ОБЪЕДИНЕННЫЙ ИНСТИТУТ ЯДЕРНЫХ ИССЛЕДОВАНИЙ

Лаборатория ядерных проблем

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ANGULAR DEPENDENCE OF THE POLARIZATION CORRELATION C_{nn} AND THE DETERMINATION OF THE SCATTERING AMPLITUDE MODULI FOR pp SCATTERING AT 640 MEV II

THE ESTIMATION OF THE SINGLET PHASE SHIFTS

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Experiments on triple proton-proton scattering are described, and the results are given of measurements of the spin correlation coefficient C_{nn} in elastic proton-proton scattering at 640 for some c.m.s. angles different from 90°.

By analyzing our experimental data and those available in the literature for the given energy, the moduli of the pp scattering amplitudes have been determined quantitatively in the wide angle range $50^{\circ} < \theta < 130^{\circ}$. Their relative contributions have been evaluated. The values of the singlet and triplet cross sections have been determined for some angles; the phase shifts have been estimated for pp system in the singlet states at the given energy.

1. Introduction

This paper discribes one of the experiments carried out at the Joint Institute synchrocyclotron in accordance with a programme of the all-sided research on pn and pp scattering /1,2/ for reconstructing the nucleon-nucleon scattering matrix at 640 MeV. At the same time it is the second part of the investigation we are making on the measurement of the correlation between the normal polarization components (the parameter C_{nn}) in pp scattering.

In the first part of this investigation the value of C_{nn} was found for the angle of 90° in the c.m.s. /3/; in this paper this parameter is determined for the angles of 54° and 72°, as well as for auxilliary angles of 126° and 108°, respectively.

Being an experiment, which, in a sense, completes by the present time a certain stage in the programme of investigations on pp scattering at 640 MeV, the measurement of C_{nn}, along with other data, allows to get much new information on pp scattering at the given energy without resorting to the phase shift analysis. This can be seen from what will follow. At the same time, as far as each of the values of C_{nn} yields, say, an independent relation between the phase shifts of the waves participating in the scattering, the data concerning the parameter C_{nn} may give valuable information on the scattering phase shifts and serve as a criterion for choosing the most plausible solution when the phase shift analysis of all the data on pp scattering will be made in the future.

2. Experimental Arrangement

A scheme of the experimental arrangement for measuring the parameter C_{nn} is shown in Fig. 1. A 640 MeV unpolarized proton beam shaped by a quadrupole lens and two collimators (20 mm) was incident on the first target (H_2) which was a cylindrical vessel filled with liquid hydrogen. The density of the proton flux at the target was usually $(3 - 3.5) \cdot 10^8 cm^2 sec^{-1}$, and, as the control experiments done in the course of preparing each run of measurements have shown, the beam was homogeneous enough at the place where it struck the target.

The protons elastically scattered on the first target passed through the collimating slots in the local shielding, were recorded by the counters 1_L and 1_R. Then, they underwent scattering on the polarization analyzer targets T_L and T_R, and were detected by groups of counters $2_L 3_L 4_L$ and $2_R 3_R 4_R$. The geometry of the second scatterings, the material and the thickness of the analyzer targets T_L and T_R are indicated in the Table.

Table 1

$\theta^\circ_{c.m.s}$	Threshold energy of telescopes (MeV)		Material and thickness of second scatterer in g/m^2		The angles of second scattering	
	E_L	E_R	T_L	T_R	θ°_L (Lab.)	θ°_R (Lab.)
54 ± 3	270	140	Al; .38	C; 8.0	10 ± 2.5	14 ± 2.5
72 ± 3	390	139	C; 21	C; 60	11 ± 2.5	14 ± 2.5

In this experiment we used the crossing connection of the counters 1_L and 1_R with the telescopes $2_L\ 3_L\ 4_L$ and $2_R\ 3_R\ 4_R$ (see Fig. 1) what allowed to identify more effectively the elastic pp scattering events against the background of the intensive processes of inelastic scattering. The parameters of the coincidence circuits CC_L, CC_R and CC_3 were the same, as in previous experiments.

3. Calibration Experiment

In elastic proton-proton scattering at 640 MeV both protons have rather a high value of the polarization. This fact was used for calibrating the analyzing power of the targets T_L and T_R, made simultaneously with the measurements of the correlation asymmetry. The analyzing powers P_L and P_R of the targets T_L and T_R of the second scattering were determined as usual, by observing the right-left asymmetry in the second scattering. In calculating the values of P_L and P_R the data on the polarization in pp scattering obtained in /4/ were used. The values of P_L and P_R found are listed in Table 3.

