ELASTIC SCATTERING OF 580-MEV NEUTRONS BY PROTONS AT SMALL ANGLES

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The differential cross section for scattering of 580 Mev neutrons by protons was measured at angles of 11.25 to 35° (in the c.m.s.). The cross section was observed to rise rapidly with decrease of the scattering angle. The results indicate that the probabilities for scattering in the forward and backward directions are approximately equal.

THE present work is a continuation of investigations of the scattering of neutrons having an average energy of 580 Mev against protons,[1] with particular interest in elastic n-p scattering at neutron energies considerably above the threshold energy for meson production. The experiment consists in measuring the differential n-p scattering cross section in the small angle region ($\vartheta \leq 35°$ in c.m.s.). The usual method for measuring the differential cross section for elastic n-p scattering by counting recoil protons in a given angular region is not convenient because of the small energy of the recoil protons. Because of this fact, the measurements described here were obtained by a method which differs from that of Ref. 1, the basic conditions of the experiment, however (energy threshold, angular resolution, and detector solid angle), are still the same as in Ref. 1.

EXPERIMENTAL ARRANGEMENT

The differential n-p scattering cross section was obtained by measuring the number of neutrons scattered at a given angle from a hydrogen target placed in the path of the neutron beam. The high energy neutrons are obtained from charge exchange scattering of 680 Mev protons against a beryllium target placed in the chamber of the synchrocyclotron of the Laboratory for Nuclear Problems (Joint Institute for Nuclear Research). The energy distribution curve for the neutrons has a maximum at 600 Mev and a half-width of 130 Mev (Rev. 2). Taking into account the threshold of the neutron detector (450 Mev) the mean effective energy of the neutrons turns out to be 580 Mev. The intensity of the neutron beam at the position of the scatterer is 2×10^4 neutrons/sec-cm^2.

The first experiments were carried out with polyethylene and graphite scatterers. The main experimental data was then obtained using a scatterer of liquid hydrogen contained in a cylindrical glass Dewar flask. The Dewar flask has a capacity of three liters and measures 10 cm in diameter and 34 cm in height; it is encased in a protective duraluminum jacket; the beam passes through a window consisting of an aluminum foil 20 μ thick. The structure of the target allows an experiment with liquid hydrogen to proceed during seven hours. The effect of elastic n-p scattering was determined in the first case by comparing results for polyethylene and carbon, and in the second case by comparing results obtained with an empty Dewar flask and one filled with liquid hydrogen; the small effect (< 3%) due to air filling the Dewar flask after evaporation of the liquid hydrogen was neglected.

The neutron detector used in this experiment for measuring the flux of scattered neutrons is made of five scintillation counters and a "converter" consisting of a polyethylene cylinder having a thickness of 5.6 gm/cm^2 and a diameter of 6 cm, placed between the first two counters (Fig. 1). The neutrons falling on the converter undergo exchange scattering. The recoil proton leaving the converter are detected by the last four counters. The first counter is used to exclude charged particles arriving from the target and operates in anticoincidence with the remaining counters. In order to decrease overloading in the anticoincidence scheme, counter 1 is originally connected in coincidence with counter 2, and then pulses resulting from their coincidences are used in the anticoincidence scheme (Fig. 1). The scintillators consist of a solution of terphyl $(C_6H_5)_2C_6H_4$ in phenycyclohexane $C_6H_5CH(CH_2)_5$ with a concentration of 3 gm/ℓ, filling plexiglass containers which meas-

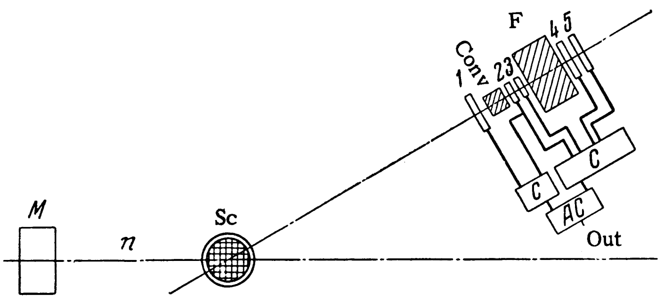

FIG. 1. Experimental arrangement. n – neutron beam; M – monitor; Sc – scatterer (Dewar flask with liquid hydrogen); 1, 2, 3, 4, 5: scintillation counters; Conv – converter; F – filter; C – coincidence arrangement; AC – anticoincidence arrangement; Out – output.

