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Preliminary data of investigating small angle elastic pp scattering at 6 and 10 GeV have already been published[1]. An experimental technique has been described in detail in[2].

This experiment has been performed with the Joint Institute for Nuclear Research synchrophasotron. An experimental layout is shown in Fig. 1. The internal beam of the accelerator multiply traversed a polyethelene target 3 microns thick. The target was hanged on the capron knits 20 microns in diameter. The dimensions and the thickness of the target were chosen so that the maximum angular and momentum resolution of the method used could be accomplished. For the same reasons the emulsion pellicles placed at a distance of 3 meters from the target were taken as a detector. The angular resolution obtained in this experiment is $1.5 \cdot 10^{-3}$ radians. The recoil protons cover all the distance from the target to the emulsion in vacuum.

Fig. 2 shows typical distribution of secondary particles by their ranges. Profound peaks correspond to elastic p-p scattering. The background is the slow particles produced due to the interactions of primary protons with the target carbon nuclei. As is seen from Fig.2, the background-signal ratio changes within the (0.07 – 1.0) range when the momentum of the recoil protons changes from 280 MeV/c down to 56 MeV/c. In order to determine the flux of the elastic recoil protons it is necessary to subtract the background particle spectrum from the total spectrum observed at the given angle of θ_{lab} where θ_{lab} is the angle of the recoil proton emission with respect to the primary beam. The spectrum of the background particles has been thoroughly studied at different angles using the same emulsions.

We would like to note that due to the high resolution of the method applied, it rules out practically completely the contribution of the quasi-elastic scattering on the bound nucleons of the nucleus. This is seen from the calculations of the kinematics of the quasi-elastic scattering and from the experiments in which the quasi-elastic proton scattering on the nucleons of the nucleus[3] has been studied.

In this experiment we obtained a relative behaviour of the differential cross section. The errors were (4.5 – 7.5)%. 22.000 elastic scattering events were detected in this experiment.

The cross section measurements at 10 GeV have covered a range of $\theta_{c.m.s.}$ from 1.5° to 7.5°, and were made at 12 points. The corresponding interval of the four-momentum transfer squared is $0.0038 \ GeV^2/c^2 \leq t < 0.081 \ GeV^2/c^2$. At 6 GeV similar measurements were carried out in the angle interval of $\theta_{c.m.s.}$ from 1,5° to 9.0°.

The purpose of this work is to study in detail the t -range where the electromagnetic scattering is essential and, therefore, the interference between the Coulomb and nuclear scattering amplitude is possible. The presently available papers devoted to the elastic proton-proton scattering in the energy range above 1 GeV contain only the qualitative data on the behaviour of the cross section in this angle interval. Most of the authors arrive at the conclusion that the scattering amplitude is purely imaginary. However, in experiments [4,5] performed in the small angle scattering range the differential cross section exceeds the optical point for spinless particles. But the statistical errors obtained in these experiments are large. In a paper of Preston et al[6] a conclusion is drawn that the real part of the scattering amplitude does not exceed 0.1 of the imaginary one at 3 GeV.

In order to normalize our data to the absolute units, the experimental values of the cross sections in the range where the Coulomb scattering is absent were extrapolated by the exponent in terms of the t coordinates to the optical point. (The following values of the optical point were made use of:

$$\left(\frac{d\sigma}{d\Omega}\right)^{10GeV} = 122 \ \frac{mb}{ster} \qquad \left(\frac{d\sigma}{d\Omega}\right)^{6GeV} = 80,5 \ \frac{mb}{ster} \ )$$

In this region the results are in good agreement with the data of other authors [5,7]. Fig. 3 shows the values of the differential *p-p* scattering cross sections at 6 and 10 GeV after the purely Coulomb cross section is subtracted. It can be clearly seen that the cross section exceeds the optical point in the range $t < 0.015\ \mathrm{GeV^2/c^2}$ for both energies. We have considered two possibilities to interpret this effect.

