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A b s t r a c t

Elastic p-p scattering is investigated at 8.5 BeV by the emulsion method. The emulsion plates were exposed to thebeam of incident protons perpendicular to the plane of emulsion. 66 events of elastic scattering have been found. The contribution of the scattering events on quasi-free protons and of other background events is 2%. The elastic scattering cross section was (8.4 ± 1.1) mb. The differential cross section up to 2.5^{o} in the center-of-mass system has been obtained. Near 0^{o} it was found to be greater than may be expected from the model of a purely absorbing proton.

Introduction

The study of elastic scattering of high energy particles is a convenient method for investigating their structure. The optical model was first applied for the analysis of neutron scattering on nuclei [1]. Now it is widely used for the analysis of experimental data on elastic scattering of π- mesons and protons on nucleons at the energies 1 BeV and higher [2-10].

Under some simplifying assumptions several authors [11-19] have recently made the phase-shift analysis of experimental data on elastic scattering of π- mesons and protons on protons at different energies. It was shown that the available experimental results may be accounted almost entirely for diffractional scattering.

The study of elastic scattering of π- mesons and high energy protons on nucleons encounters some experimental difficulties. Firstly, the cross section is small (5 ÷ 10 mb); secondly, the corresponding experiments require that very small scattering angles would be recorded ($\sim 1^{o}$ in the lab.system). At the same time in [2-9,20] the scattering events at the angles up to 5^{o} in the lab.system were missed.

In [21] the differential cross section was measured at the angle $> 2^{o}$ in the lab.system (E = 6.15 BeV). Thirdly, the scattering events on protons bound in a nucleus [2,3,5] are difficult to identify since this requires a great accuracy in the measurements of angles.

In this paper an attempt is made to overcome thise diffioulties.

Experimental Procedure

In this paper the elastic proton-proton scattering is being studied at an energy 8.5 BeV by the photoemulsion method.

To find similar events the emulsion is usually scanned along the track. However, if suoh a method of search is used the efficiency of recording the scattering events at small angles is insufficient [2]. This concerns espeoially the events the scattering plane of which forms a large angle with the emulsion plane [6]. The azimuthal asymmetry is observed by area-scanning if the emulsion is exposed parallel to its plane [22].

It follows from the optical model that almost áll scattering at 8.5 BeV is concentrated in the angles $< 3^{\circ}$ in the lab.system. Therefore, a usual scanning along the track will considerably distort the result. Besides it has a oomparable small velocity of finding the events.

For studying elastic scattering at E = 8.5 BeV by the emulsion method it is convenient to direct the proton beam perpendicular to the plane of emulsion pellicles and to area-scan them. Since in most cases the recoil proton* has a small momentum and is directed almost perpendicular to the incident proton, i.e., in the given case practically it is lying in the emulsion plane, the effioiency of finding the events appeared to be high and is independent of the azimuthal angle. The beam density in the perpendicular exposure may be increased some times if compared with that in the parallel exposure [23]. This increases the velocity of finding the events. Moreover, by such a geometry it was possible to measure the angle of the scattered proton with a great accuracy (~3').

The above mentioned advantages of such a method are essential. It seems to us that this method may also be used at somewhat higher energies.

This experiment has been performed with the stack of 10 x 10 x 2 om^3, 400 μ NIKFI-BR stripped emulsions, exposed to the internal proton beam of the Joint Institute synchrophasotron at 8.5 BeV. The beam was directed perpendicular to the plane of emulsion.

An analysis was made to determine the hydrogen nucleus density in the emulsion. It turned out that 1 cm^3 of the exposed emulsion oontains $(2.90 \pm 0.06).10^{22}$ hydrogen atoms.

The emuslion was area-scanned with an oil emersion objective under a magnification of 630 X in the central part of the plates 2 x 2 cm^2. The mean density of the beam in this zone was found to be $(1.97 \pm 0.05).10^5$ particles/cm^2. We have scanned 1.53 cm^3 of emulsion.

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* We agree to call the proton flying at a greater anglé a reooil proton, and that flying at a smaller angle to the direction of the primary particle a soattered one.

