PROTON-PROTON ELASTIC SCATTERING AT 2.8 BeV

S. A. AZIMOV, DO IN SEB, L. F. KIRILLOVA, É. M. KHABIBULLINA, É. N. TSYGANOV, M. G. SHAFRANOVA, B. A. SHAKHBAZYAN, and A. A. YULDASHEV

Joint Institute for Nuclear Research; Physico-technical Institute, Academy of Sciences, Uzbek S.S.R.

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Proton-proton elastic scattering at 2.8 BeV was investigated with the aid of photographic emulsions. Altogether 492 cases of elastic scattering were found. The differential cross section for proton-proton elastic scattering through c.m.s. angles from 2.5 to 20.5° was determined. The experimental data are not in agreement with the assumption that the spin interaction and real part of the phase shift are small. The rms proton-proton interaction is found to be 1.06 ± 0.10 F.

INTRODUCTION

THE study of high energy proton-proton elastic scattering is one of the methods of investigating the nuclear structure of the nucleon. However, the construction of the scattering matrix from the experimental data, even on the basis of a large number of experiments, is an exceptionally complex task in view of the fact that a large number of partial waves take part in the scattering. Since the de Broglie wavelength at high energies is much smaller than the interaction range of the nucleons, it is possible to use the quasi-classical approximation, which facilitates the analysis of the experimental results and makes it possible to obtain information on certain characteristics of the nucleon.

In the present experiment, we studied proton-proton elastic scattering at ~ 2.8 BeV by the photoemulsion technique.

EXPERIMENTAL ARRANGEMENT

We used for the experiment two emulsion stacks $10 \times 10 \times 2$ cm consisting of NIKFI-BR emulsion pellicles 400 μ thick. The stacks were exposed to the internal proton beam of the proton synchrotron at the Joint Institute for Nuclear Research perpendicularly to the plane of the emulsion pellicles. Kinematical analysis of protons scattered elastically on free protons showed that the primary proton energy was 2.7 BeV in stack No. 1 and 2.9 BeV in stack No. 2. The work on both stacks was conducted independently by a technique identical to that developed in [1]. The elastic events were found by area scanning in the central zone of the pellicles on scanning microscopes under a magnification of $5 \times 1.5 \times 60$ with an immersion objective.

MEASUREMENTS AND RESULTS

During the separation of the cases of elastic scattering in stack No. 1, it was found that the primary proton beam was not monochromatic. It turned out that a number of cases did not satisfy the kinematics for elastic scattering at 2.7 BeV, but were in good agreement with the kinematics for a lower energy. The relation between the momentum and angle of emission of the slow proton, which changes weakly with the energy for elastic scattering and changes strongly for background events, and the coplanarity criterion allow one to establish with sufficient reliability that the events are elastic scatterings on hydrogen nuclei.

From the measurements of the kinematical characteristics of these events, we constructed the energy spectrum of the mixture in the primary proton beam. This spectrum is shown in Fig. 1. It is seen that the particles are mostly of energy ~ 1.6 BeV. Knowing the cross section for elastic scattering at this energy,[2] we estimated that $(5.5 \pm 1.6)\%$ of the beam particles were of the lower energy.

The incident proton flux was measured over the entire scanned region. It proved to be $(2.46 \pm 0.07) \times 10^5$ particles/cm^2 for the first stack and $(2.60 \pm 0.06) \times 10^5$ particles/cm^2 for the second stack. The angular divergence of the beam was 19′.

In order to determine the hydrogen content in the emulsion at the time of exposure, we made an analysis of the moisture and of the hydrogen con-

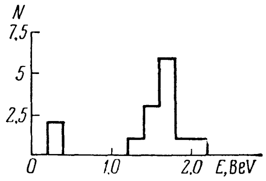

FIG. 1. Energy spectrum of mixture in primary proton beam for stack No. 1.

tent in the emulsion pellicles. The analysis for the moisture was performed at the Joint Institute for Nuclear Research immediately after exposure and the hydrogen content in the dry emulsion pellicles was determined at the Motion Picture and Photography Research Institute (NIKFI). Stacks Nos. 1 and 2 contained $(2.80 \pm 0.06) \times 10^{22}$ and $(2.82 \pm 0.06) \times 10^{22}$ atoms of hydrogen per cc, respectively.

The technique for measuring the kinematical parameters and the selection criteria for cases of elastic scattering have been described earlier in detail.[1]

The angles of emission were measured to an accuracy of $\sim 1.5°$ for the slow proton and $\sim 4'$ for the fast proton. This permitted the contribution from background events (quasi-elastic scattering etc.) to be reduced to 0.5%. An event was considered to be an elastic scattering if it satisfied the selection criteria within three standard deviations. The selection criteria were satisfied by 196 cases in stack No. 1 and 296 cases in stack No. 2.

