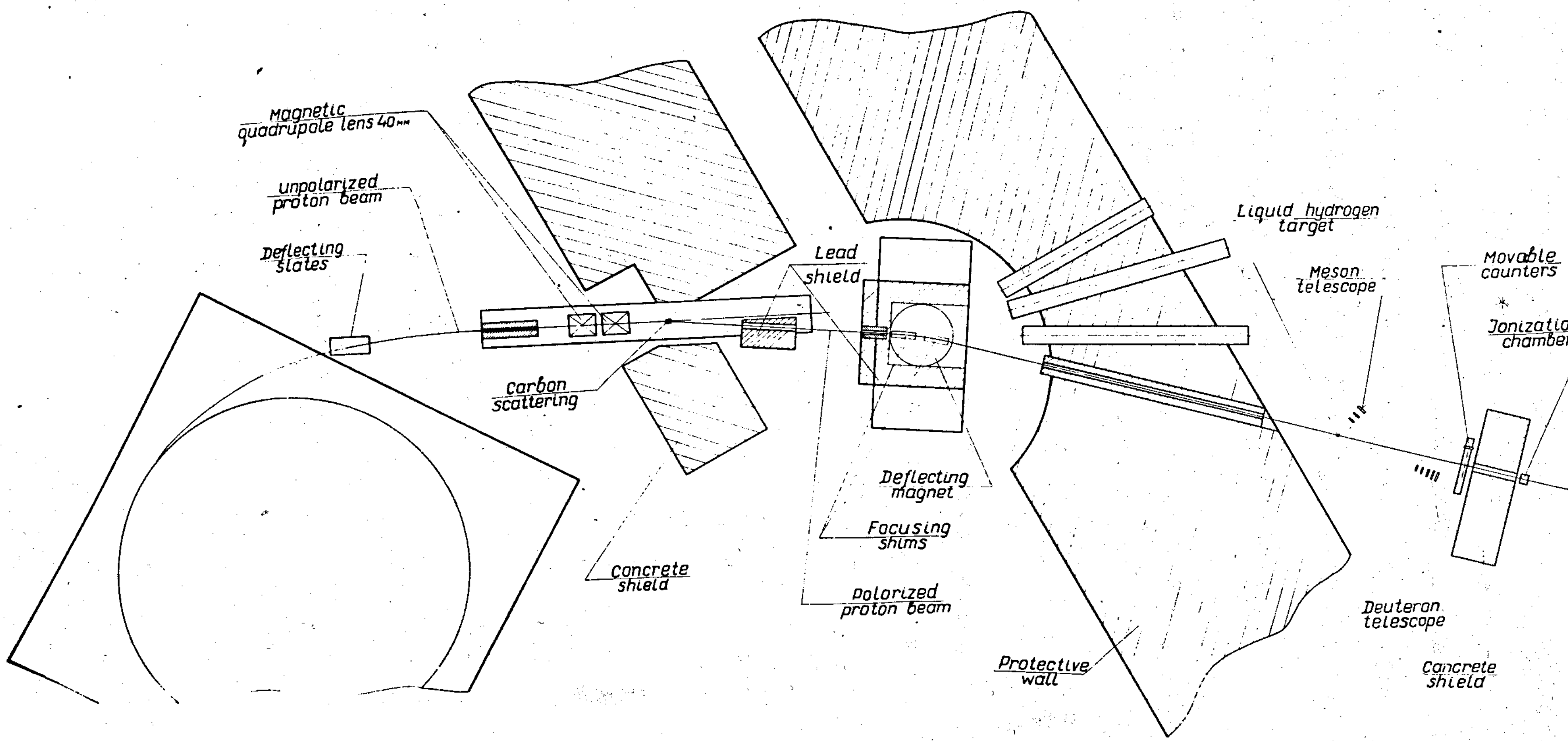

FIG.1 THE SCHEME OF THE EXPERIMENT

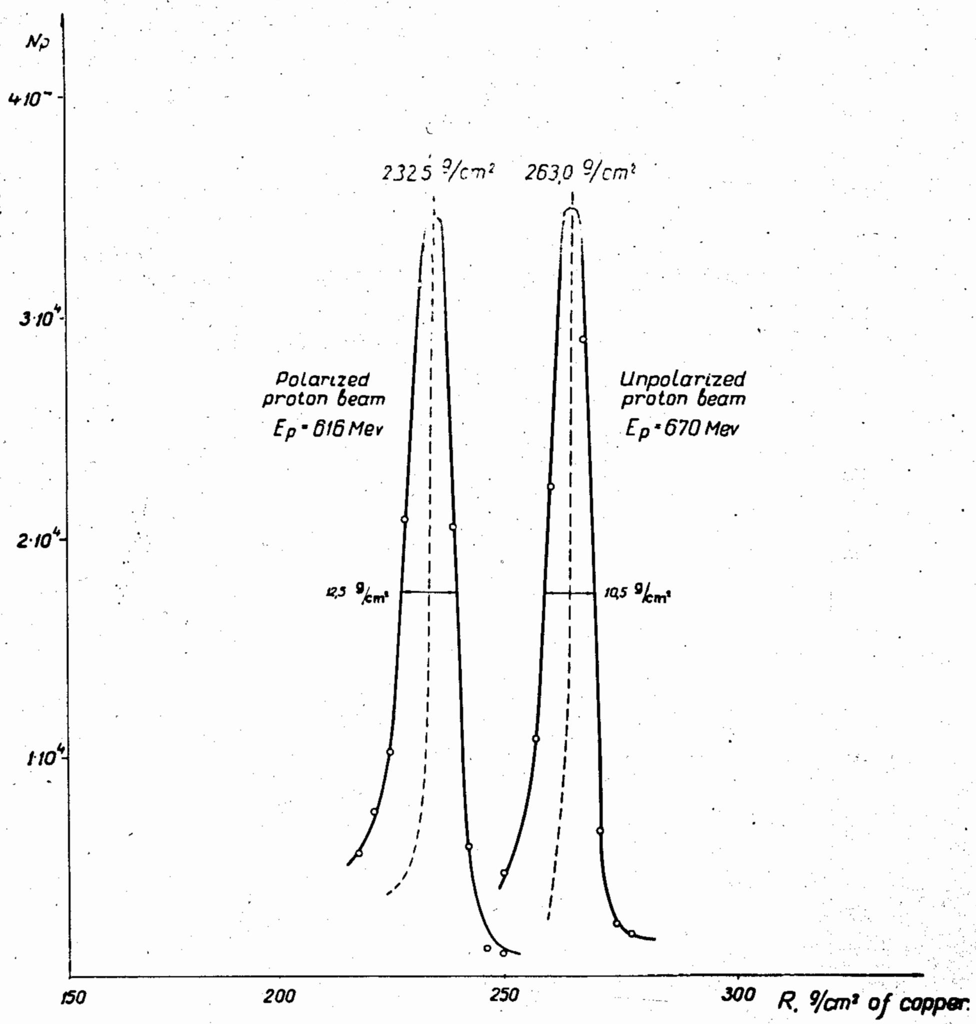

Fig 2. Differential curves of proton range in copper

