Elastic Scattering of Neutrons by 580 MEV Protons

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Differential cross sections were measured for elastic scattering of neutrons by 580 mev protons in the angular region $\vartheta = 35$ to $180°$ (in the system of the center of inertia) with a $2°$ angular resolution. The character of the obtained $\sigma_{np}(\vartheta)$ dependency indicates that at ~ 600 mev there arises in the neutron-proton system a noticeable interaction in states with orbital moments up to $l \approx 6$. The results obtained do not contradict the hypothesis of charge independences.

THERE exists at the present time a sufficiently large number of published papers pertaining to investigation of elastic collisions of neutrons with high energy (100 to 400 mev) protons. However, the known experimental data refer to the energy region where the processes of meson formation are either completely absent, or the total cross section of meson formation in (n-p) collisions comprises a very small fraction of the total (n-p) interaction cross section. It may be supposed[1,2] that the increased probability of inelastic scattering observed in the region of higher energies* will have a noticeable influence on the character of elastic scattering of neutrons by protons. Experiments in measurements of differential cross sections for elastic scattering of neutrons by 580 mev protons were conducted using the synchrocyclotron of the Institute for Nuclear Problems, Academy of Sciences, USSR, in order to investigate the changes in the process of neutron scattering by protons at nuclear energies which exceed substantially the threshold of pion formation. This communication contains results of these experiments.

1. EXPERIMENTAL ARRANGEMENT

Measurement of differential cross sections in the scattering angle interval $\vartheta = 35.5 - 180°$ (in the center of inertia system) was made by the method of recording the recoil protons from elastic (n-p) collisions. Here the difference in the number of recoil protons was determined at angles $\vartheta = 0$ to $70°$ for paraffin ($CH_{2.09}$) and graphite (C) scatterers placed in the path of the neutron beam. The experimental arrangement is shown in Fig. 1. The neutron beam used in the experiments was obtained as a result of exchange scattering of 680 mev protons with a beryllium target. The energy distribution in the neutron beam had a maximum at 600 mev and a half width of ~ 130 mev[3]. The average energy of the neutrons for the detector threshold (450 mev) was found to be equal to 580 mev. The intensity of the neutron beam incident on the target was 2×10^4 neutron cm^{-2} sec^{-1}.

Discs of paraffin and graphite of equal stopping power for the recoil protons served as scatterers. The thickness of the scatterers was changed for measurements at different angles and in the recoil angle intervals $\Phi = 0$-$15°$, 25-$60°$ and 60-$70°$ (referred to the laboratory system) was for graphite scatterer 5, 3, 0.5 gram/cm^2, respectively.

The detector consisted of three scintillation counters (*1, 2, 3*) connected for coincidence counting. The scintillation counters were operated with photomultipliers type FEU-19 and toluene crystals. The selected geometry insured a $2°$ angular resolution. The energy threshold of the detector was set by a wolfram or copper filter placed between the two last counters of the detector. The thickness of the filter depended on the scattering angle and was selected to make the detector operate only if the neutron energy exceeded 450 mev. This made it possible to exclude the effect produced by lower energy particles which were present in sufficient quantity in the neutron beam. The counting characteristic of the detector had a plateau of 150-200 volts.

The process of measuring the angular distribution of recoil protons (in relative units) was reduced to determining the number of charged particles which are emitted from the scatterer in a given direction as a result of (n-p) collisions, with a subsequent correction for the admixture of mesons and the absorption of protons in the filter of the detector.

The correction for the admixture of charged π-mesons at angles $\Phi \geq 60°$ was determined by means

* The overall cross section of pion formation at 400 mev is $\sim 3\%$ of the total (n-p) interaction cross section, and increases to 25-30% at 590 mev[3].

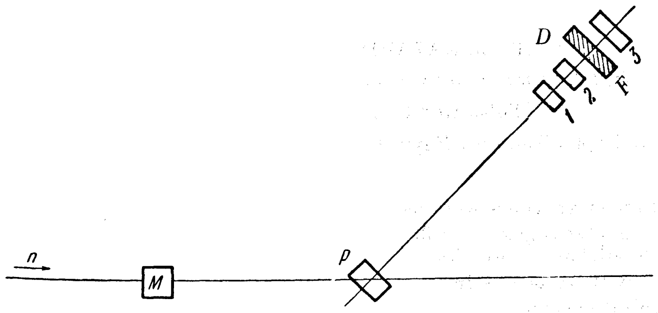

FIG. 1. Arrangement of the apparatus. n – neutron beam; P – tterer; D – detector; *1, 2, 3* – scintillation counters; F – filter; monitor.