Since it turned out that the scanning efficiency dropped near the surface of the emulsion pellicles and near the glass, the volume lying within 20 μ from the surface and from the glass in unprocessed emulsion was excluded from the analysis. The table lists the scanning efficiency for different c.m.s. angular intervals separately for stacks Nos. 1 and 2. The scanning efficiency for the double scan is denoted by ϵ.

The scanning efficiency was calculated from all events selected for measurement in the same way as in the previous work.[5] It was assumed here that this efficiency is the same for all events of a given type and is constant over the entire scanned volume. It is readily shown that a departure from these conditions leads to an overestimation of the scanning efficiency. However, under the very high efficiency encountered in our case, this systematic error cannot be important.

Since the scanning efficiency for c.m.s. angles greater than 20.5° proved to be small (70 — 50% and less), we did not list any data on the differential cross section in this angular region.

The elastic scattering cross section in the angular interval between 0.5 and 20.5° was found to be 10.00 ± 0.77 and 10.20 ± 0.64 mb, respectively, for stacks Nos. 1 and 2. In the table, the data on the differential cross sections are shown separately for each stack and are combined (for the average energy 2.8 BeV).

RESULTS AND DISCUSSION

The obtained experimental data are not in agreement with the assumption that the spin interaction and the real part of the phase shifts are small. In fact, the differential cross section for the angle 0° calculated from the optical theorem for a total cross section $\sigma_{tot} = 43.5 \pm 1.0$ mb[3] is 41.7 $\pm$ 1.9 mb/sr, while the experimental values of the differential cross sections for the c.m.s. angles 3.5, 5.5, and 7.5° are 63.3 ± 10.3, 51.7 ± 7.4, and 48.2 ± 6.1 mb/sr, respectively. At 3.5° the Coulomb scattering is already small.

The results of the experiment were analyzed according to the schemes described earlier.[4,5] It was assumed in the calculations that the potential of the nuclear forces is different for the singlet and triplet states and its dependence on the distance is Gaussian. For simplicity, it was assumed that the ratio of the real part to the imaginary part was the same for the singlet and triplet potentials:

$$V_s = -(u + iw)\, e^{-\gamma^2 r^2}, \qquad V_t = \varkappa V_s.$$

In one variant, we calculated the differential and total cross sections from the phase shifts determined from this potential with the aid of the expressions for the elements of the M matrix. In a second variant we used the optical model in which the Coulomb interaction was taken into account. Using least squares, we found the best fit and the

θcms deg	ε (E_p =2.7 BeV)	$d\sigma/d\Omega$ (E_p =2.7 BeV)	ε (E_p =2.9 BeV)	$d\sigma/d\Omega$ (E_p =2.9 BeV)	$d\sigma/d\Omega$ (E_p =2.8 BeV)
2.5—4.5	91.5±4.0	53.0±15.0	95.7±3.5	72.5±14.3	63.3±10.3
4.5—6.5	97.4±2.3	55.3±11.8	97.8±1.7	49.5±9.4	51.7±7.4
6.5—8.5	98.1±1.3	59.8±10.5	98.1±1.6	42.5±7.4	48.2±6.1
8.5—10.5	96.6±2.1	35.5±7.2	97.3±1.7	43.3±6.7	39.7±4.9
10.5—12.5	96.8±1.8	24.2±5.4	97.1±1.6	28.0±4.9	25.7±3.6
12.5—14.5	93.2±3.4	25.6±5.2	94.2±2.5	28.2±4.9	26.9±3.6
14.5—16.5	91.7±5.6	13.1±3.5	92.9±3.7	21.3±3.8	17.0±2.6
16.5—18.5	86.6±4.7	14.2±3.6	90.4±6.1	11.9±2.7	12.9±2.2
18.5—20.5	71.0±8.0	13.5±3.7	83.1±9.9	9.8±2.6	11.1±2.2

corresponding values of the parameters κ, γ, u, and w. In both schemes of calculation we determined the value of χ^2 to characterize the deviation of the calculated curves from the experimental points. For the mean value of χ^2 we have $\overline{\chi^2} = n - m$, where n is the number of experimental points and m is the number of unfixed parameters in the model. When one of the parameters of the model is varied by one standard deviation from the value at its minimum and all the remaining parameters are minimized, χ^2 increases by 1, and for a change of 2 standard deviations χ^2 increases by 4, etc. The results of the calculations by both variants are in agreement, and we shall henceforth use the results obtained from the scheme of calculations involving the elements of the M matrix.

