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SMALL-ANGLE ELASTIC p-p AND p-d SCATTERING IN THE ENERGY RANGE OF 2-10 GeV

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Procedure

The experiment was done by the technique described in [1] and [2]. Fig. 1 shows the experimental layout. The internal proton beam multiply traverses the $(CH_2)_n$ target, about 10^{-4} g/cm^2 thick. Two triple telescopes ($S_1 - S_2 - S_3$ and $S_4 - S_5 - S_6$) employing scintillation counters are used for monitoring. The angular resolution of the experiment is $10^{-3} - 10^{-4}$ rad. The recoil protons are detected by the photoemulsion stacks. The particles travel from the target to the detector in vacuum. For the region of very small scattering angles ($|t| \leq 1.10^{-2}$ $(GeV/c)^2$ we used a 4-fold gelatine emulsion pellicles situated perpendicular to the direction of the recoil protons. The latter circumstance reduced to the minimum the error in determining the solid angle (< 1%), and the use of the deluted emulsions improved the energy resolution of the experiment by several times. In the remaining cases use was made of the stacks with standard emulsion pellicles 600 microns thick which were situated perpendicular to the direction of the recoil protons for $|t| < 4.10^{-2}$ GeV^2/c^2, as well as parallel (the region for $|t| > 4.10^{-2}$ GeV^2/c^2). The recording efficiency of the tracks was $100 {}^{+0}_{-0.5}$ %.

Fig. 2a shows the range distribution of particles in the deluted emulsion for the angle $\phi = 87.5^{\circ}$ at the primary proton momentum of 10.9 GeV/c. The corresponding value of the squared momentum transfer of the recoil protons in elastic p - p scattering is $|t| \approx 5.10^{-3}$ $(GeV/c)^2$. The background consisting of the products of the proton interaction with the C^{12} nucleus is about 80% of the effect. A thorough investigation of the background at different scattering angles allows to take it into account with an accuracy of about 2%. Fig. 2b shows the range distribution of particles for the angle $\phi = 82.2^{\circ}$ (for elastically scattered protons $|t| \approx 5.10^{-2}$ GeV^2/c^2). Here the background is less than 10% of the effect. We showed in paper [2] on the basis of the calculation and indirect experiments that the contribution of quasielastic events will be negligibly small. In order to check this, a direct experiment was done with a target which did not contain hydrogen. Fig. 2d shows the spectrum of particles going from this target at an angle of 81.5°. The arrow indicates the place in the spectrum where the recoil proton peak from elastic p - p scattering would have been expected ($|t| \approx 7.10^{-2}$ GeV^2/c^2), if the target contained hydrogen. The analysis of the spectra obtained by means of this target has shown that the contribution of quasielastic events is negligibly small. It is (0.2 ± 1.5)% of the number of elastic events in the peak.

An investigation of elastic p - d scattering was made by a similar method with the help of the deuteried polyethelene targets, the deuterium contents was

93.1% and 95.0%. Fig. 2c illustrates the distribution of particles travelling from the target $(CD_2)_n$ at the angle $\phi = 86.4^o$. The pronounced peak corresponds to the recoil deuterons from the process $p+d \to p+d$. The absolute values of the differential cross sections were obtained by measuring in the target of the induced activity of C^{11} in the reaction $C^{12}(p,pn)C^{11}$ [3]. For this purpose we investigated the cross section of such a reaction and the diffusion of C^{11} nuclei from the target [4]. By the working exposure the major part of C^{11} nuclei does not come to rest in the target due to its small thickness. ($\lesssim$ 1 micron). Therefore in order to measure the absolute cross sections the gauge experiments were performed (for each energy - twice) with a thicker target ($\approx 5.10^{-3}$ g/cm^2) in which the correction for the C^{11} nuclei emission due to the recoil momentum was $\approx$ 3%. The connection between the working exposure and the gauge one could have been accomplished by four different methods: two electronic telescopes which detect fast particles travelling from the target and an emulsion stack in which a) the relativistic particles going from the target are recorded and b) the peak of the recoil protons (or deuterons) corresponding to elastic scattering was recorded. It was found that the error in the measurement of the absolute value of the differential elastic p-p and p-d scattering cross section does not exceed 7%.

The measurements were made in several angular intervals (about 10) for each energy, the number of the detected elastic scattering events was $\gtrsim 10^4$ and, correspondingly, the statistical accuracy in every angular interval was (2.5-5)%. In contrast to paper [5] the target was essentially modified: instead of the capron strings holding (CH_2) -film, the glass strings ϕ 7 microns were used. Therefore, the correction for the admixture of the recoil protons from the strings were excluded [2].