To determine the scanning efficiency and the reliability of the results all the area was scanned twice. About 9000 stars were found, 451 of them were two-prong. Those alike elastic p-p scattering have been chosen out of two-prong stars. These events were divided into two groups.

1. Events involving the "black" recoil proton ($\frac{J}{J_{min}} > 4$, $J_{min} \sim 40$ grains/100 μ).

2. Events with a "grey" recoil proton ($4 \geqslant \frac{J}{J_{min}} \geqslant 2$).

The scanning efficiency in the first scanning turned out to be (68.7 ± 2.9)% for the events of the first group and (34.5 ± 9)% for those of the second group. For the second scanning these values were found to be (84.0 ± 2.6)% and (56.5 ± 12)% respectively.

The efficiency of twofold scanning proved to be (95 ± 1)% and (71 ± 9)% for the events of the first and the second grounp respectively. Since further it turned out that an overwhelming majority of the found events (90%) belongs to the first group the scanning efficiency of the second group was not investigated in detail. On the average a scanner is able to scan 12 mm^2 for six hours that corresponds to 10 m of the primary proton tracks.

Analysis of the Events and Methods of Measurements

To identify the events of elastic scattering on free hydrogen the following criteria were used:

1) The relationship between the recoil proton range R and its scattering angle φ satisfies the kinematics of elastic scattering.

2) The angle γ between the plane of the tracks of the primary and scattered protons and that of primary and recoil protons must be equal to zero (Coplanarity condition).

3) The relationship between the recoil proton range R and the angle ψ between the scattered proton and the direction of the primary proton must satisfy the kinematics of elastic scattering.

4) In the point of scattering there must be no recoil nucleus and β-electron.

If the recoil proton does not stop in the stack and its momentum determined by the ionization measurements is known with a great experimental error one makes use of the relation between the angles ψ and φ of the scattered and the recoil proton, which are angles valid for elastic scattering.

The recoil proton range R was measured, the error being not more than 5%.

To determine the angle of the recoil proton it is necessary to know its direction and that of the primary particle. Since the half-width of the angular distribution of the primary particles was 0.2° (Fig.1), the direction of the beam was taken as that of the incident particle. To determine this direction in the given point of the emulsion plate the projections of the beam particle tracks on the x and y axes were measured in the emulsion plane.

The axes x and y were chosen along the marking lines |light marking| which were paralles with the accuracy $0.1^{\circ} - 0.2^{\circ}$. The measurements in the given point were made on 37 plates. Due to distortions these measurements in different plates fail to give one and the same value of the angle. The results of these measurements were distributed with the halfwidth about 1°. The mean value for the angle shows the real direction of the beam in the given point.

The direction of the beam was determined in 5 such points - at the edges of the working zone and in the middle. These values coincided within the limit 0.2°. The inaccuracy in the measurement of the dip angle gave the main error in the determination of the recoil proton angle. On the average this error does not exceed $1^{\circ} \div 1.5^{\circ}$ except the events with a short range of a recoil proton ($R < 500\,\mu$).

The measurements of the scattered proton angle Ψ were made by two methods.

1. The angle between the mean direction of the beam particles and that of a scattered proton was measured. This method yielded the accuracy of the order of the halfwidth of the beam, i.e., 0.2°.

2. In the vicinity of the scattering act at a distance of $20-30\,\mu$ beam reference track was chosen which did not undergo an interaction. To determine the scattering angle Ψ four measurements of the projections of the distance between the reference track and the track undergoing the scattering on the x and y axes were made in the emulsion plane. Two measurements were carried out before the scattering act on the basis of $2000\,\mu$ (the thickness of five plates) and two after the scattering act on the same basis. The accuracy of the measurements of the projections was $\sim 1\,\mu$. This allowed to measure the scattering angle with the accuracy of $2' \div 3'$.

When determining the scattering angle Ψ the contribution of multiple scattering might be neglected. The error in the determination of the plate thickness was also small. To eliminate the accidental errors simultaneous independent measurements were made with respect to three reference tracks.

One may determine the angle of noncoplanarity γ from these measurements if the direction of the recoil proton is known. The error in the magnitude of γ is mainly due to an error of the measurement of the scattering angle $\Delta\Psi$ and depends upon the magnitude of this angle. So, for $\Psi = 1^{\circ}$, $\Delta\gamma = 3^{\circ}$, if $\Delta\Psi = 3'$.

