ANGULAR DEPENDENCE OF THE POLARIZATION CORRELATION C_{nn} AND CONSTRUCTION OF THE AMPLITUDE MODULI FOR *pp* SCATTERING AT 640 MeV. ESTIMATE OF THE SINGLET PHASE SHIFTS. II

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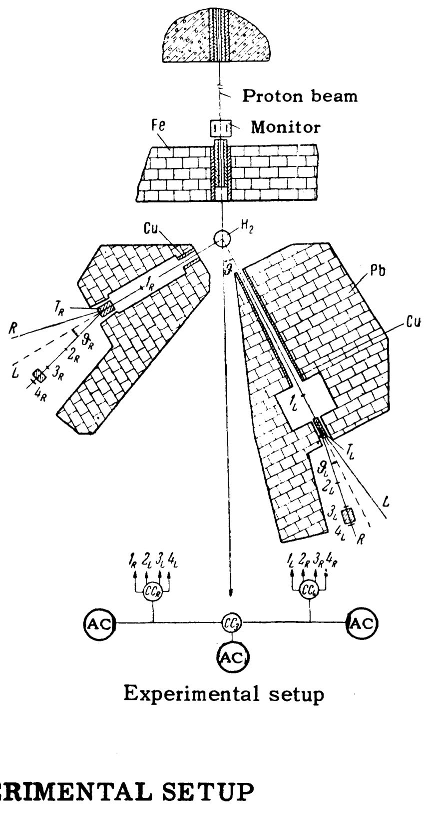
Experiments on triple scattering of protons are described and the results of measurement of the spin correlation coefficients C_{nn} for 640-MeV protons elastically scattered by protons are presented for a number of c.m.s. angles other than 90°. On the basis of the experimental data obtained in the present work and available in the literature, the moduli of the pp-scattering amplitudes are qualitatively determined in a broad angular range $50° < \theta < 130°$ and their relative contributions are given. The values of the singlet and triplet cross sections for some angles are also determined. The phase shifts for a pp-system at the indicated energy in singlet states are estimated.

1. INTRODUCTION

THE present work is one of a set of experiments carried out with the synchrocyclotron of the Joint Institute for Nuclear Research in accordance with the program for a complete experiment on np and pp scattering [1,2] to determine the nucleon-nucleon scattering matrix at 640 MeV. At the same time it represents the second part of a work we did on the measurement, at the indicated energy, of the correlation of the normal polarization (the parameter C_{nn}) in pp scattering. In the first part of this investigation the value of C_{nn} was found for an angle 90° in the c.m.s. [3]; in the present investigation this parameter is determined for angles 54 and 72° and, accordingly, for their complementary angles 126 and 108°.

Since this experiment completes in a certain sense a definite stage in the program of experiments on pp scattering at 640 MeV, the measurement of C_{nn} yields even now (together with other data as will be seen later on) appreciable new information on pp scattering at this energy without resorting to phase-shift analysis. At the same time, since each of the values of C_{nn} yields, roughly speaking, an independent relation between the phase shifts of the waves participating in the scattering, in a future phase shift analysis of the entire aggregate of data on the pp scattering data on the parameter C_{nn} can yield valuable information on the scattering phase shifts, and can also serve as a criterion for the choice of the most probable solution.



Experimental setup

2. EXPERIMENTAL SETUP

The setup for the measurement of the parameter C_{nn} is shown in the figure. An unpolarized proton beam with energy 640 MeV, formed by a quadrupole lens and two collimators (20 mm in diameter), was incident on the first target, which was a cylindrical vessel with liquid hydrogen (H_2). The proton flux density at the location of the target usually amounted to (3—3.5) × $10^8 cm^2$/sec; as

Table I

$\theta_{c.m.s.}$, deg	Threshold energies of telescope; MeV		Material and thickness of second scatterers, g/cm²		Angles of second scattering, deg	
	E_L	E_R	T_L	T_R	ϑ_L	ϑ_R
54±3	270	140	Al; 38	C; 8.0	10±2.5	14±2.5
72±3	390	130	C; 21	C; 6.0	11±2.5	14±2.5

Table II

$\theta_{c.m.s.}$, deg	C_{nn} (θ)	ε (θ)	P_L (θ)	P_R (θ)
54	0.57±0.14	0.15±0.04	0.40±0.03	0.68±0.05
72	0.65±0.15	0.22±0.03	0.55±0.07	0.62±0.07
90	0.93±0.21 [3]	0.26±0.04	0.51±0.06	0.54±0.06
108	0.65±0.15			
126	0.57±0.14			

shown by control experiments carried out during the preparation for each series of measurements, the beam was sufficiently homogeneous at the place where it struck the target.

