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SMALL-ANGLE PROTON-PROTON ELASTIC SCATTERING AT 6 *AND* 10 GeV

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PRELIMINARY results of a study of the elastic small-angle pp scattering at 6 and 10 GeV have been published earlier.[1] The experimental method has been discussed in detail in [2].

The experiment was carried out using the proton synchrotron of the Joint Institute for Nuclear Research. The internal beam of the accelerator traversed a large number of times a polyethylene film 3 μ thick. The target was suspended on nylon threads 20 μ thick. The dimensions and the thickness of the target film were selected for best angular and momentum resolution. From the same considerations, we used an emulsion placed three meters from the target as the detector of the recoil protons. The angular resolution amounted to $\pm 1.5 \times 10^{-3}$ rad. The whole path of the recoil protons from the target to the emulsion was in vacuum.

Characteristic range distributions of secondary particles for various values of $\theta_{\text{c.m.s.}}$ are shown in Fig. 1 for 10 GeV primary beam energy. The sharp peaks correspond to elastic pp scattering. The main source of the background are slow particles produced as a result of the interaction of primary protons with carbon nuclei in the target. As can be seen from the figure, the signal-to-noise ratio varies from 0.07 to 1.0 for a recoil proton momentum variation from 280 to 56 MeV/c. In order to determine the density of the recoil proton flux it is necessary to subtract the spectrum of the background particles from the total spectrum observed at a given angle θ_{lab}, which is the angle of emission of the recoil proton with respect to the primary beam. The spectrum of background particles was carefully studied at various angles using the same emulsions.

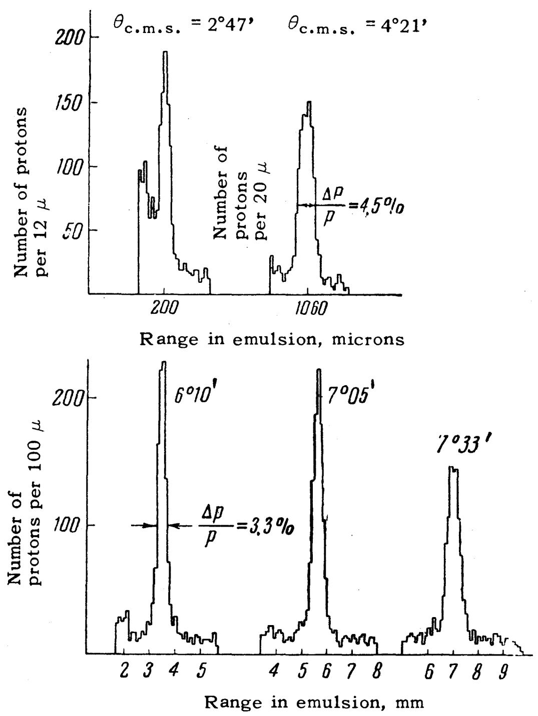

FIG. 1

It should be noted that the large resolving power of the method used almost completely excludes a contribution of the quasi-elastic scattering by bound nucleons of the nucleus. This is brought out by kinematic calculations of the quasi-elastic scattering and by experiments on the quasi-elastic scattering of protons on nucleons in the nucleus.[3]

In the experiment we have obtained the relative form of the differential cross section. The measurements were carried out with an error of 4.5—7.5% and were based on 22,000 scattering events. At 10 GeV the cross section was measured at 12 points in the angle interval $1.5° < \theta_{\text{c.m.s.}} < 7.5°$. The corresponding interval of the squared four-momentum transfer is $0.0038\ \text{GeV}^2/c^2 < t < 0.081\ \text{GeV}^2/c^2$. At 6 GeV analogous measurements were carried out in the angle interval $1.5° < \theta_{\text{c.m.s.}} < 9°$.