Out of 451 two-prong stars 170 were rejected as those not corresponding obviously to the selection criteria. In other cases the range R and the angle of the recoil proton were measured. All the measurements were made twice. Then the measurements of the scattered angle Ψ were made using the first method. They were also made twice. For a final identification of the elastic scattering events the measurements of the angle Ψ were made using the second method i.e. with the accuracy of $2' \div 3'$.

Identification of Scattering Events on Free Protons

One may try to evaluate the expected contribution of quasielastic events which will be recorded as scattering on free hydrogen. It is well-known [24-27] that proton distribution in a nucleus by momenta is close to

$$\mathcal{N}(|P|)\,dp_x\,dp_y\,dp_z = \exp\left(-\frac{P_x^2+P_y^2+P_z^2}{P_0^2}\right),$$

where P_0 corresponds to an energy of ~20 MeV. The distributions of the projections of the proton momenta along the coordinate axes (Fig. 2) will be the same. At this P_0 corresponds to an energy of ~ 7 MeV.

Let us consider how each of the three momentum componenets affects the kinematics of elastic scattering. The component of the momentum P_x affects mainly the relation $R-\varphi$, P_y – the relation $R-\Psi$, P_z violates the coplanarity. The recoil proton angle φ is plotted in Fig. 3 against its momentum for 8.5 BeV proton elastic scattering on a proton of the momentum $P = 0$, $\pm$ 20 MeV/c, $\pm$ 42 MeV/c. In the intervals (0-20)$\frac{\text{MeV}}{c}$ and (0-42)$\frac{\text{MEV}}{c}$ there are 20% and 40% of all quasifree protons correspondingly.

It can be seen from the Figure that it is possible to separate not less than 80% of all scattering events on quasi-free protons with the available accuracy of the measurements of the momentum (3%) and the recoil proton angle (1° – $1{,}5^\circ$). In Fig. 4 is shown the dependence of the noncoplanarity angle μ upon recoil proton momentum for two values of P_z in case when the criterion $R-\varphi$ is fulfilled. It is seen that using the ooplanarity criterion it is possible to separate independently 80% of the remaining quasi-elastic events.

In Fig. 5 the scattered proton angle is plotted against the recoil proton momentum for the values $P_y = 0, \pm 20$ MeV/c. According to this criterion 80% of the quasielastic events may be also independently rejected. Therefore, with the available accuracy of the measurements the contribution of quasielastic events to the number of the identified events will be of the order of a percent.

For each measured event the errors in measurements were evaluated and the events satisfying the kinematics within the limits of threefold errors were chosen. In Fig. 6,7, 8 are given the distributions of these events by $|\Delta\varphi|$, $\Gamma = \left|\frac{\mu}{\Delta\mu}\right|$ and $|\Delta\Psi|$. It is seen from Fig. 6 that root-mean-square error in the measurement of the angle φ is ~ 1.5°.

It can be also seen from the distribution of the chosen events by Γ that the errors in the measurements of the noncoplanarity angles are estimated correctly.

The distribution of events by $|\Delta\Psi|$ is presented in Fig. 8. The events with a stopping recoil proton satisfying the kinematics by the first two criteria in the limits of a threefold root-mean-square error were chosen for this histogram. Scattering events on quasifree protons having the momentum P_y are also shown in this Figure, since P_y does not violate the coplanarity and violates the criterion $R-\varphi$ rather weakly (Fig. 9). A considerable part of these events belongs to the region $|\Delta\Psi| > 12'$ (i.e. beyond the threefold halfwidth of the distribution) where there are no scattering events on free protons. By the number of such events it is possible to evaluate the contribution of quasielastic and other background events to the region of $|\Delta\Psi| \leq 12'$. This contribution is found to be ~2 %.

Experimental Results

66 events satisfy the selection criteria within the threefold root-mean-square error. Only 2 of these events have a recoil proton emerging from the emulsion stack.

In Fig. 10 is plotted the angular distribution in the centre-of-mass system for the events with the angle $\leq 6.3^o$. In the region $0^o - 2.5^o$ a somewhat less number of events is observed than in the neighbouring intervals.