The protons elastically scattered by the first target passed through collimating slots in the local shield, were registered by counters 1/L and 1/R, and after being scattered by analyzer targets T_L and T_R were detected by the counter groups $2_L3_L4_L$ and $2_R3_R4_R$. The geometry of the second scatterings, the material, and the thicknesses of the scatterers T_L and T_R are indicated in Table I.

The cross connection used in the present work of counters 1_R and 1_L with the telescopes $(2_L3_L4_L)$ and $(2_R3_R4_R)$, as shown in the figure, made it possible to separate the cases of elastic pp scattering against the background of the intense inelastic-scattering processes more effectively than in the connection which we used earlier [3]. The parameters of the coincidence circuits CC_L, CC_R, and CC_3 remained essentially the same as before.

3. CALIBRATION EXPERIMENT

In elastic scattering of protons by 640-MeV protons both scattered beams have a rather large polarization. This circumstance was used to calibrate the analyzing abilities of targets T_L and T_R, which was carried out simultaneously with measurement of the correlation asymmetry. The analyzing abilities P_L and P_R of the targets T_L and T_R of second scattering were determined by the usual method, of observing the right-left asymmetry in the second scatterings. In calculating P_L and P_R the data on polarization in pp scattering employed were those obtained by Meshcheryakov, Nurushev, and Stoletov [4]. The values obtained for P_L and P_R are listed in Table II below.

4. CORRELATION ASYMMETRY AND THE COEFFICIENT C_{nn}

The value of the correlation asymmetry was determined from the known formula

$$\varepsilon' = \frac{N_{LL} + N_{RR} - N_{LR} - N_{RL}}{N_{LL} + N_{RR} + N_{LR} + N_{RL}},$$

where N_{LL}, N_{RR}, etc. are the counting rates, corrected for the background, of the coincidence circuit CC_3 at the corresponding positions of the telescopes that measure the counting rates in the second scatterings. The apparatus background in the measurements of N_{LL}, N_{RR}, etc is determined in the manner similar to that used in our earliest work [3]. The corrections for the random coincidences in the circuit CC_3 were measured with a delay line connected in one of its channels. Random coincidences in the CC_3 circuit were negligibly small when delays in the channels with counters 1_L or 1_R were introduced, and were disregarded in the calculations [1)] In the measurements of N_{LL}, N_{RR}, etc at different angles the summary background determined in this manner

[1)]In measurement of the background of the random coincidences, the lengths of the lines used for pulse delay were chosen on the basis of the known time structure of the proton beam extracted from the accelerator.

fluctuated between 15 and 30 per cent of the total counting rate of the CC_3 circuit.

To determine the true correlation asymmetries ϵ, small corrections ϵ_{false} were introduced into the experimentally obtained values of ϵ' to account for the false correlations due to the geometry of the setup. The values of the false correlation of symmetry for different angles were:

$\theta_{c.m.s.}$, deg:	54	72	90
ε_{false} (θ):	-0.01 ± 0.01	0.01 ± 0.01	0.01 ± 0.004

Table II lists the values of the correlation asymmetry $\epsilon(\theta) = \epsilon'(\theta) - \epsilon_{false}(\theta)$ and the values of the coefficient $C_{nn}(\theta)$, calculated from the formula $C_{nn} = \epsilon/P_L P_R$. The same table gives the value of C_{nn} for the angle $\theta_{c.m.s.} = 90°$, which we have determined previously. The values $C_{nn}(126°)$ and $C_{nn}(108°)$ listed in the tables were taken to be equal to $C_{nn}(54°)$ and $C_{nn}(72°)$, respectively, in view of the symmetry properties of the parameter $C_{nn}(\theta)$[1] in pp scattering.

5. DISCUSSION OF RESULTS

The completion of the measurements of the angular dependence of the parameter C_{nn} makes available for analysis data from a large number of independent experiments on pp scattering, carried out with 640-MeV protons: $\sigma(\theta)$[5]; C_{nn}, $P(\theta)$[4]; $D(\theta)$, $K(\theta)$[6]; $C_{kp}(90°)$[7]; $R(\theta)$[8]; etc. This circumstance, and also the definite success attained by Kazarinov and Silin[9], who made a phase-shift analysis of data on nucleon-nucleon scattering in the energy region below the meson production threshold, enabled us to start a phase-shift analysis of the entire aggregate of experimental data at 640 MeV (Zul'karneev, Lapidus, Silin).