The purpose of the experiment was to study in detail the angular interval in which an essential role is played by the electromagnetic scattering and, consequently, an interference between the Coulomb and the nuclear scattering amplitude is possible. In the papers published so far on the elastic proton-proton scattering at energies greater than 1 GeV there are only qualitative data on the behavior of the cross section in this interval. The majority of authors conclude that the scattering pattern is close to a purely diffractive one. However, in experiments carried out at small angles [4,5] one obtains a larger cross section than predicted by the optical theorem for a spinless particle. The statistical accuracy of these experiments, carried out with emulsions, is not sufficient. Preston et al [6] conclude that at 3 GeV the real part of the scattering amplitude is smaller or equal to 0.1 of the imaginary part.

In our experiment, in order to normalize the data to absolute units, the experimental values of the cross section in the range in which the Coulomb scattering is negligible were extrapolated by an exponential function in t-coordinates to the optical-theorem point. We have used the following values of the optical-theorem point:

$$(d\sigma/d\Omega)_{0;\,10\mathrm{GeV}} = 122\ \mathrm{mb/sr}$$
$$(d\sigma/d\Omega)_{0;6\mathrm{GeV}} = 80.5\ \mathrm{mb/sr}$$

In this range the results agree well with the data of other authors.[5,7] The differential cross section for pp scattering at 6 and 10 GeV, after subtracting the purely Coulomb cross section, is shown in Fig. 2. It can be seen that the cross section is greater than the optical-theorem point in the range $t < 0.015\ \mathrm{GeV}^2/c^2$ for both energies. We have ccnsidered two possible interpretations of this fact.

1. The fact that the cross section is greater than the optical theorem prediction for a spinless particle may indicate that the scattering amplitude has a real part. Let us write the nuclear scattering amplitude in the form

$$A = \alpha g_r(\theta) + i g_y(\theta);$$
$$\alpha = \mathrm{Re}\,A(0)/\mathrm{Im}\,A(0),\quad g_y = (d\sigma/d\Omega)^{1/2}_{\mathrm{opt}} \exp\left(-\theta^2 \ln 2/2\theta^2_{0y}\right),$$
$$g_r = (d\sigma/d\Omega)^{1/2}_{\mathrm{opt}} \exp\left(-\theta^2 \ln 2/2\theta^2_{0r}\right),\quad (d\sigma/d\Omega)_{\mathrm{opt}} = (k\sigma_t/4\pi)^2.$$

where α, θ_{0y}, and θ_{0r} are constants characterizing the amplitude A, which have to be determined from the experiment. The differential cross section for elastic pp scattering can be expressed through the amplitude A and the amplitude of the Coulomb scattering $g_C = (2/137\ k\beta_{\mathrm{lab}})\theta^{-2}F(\theta)$ by the following formula obtained by Bethe:[8]

$$\frac{d\sigma}{d\Omega} = C\left[g_C^2 + g_y^2 + \alpha^2 g_r^2 - 2g_C\left(\alpha g_r + 2\frac{g_y}{137\beta_{\mathrm{lab}}}\ln\frac{1,06}{ka\theta}\right)\right]. \tag{1}$$

where $F(\theta)$ is the magnetic form factor of the nucleon, which for small t can be approximated by the formula $F(\theta) = \exp(-\theta^2 \ln 2/2\theta^2_{0y})$; $k = 1/\lambdabar$ is the wave vector of the proton in the c.m.s.; a is the size of the nucleon; β_{lab} is the proton velocity in the laboratory system; and C is a constant which reflects the fact that experimental data are measured in relative units, and which is determined in the experiment together with other parameters.