This accounts for the fact that some part of the events with the recoil proton range $R \leq 10\,\mu$ is missed in the scanning. Therefore, for the angle interval $0^o - 2.5^o$ the correction 3.4 ± 1.2 is introduced under the assumption that the differential cross section in this interval is equal to the mean value of the differential cross section in the interval $2.5^o - 6.3^o$. The calculations have shown that the contribution of the Coulomb interaction in the differential cross section for angles $> 2.5^o$/c.m.s./ is negligibly small. To evaluate the effect of the Coulomb scattering in the angle interval less than 2.5^o much richer statistics is necessary.

Taking into account the contribution of quasi-elastic events, the missing of scattering events at small angles, the efficiency of scanning, the general number of elastic scattering events on free protons is found to be 73.9 ± 9.1. Thus, the cross section of elastic interaction was

$$\sigma_{el} = (8.4 \pm 1.1)\ \text{mb}.$$

According to the data of [29] the cross section for elastic scattering at E = 9 BeV is (10 ± 4)mb.

In Fig. 11 is presented the differential cross section for elastic p-p scattering in the centre-of-mass system in the form of a hystogram. The curve I is obtained by the results of [19]. The optical model is used here and for the energy of a primary proton more than 5 BeV the refraction coefficient being considered equal to unity, whereas the dependence of absorption coefficient upon the radius is taken from [18]. The curve 2 is calculated for the model of purely absorbing disk with a constant absorption coefficient. The total cross section for proton-proton interaction is assumed to be 30 mb. [30]

The obtained differential cross section cannot be brought into agreement with the model of a purely absorbing proton. According to this model without taking into account the spins the differential cross section under 0° is obtained from the optical theorem

$$\left(\frac{d\sigma}{d\Omega}\right)_{0^{\circ}} = \left(\frac{k\sigma_t}{4\pi}\right)^2 ,$$

where k is the wave number of the colliding protons in the center-of-mass system and σ_t is the total cross section for p-p interaction. For σ_t = 30 mb the differential cross section under 0° is found to be 57 mb/sterad, while from Fig. 11 it is seen that in the region close to 0° the differential cross section is considerably greater.

The agreement of the calculations by the optical model with the experimental data is obtained if the refraction coefficient is assumed not equal to unity, i.e. the potential scattering occurs. The agreement is also obtained if we assume that the interaction cross sections in the singlet and triplet states are different. The research has been going on, a more detailed analysis of experimental data will be made after the statistics is increased.

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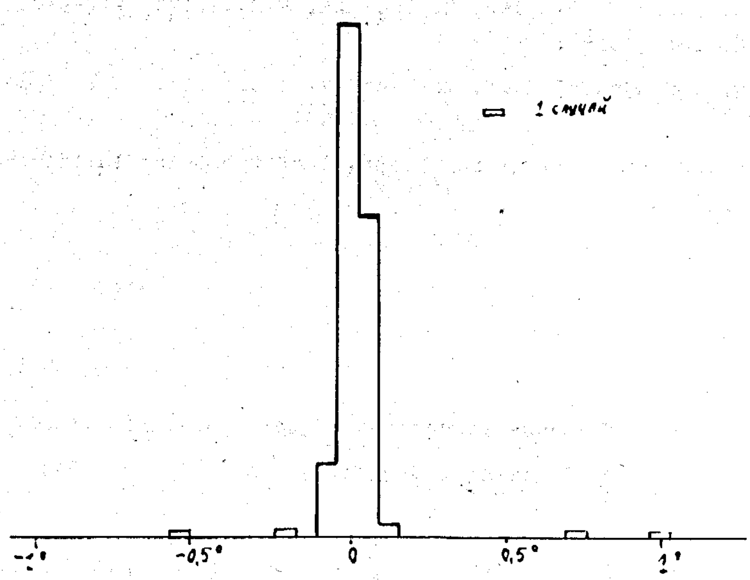

Fig.1. Distribution of the projected angles of primary protons in an arbitrary plane drawn through the axis of the beam.