4. Correlation Asymmetry and the Coefficient C_{nn}

The magnitude of the correlation asymmetry was found by the well-known formula

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

where N_{LL}, N_{LR}, etc are the counting rates of the coincidence circuit CC_3 corrected for the background, at the corresponding positions of the telescopes measuring the counting rates in the second scattering. In measuring N_{LL}, N_{RR} etc the background of the arrangement was determined like in our previous paper /3/. At the same time the corrections for the accidental coincidences in the circuit were evaluated when the delay line was connected with one of its channels. In introducing the delay in the channels 1_L and 1_R the accidental coincidences in the circuit CC_3 were negligibly small and not taken into account in the calculations*. The total background determined in the measurements of N_{LL}, N_{RL}, ... at different angles varied within 15-30% of the total counting rate of the circuit CC_3.

To find the true correlation asymmetries ϵ, small corrections for spurious correlations ϵ_f due to the geometry of the arrangement were introduced into the experimentally found values of ϵ'. The magnitudes of the spurious correlation asymmetry are listed in Table 2 for different angles.

Table 2.

θ^0 c.m.s.	54	72	90
$\epsilon_f(\theta)$	-0.01 ± 0.01	$0.01 + 0.01$	0.01 ± 0.04

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* In measuring the background of the accidental coincidences the lengths of the introduced delayed lines were specified by the known time structure of the extracted proton beam.

In Table 3 are given the values of the correlation asymmetry $\epsilon(\theta) = \epsilon'(\theta) - \epsilon_f(\theta)$ and the magnitudes of the coefficient $C_{nn}(\theta)$ calculated by the formula $C_{nn} = \frac{\epsilon}{P_L \cdot P_{Ro}}$. The value of C for the angle θ c.m.s. 90^0 we have found earlier is also tabulated. The values of $C_{nn}(126^0)$ and $C_{nn}(108^0)$ are taken to be $C_{nn}(54^0)$ and $C_{nn}(72^0)$, respectively, because of the symmetry properties of the parameter $C_{nn}(\theta)$ [1] in pp -scattering.

Table 3.

$\theta^0_{c.m.s.}$	$C_{nn}(\theta)$	$\epsilon(\theta)$	$P_L(\theta)$	$P_R(\theta)$
54^0	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	0,26 ± 0,04	0,51 ± 0,06	0,54 ± 0,06
108	0,65 ± 0,15	–	–	–
126	0,57 ± 0,14	–	–	–

Discussion of Results

After the measurements of the angular dependence of the parameter C_{nn} have been completed, there became possible to analyze the data of a great number of independent experiments on pp -scattering performed at the proton energy of 640 MeV; $\sigma(\theta)$ [5], C_{nn}, $P(\theta)$ [4] $D(\theta)$, $K(\theta)$ [6], $C\ kp(90^0)$ [7], $R(\theta)$ [8], etc. This circumstance, and a certain success achieved in the investigations of Kazarinov and Silin [9] who made the phase shift analysis of the data on nucleon-nucleon scattering in the energy region below the pion production threshold allowed to start the phase shift analysis of all the experimental data at 640 MeV (Zul'kameev, Lapidus, Silin).

However, on the basis of the material available now, it is already possible to proceed to a direct reconstruction of the pp -scattering amplitude and to the determination of the scattering matrix elements at the given energy without completing the phase shift analysis. Below we give the results of this analysis.

1. Determination of the Values of the Moduli Squared of the pp Scattering Amplitude

In the Oehme representation [10] the amplitude of elastic pp -scattering is put as

$$M = \tfrac{1}{2}\{(a+b) + (a-b)\vec{\sigma}_1\vec{n}\cdot\vec{\sigma}_2\vec{n} + e(\vec{\sigma}_1+\vec{\sigma}_2)\vec{n} + (c+d)\vec{\sigma}_1\vec{m}\cdot\vec{\sigma}_2\vec{m} + (c-d)\vec{\sigma}_1\vec{\ell}\cdot\vec{\sigma}_2\vec{\ell}$$

When M is written in such a way, the experimentally measured magnitudes of the elastic pp scattering cross sections and of the Wolfenstein parameters, C_{nn}, D, etc are described by the following expressions [1]

$$\sigma(\theta) = \tfrac{1}{2}(|a|^2 + |c|^2 + |d|^2 + |e|^2); \qquad P(\theta) = \frac{Re\, a e^*}{\sigma(\theta)}$$

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

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

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

A simultaneous solution of this system of equations using the experimental data of ours and above mentioned papers permitted to calculate the moduli squared of the pp scattering amplitude and to find their relative contributions to the cross section at different angles. The results of the calculations are presented in Table 4.