of a telescope consisting of three scintillation counters similar to the detector used in measuring the angular distribution of the charged particles. Evaluations made on the basis of data in Ref. 4 showed that if the threshold of the detector is raised above the maximum energy of the recoil protons for a given angle $\Phi \geq 60°$, the detector will register only π – mesons with a registration effectiveness of 70 to 80%. Velocity selections of particles was used for separation of π – mesons in measurements at angles $\Phi < 60°$. For this, the first counter of the detector was replaced by a Cerenkov counter. Plexiglass was used as the radiator for the Cerenkov counter at angles $\Phi = 30$ to $60°$ and water for angles $\Phi < 30°$. The correction was determined by comparing the number of particles registered by the detector under ordinary conditions in corresponding experiments on (n-p) scattering cross section measurements with the number of particles registered by the detector when the first counter is replaced by a Cerenkov counter. The effectiveness of the Cerenkov counter was taken as 80% [5]. It should be noted that at proton recoil angles $\Phi < 45°$ the maximum energy recoil protons could also have been registered by the Cerenkov counter. For this reason, when making measurements at the indicated angles, a portion of the filter used to lower the energy of the protons to the threshold value of the Cerenkov counter was placed in front of the detector.

To determine the corrections for nuclear absorption by the method of coordinated telescopes* there were registered the events of (p-p) collisions taking place in the scatterer placed in the 667 mev proton beam. The correction was determined as the ratio of (p-p) collisions recorded when the detecting telescope is operating without a filter to the number of registered collisions when a filter of a given thickness is present in the telescope. The geometry of the detector used in these experiments corresponded exactly to the experimental conditions when making measurements of differential (n-p) scattering cross sections.

The angle at which the telescope was set was selected so that the energy of scattered protons entering the telescope was equal to the average energy of the recoil proton at the angle for which the absorption correction is being measured.

Absolute values of (n-p) scattering differential cross sections were determined by normalizing the obtained angular distribution of the recoil protons to the complete cross section of elastic scattering of neutrons by protons. The value of this cross section for 580 mev was obtained from the data contained in Ref. 6 as the difference between the total cross section for (n-p) interaction $\sigma_t(np) = (36 \pm 2) \times 10^{-27}$ cm^2 and the overall cross section for meson formation in (n-p) collisions $\sigma_\pi(np) = (10 \pm 2) \times 10^{-27}$ cm^2, which amounts to $(26.0 \pm 3) \times 10^{-27}$ cm^2. For normalization it was assumed that in the angular region $\vartheta < 35°$ (center of inertia system) the differential (n-p) scattering cross section is substantially constant in magnitude and is equal to the value of the cross section at 35° just as in the case of lower energies (300-400 mev) where it has been confirmed by experiments[7].

It should be noted, however, that deviation of the true distribution from that assumed in normalizing cannot significantly distort the obtained results, since scattering in the angular region $0 \leq \vartheta < 35°$

* A method in which two telescopes are connected in coincidence and register simultaneously the scattered particle and the recoil particle.

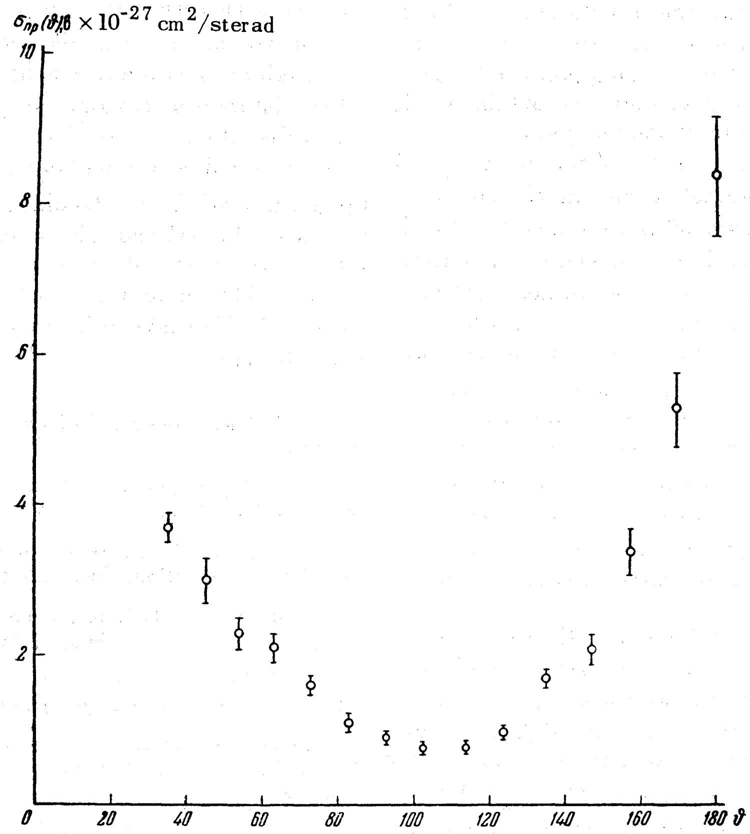

FIG. 2. Dependence of the differential cross section of angular (n-p) scattering on the scattering angle (in the center of inertia system).

constitutes only a very small portion of the total of (n-p) elastic scattering cross section. If we assume the $\sigma_{np}(\vartheta)$ curve to be symmetrical about the 90° point, this fraction does not exceed 20%.

