SCATTERING OF 200 MeV NEUTRONS BY PROTONS

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Submitted to JETP editor February 20, 1962

J. Exptl. Theoret. Phys. (U.S.S.R.) **43**, 35-39 (July, 1962)

The total and the differential cross sections for the scattering of 200-MeV (effective energy) neutrons by protons were measured. The total cross section is $\sigma_t = (42.7 \pm 0.9) \times 10^{-27}$ cm^2. The function $\sigma(\vartheta)$ is appreciably asymmetric with respect to the angle $\vartheta = 90°$. The pion-nucleon interaction constant, determined from the angular distributions of the scattered particles, is $f^2 = 0.08 \pm 0.02$.

ATTEMPTS to determine the π meson-nucleon interaction constant directly from nucleon-nucleon scattering experiments [1-5] have shown that the quantity f^2 found in such a way is apparently consistent with the value $f^2 = 0.08$ obtained from πp scattering experiments. It should be noted, however, that all mean values of f^2 from nucleon-nucleon scattering are systematically smaller than 0.08.

The differential np cross sections at 200 MeV energy were measured in order to compare the values of f^2 from np and πp scattering, and also to obtain data necessary to carry out a phase analysis. Errors were reduced to 3—5% throughout the principal part of the curve.

EXPERIMENTAL METHOD

The neutron beam was obtained by stripping deuterons accelerated to an energy $E_d = 400$ MeV in the Joint Institute for Nuclear Research synchrocyclotron. The neutron energy distribution, found by differentiating the absorption curve of the recoil protons from elastic np collisions had a maximum at $E_n = 192$ MeV (Fig. 1) and fitted well the distribution given by the Serber formula for an opaque nucleus: [6]

$$N(E_n) = \frac{\varepsilon^{1/2} E_d^{3/2}}{[(E_n - E_d/2)^2 + \varepsilon E_d]^{3/2}}, \quad (1)$$

where ϵ is the deuteron binding energy.

The mean effective energy amounted to 205 MeV assuming that the np scattering cross section is constant throughout the range 170—400 MeV, and for a 170 MeV detector threshold. The data given in [7] for energies of 90 to 400 MeV indicate a slow decrease in the differential cross sections $\sigma(\vartheta)$ with increasing energy. The energy dependence of $\sigma(\vartheta)$ in this range can be written as

$$\sigma(\vartheta, E) = \sigma(\vartheta, E_0)[1 - b(E - E_0)],$$

where b equals 6, 17, 15, 16×10^{-4} MeV^{-1} for $\vartheta = 180$, 140, 90, and 36° respectively; and $E_0 = 300$ MeV. This slow change of the cross section (b = 15×10^{-4} MeV^{-1} lowers the mean energy in the spectral range under consideration to 200 MeV.

Recoil protons were used to measure the differential np scattering cross sections in the range of l.s. recoil angles $0 \le \Phi \le 55°$ ($67°30' \le \vartheta \le 180°$ in the c.m.s.). The recoil-proton yield was determined from the difference in the effects from polyethylene (CH_2) and graphite targets which were alternatively placed in the neutron beam. A telescope consisting of three scintillation counters served as detector. The detector threshold was determined by a copper absorber placed before

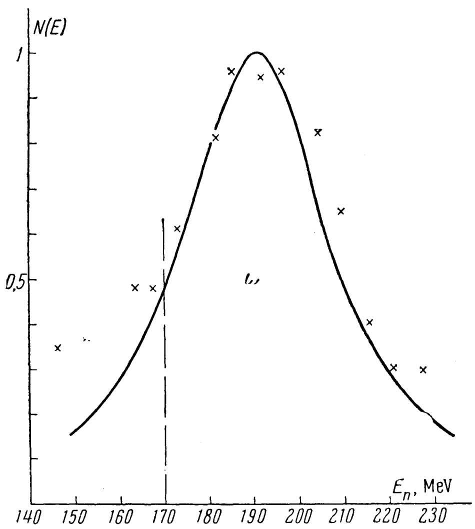

FIG. 1. Energy distribution of neutrons from the deuteron stripping reaction at 400 MeV. The solid curve has been calculated according to the Serber formula, × – result of the differentiation of the recoil proton absorption curve.

the last counter of the telescope. Polyethylene and graphite discs of identical retarding power were used as the scattering targets. The graphite thickness was equal to 3, 1.5, and 0.5 g/cm^2 for the measurements in the ranges of angles Φ 0—20, 20—40, and 40—55° respectively. The angular resolution amounted to 2° for measurements in the middle part of the curve ($67°30' \le \vartheta \le 160°$) and decreased to 1° in the range $160 \le \vartheta \le 180°$. Ionization energy losses of the recoil protons in the targets were, on the average, not greater than 10% of the mean energy of the particles.