The calculation shows that the model with $u = 0$ and $\kappa = 1$ and with the total cross section taken as 43.5 ± 1.0 mb does not satisfy the χ^2 criterion ($\chi^2 = 16.71$ with $\overline{\chi^2} = 8$). If σ_{tot} is left free, we obtain $\chi^2 = 7.71$, but we then obtain $\sigma_{tot} = 52.6 \pm 2.2$ mb. It is seen that the difference $(\sigma_{tot})_{cal} - (\sigma_{tot})_{expt}$ is more than 3.7 standard deviations of the measurement error. If κ is set equal to unity, then the value of the real part of the potential is determined from the experiment with a rather small error: $u = -40.0 \pm 6.5$ MeV or $u = 38.7 \pm 4.9$ MeV; however, we obtain no indication as to its sign. The imaginary part of the potential then turns out to be $w = 32.7 \pm 7.0$ MeV or $w = 52.3 \pm 12.1$ MeV. There is also a solution with $\kappa < 1$ for $u > 0$ and $u < 0$, namely, $\kappa = 0.19 \pm 0.06$ and $\kappa = 0.13 \pm 0.04$. In the region $\kappa > 1$, we cannot determine the parameters with any reasonable accuracy. The detailed calculation shows that it is necessary to have greater statistical material before one can explain unambiguously the clearly higher value of the experimental points for small angles in comparison with the optical theorem calculations.

The rms radius associated with the parameter γ by the relation $\sqrt{\overline{r^2}} = \sqrt{(3/2)}\gamma^{-1}$ has approximately the same value 1.06 ± 0.10 F for different values of the parameters. It is of interest to analyze by this scheme the experimental data of Preston et al[6] on elastic pp scattering for small angles at 3 BeV. The calculation shows that for parameters $\kappa = 1$ and $u \neq 0$ the model stands up to the χ^2 test ($\chi^2 = 15.7$, $\overline{\chi^2} = 15$). The real part of the potential is then $u = -73.0 \pm 65.8$ MeV, i.e., it differs from the value $u = 0$ by one standard deviation. The imaginary part of the potential is $w = 227.8 \pm 146.0$ MeV. The rms interaction range in this case is 0.75 ± 0.11 F, which is compatible with our results within two standard deviations.

We also analyzed the combined data of our work and that of Preston et al[6] for an effective energy of 2.9 BeV. If we take $\kappa = 1$ and $u = 0$, we then obtain the value $\sigma_{tot} = 48.6 \pm 0.93$ mb, while the experimental value is 42.5 ± 1 mb, i.e., the difference between them is more than three standard deviations. The assumption that $\kappa = 1$ for $u \neq 0$ with the total cross section fixed does not stand up to the χ^2 test: $\chi^2 = 31.0$ with $\overline{\chi^2} = 24$. This indicates that it is necessary to assume that $\kappa \neq 1$. In fact, for $\kappa = 1$ we obtain the following solutions satisfying the experimental data:

$$\varkappa = 0.18 \pm 0.04,$$

$$u = 4.1 \pm 42.8 \text{ MeV and } w = 333.4 \pm 112.8 \text{ MeV}.$$

A solution also exists when

$$u \equiv 0, \quad \varkappa = 0.18 \pm 0.04 \quad \text{and} \quad w = 334.2 \pm 113.3 \text{ MeV}.$$

Hence, this calculation shows that it is necessary to assume that there is a difference in the total cross sections for the singlet and triplet states. The small value of the real part of the potential in combination with the small value of the spin-orbit interaction at high energies[4] explains qualitatively the small value of the polarization in pp interactions at 2.85 BeV obtained by Smith et al.[7]

It is interesting to note that the data for pp elastic scattering at different energies in the 2.8 — 8.5 BeV range shown in Fig. 2 in units of $k^{-2}d\sigma/d\Omega$, $q = p \sin\theta$ (k is the wave number and p is the momentum of the incident particle) do not lie on one curve; the value of $k^{-2}d\sigma/d\Omega$ for a given q decreases with the energy for all values of q

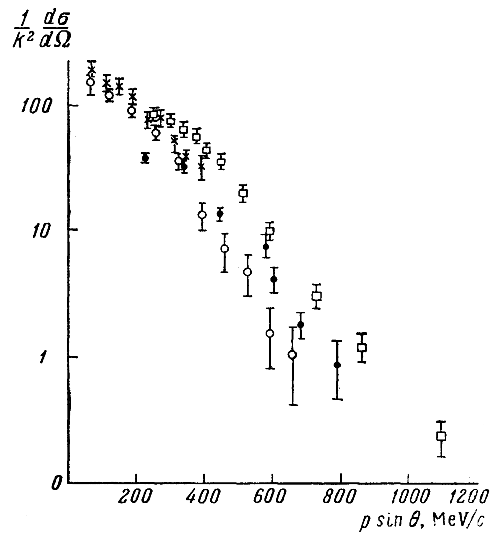

FIG. 2. Proton-proton elastic scattering data for different energies: ×– 2.8 BeV (present work), □– 2.85 BeV,[7] ●– 6.2 BeV,[8] ○– 8.5.[5]

and particularly rapidly for large q. This signifies that in the given energy region the optical characteristics of the proton-proton interaction change.

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