1. The large value of the differential forward scattering cross section may imply that the scattering amplitude has a real part. We represent the nuclear scattering amplitude as

$$A = a g_r(\theta) + i g_I(\theta)\ ; \qquad a = \frac{\mathrm{Re}\,A(0)}{\mathrm{Im}\,A(0)}$$

$$g_I = \sqrt{\left(\frac{d\sigma}{d\Omega}\right)_{opt}} \cdot \exp\left(-\frac{\theta^2 \ln 2}{2\theta_{0I}^2}\right)$$

$$g_r = \sqrt{\left(\frac{d\sigma}{d\Omega}\right)_{opt}} \cdot \exp\left(-\frac{\theta^2 \ln 2}{2\theta_{0r}^2}\right)$$

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

Here a, θ_{0I}, and θ_{0r} are the constants which characterize the amplitude A and should be determined experimentally. The differential cross section for elastic *pp*-scattering is expressed in terms of the amplitude A and of the Coulomb scattering amplitude $g_c = \frac{2}{137\, k\, \beta_{lab}} \frac{F(\theta)}{\theta^2}$ by the formula obtained in Bethe's paper [8]

$$\left(\frac{d\sigma}{d\Omega}\right) = c\left[g_c^2 + g_I^2 + a^2 g_r^2 - 2 g_c \left(a\, g_r + 2\frac{g_I}{137\beta_{lab}} \ln\frac{1.06}{ka\theta}\right)\right] \qquad (1)$$

Here $F(\theta)$ is the electrical nucleon form-factor which can be approximated for small t by

$F(\theta) = \exp\left(-\frac{\theta^2 \ln 2}{2\theta_{0I}^2}\right)$, $k = \frac{1}{\lambda}$ is the proton wave number in the c.m.s., a is the nucleon radius, β_{lab} is the proton velocity in the lab. system. c is the constant which points out that the experimental data are measured in relative units. It is determined experimentally together with other parameters.

The analysis of the experimental data by the least square method and formula (1) leads to the following conclusions: a) The purely diffraction scattering (i.e., $a = 0$) contradicts this experiments. When $a = 0$, $\chi^2 = 60$ for 10 degrees of freedom; the corresponding probability being 10^{-3}. If we assume $\mathrm{Re}A(\theta)$ and $\mathrm{Im}A(\theta)$ to have the same angular dependence (i.e., assume $\theta_{0r} = \theta_{0I}$), then the experimental data are also described unsatisfactorily by formula (1) for any values of the parameter a. In order to bring the cross section described by formula (1) into agreement with the experimental results it should be considered that $\mathrm{Re}A(\theta)$ falls rapidly with the increase of the angle θ. So, at sufficiently large angles ($\theta_{c.m.s.} > 3^\circ$) the elastic *pp*- scattering cross section may be described by the imaginary part of the scattering amplitude only. The values obtained by the least square method are listed in Table 1. Fig.4 shows the experimental data for *p-p* scattering at 10 GeV. The curve in this figure is drawn by formula (1) in which the best parameters θ_{0r} and a were used.

Table I

E_{kin}	θ°_{oi}	θ°_{or}	a	χ^2	The number of degrees of freedom
6 GeV	10	2,5±1	−0.40±0.15	15	9
10 GeV	8	1.3±0.4	−0.7 ±0.3	10	10

2. In the framework of the diffraction model with purely imaginary amplitudes we shall consider the proton-proton interaction to be different in the triplet and singlet states. In this case the cross section may be described by the following formula taking into account the dependence of the nuclear forces on the proton spins in the simplified form

$$\frac{d\sigma}{d\Omega} = c\ [\ g_c^2 + \tfrac{1}{4} a_1^2\ g_1^2 + \tfrac{3}{4}\ a_3^2\ g_3^2\ ] \qquad (2)$$

$a_1\ g_1$ is the amplitude of the nucleon scattering in the singlet state; $a_3\ g_3$ is the scattering amplitude in the triplet state. The angular dependence of these amplitudes is chosen to be

$$g_1 = \sqrt{\left(\frac{d\sigma}{d\Omega}\right)_{opt}} \cdot \exp\left(-\frac{\theta^2 \ln 2}{2\ \theta_1^2}\right)$$

$$g_3 = \sqrt{\left(\frac{d\sigma}{d\Omega}\right)_{opt}} \cdot \exp\left(-\frac{\theta^2 \ln 2}{2\ \theta_3^2}\right)$$

The constants a_1, a_3, θ_1, and θ_3 must be determined experimentally. Being written down in such a form, a_1 and a_3 have the meaning of the amplitudes of the singlet and triplet scatterings at $\theta=0$ in terms of the units $\sqrt{\left(\frac{d\sigma}{d\Omega}\right)_{opt}}$ for the spinless particles.