The sharp decrease in the recoil proton energy at angles $\Phi < 55°$ made it necessary to detect directly the scattered neutrons (scattering angles $\theta < 67°30'$ in the l.s.) in order to measure the differential np scattering cross sections in the range $\theta < 32°30'$. The neutron detector did not differ basically from the one used earlier [8] and will therefore not be described here. The angular resolution of the neutron detector amounted to 3° for measurements at angles $\theta \ge 20°$, and to 2° at $\theta < 20°$. The energy threshold was determined by a copper absorber. In calculating the thickness of the absorber, it was assumed that the average losses of neutrons in exchange scattering in the converter (CH_2) amount to 15%.

Polyethylene and graphite discs (3.5 g/cm^2 thick) were used as scatterers for the measurements using the neutron detector at angles $\theta > 10°$, while a dewar filled with liquid hydrogen (1.0 g/cm^2 H_2) was used for this purpose at angles $\theta \le 10°$. The neutron beam had a rectangular section 1.5 cm × 6 cm. The counting rate ratio with the converter and without it amounted to 6 : 1. The data obtained by different methods were corrected for the detection efficiency and joined at the angle $\vartheta = 65°30'$ in the c.m.s. They were then normalized to a total np scattering cross section of $(42.7 \pm 0.9) \times 10^{-27}$ cm^2.

The measurement of the total np cross section was carried out in a "good geometry" neutron beam absorption experiment. The angular resolution of the detector was equal to 0.15°. The energy threshold for primary neutrons was equal to 170 MeV. The difference in the effect for polyethylene (59 g/cm^2) and graphite (54 g/cm^2) absorbers placed in the neutron beam was measured. Corrections for the detection efficiency of recoil protons, due to their absorption and scattering in the absorbers determining the detector threshold, were found experimentally. A 500-MeV proton beam was used for this purpose; elastic pp scattering events were detected by two telescopes connected in coincidence. The scattering angle was

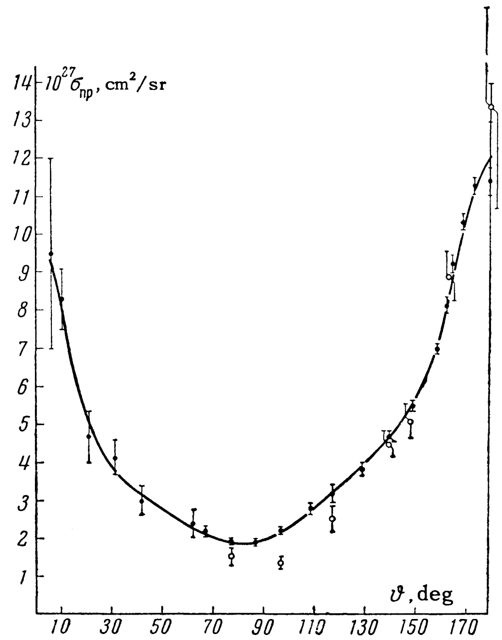

FIG. 2. Dependence of the differential cross section on the scattering angle. ○ – according to [9], ● – present work.

chosen in such a way that the scattered proton energy was equal to the mean energy of the recoil protons for which the absorption correction was measured. The correction was defined as the ratio of the counting rates with the absorber in the telescope and without it, and measured with an accuracy to within 2% for angles Φ = 0, 10, 15, 20, 25, 30, 45, and 55°. For intermediate angles Φ, the correction was found by linear interpolation. The magnitude of the correction varied from 1.19 ± 0.02 ($\Phi = 0°$) to 1.04 ± 0.02 ($\Phi = 55°$).