ure as follows: (1) 12 × 12 × 1 cm, (2) 5 × 5 × 1 cm, (3) 5 × 5 × 1 cm, (4) 12 × 12 × 1 cm, and (5) 12 × 12 × 1 cm. The energy threshold of the neutron detector is set by a copper filter placed between counters 3 and 4. In computing the thickness of the filter for scattering angles Φ = 15, 10, 5° (in the laboratory system), it was assumed on the basis of the results obtained in Refs. 2 and 3, that the average energy loss due to charge exchange of the neutron in light materials is about 15% of the initial energy and remains constant in a large energy interval (170 — 680 Mev). Estimates indicate that the average effective energy of neutrons scattered at small angles of 15, 10, 5° (in the laboratory system) changes by a relatively small amount (in our case 40 Mev), which permits one to assume that the neutron detector has constant efficiency over the given angular interval. The angular resolution of the detector is 2°.

In measuring the differential cross section for elastic n-p scattering, the scatterer is placed in the path of the neutron beam, the neutron detector is set up at a given angle with respect to the direction of the beam and one measures for a given scatterer the difference of the counting rate with the converter placed between the first and second counters, and with no converter. The relative differential cross section is then found from the formula:

$$(H^C_{H_2} - N^0_{H_2}) - (N^C_d - N^0_d) = n\sigma_{np}(\Phi), \qquad (1)$$

where $N^C_{H_2}$, $N^0_{H_2}$, N^C_d, N^0_d are respectively the counting rates with and without converter, when the Dewar flask is filled with hydrogen, and when it is empty; $\sigma_{np}(\Phi)$ is the differential cross section at a given angle Φ (in the laboratory system); n is a proportionality factor which depends on the geometry of the detector and the intensity of the neutron beam (it remains constant under the experimental conditions).

Thus the measurement of the neutron count scattered at a given angle allows one to compute the differential cross section for n-p scattering in relative units at angles of 5, 10, 15° (in the laboratory system). The absolute value of the cross section was obtained from the knowledge of the cross section at 15° found in Ref. 1. The counting rate $N^0_{H_2}$ was 50% of the counting rate $N^C_{H_2}$ at angles of 15° and 10°, and 60% at an angle of 5°. Background due to accidental coincidences did not exceed 3%.

It must be noted that the small efficiency of the neutron detector (1 — 2%) imposes severe conditions on the efficiency of the anticoincidence scheme. Indeed, a change in position of the converter, when measuring with and without it, noticeably (about 20 Mev in our case) changes the detector threshold for charged particles which are erroneously allowed by the anticoincidence channel and because of this, registered by the detector. An estimate based on a known neutron spectrum at the given converter thickness (5.6 g/cm^2 CH_2), indicates that the relative increase in the number of charged particle due to the indicated change in detector threshold, is $\Delta N/N = 1/19(1 - \epsilon)$, where ϵ is the efficiency of the anticoincidence channel.

The efficiency of the anticoincidence channel was obtained in a special experiment on the 660 Mev proton beam and turned out to be 99.9 ± 0.1%. Therefore in our case, $\Delta N/N = 0.005\%$, and the error in the measured number of registered neutrons due to inefficiency of the anticoincidence channel did not exceed one percent and was thus neglected.