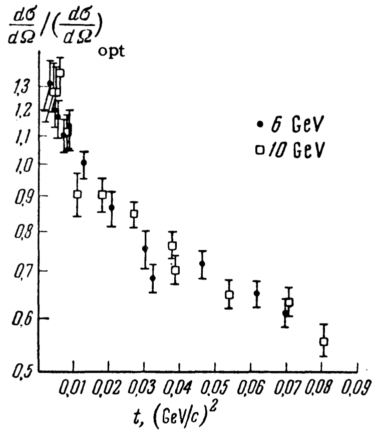

FIG. 2

The reduction of the data by a least-squares fit to Eq. (1) leads to the following conclusions: a) a purely diffractive pattern of the scattering (i.e., $\alpha = 0$) contradicts the experiment. For $\alpha = 0$, $\chi^2 = 60$ for 10 degrees of freedom; the corresponding probability is $\sim 10^{-3}$; b) if we assume the same angular variation of Re $A(\theta)$ and Im $A(\theta)$, i.e., if we put $\theta_{0r} = \theta_{0y}$, then the experimental data also cannot be described satisfactory by Eq. (1) for any value of the parameter α. In order to obtain an agreement between the cross section given by Eq. (1) with the results of the experiment, we have to assume that Re $A(\theta)$ falls rapidly with increasing angle θ, so that for sufficiently large angles, $\theta_{\mathrm{c.m.s.}} > 3°$, the cross section for the elastic pp scattering can be described by the imaginary part of the scattering amplitude only. The parameters in Eq. (1) obtained by the least-squares method are given in the table.

Figure 3 represents the experimental data for pp scattering at 10 GeV and their approximation by Eq. (1) with best-fit parameters (curve 2). Curve 1 in the same figure corresponds to a pure diffraction scattering of spinless particles ($\alpha = 0$).

E_{kin}, GeV	θ_{0y}, deg	θ_{0r}, deg	α	χ^2	No. of degrees of freedom
6	10	2.5±1	−0.40±0.15	15	9
10	8	1.3±0.4	−0.70±0.3	10	10

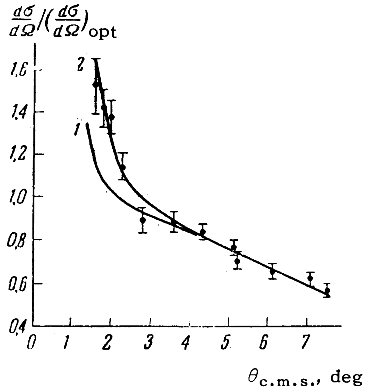

FIG. 3

2. Remaining within the framework of the diffraction model with a purely imaginary amplitude, let us assume that the interaction of protons in the triplet and singlet states is different. In that case the cross section can be described by the following formula which takes the spin dependence of the nuclear force in an approximate way into account:

$$d\sigma/d\Omega = C[g_C^2 + {}^1/_4\, \alpha_1^2 g_1^2 + {}^3/_4\, \alpha_3^2 g_3^2], \qquad (2)$$

where $\alpha_1 g_1$ and $\alpha_3 g_3$ are the nucleon scattering amplitudes in the singlet and triplet state, respectively. The angular dependence of these amplitudes is taken in the form

$$g_1 = (d\sigma/d\Omega)_{opt}^{1/2} \exp(-\theta^2 \ln 2/2\theta_1^2),$$

$$g_3 = (d\sigma/d\Omega)_{opt}^{1/2} \exp(-\theta^2 \ln 2/2\theta_3^2).$$

The constants α_1, α_3, θ_1, and θ_3 have to be determined from the experiment. In this form, α_1 and α_3 represent the amplitudes of the singlet and triplet scattering at $\theta = 0$, expressed in units of $(d\sigma/d\Omega)_{opt}^{1/2}$ for spinless particles.

The assumption that the cross section is described by the singlet scattering amplitude at large angles and by the triplet state amplitude at small angles contradicts a known experimental result: the cross section extrapolates roughly to the optical point and not to $4(d\sigma/d\Omega)_{opt}$. We have considered the inverse variant, i.e., that at large angles, the triplet scattering amplitude is greater than the singlet amplitude, and the singlet scattering amplitude is essential only at small scattering angles. By the least-squares method we have determined the constants α_1, α_3, and θ_1 (see below); the quantity θ_3 and C were taken from the calculation in Sec. 1. We have

$$E_{kin} = 10\,\text{GeV}, \quad \alpha_1 = 2.4 \pm 0.7, \quad \alpha_3 = 1.15 \pm 0.01,$$
$$\theta_1 = 1.3° \pm 0.2°, \quad \theta_3 = 8°, \quad \chi^2 = 10.$$

Number of degrees of freedom = 9

Thus, at energies of 6 and 10 GeV we have found that at small angles the differential cross section for elastic pp scattering is greater than the prediction of the optical-theorem point for spinless particles. The observed effect can be interpreted in two ways: either the scattering amplitude has a real part which causes constructive interference ($\alpha < 0$), or the scattering amplitudes of the different spin states of the nucleons (triplet and singlet) are different; both effects may play a role. The result agrees best with the hypothesis that the real part of the scattering amplitude in the first case, or the scattering amplitude of the singlet state in the second case, contributes in the range of small scattering angles ($\theta_{0r, c.m.s.}$, $\theta_{1, c.m.s.} \sim 2°$).