The assumption that the cross section in the large angle interval is described by the amplitude of the singlet scattering and that in the region of small angles there appears the triplet scattering amplitude contradicts the well-known experiments: the cross section is extrapolated approximately to the optical point but not to $4\left(\frac{d\sigma}{d\Omega}\right)_{opt}$. We have treated the opposite case: in the region of large scattering angles the triplet scattering amplitude is predominant over the singlet one, and the singlet scattering amplitude is essential for the small scattering angles only. Using the least square method the constants a_1, a_3, θ_1 were determined (see Table 2). We chose the magnitudes of θ_3 and c according to the calculations made in the previous point.

Table 2.

E_{kin}	a_1	a_3	θ°_1	θ°_3	χ^2	The number of degrees of freedom
10 GeV	2.4±0.7	1.15±0.01	1.3±0.2	8	10	9

Conclusions

It was found that the value of the differential cross section at small t is larger than that calculated by the optical theorem for spinless particles. There can be two interpretations of this effect: either the scattering amplitude has the real part and then the constructive interference takes place ($\alpha < 0$), or the scattering amplitudes in different spin states of nucleons (triplet and singlet) are different or both effects take place. Experiment is in better agreement with the assumption that the real part of the scattering amplitude in the first case or the scattering amplitude in the singlet state (the second case) are concentrated in the small scattering angle region.

In order to draw unambiguous conclusions it is necessary to get additional information, for instance, on pn scattering at small angles and at angles close to 180° (charge exchange). It is obvious that ReA in the reaction $pn-pn$ does not interfere with the Coulomb amplitude, but may give the main contribution to the charge exchange cross section.

The experiment is in progress. The authors hope to obtain a higher accuracy in the small angle region and the absolute values of the differential cross sections.

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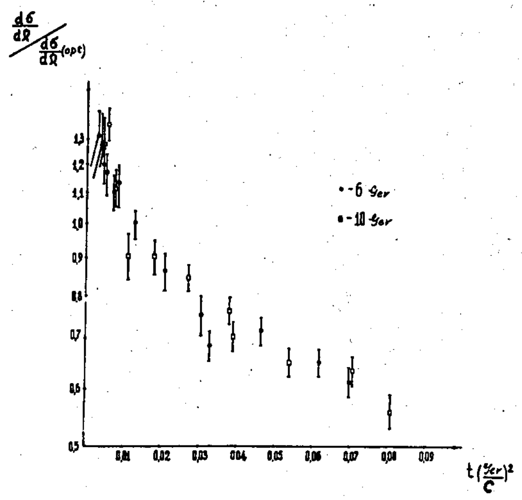

Fig.3

Differential elastic *p-p* scattering cross section at 6 and 10 GeV obtained after the subtraction of purely Coulomb cross section.

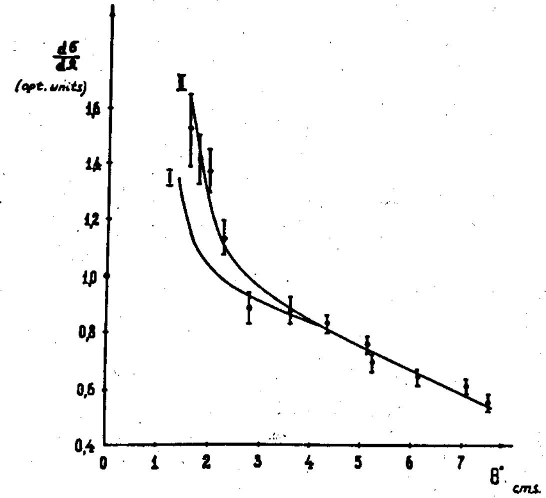

Fig.4.

Differential elastic *pp* scattering cross section at 6 GeV. Curve 1 corresponds to purely diffraction scattering of spinless particles ($a = 0$).

Curve 11 approximates the experimental cross section by Bethe formula (1) in which the following parameters, found by the least square method , enter:

$$a = -0.7 \pm 0.3; \quad \theta_{or} = (1.3 \pm 0.4)^{\circ}; \quad \theta_{oI} = 8.0^{\circ}$$