NEUTRON SPECTRA FROM THE d + p REACTION

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Neutron spectra from the reactions H(d, n)2p with E_d = 18.6 Mev and D(p, n)2p with E_p = 8.6 Mev have been measured at an angle of 0° by the time-of-flight method. The spectrum shapes can be satisfactorily explained by pair interaction between the nucleons in the final state.

IN fast-deuteron collisions with light nuclei there is a large probability for the breakup of the deuterons with emission of nucleons which have a continuous spectrum.[1,2] The spectra have a complex shape which depends considerably on the form of the target nucleus. This indicates the large role played by the interaction of the reaction products in their final state. A simpler case is the breakup of a deuteron by a proton. In this reaction only free nucleons are produced, whose pair interaction can be taken into account on the basis of data on nucleon-nucleon scattering.

In this paper the neutron spectra from the reactions H(d, n)2p with 18.6-Mev deuterons and D(p, n)2p with 8.6-Mev protons are investigated by the time-of-flight method (the total c.m.s. energy of the three nucleons is 4 and 3.5 Mev, respectively), and it is shown that the spectrum shape is basically determined by the pair interaction of the nucleons in the singlet S state, produced in the reaction.

The first results of the study of neutron spectra from the D(p, n)2p reaction, obtained in our laboratory, were reported at the Paris Conference in the summer of 1958. Analogous results for this reaction were obtained by other authors.[3-5]

MEASUREMENT METHOD

The work was carried out on the 1.5-m cyclotron of the Atomic Energy Institute of the U.S.S.R. Academy of Sciences. Gas targets 3.5 cm thick with a window of thin nickel or platinum foil were filled with hydrogen up to a pressure of 5 atm, and with deuterium up to a pressure of 2 atm. The bottom of the target was made of lead. The neutron spectra were measured at 0° to the cyclotron beam. The neutrons were registered by a scintillation counter with a stilbene crystal (3 cm in diameter and 2 cm high) for flight distances up to 3 m, and with a tolane crystal (8 cm in diameter and 3 cm high) for larger distances. The counter was connected to the circuit of a multi-channel neutron time-of-flight spectrometer.[6,7]

The spectrometer operates by utilizing the natural modulation of the cyclotron beam. The time analyzer operates on the "vernier" principle. The time resolution of the spectrometer is 2.5 mμsec. The channel width of the time analyzer is about 0.8 mμsec. The recording system has 256 channels with a capacity of 2^{16} pulses per channel, and a digital printing device for data extraction.

The time distribution of the scintillation-counter pulses is measured within an interval equal to two cyclotron periods. The presence of two analogous peaks (two γ-ray peaks, for instance) in this spectrum makes it possible to monitor the time scale.

As an illustration of the experimental conditions, Fig. 1 shows the time-of-flight distribution of neutrons emitted at 0° in bombarding hydrogen with deuterons. The measurements were conducted in turn in a gas-filled and in an empty target. The figure shows the difference between the results of these measurements (filled circles) and the background from the empty target. For the case of bombarding deuterium with protons the background was considerably smaller.

MEASUREMENT RESULTS

Figures 2 and 3 show the obtained energy spectra of the neutrons. The apparatus "width" (defined as the γ-peak width at half the height) corresponds to three intervals between the points. The statistical precision of the measurements is fully characterized by the observed spread of the points.

The cross section for neutron production (the area under the experimental points) at an angle of 0° is (150 ± 15) mb/sr for the H(d, n)2p, and (47 ± 5) mb/sr for the d(p, n)2p reaction.