To reach a unique conclusion it is necessary to obtain additional information, e.g., on pn scattering at small angles and at angles close to 180° (charge exchange). Obviously, Re A in the reaction pn → pn does not interfere with the Coulomb amplitude, but may produce the main contribution to the charge-exchange scattering.

The experiment is being at present continued. The authors hope to obtain a better accuracy in the small-angle range, and the absolute differential cross section.

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STATIC SKIN EFFECT IN SINGLE-CRYSTAL SAMPLES OF CADMIUM

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THE following are the characteristic properties of the static skin effect[1] in metals with equal numbers of holes and electrons $(n_1 = n_2)$ in a strong oblique magnetic field: the current lines are concentrated near the surface in the case of cylindrical cross sections, or at the vertices in the case of polygonal cross sections of single-crystal samples; the depths of these regions of current concentration are of the order of the electron mean free path l. Obviously such a redistribution of the current density will alter the intrinsic inner (H_1) and outer (H_2) magnetic fields, and the phenomenon may be detected and investigated by measuring these fields.

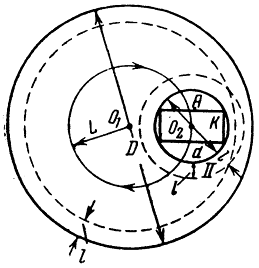

FIG. 1. Cross section of cylindrical cadmium samples Cd1, Cd2, Cd3.

For this purpose we used a ballistic method which is not sensitive to the constant external magnetic field H but which is selectively sensitive to the components H_1 and H_2. To detect the redistribution of current over the cross section in cylindrical single-crystal samples of cadmium, an internal cylindrical channel A (Fig. 1) was formed during growth and later a test coil K was placed in it. The plane of the coil windings coincided with the plane of the parallel axes O_1 and O_2 and therefore the ballistic "kick" on switching on the current through the sample was due to the component H_1 perpendicular to O_2. If the current lines were concentrated in the layers I and II, then the change in the magnetic flux which governs the galvanometer kick was $\Delta\Phi = \Delta\Phi_{I} + \Delta\Phi_{II}$, where $\Delta\Phi_{I}$ and $\Delta\Phi_{II}$ are due to the magnetic field in the layers I and II respectively. When $H_1 \ll H$ we may assume that these magnetic fields are axially symmetric with respect to their axes. Therefore $\Delta\Phi_{II} = 0$ and $\Delta\Phi_{I}$ is, in accordance with the theorem on circulation, determined by the magnetic field of the current J_L flowing inside a force line of radius L. Consequently

$$\Delta\Phi = \Delta\Phi_{I} = C2J_L/L,$$

where C is a constant of the measuring circuit. Thus in the presence of the static skin effect we may expect the ballistic kick, $\Delta k \sim \Delta\Phi$, to decrease due to reduction of J_L.

Samples of 9—10 mm length and with D = 5.5—6 mm, d = 1.6 mm and L = 1.5 mm (Fig. 1) were cut from single-crystal cadmium with the resistance ratio $R(4.2°K)/R(293°K) \leq 1.6 \times 10^{-5}$; they were then treated chemically 1).

The angle between the six-fold axis and the single-crystal axis was determined optically and amounted to ≈4°. In order to ensure a uniform distribution of the current density at the ends, the samples were soldered with Wood's alloy to the busbars of a sample holder made of niobium. The induction due to the magnetic field of the supply leads and ponderomotive forces were minimized by the special construction of the sample holder. Since the results of the measurements could have been affected by persistent eddy currents, their absence was checked by indpendent experiments. In all measurements the ballistic kick per unit current through the sample was recorded.

Figure 2 gives the results of measurements,