SCATTERING OF 590 Mev NEUTRONS BY PROTONS IN THE SMALL ANGLE REGION

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The ring scatterer method was used to determine the differential elastic n-p scattering cross section for 590 Mev neutrons for angles from 5 to 35° in the c.m.s. A strong increase of the cross section was found with decrease of scattering angle. Furthermore, the forward scattering cross section was found to exceed the backward cross sections. A comparison of the results obtained with the prediction of the optical theorem shows that it is incorrect to treat nucleon-nucleon scattering at ~ 600 Mev on the basis of the opaque-nucleon concept.

INTRODUCTION

ONE of the problems arising in the investigation of nucleon-nucleon interactions is the synthesis of the elastic-scattering amplitude.

$$M = \alpha + \beta(\sigma_1 + \sigma_2)\cdot\mathbf{n} + \gamma(\sigma_1\cdot\mathbf{n})(\sigma_2\cdot\mathbf{n}) + \delta(\sigma_1\cdot\mathbf{l})(\sigma_2\cdot\mathbf{l}) + \varepsilon(\sigma_1\cdot\mathbf{m})(\sigma_2\cdot\mathbf{m}), \quad (1)$$

i.e., the determination of the complex quantities α, β, γ, δ, and ϵ from the experimental data for each scattering angle and for all energies of incident nucleons. The presently available experimental data are quite inadequate for the solution of this problem. It is therefore of interest to obtain from individual experiments numerical values of various independent combinations of amplitude coefficients. In the particular case of forward scattering ($\vartheta = 0°$) the expression (1) simplifies somewhat because the coefficient γ ($\vartheta = 0°$) vanishes. As a result, the scattering cross section at $\vartheta = 0°$ becomes:

$$\sigma(\vartheta = 0°) = |\alpha|^2 + |\beta|^2 + |\delta|^2 + |\varepsilon|^2.$$

On the other hand, the optical theorem makes it possible to find the imaginary part of the spin-free term α of the forward scattering amplitude, from data on the total cross sections σ_t of the nucleon-nucleon interactions at the same energy

$$\mathrm{Im}\,\alpha(\vartheta = 0°) = k\sigma_t / 4\pi, \quad (2)$$

where k is the wave number of the incident nucleon. The difference

$$\sigma(\vartheta = 0°) - [\mathrm{Im}\,\alpha(\vartheta = 0°)]^2 = |\mathrm{Re}\,\alpha|^2 + |\beta|^2 + |\delta|^2 + |\varepsilon^2| \quad (3)$$

determines the contribution of the real part of the spin-free and spin-dependent terms of the amplitude in the forward scattering of the nucleus. Thus, knowledge of the total interaction cross sections and of the differential scattering cross section at $\vartheta = 0°$ makes it possible to find the numerical values of the two independent functions (2) and (3) from the scattering amplitude coefficients for this angle.

EXPERIMENTAL PROCEDURE AND DATA

We determined the differential n-p scattering cross sections at a mean neutron energy $E_n = 590$ Mev in the interval from 5 to 35° in the c.m.s. We used for the measurement a specially constructed setup with ring scatterers (described in detail in reference 1), shown schematically in Fig. 1. A collimated neutron beam with a spread $\varphi = 0.5°$ and an annular cross section was incident on the scatterer; the beam and scatterer had a common axis. The scatterer was a ring, or more accurately a polygon built up of cylindrical blocks 62 mm in diameter, arranged in a circle of mean radius R = 32 cm. The neutrons were scattered by an angle

$$\Phi_{\mathrm{l.s.}} = \tan^{-1}(R/x) + \varphi, \quad (4)$$

and registered with a neutron telescope, mounted at a distance x from the ring scatterer. By moving the telescope along the axis of the neutron beam (by varying the distance x) it was possible to investigate neutron scattering at various angles. The effect due to the scattering of neutrons by protons was determined by taking the difference of the counts produced by polyethylene and graphite scatterers.

Only the realtive values of the cross sections were determined directly in this experiment, so that it was possible to dispense with the determination of the absolute value of the neutron cur-

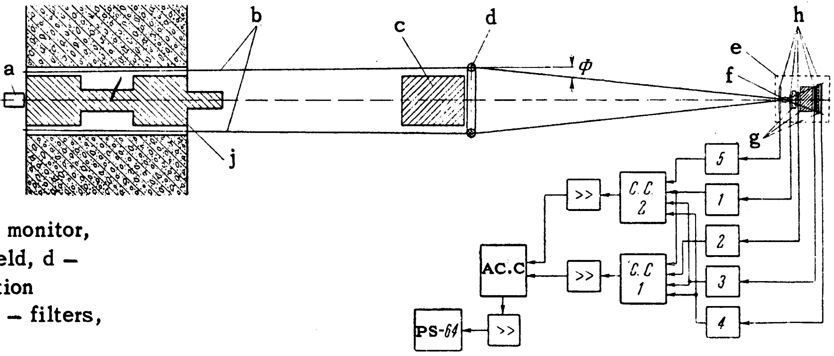

FIG. 1. Overall diagram of the experiment. a – monitor, b – annular neutron beam, c – additional lead shield, d – ring scatterer, ϕ – scattering angle, e – scintillation counters, f – neutron telescope, g – converters, h – filters, j – brass core of the collimator.

rent and of many characteristics of the neutron telescope. The relative cross sections were normalized to the n-p scattering cross section for $\vartheta = 35°$, which is known for this energy.[2] The results of the measurements are given in Table I. The deviations indicated include statistical measurement errors and deviations in the cross section used for normalization.