However, at the present stage of the experiments, on the basis of processing of the available material and before the phase-shift analysis is performed, it is already possible to advance in definite fashion and to proceed to a direct determination of the amplitude of the pp scattering and a determination of the elements of the scattering matrix at the indicated energy. We present below the results of the data analysis performed.

A. Determination of the values of the squares of the moduli of the amplitudes of pp scattering. In the Oehme representation [10] the elastic pp-scattering amplitude is written in the form

$$M = \frac{1}{2}\{(a+b) + (a-b)(\boldsymbol{\sigma}_1\mathbf{n})(\boldsymbol{\sigma}_2\mathbf{n}) + e(\boldsymbol{\sigma}_1+\boldsymbol{\sigma}_2)\mathbf{n} + (c+d) \times (\boldsymbol{\sigma}_1\mathbf{m})(\boldsymbol{\sigma}_2\mathbf{m}) + (c-d)(\boldsymbol{\sigma}_1\mathbf{l})(\boldsymbol{\sigma}_2\mathbf{l})\}. \quad (1)$$

With M so written, the experimentally measured values of the elastic pp-scattering cross section $\sigma(\theta)$ and of the Wolfenstein parameters C_{nn}, D, etc. are described by the following expression [1]

$$\sigma(\theta) = \frac{1}{2}(|a|^2 + |b|^2 + |c|^2 + |d|^2 + |e|^2),$$

$$P(\theta') = \frac{\operatorname{Re} ae^*}{\sigma(\theta)},$$

$$C_{nn} = \frac{1}{2\sigma(\theta)}(|a|^2 - |b|^2 - |c|^2 + |d|^2 + |e|^2),$$

$$D(\theta) = \frac{1}{2\sigma(\theta)}(|a|^2 + |b|^2 - |c|^2 - |d|^2 + |e|^2),$$

$$K(\theta) = \frac{1}{2\sigma(\theta)}(|a|^2 - |b|^2 + |c|^2 - |d|^2 + |e|^2).$$

Simultaneous solution of this system of equations using the experimental data of our work and of the previously indicated investigations has made it possible to calculate the square of the moduli of the pp-scattering amplitudes and to determine their relative contributions to the cross section at different angles. The results of the calculations are listed in Table III.

It can be seen that the strongly predominant contribution to the pp-scattering cross section in the entire considered angle interval is made by the terms $|a|^2 + |e|^2$, where e is the term responsible for the spin-orbit interaction. For 90°, the contribution of the term e is particularly large (on the order of 90 per cent, as was already noted earlier [3]). The contribution of the terms $|d|^2$ at practically all angles, and of the terms $|c|^2$ at angles $\theta \le 90°$, is small. This makes it possible to determine the amplitude of the pp scattering (1) for angles $90° \ge \theta \ge 50°$ approximately only from the first three terms, which can subsequently simplify the analysis.

B. Determination of the moduli of the matrix elements. The available experimental data enable us to find for certain scattering angles the moduli of the matrix elements $|M_{ss}(\theta)|$ of the scattering matrix (the Stapp representation [11]) and to determine at 640 MeV the cross sections of the singlet pp-scattering $\sigma_s(\theta) = (1/4)|M_{ss}(\theta)|^2$. For 90° this cross section is also determined directly from the relation $\sigma_s(90°) = (1/2)[1 - C_{nn}(90°)]\sigma_{pp}(90°)$ and amounts to

$$\sigma_s(90°) = (0.07 \pm 0.2)\cdot 10^{-27}\ \text{cm}^2,$$

since, according to our data (Table II).

$$C_{nn}(90°) = 0.93 \pm 0.21,$$

and

$$\sigma_{pp}(90°) = (2.1 \pm 0.2)\cdot 10^{-27}\ \text{cm}^2\ [5].$$

The cross section in the triplet is

$$\sigma_{tr}(90°) = \sigma_{pp}(90°) - \sigma_s(90°) = (2.0 \pm 0.3)\cdot 10^{-27}\ \text{cm}^2.$$