To decrease the effect of the magnetic field of the accelerator on the particle trajectory the whole channel was protected by the magnetic screen. A careful measurement of the magnetic field and its gradients and the calculation of their focusing effect on the recoil protons have shown that the appearing focusings do not cause any distortions which would exceed 0.2%.

Analysis and Results

This experiment confirmed the principal result of paper [5]: in the small-angle region the differential elastic p-p scattering cross section (without the Coulomb scattering) exceeds the cross section calculated by the optical theorem for the spinless particles. There are two possibilities of interpreting this peculiarity: either we may consider that the scattering amplitude has a real part or we may assume that the proton interaction in the singlet and triplet states is different. Let us point out that in order to describe the experimental data satisfactorily, in the second case it has to be supposed, just as in[5] that the amplitudes of the singlet and the triplet scattering have different angular dependence. If the behaviour of the cross section is accounted for with the aid of the real part in the scattering amplitude, then, as will be shown below, it is not required to introduce the angular dependence different from the imaginary part: the specific features of the small-angle scattering is naturally explained by the interference with the Coulomb scattering. Therefore, we are concerned here only with one possibility of analysing the experimental data.

The differential elastic $p-p$ scattering cross section is expressed in terms of the nuclear ($A(\theta) = g_R + i g_I$) and Coulomb (g_c) scattering amplitudes with the aid of the Bethe formula[6]

$$\frac{d\sigma}{d\Omega}(\theta) = g_o^2 + g_I^2(1+\beta^2) + a^2 g_R^2 - 2 g_o [a\, g_R + \frac{2}{137}\frac{g_I}{\beta_\ell}\ln\frac{1.06}{ka\theta}].$$

Here θ is the scattering angle in the c.m.s., $a = \frac{\mathrm{Re}\,A(0)}{\mathrm{Im}\,A(0)}$, β is the parameter introduced for describing a possible exceeding of the cross section over the optical point and which is not associated with the real part, β_ℓ is the proton velocity in the lab. system, k is the wave number of the proton in the c.m. s., $a = 1.10^{-13}$ cm is the nucleon radius. For the region $|t| < 0.2\ \mathrm{GeV}^2/c^2$ the angular dependence of the amplitudes can be represented with a good accuracy as

$$g_{I,R}(\theta) = \sqrt{\left(\frac{d\sigma}{d\Omega}\right)_{opt}}\cdot \exp\left[-\frac{\theta^2\ln 2}{2\theta_{I,R}}\right]$$

$$g_o(\theta) = \frac{2}{137\,k\,\beta_\ell}\;\frac{1}{\theta^2}\;\exp\left[-\frac{\theta^2\ln 2}{2\,\theta_I^2}\right].$$

The parameters a, β, θ_I, θ_R characterizing the scattering amplitude A are determined from the experiment. As far as it turned out within the experimental error that $\theta_I = \theta_R$, then the final analysis of the experimental data was made under the assumption that $\theta_I = \theta_R$.

The results of the experiment are presented in Table I:

Table I.

pc GeV	$-a$	$\theta_I = \theta_R$	β^2
2,78	0.17 ± 0.07	18.1 ± 0.6	-0.09 ± 0.09
6.87	0.26 ± 0.09	9.4 ± 0.2	0.0 ± 0.1
8.89	0.20 ± 0.09	7.8 ± 0.2	0
10.90	0.25 ± 0.07	7.5 ± 0.2	0.0 ± 0.1

It is seen from the Table, that throughout the investigated energy region the scattering amplitude has a negative real part (the constructive interference is observed, i.e., the forces have a repulsive character). The differential cross section for the proton scattering with $pc = 10{,}90$ GeV is shown in Fig.3. The solid curve ($\chi^2 = 10{,}9$ for 11 degrees of freedom) approximates well the experimental data by the Bethe formula with the parameters given in Table 1. If one tries to choose, by the Bethe formula in which $a = 0$ is fixed, a curve passing through the experimental points, then $\chi^2 = 141$ at 16 degrees of freedom points out that the hypothesis $a = 0$ is not valid. The results for other energies under investigation are similar. Papers /7,8,9,14/ in which other methods were used, confirmed also the presence of the real part in the $p-p$ scattering amplitude with $a < 0$.

Fig. 4 shows the energy dependence of the real part of the scattering amplitude for $pc > 1.5$ GeV/c. The experiments are in agreement with the results of the calculation of the real part on the basis of dispersion relations /11,12/.