The 11° and 23° n-p scattering cross sections for neutrons having the same energy were measured earlier in our laboratory by a different procedure.[3] The values of the cross sections obtained for these angles are in good agreement with the corresponding quantities determined in this investigations

GENERAL REMARKS ON THE CHARACTER OF n-p SCATTERING AT ~600 Mev

The data of Table I show a strong increase in cross section with diminishing scattering angle. Furthermore, a comparison of the cross sections for angles close to 180°,[2] shows that the "forward" scattering ($\vartheta = 0°$) at 590 Mev becomes even more probable than the "backward" scattering ($\vartheta = 180°$), in contrast with what was observed at lower neutron energies. One of the causes of this change in the energy dependence of the elastic n-p scattering is the sharp increase in the contribution of inelastic processes to the n-p interaction cross section at energies exceeding 400 Mev, imparting a diffraction character to the scattering.

The great scattering anisotropy, characterized by the fact that at 590 Mev the cross section

TABLE I

Scattering angle ϑ^0 c.m.s.	Relative n-p scattering cross section	n-p scattering cross section, 10^{27} cm²/sterad
5	2.7±0.4	10±1.5
8	2.2±0.3	8.2±1.4
11.5	1.7±0.2	6.4±0.9
23	1.2±0.1	4.3±0.5
35 (normalization)	1	3.7±0.2 [2]

$\sigma_{np}(5°)$ is eleven times greater than the cross section $\sigma_{np}(90°)$ (which, according to reference 2, equals $(0.91 \pm 0.06) \times 10^{-27}$ cm²/sterad) and the sharp increase in the cross sections in the region of small angles ($\vartheta = 10° - 5°$) are additional arguments in favor of the necessity, demonstrated in reference 3, of accounting for states with orbital moments on the order of six and higher in the analysis of data on elastic n-p scattering at this energy.

NUMERICAL VALUES OF EQUATIONS (2) AND (3); CONCLUSIONS

The experimental data in the current literature permit a determination of the imaginary part of the coefficient α in Eq. (1) for $\vartheta = 0°$ over a wide range of energies. The corresponding values for the interaction of nucleons in states with isotopic spins T = 0 and T = 1, calculated from the following formulas

$$\operatorname{Im}\alpha_{T=1}(\vartheta = 0°) = k\sigma_t(pp)/4\pi,$$
$$\operatorname{Im}\alpha_{T=0}(\vartheta = 0°) = [2k\sigma_t(np) - k\sigma_t(pp)]/4\pi, \qquad (5)$$

are shown in Fig. 2. We used here total cross sections obtained both in our laboratory and abroad, as listed in the surveys.[4] It is seen that, at neutron energies less than 200 Mev, the value of Im α ($\vartheta = 0°$) is determined essentially by the contribution from states with T = 0, while at energies ~ 600 Mev the contributions from both types of states become equal.

To find the second of the foregoing combinations of amplitude coefficients [Eq. (3)] it is necessary to know the differential n-p scattering cross section

FIG. 2. Measurement dependence of Im α (ϑ = 0°) for the interaction of nucleons in states with T = 0 and T = 1(accuracy ~ 10%).

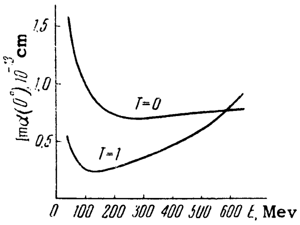

TABLE II

E_n, Mev	$\sigma_{extr.}(0°)$,	$\sigma_{extr.}(0°) - [\mathrm{Im}\,\alpha_{np}(0°)]^2$,
	10^{-27} cm^2/sterad	
90 [5]	14	10
137 [6]	11	8.5
400 [7]	4.0	0.5
590, present work	12	6

for $\vartheta = 0°$. Since such data cannot be found in any of the known investigations, we chose those investigations, in which the angular dependences of the cross sections were investigated for angles closest to 0°, and extrapolated these to $\vartheta = 0°$. The extrapolation of the cross section for four energies, and the resultant contributions to the real part of the spin-free and spin-dependent terms of the amplitude in the n-p forward scattering amplitude, are listed in Table II (accuracy 10 – 20%).

The optical theorem, inasmuch as it permits calculation of the imaginary part of the spin-free term of the scattering amplitude, determines thereby the minimum possible forward scattering cross section, which for 590 Mev neutrons is

$$\sigma_{min}(\vartheta = 0°) = [\mathrm{Im}\,\alpha_{np}(\vartheta = 0°)]^2 = 5.8 \cdot 10^{-27}\mathrm{cm}^2/\mathrm{sterad}.$$

A comparison of our results with the predictions of the optical theorem shows that the n-p scattering cross section for $E_n = 590$ Mev reaches a value $\sigma_{min}(0°)$ even at $\vartheta = 11°$ and continues to increase with diminishing angle. The value found for the difference $\sigma_{extr}(0°) - [\mathrm{Im}\,\alpha_{np}(0°)]^2$ (see Table II) is evidence that at this energy the real part of the spin-free amplitude and the spin-dependent terms of the amplitude make a considerable contribution to the n-p forward scattering. This fact, together with the data obtained by us on the considerable polarization of nucleons in n-p scattering,[8] leads to the conclusion that there is no justification for attempting to consider the scattering of neutrons by protons at approximately 600 Mev by using the concept of the nucleon as a black sphere, since the forward scattering amplitude for such a model reduces to the imaginary part of the spin-free term, and there is no polarization.[9] This conclusion can be extended to include p-p scattering at the same energies, since in this case, too, the polarization is considerable,[10] and the differential cross sections, increasing rapidly with diminishing angle, reach the minimum value predicted by the optical theorem even at $\vartheta = 15°$.[11]

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