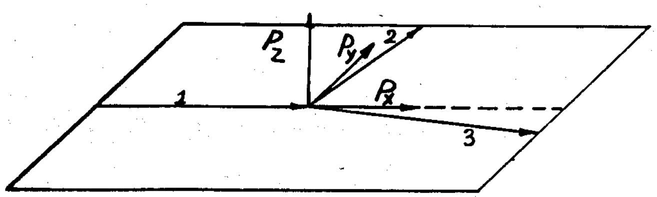

Fig.2. The momentum components of the quasi-free protons with respect to the scattering plane; 1,2,3 are the directions of the primary and secondary protons.

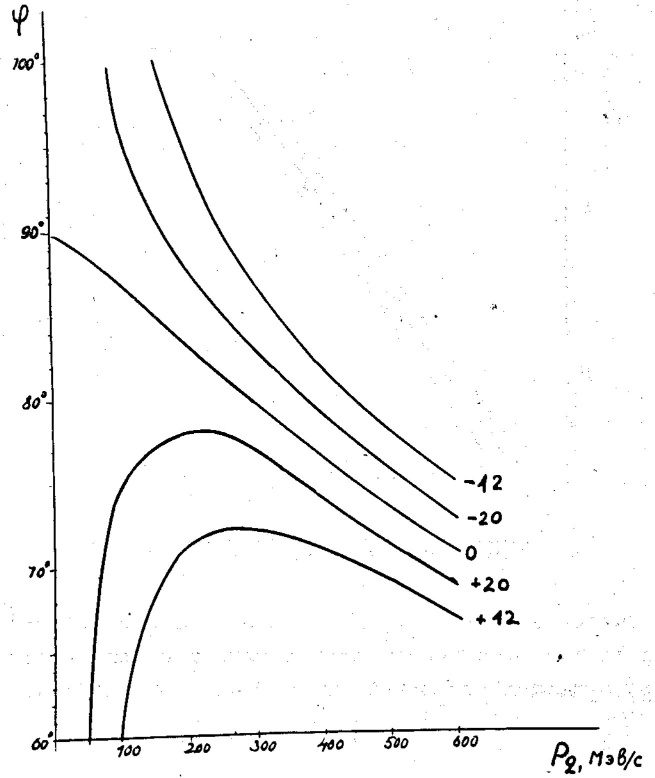

Fig.3. The recoil proton angle φ (the proton scattered at the larger angle) is plotted against its momentum for different values of the quasi-free proton momentum component P_x /0, ±20 Mev/c, ±42 Mev/c/.

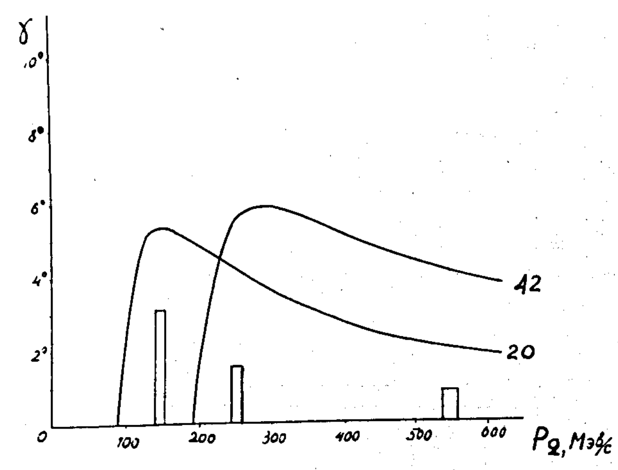

Fig. 4. The noncoplanarity angle γ is plotted against the recoil proton momentum for two values of the quasi-free proton momentum component P_z = 20 MeV/c and 42 MeV/c. The rectangles show the experimental errors.