The parameter β^2 is equal to zero within the experimental error. In other words, an exceeding of the cross section over the optical point is due to the real part of the scattering amplitude.

Fig. 5 shows the differential scattering cross sections at 2.78, 6.87 and 10.90 GeV/c. The curves approximate the experimental data by the Bethe formula at 10,90 GeV/c (solid) and 2.78 GeV/c (dashed). One can see that for the small momentum transfers ($0.002 < |t| < 0.14$ GeV^2/c^2) as well as for $|t| > 0.2$ GeV^2/c^2 (e.g., /13/ a shrinkage of the diffraction cone takes place). The corresponding slope parameters of the differential cross section and the interaction radii are shown in Fig. 6a.

Fig. 7 shows the differential elastic p-d scattering cross section for the proton momenta in the lab. system of 2.78, 4.67, 6.87, 8.89 and 10.90 GeV/c. The slope parameters of the differential elastic p-d scattering and the corresponding values of the interactions radius are given in Fig. 6b. Table 2 presents the values of the total cross section for elastic p-d scattering.

Table 2

$P_{lab}\ \frac{GeV}{c}$	2,78	6.87	8.89	10.90
σ_{tot} (p-d) elastic	10.6 $\pm$ 0.7	10.0 $\pm$ 0.7	11.5 $\pm$ 1.5	11.5 $\pm$ 0.8

Just as for p-p scattering, there is observed an exceeding of the cross section over the optical point in the small-angle region. A detailed analysis of the experimental data on p-d scattering will be made in another paper.

In conclusion we would like to thank the Director of the High Energy Physics Laboratory Veksler V.I. for providing the experimental facilities .

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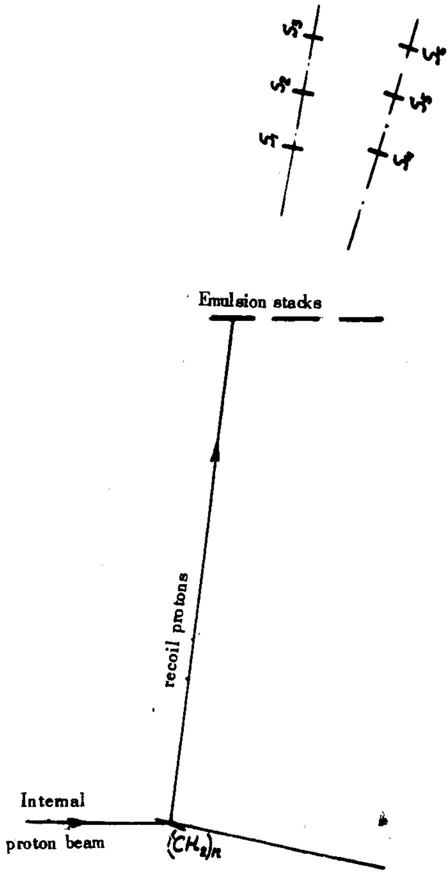

Fig.1. Experimental layout.

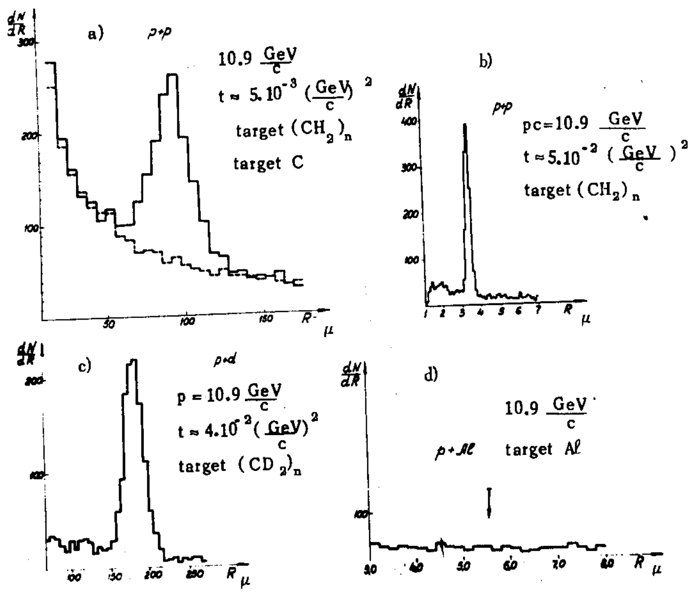

Fig. 2. The range distribution of particles emitting from the target at an angle ϕ to the direction of primaries (pc = 10.9 GeV), a) $\phi = 87{,}5^{\circ}$, the solid curve shows the $(CH_2)_n$ target, the dashed line shows the Ctarget. b) $\phi = 82.2^{\circ}$. The target - $(CH_2)_n$ c) $\phi = 86.4^{\circ}$. The target $(CD_2)_n$, d) $\phi = 81.5^{\circ}$, Target - Al.