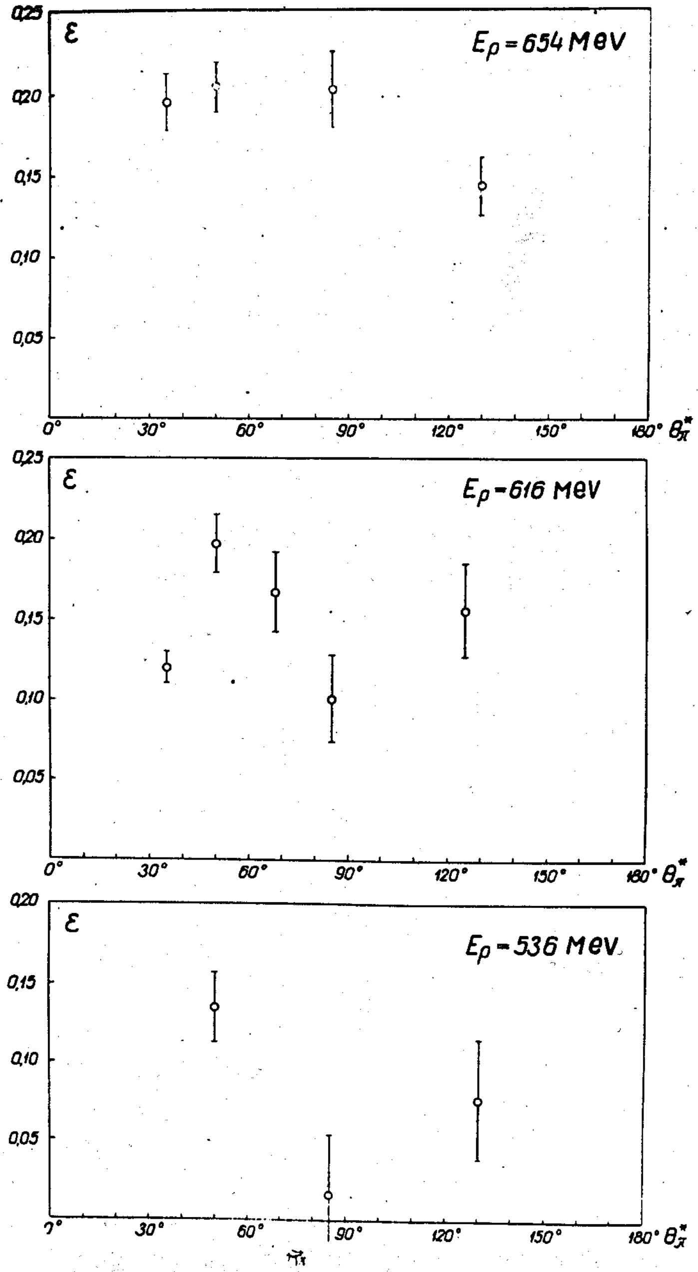

Fig.3 Measured values of the asymmetry ε in the reaction $p+p \to d+\pi^+$ on the polarized proton beam.