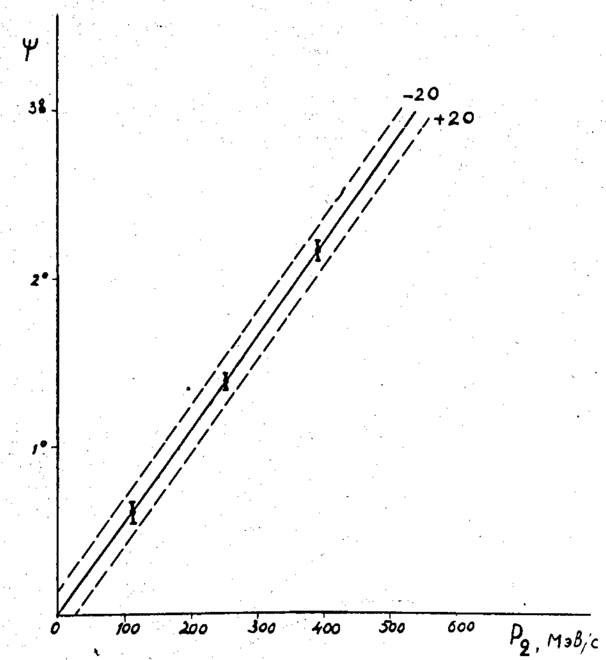

Fig.5. The scattered proton angle Ψ (the proton scattered at the smaller angle) is plotted against the recoil proton momentum for different values of quasi-free proton momentum component P_y = 0 and ± 20 MeV/c.

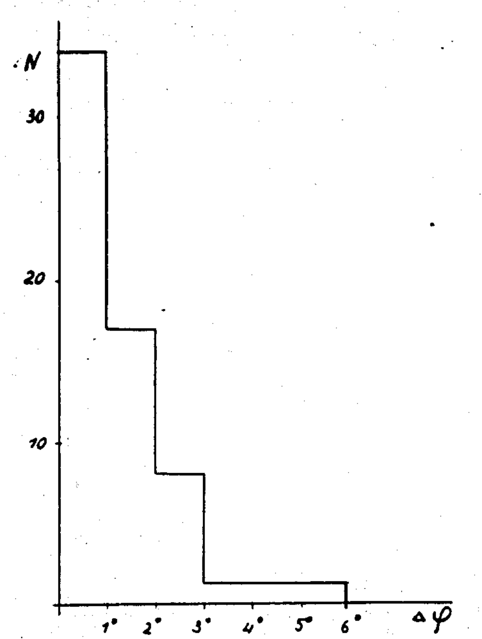

Fig.6. Distribution of elastic scattering events by |Δφ|. Δφ is the difference between the measured recoil proton angle and that corresponding to its range according to the kinematics.

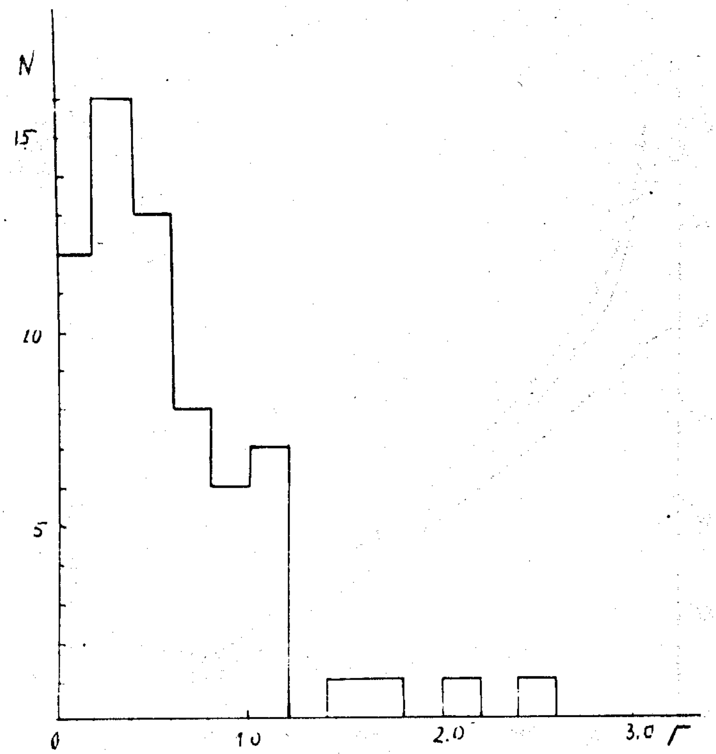

Fig.7. Distribution of elastic scattering events by $\Gamma = |\frac{\gamma}{\Delta\gamma}|$ where γ is the non-coplanarity angle, and $\Delta\gamma$ denotes its error.