Table 4.

$\theta_{c.m.s.}$	$\frac{\|a\|^2+\|e\|^2}{2\sigma(\theta)}$	$\frac{\|b\|^2}{2\sigma(\theta)}$	$\frac{\|c\|^2}{2\sigma(\theta)}$	$\frac{\|d\|^2}{2\sigma(\theta)}$	$\frac{\|a-e\|^2}{2\sigma(\theta)}$
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

One can see that the strongly predominant contribution to the cross section for pp scattering in the whole angular interval under consideration is given by the terms $|a|^2 + |e|^2$, where e is the term responsible for the spin orbital interaction. At the same time for the angle of 90° the contribution of the term $|e|^2$ is especially great (of the order of 90%; this was pointed out earlier[2]). The contribution of the terms $|d|^2$ is small practically for all the angles, and that of $|c|^2$ for the angles $\theta \leq 90°$. This leads to the fact that for the angles $90° \geq \theta \geq 50°$ the pp scattering amplitude (1) may be approximately defined by the three first terms only, what may further simplify the analysis.

2. The Determination of the Moduli of the Matrix Elements

The available experimental data allow to find also the moduli of the element of the scattering matrix (the Stapp representation[11]) for some angles and to determine the cross sections of the singlet pp - scattering $\sigma_s(\theta) = \tfrac{1}{4}|M_{ss}(\theta)|^2$. For the angle of 90° this cross section is defined directly from the relation $\sigma_s(90°) = \frac{1 - C_{nn}(90°)}{2}\sigma_{pp}(90°)$ It is found to be $\sigma_s(90°) = (0{,}07 + 0{,}2)\cdot 10^{-27}$ cm^2 since, according to our data, (Table 3) $C_{nn}(90°) = 0{,}93 + 0{,}21$, and $\sigma_{pp}(90°) = (2{,}1 \pm 0{,}2)\cdot 10^{-27}$ cm^2 [5]. The triplet cross section is $\sigma_{tr}(90°) = \sigma_{pp}(90°) - \sigma_s(90°) = (2,0 + 0,3)\, 10^{-27}\ cm^2$. Note, that recently in the analysis of the experimental data on pp -scattering involving the measurements of the parameter R ($90°$) for $|M_{ss}(90°)|$ at 640 MeV, the value $(0.24 \pm 0.11) \cdot 10^{-13}$ cm [8] has been obtained. This leads to the cross section $\sigma_s(90°) = (0,14 + 0,13)\, 10^{-27}\ cm^2$ which is in agreement with that found just by $C_{nn}(90°)$ within the error.

As far as, according to the experiment [6], the depolarization parameter D for the angle of $54°$ is close to unity ($D(54°) = 0,99 \pm 0,25$), then assuming $D(54°) = 1$ in the Stapp [11] expression for C_{nn} and D in terms of the matrix elements we are able to estimate the magnitude of the singlet matrix element for this angle. Under these assumptions:

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

Hence, by using the value of $C_{nn}(54°)$ we have $|M_{ss}(54°)| = (0.40 \pm 0.07) \cdot 10^{-13}$ cm. This gives the singlet cross section $\sigma(54°) = (0.4 + 0.14) \cdot 10^{-27}\ cm^2$ The pp scattering cross section in the triplet states for this angle is $\sigma_{tr}(54°) = (3.3 \pm 0.2) \cdot 10^{-27}\ cm^2$ (since $\sigma_{pp}(54°) = (3.7 \pm 0.2) \cdot 10^{-27}\ cm^2$ [5] ,

It should be especially pointed out that the contribution of the singlet scattering to the total scattering cross section at the given angle increases essentially with the decrease of the scattering angle from $90°$ down to $54°$.