2. RESULTS OF MEASUREMENTS

Results of the measurements are shown in Fig. 2. The errors shown on the graph are the standard statistical errors in the determination of angular distribution for recoil protons. Not included are the errors in determining the total (n-p) elastic scattering cross section (12%) and some uncertainty in the normalization (about 10%) due to the absence of accurate data on the $\sigma_{np}(\vartheta)$ dependence in the region $\vartheta < 35°$.

The dependence of the obtained differential cross section on the scattering angle indicates that at 580 mev as well as in the region of lower energies, exchange forces play an important role in the (n-p) interaction. The contributions of the usual and exchange interactions to the total elastic scattering cross section are of the same order. The results also show that, with increase of energy, the nature of the scattering changes. The anisotropy of the scattering is increasing, the ratio of the cross sections $\sigma_{np}(180°)$ to $\sigma_{np}(90°)$ reaches the value 9 ± 1.2. The asymmetry of the curve $\sigma_{np}(\vartheta)$ about the angle $\vartheta = 90°$ is clearly noticeable even in the angular region very close to $\vartheta = 90°$.

Analysis of obtained results permits us to make the following conclusions:

1. The results do not contradict the hypothesis of isotopic invariance. The values of differential scattering cross sections $\sigma_{np}(90°)$ and $\sigma_{pp}(90°)$[8] for 580 mev nucleons satisfy sufficiently close the known relation $4\sigma_{np}(90°) \geq \sigma_{pp}(90°)$ which follows from the above hypothesis;

2. The contributions of the states of the (n-p) system with isotopic spins $T = 0$ and $T = 1$to the scattering cross section at $\vartheta = 90°$ are of the same order of magnitude [$\sigma_{T=1}(90°) = 3 \times 10^{-27}$; $\sigma_{T=0}(90°) = 1 \times 10^{-27}$ cm^2 sterad^{-1}]. This is possibly

connected with the existence in both states ($T = 0$ and $T = 1$) of a very strong interaction. It should be noted, however, that convincing proof in favor of this assumption can, seemingly, be obtained only by performing a complete phase analysis;

3. The noticeable asymmetry of the curve $\sigma_{np}(\vartheta)$ about the angle 90° indicates that interference between the waves corresponding to states $T = 0$ and $T = 1$ exerts a considerable influence on the nature of the scattering. It is interesting to note that at the neutron energy of 90 mev[9] where, according to the angular distribution of $\sigma_{np}(\vartheta)$, it can be concluded that scattering is described by S, P and D waves, interference between waves corresponding to states $T = 0$ and $T = 1$ is practically absent, and the curve $\sigma_{np}(\vartheta)$ is symmetrical about the angle $\vartheta = 90^\circ$[10]. Thus, the asymmetry of the curve is apparently the result of interaction between two nucleons in system states characterized by high orbital moments $l > 2$;

4. The absence of a relativistic theory of scattering does not permit a strict interpretation of the obtained data. In the nonrelativistic approximation, however, it can be shown[11] that the highest number of the Legendre polynomial entering into the angular distribution is equal to $2l_{max}$, where l_{max} denotes the maximum value of the orbital moment of motion corresponding to the highest state in which, for a given nucleon energy, noticeable interaction takes place. Computations show that the angular distribution $\sigma_{np}(\vartheta)$ can be approximated by the expression $\sigma_{np}(\vartheta) = \bar{\lambda}^2[(1.29 \pm 0.05) + (0.24 \pm 0.13)P_1 + (1.42 \pm 0.2)P_2 - (0.87 \pm 0.24)P_3 + (0.28 \pm 0.22)P_4 - (0.5 \pm 0.16)P_5 + (0.14 \pm 0.1)P_6 - (0.33 \pm 0.1)P_7 + (0.19 \pm 0.18)P_8 - (0.2 \pm 0.24)P_9 + (0.39 \pm 0.26)P_{10} + (0.1 \pm 0.19)P_{11} + (0.25 \pm 0.15)P_{12}]$, where $P_{1,2\ldots}$ are Legendre polynomials. Thus, the maximum value of the orbital momentum corresponds to $l_{max} \approx 6$. If we now make use of the target parameter concept, it is possible to evaluate roughly the effective size of the interaction region. An evaluation yields for the value of r 2.2×10^{-13} cm.

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35