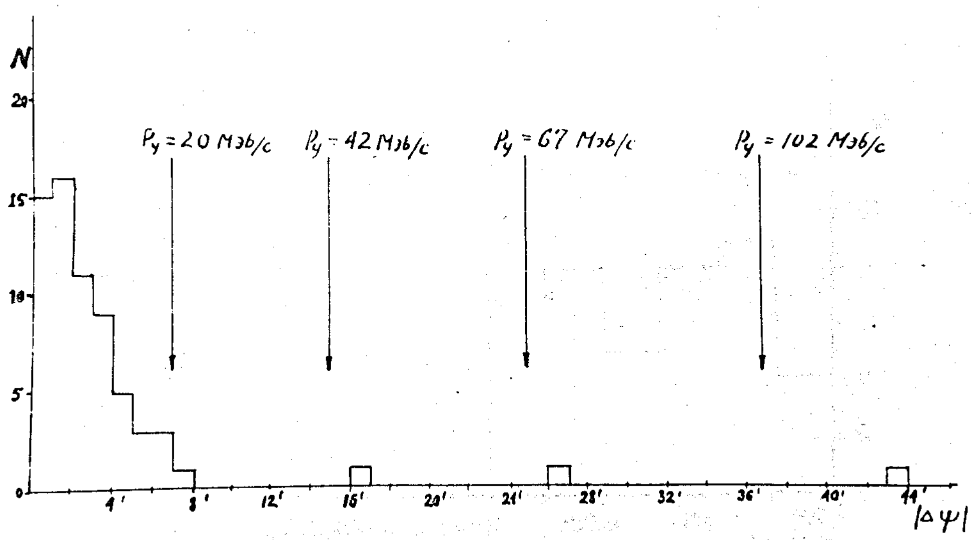

Fig.8. Distribution of events by $|\Delta\Psi|$ selected on the basis of the first two criteria($|R-\varphi|$ and coplanarity).

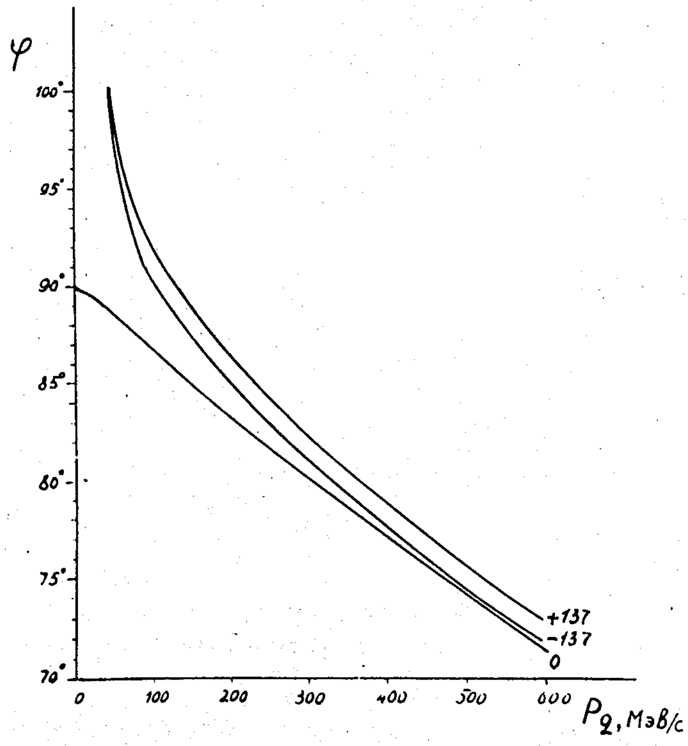

Fig.9. The recoil proton angle φ is plotted against its momentum P_2 for different values of the quasi-free proton momentum component $P_y = 0, \pm 137$ MeV/c.