The relative efficiency of the neutron detector depends both on the absorption of the protons emitted from the converter and on the probability of charge exchange in the converter of neutrons with a given energy. The correction for the absorption was also found experimentally, for angles θ = 0, 15, and 35°. Its magnitude varied from 1.26 ± 0.03 ($\theta = 0°$) to 1.1 ± 0.04 ($\theta = 32°30'$). The de-

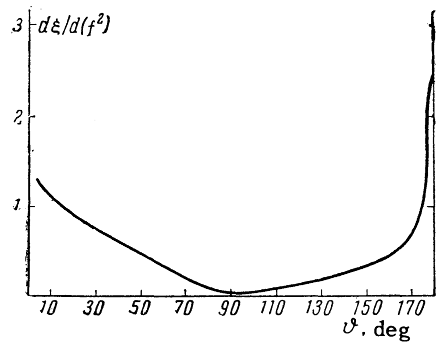

FIG. 3. Dependence of the derivative of the information function ξ with respect to the constant f^2 on the scattering angle.

tection probability of the charge exchange events K(E) was calculated under the assumption that the angular distribution of protons emitted from a converter bombarded by neutrons with a given energy coincides with the angular distribution of scattered particles in elastic np collisions, and that the mean proton energy varies as $\cos^2\varphi$, where φ is the emission angle of the protons from the converter. Calculations carried out using the data on $\sigma(\vartheta)$ for 90, 156, and 300 MeV energy [7] showed that, under actual conditions, K(E) varies little with the energy of neutrons incident upon the converter and with the angle $\Delta\varphi$ subtended by the telescope detecting the protons emitted from it. Thus, for an energy change from 200 to 130 MeV (scattering angles $0 \leq \theta \leq 63.5°$) K(E) changes by less than 25%. A similar variation occurs for the decrease in $\Delta\varphi$ from 40 to 10° for a given value of E. For the correction of the data, we have used the values of K(E) for $\Delta\varphi = 30°$. The magnitude of the correction in the range $32.5° \geq \theta \geq 3°$ varies then from 1.0 ± 0.05 to 1.2 ± 0.05.

RESULTS

The results of the measurements are shown in Fig. 2. The errors shown are due to the statistical fluctuations in the counting rate and to the errors in the determination of the relative efficiency (2% and 6% for recoil and scattered protons respectively). The measured dependence of the differential cross section on the scattering angle is markedly asymmetric with respect to the angle $\vartheta = 90°$. The ratio of the particles scattered into the forward and backward hemisphere is 0.7.

The data was analyzed in order to obtain the constant f^2 of the pion-nucleon interaction by the method given in [4]. For this purpose, $\sigma(\vartheta)$ was approximated by the expression

$$\sigma(\vartheta) = a_1\left[\frac{1}{(x_0-x)^2} + \frac{4}{(x_0+x)^2}\right] + \frac{a_2}{x_0-x} + \frac{a_3}{x_0+x} + \sum_{n=0}^{n_{max}} b_n x^n, \qquad (2)$$

where $x = \cos\vartheta$, $x_0 = 1 + \mu^2/2k^2$, μ is the π-meson mass, k is the momentum in c.m.s., and a and b are unknown coefficients. The quantity n_{max} in the approximating expression was determined so that the single-meson part of the scattering amplitude did not contribute to the polarization $P(\vartheta)\sigma(\vartheta)$ [5] and was put equal to 6. The coefficients a and b were determined by the least-square method. The resulting value of the coefficient a_1 gives $f^2 = 0.08 \pm 0.02$. It should be mentioned, however, that the accuracy of the experimental results is insufficient to carry out a consecutive χ^2 test and thus find the value of n_{max} in the approximating expression without using the polarization data.

Experiment design by the method of Sokolov [10] shows that, for a more exact determination of f^2, it is desirable to increase the accuracy in the range of $\vartheta < 50°$ and at the angle $\vartheta = 180°$ (Fig. 3).

Using the obtained values of a and b, the differential scattering cross section at 0° was found to be equal to $(9.1 \pm 1.1) \times 10^{-27}$ cm²/sr. From the optical theorem, the contribution of the imaginary part of the scattering amplitude to $\sigma(0)$ is then equal to $(2.7 \pm 0.1) \times 10^{-27}$ cm²/sr, i.e., amounts to about 30%. According to [4], the data available on the np scattering at 90 MeV give $\sigma(0) = 11.7 \times 10^{-27}$ cm²/sr,[7] and the contribution of the imaginary part of the scattering amplitude to $\sigma(0)$ is equal to $(3.9 \pm 0.4) \times 10^{-27}$ cm²/sr, i.e., also about 30%. Thus, at the energies of 90 and 200 MeV, the real part of the scattering amplitude gives a very large contribution to the scattering cross section at 0°.

The authors are greatly obliged to I. N. Silin and V. S. Kiselev for help in carrying out the work.

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Translated by H. Kasha
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