3. Estimation of the Singlet Phase Shifts

We attempted to estimate the phase shifts of the singlet pp -scattering at 640 MeV. This was done under the assumption that the contribution of the partial waves with $\ell \geq 4$ can be calculated in the one-pion approximation. In these calculations the phase shifts $^1S_0$, $^1G_4$ etc, were assumed to be real, while the modulus of the S -matrix for $\ell = 2$ was taken from a theoretical paper of Soroko [12] which was devoted to the analysis of the data concerning the reaction

$$p + p \rightarrow \begin{cases} \pi^+ + d \\ \pi^+ + n + p \\ \pi^0 + p + p \end{cases}$$

on the polarized and unpolarized proton beams. The numerical values of the real parts of the phase shifts of the waves $^1S_0$ and $^1D_2$ in the notations of [9] defined according to the above mentioned magnitudes $|M_{ss}|^2$ for the angles $54°$ and $90°$ are given in Table 5*. In order to illustrate the changes in these phase shifts with energy the Table presents their values at energies below the pion production threshold (set 1 from paper [9]).

Table 5.

State	Energy in MeV						
	40	90	147	210	310	640 a–solution	640 b–solution
$^1S_0$	$44,5° \pm 1,9°$	$29,2° \pm 1,6°$	$16,80° \pm 0,63°$	$4,52° \pm 0,50°$	$-7° \pm 1,8°$	$-30° \pm 7°$	$40° \pm 6,5°$
$^1D_2$	$1,48° \pm 0,18°$	$1,12° \pm 1,98°$	$7,07° \pm 0,23°$	$7,14° \pm 0,19°$	$11° \pm 0,6°$	$-7,5° \pm 5°$	$7,5° \pm 5°$

* A more detailed description of the methods for calculating the above-mentioned phase shifts will be given in a special paper concerned with an attempt to make the phase shift analysis of all the available experimental data on pp scattering at 640 MeV.

In conclusion we note, that the value of the parameter $C_{nn}(54^\circ)$ we have found experimentally does not agree with that calculated theoretically (see [8]). This seems to indicate that the assumptions made by the authors of the mentioned paper in calculating the parameter C_{nn} may not be completely well founded.

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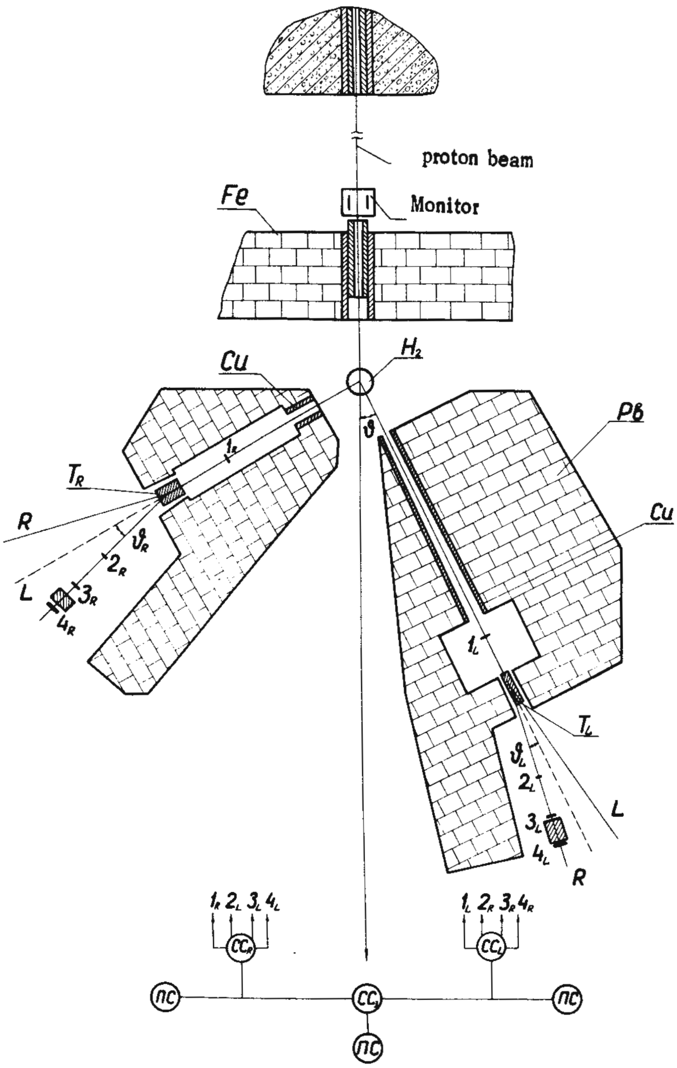

Fig. 1.