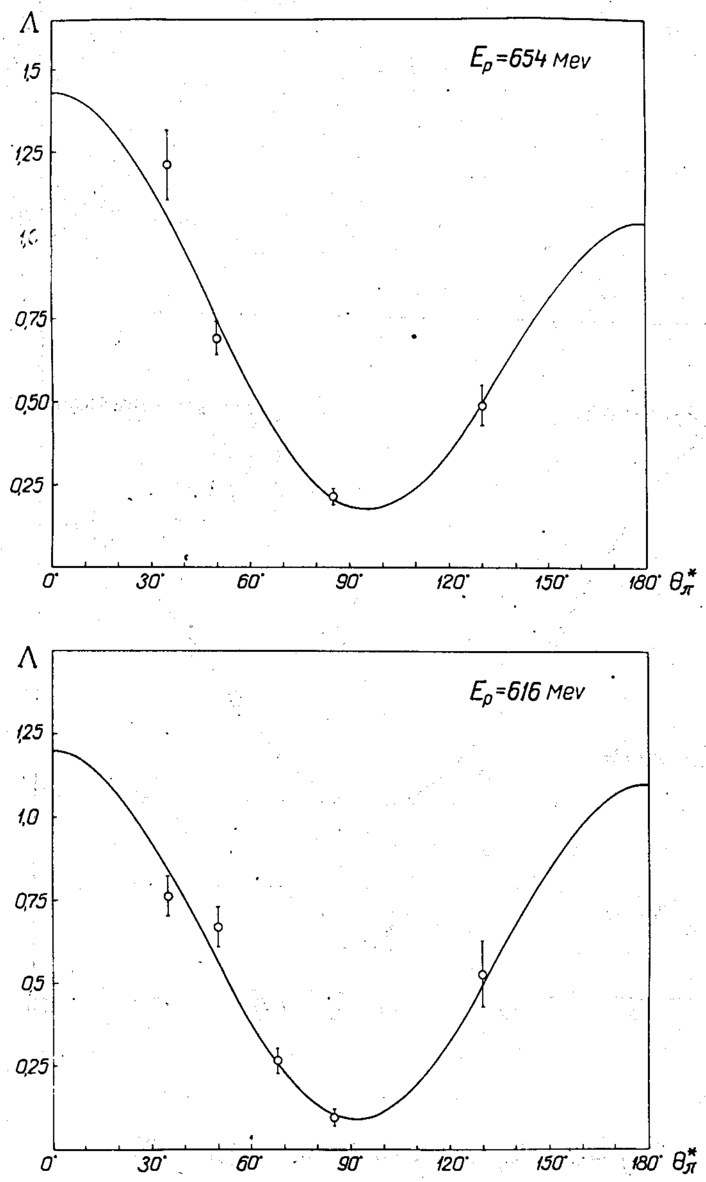

Fig.4. Dependence curves $\Lambda(\theta_\pi)$

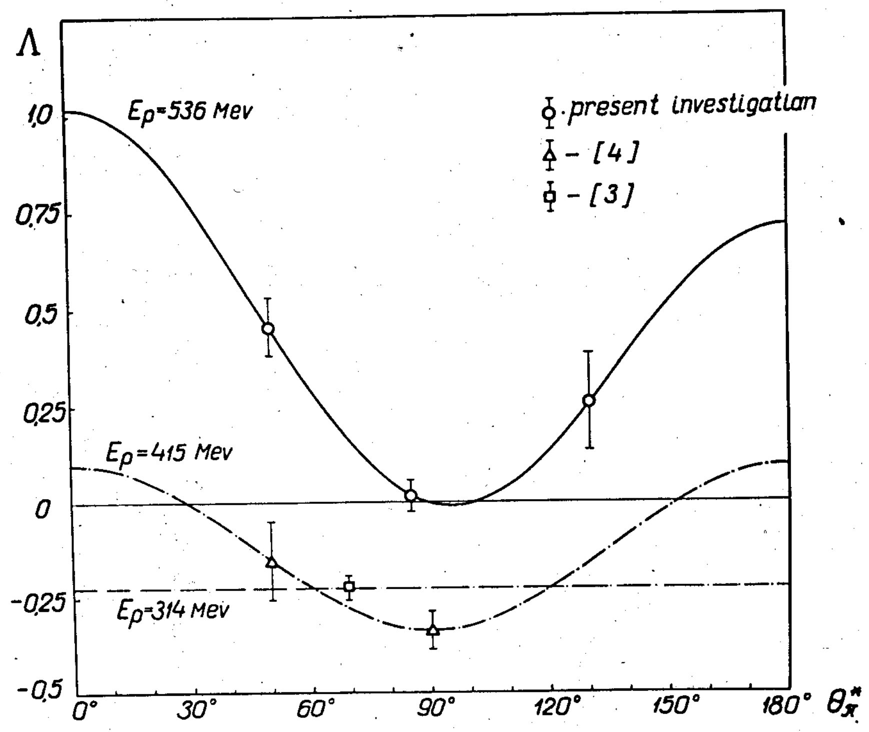

Fig. 4a. Dependence curves $\Lambda(\theta_\pi)$

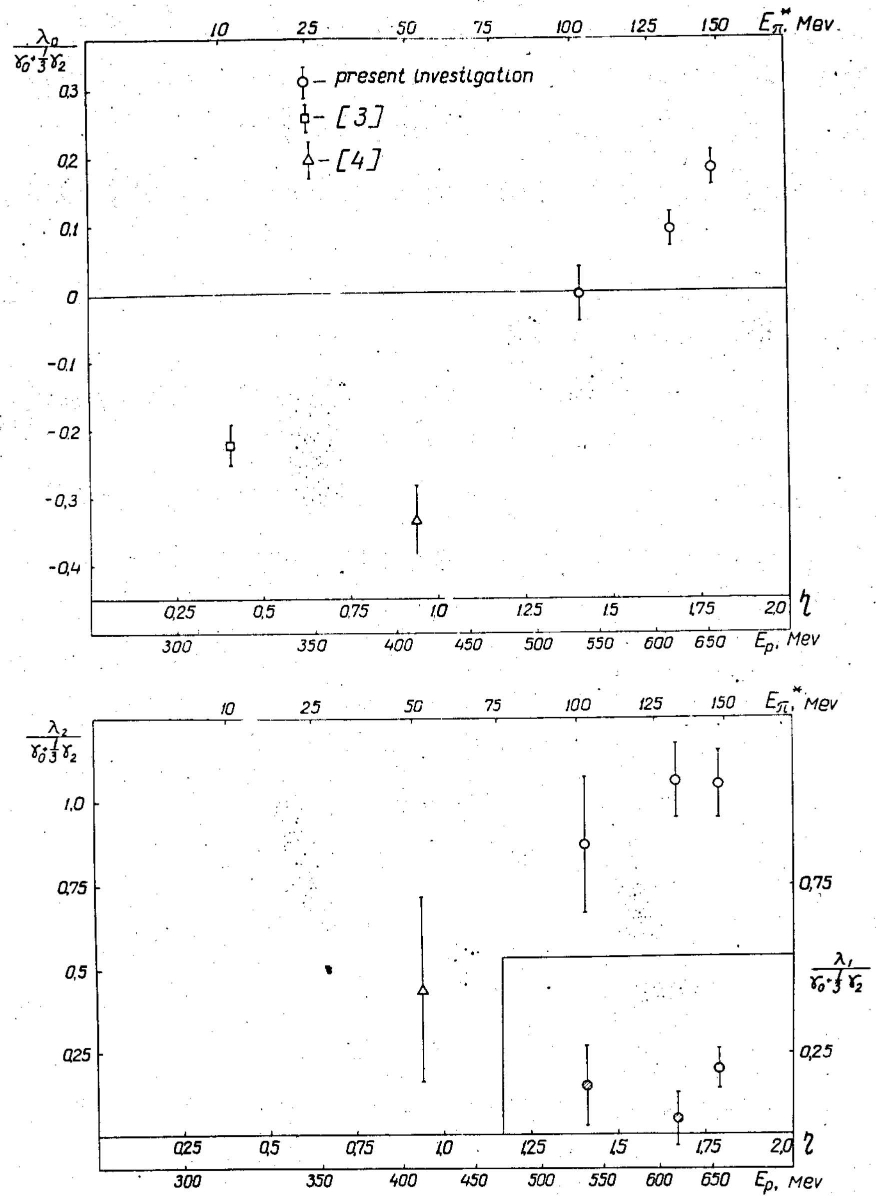

Fig. 5 Measured values of the coefficients $\frac{\lambda_0}{\gamma_0+\frac{1}{3}\gamma_2}$, $\frac{\lambda_1}{\gamma_0+\frac{1}{3}\gamma_2}$, $\frac{\lambda_2}{\gamma_0+\frac{1}{3}\gamma_2}$ *in the dependence upon the pion momentum*

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