Table III

$\theta_{c.m.s.}$, deg.	$\frac{\vert a\vert^2+\vert e\vert^2}{2\sigma(\theta)}$	$\frac{\vert b\vert^2}{2\sigma(\theta)}$	$\frac{\vert c\vert^2}{2\sigma(\theta)}$	$\frac{\vert d\vert^2}{2\sigma(\theta)}$	$\frac{\vert a-e\vert^2}{2\sigma(\theta)}$
54	0.78±0.09	0.21±0.08	0.00±0.08	0.00±0.08	0.42±0.09
72	0.66±0.07	0.19±0.07	—0.02±0.07	0.17±0.07	0.53±0.07
90	0.95±0.08	0.02±0.05	0.02±0.05	0.02±0.08	0.95±0.08
108	0.66±0.07	—0.02±0.09	0.19±0.09	0.17±0.07	0.79±0.07
126	0.78±0.09	0.00±0.07	0.21±0.07	0.00±0.09	1.14±0.09

We note that in a recent analysis of the experimental data on pp-scattering, including measurements of the parameter R(90°), the value obtained for $|M_{ss}(90°)|$ at 640 MeV was $(0.24 \pm 0.11) \times 10^{-13}$ cm [8]. This leads to a cross section

$$\sigma_s(90°) = (0,14 \pm 0.13) \cdot 10^{-27}\,\text{cm}^2,$$

which agrees within the limits of error with the cross section directly obtained from $C_{nn}(90°)$.

Inasmuch as in accordance with experiments [6] the depolarization parameter D for the angle 54° is close to unity [D(54°) = 0.99 ± 0.25], then by putting D(54°) = 1 in Stapp's expression [11] for C_{nn} and D in terms of the matrix elements, we are able to estimate the value of the singlet matrix element for this angle. Under these conditions we get

$$|M_{ss}(54°)|^2 = \{1 - C_{nn}(54°)\} \cdot \sigma_{pp}(54°).$$

Hence, using the value of $C_{nn}(54°)$ which we determine, we get

$$|M_{ss}(54°)| = (0.40 \pm 0.07) \cdot 10^{-13}\,\text{cm}.$$

This gives a singlet cross section

$$\sigma_s(54°) = (0.4 \pm 0.14) \cdot 10^{-27},$$

The cross section of the pp scattering in the triplet states for this angle amounts to

$$\sigma_{tr}(54°) = (3.3 \pm 0.2) \cdot 10^{-27}\,\text{cm}^2$$

inasmuch as

$$\sigma_{pp}(54°) = (3.7 \pm 0.2) \cdot 10^{-27}\,\text{cm}^2\ [5].$$

Worthy of attention is the fact that the contribution of the singlet scattering to the total scattering cross section at a given angle, observed as the scattering angle decreases from 90 to 54°, increases appreciably.

C. Estimate of singlet phase shifts. We have further attempted to estimate the phases of the singlet pp scattering at 640 MeV. This was done under the assumption that the contribution of the partial waves with $l \geq 4$ can be calculated in the one-meson approximation. In these calculations the phase shifts $^1S_0$ and $^1G_4$, etc were assumed to be real, and the modulus of the S matrix for $l = 2$ was taken from the theoretical paper by Soroko, [12], worked out earlier in our laboratory and devoted to the processing of data obtained in the study of the reactions $p + p \rightarrow \pi^+ + d$, $p + p \rightarrow \pi^+ + n + p$, and $p + p \rightarrow \pi^0 + p + p$ on polarized and unpolarized proton beams. The numerical values of the real parts of δ^R of the phase shifts of the waves $^1S_0$ and $^1D_2$ (in the notation of the paper by Kazarinov and Silin [9]) determined on the basis of the previously given values of $|M_{ss}(\theta)|^2$ for 54° and 90° are listed in Table IV[2]. To illustrate the variation of these phases with energy, the same table lists also their values for energies smaller than the meson-production threshold (set 1 from [9]).

Table IV

E, MeV	δ^R, deg $^1S_0$	δ^R, deg $^1D_2$
40	44.5±1.9	1.48±0.18
90	29.2±1.6	1.12±1.98
147	16.80±0.63	7.07±0.23
210	4.52±0.50	7.14±0.19
310	—7±1.8	11±0.6
640 solution a	—30±7°	—7.5±5
640 solution b	40±6.5	7.5±5

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Note added in proof (December 10, 1962). After the present article went to press, Zul'karneev and Silin made a phase-shift analysis of all the experimental data on elastic pp scattering at 660 MeV (Preprint, Joint Inst. Nuc. Res. D-1107, 1962). Our estimates of the singlet pp-scattering phase shifts for 640 MeV (Table IV) and the values of the parameter $A(\pi/2)$ predicted in [3] agree with the values obtained by Zul'karneev and Silin.

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