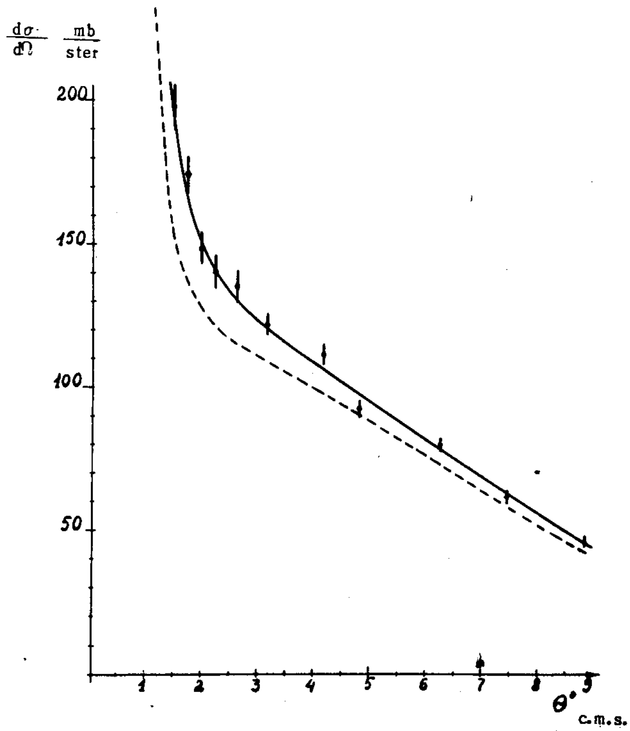

Fig.3. The differential elastic p-p scattering cross section at pc = 10.90 GeV. The solid curve is a least squares fit obtained by the Bethe formula, and corresponds to a = 0.25. The dashed curve corresponds to a = 0.

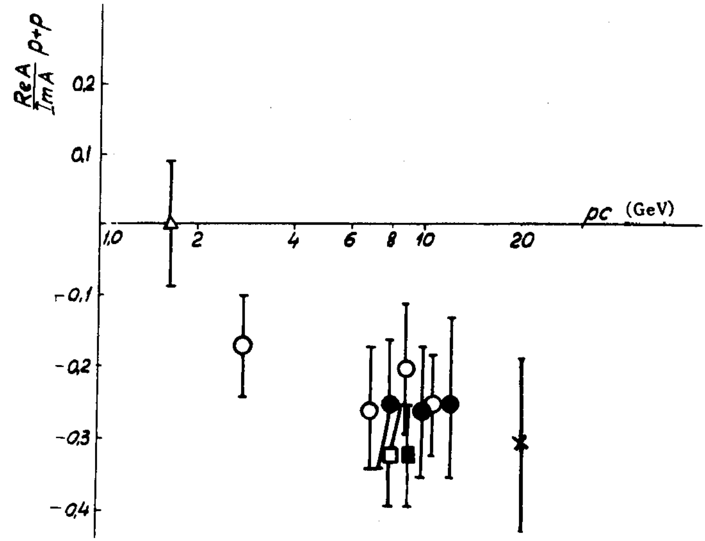

Fig.4. The ratio of the real part of the p-p scattering amplitude to the imaginary part in the region pc > 1 GeV/c.

O - the present experiment
■ - L.Kirillova et al. /14/
△ - J.D.Dowell et al. /10/
□ - A.E.Taylor et al. /8/
● - K.J.Foley et al. /7/
X - G.Bellettini et al. /9/