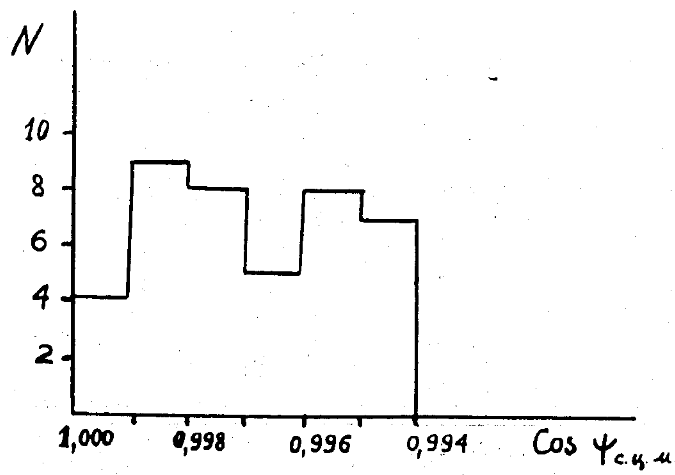

Fig.10. Angular distribution of elastic scattering events for the angles $< 6.3^{o}$ in the c.m.s.

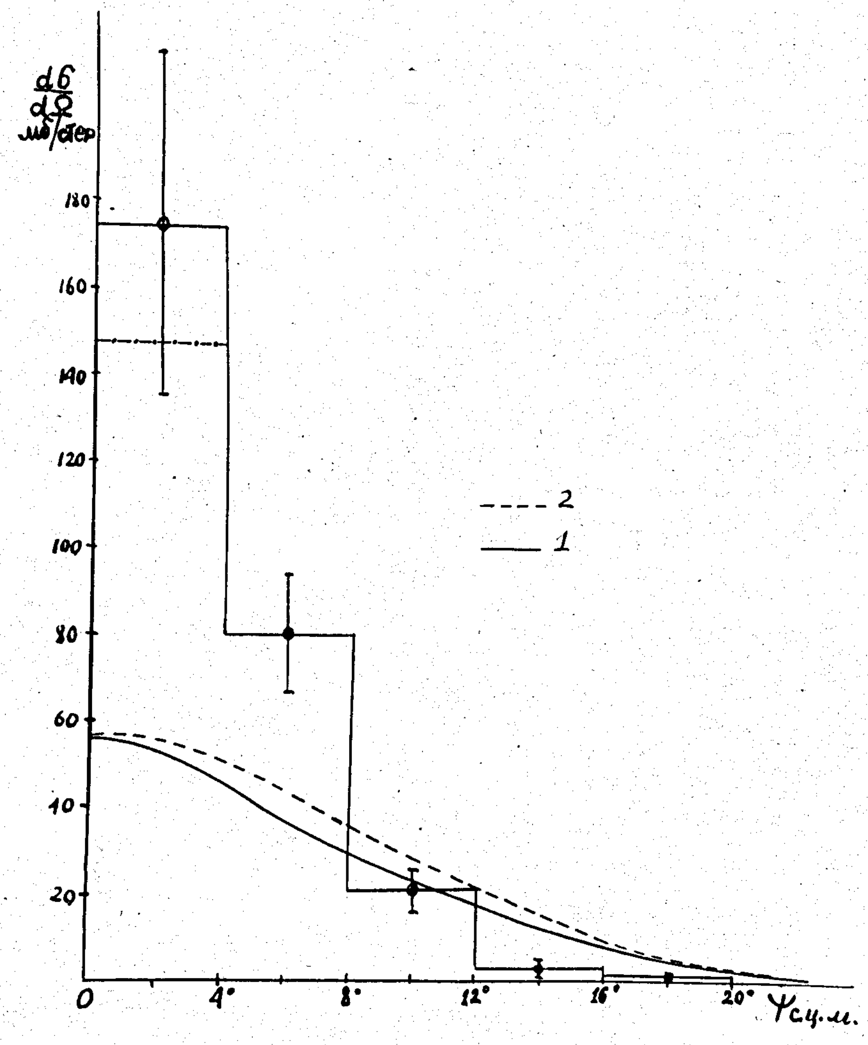

Fig.11. Differential cross section for elastic p-p scattering at 8.5 BeV in the c.m.s. Point-dash line in the first interval shows the value of the differential cross section without any correction. The curves 1 and 2 are drawn according to the optical model calculations for a purely absorbing proton under different assumptions about the dependence of the absorption coefficient upon the radius.