RESULTS OF THE MEASUREMENTS

The differential scattering cross section measured at angles of 11° and 23° (in the c.m.s.) were found to be as follows: $\sigma_{np}(11°) = (7.5 \pm 1) \times 10^{-27}$ cm^2/sterad and $\sigma_{np}(23°) = (5 \pm 0.8) \times 10^{-27}$ cm^2/sterad. The indicated errors are due to the standard statistical deviations. As in Ref. 1, the uncertainty in the total cross section for elastic n-p scattering from which the differential scattering cross section is normalized, is not included in the indicated error.

The differential cross section for elastic scattering of 580 Mev neutrons against protons, $\sigma_{np}(\vartheta)$ in the angular region 11° to 180° (in the c.m.s.) is shown in Fig. 2. For the sake of comparison, the results of n-p scattering at 90 Mev (Ref. 4) and 400 Mev (Ref. 5) are also shown.

The behavior of $\sigma_{np}(\vartheta)$ in the region of small angles ($\vartheta \le 35°$) at 580 Mev, shows a strong increase in differential cross section with decrease in the scattering angle. Comparison of the data shown in Fig. 2 indicates that the character of the scattering in this angular region varies considerably as the neutron energy grows from 400 to 580 Mev. The approximate constancy of the scattering cross section for angles $\vartheta \le 35°$ observed at 400 Mev, disappears and the symmetry in "forward" ($\vartheta \sim 0°$) and "backward" ($\vartheta \sim 180°$) cross section which is present at an energy of 90 Mev, is reestablished to a considerable extent. The ratio of the scattering cross section at angles of 10° and 170°, $\sigma_{np}(170°)/\sigma_{np}(10°)$, equals 1, 2.4 and 8 at energies of 90, 400, and 580 Mev. Thus the relation between "ordinary" and "exchange" scattering at 580 Mev, apparently approaches the relation which exists at 90 Mev, when the curve for $\sigma_{np}(\vartheta)$ is symmetrical about $\vartheta = 90°$ (in the c.m.s.), and the two types of scattering contribute about equally to the total interaction cross section. This change in the character of the elastic scattering of neutrons against protons in the angular region $\vartheta \le 35°$, is apparently related to the growth of the probability for the process of π meson production in n-p collision, with increase in nucleon energy from 400 to 580 Mev (Ref. 6).

It is interesting that the increase in the differential cross section at small angles near 0° as the energy grows from 400 to 580 Mev is predicted by the optical theorem[7]

$$\sigma_{np}(0) \geqslant k^2\sigma_t^2/16\pi^2, \tag{2}$$

where $\sigma_{np}(0)$ is the differential cross section for elastic n-p scattering at 0° (c.m.s.); k is the wave number of the incident neutron; σ_t is the total n-p interaction cross section. The smallest possible value of $\sigma_{np}(0)$ at 580 Mev is about $6 \times 10^{-27}\,\mathrm{cm}^2$ according to the inequality (2), while the experimental value of $\sigma_{np}(0)$ at 400 Mev does not exceed $4 \times 10^{-27}\,\mathrm{cm}^2$ (Fig. 2). Therefore the differential cross section for elastic scattering of neutrons against protons at 0° (c.m.s.) must go through a minimum in the energy range 300 — 400 Mev, and must increase as the energy of the colliding nucleons goes up.

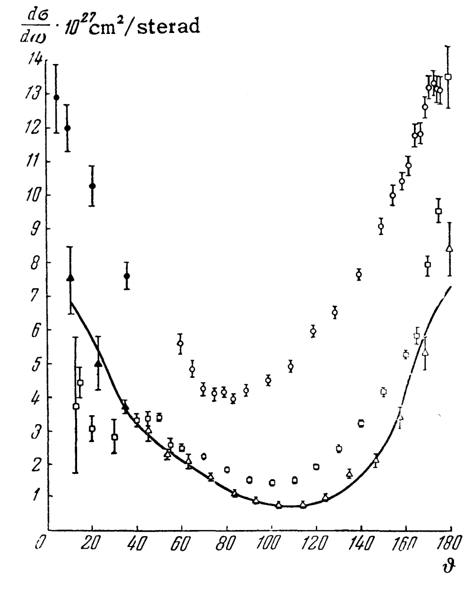

FIG. 2. Differential cross section for elastic n–p scattering. ●, ○ – Ref. 5, E_n = 91 Mev; □ – Ref. 4, E_n = 400 Mev; Δ – Ref. 1, E_n = 580 Mev; ▲ – Present work. Solid curve – graph of the approximate expression (3).