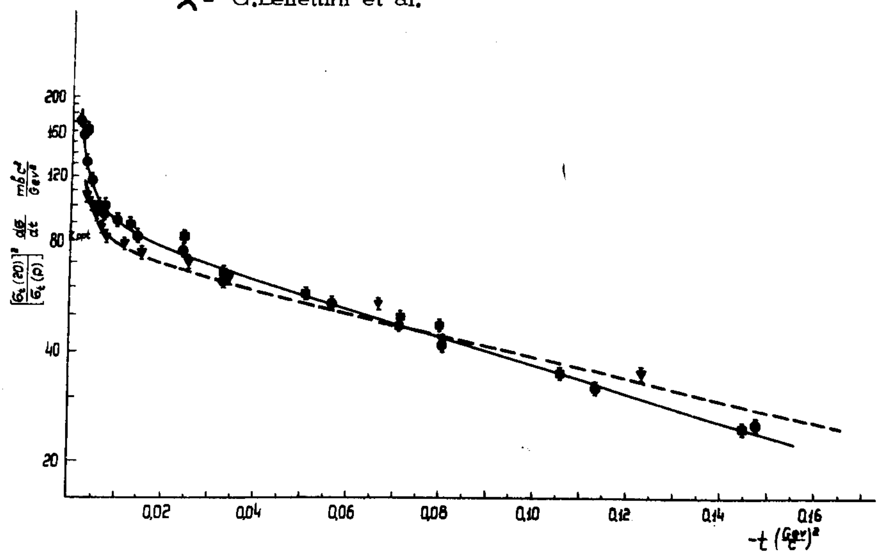

Fig.5. The differential elastic p-p scattering cross section at the momenta: ● - 10.90 GeV/c, ■ - 6.87 GeV/c, ▼ - 2.78 GeV/c. The solid curve approximates the experimental data by the Bethe formula for 10.90 GeV/c, the dashed line - for 2.8 GeV/c.

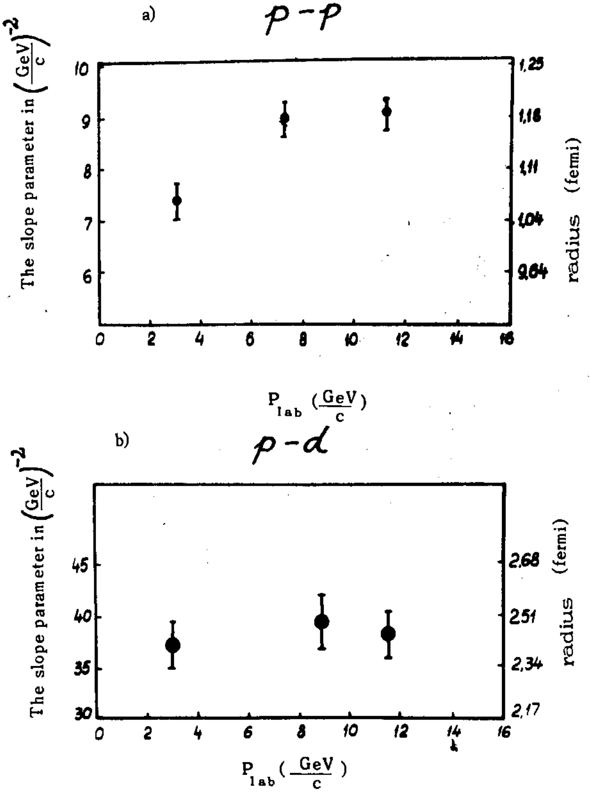

Fig.6. The energy dependence of the slope parameter of the differential cross section: a) p-p scattering in the range $0.002 < |t| < 0.15$ GeV^2/c^2; b) p-d scattering.

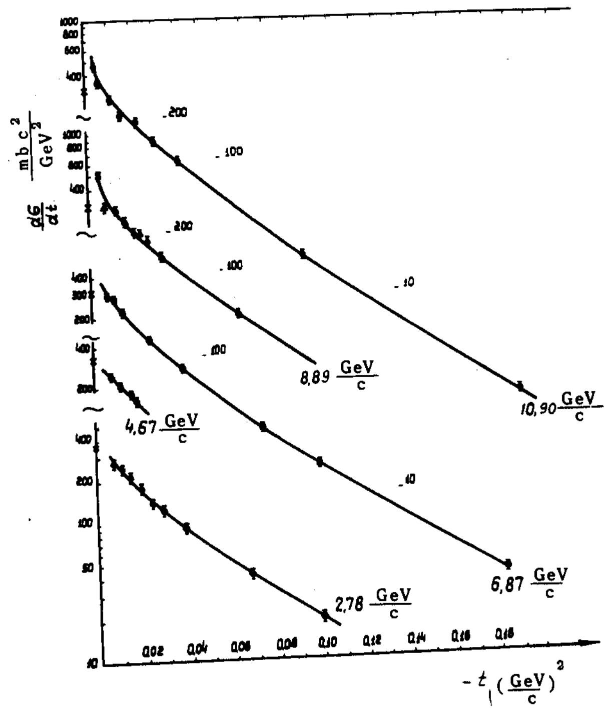

Fig.7. The differential p-d scattering at the momenta of the primary proton 2.78, 4.67, 6.87, 8.89, 10.90 GeV/c.