In Ref. 1, an approximation was obtained by least squares to $\sigma_{np}(\vartheta)$ in the form of a series of Legendre polynomials up to and including L = 12. The behavior of $\sigma_{np}(\vartheta)$ for $\vartheta \le 35°$, found in the present work, noticeably changes the character of the approximate expression which in our case has the form

$$\begin{aligned}\sigma_{np}(\vartheta) = \lambda\!\!\!^{-}{}^2\,[&1.38 \pm 0.07 - (0.7 \pm 0.08)\,P_1(\cos\vartheta)\\ &+ (1.92 \pm 0.08)\,P_2(\cos\vartheta) - (0.12 \pm 0.09)\,P_3(\cos\vartheta)\\ &+ (0.92 \pm 0.1)\,P_4(\cos\vartheta) - (0.03 \pm 0.1)\,P_5(\cos\vartheta)\\ &+ (0.58 \pm 0.11)\,P_6(\cos\vartheta) - (0.15 \pm 0.12)\,P_7(\cos\vartheta)\\ &+ (0.33 \pm 0.14)\,P_8(\cos\vartheta) - (0.23 \pm 0.15)\,P_9(\cos\vartheta)\\ &+ (0.11 \pm 0.15)\,P_{10}(\cos\vartheta) - (0.04 \pm 0.15)\,P_{11}(\cos\vartheta)\\ &- (0.14 \pm 0.11)\,P_{12}(\cos\vartheta)],\end{aligned} \tag{3}$$

where $\lambda\!\!\!^{-}$ is the wave length of the nucleon in the center-of-mass system.

The discovery that the probability for scattering is about the same at $\vartheta = 0°$ and 180° leads to the fact that the odd order terms in the polynomial expansion have small coefficient. Deviations from symmetry with respect to $\vartheta = 90°$ are characterized in the given expression by the main term containing $P_1(\cos\vartheta)$. Contributions to the scattering cross section of interference waves corresponding to isotopic spin states T = 0 and T = 1 of the n-p system are much smaller for $\vartheta = 0°$ and 180° in the 580 Mev region than in the regions of 300 — 400 Mev where a strong asymmetry is observed between forward ($\vartheta = 0°$) and backward ($\vartheta = 90°$) scattering.

It is worth noting that an estimate of the accuracy of the expansion (3) is given by the criterion[8]

$$\sum_i \Big[\sigma_{np}(\vartheta_i) - \sum_L \alpha_L P_L(\cos\vartheta)\Big]^2 \Big/ (\Delta\sigma_i)^2 = m - l; \tag{4}$$

$\sigma_{np}(\vartheta_i)$ is here the measured value of the differential cross section at the point ϑ_i; $\sum_L \alpha_L P_L(\cos\vartheta)$ is the cross section computed from expansion (3); $(\Delta\sigma_i)^2$ is the weight of a given measurement, $\Delta\sigma_i$ being the experimental error; m is the number of points at which the cross section is measured, and ℓ the number of coefficients in (3); such an estimate does not yield a completely satisfactory result. It is found that the sum of the squares of the deviations of the computed curve from the measured values of the cross section which appear on the left-hand side of Eq. (4), equal 7.7 when $\ell = 4$. The largest deviations are found in the angular region around 180°, which apparently indicates the need for increasing the number of terms in the expansion (3). However, the magnitude of the errors in the coefficients α_L of expansion (3), shows that in view of the existing experimental uncertainty, an increase in the number of terms for expansion (3) is hardly sensible.

Finally it must be noted that comparison of the present results with the data on elastic p-p scattering at the same energy[9] confirms the hypothesis of isotopic invariance.

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