In the center-of-mass system of the three nu-

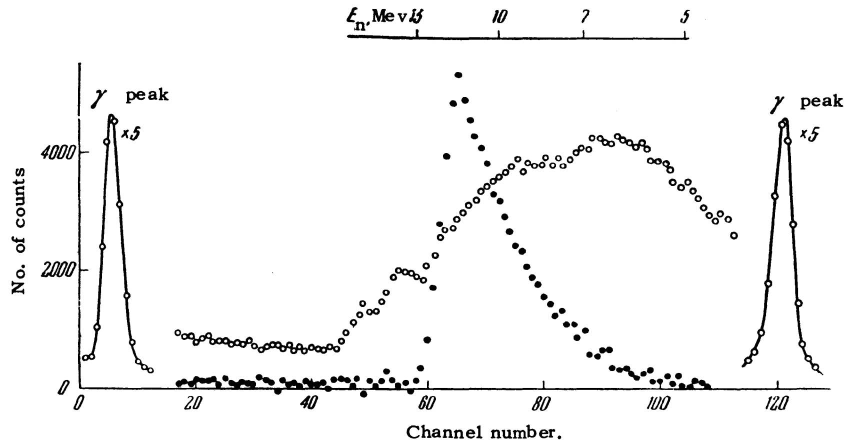

FIG. 1. Time-of-flight distribution of neutrons from the H(d, n)2p reaction at 0° to the directions of 18.6-Mev deuterons. The distance between the target and the counter was 2.8 m. The channel width of the time analyzer was 0.836 mμsec. The counter threshold was 3.2 Mev.

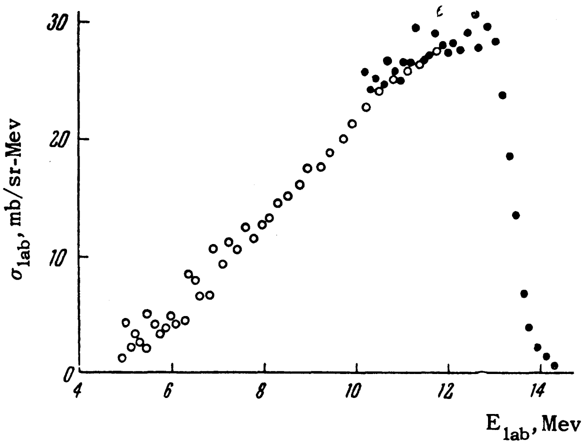

FIG. 2. The spectrum of neutrons produced at 0° by bombarding hydrogen with 18.6-Mev deuterons. The filled circles correspond to a flight distance of 7 m, and the open ones to a flight distance of 1.58 m.

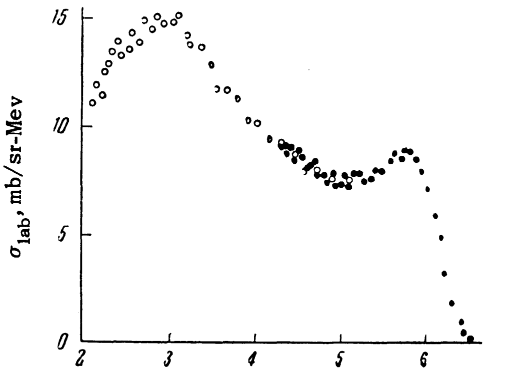

FIG. 3. The spectrum of neutrons produced at 0° by bombarding deuterium with 8.6-Mev protons. The filled circles correspond to a flight distance of 5.15 m, and the open ones to a flight distance of 1.58 m.

cleons, the cross sections for neutron production are (20 ± 2) mb/sr, and (11 ± 1) mb/sr at 0° and 180° to the incident deuterons, respectively.

DISCUSSION OF RESULTS

Figures 4 and 5 show the obtained neutron spectra in the c.m.s. In the spectrum observed at 0° to the direction of the incident deuterons only the maximum at the upper bound is distinct; this maximum corresponds to the production of two protons with a small relative velocity. In the spectrum observed at 180°, in addition to the peak at the bound, there is also a maximum for a neutron energy of 0.6 Mev, which by its position corresponds to a velocity of the neutron relative to one of the protons in its final state.

Thus, it is evident from the obtained spectra that as a result of the d + p ⟶ 2p + n reaction there is a large probability for the production of nucleon pairs with a small energy of relative motion; this can be explained by their attractive interaction in the final state.

In reference 8 it was shown that in the collision of a fast deuteron with a nucleon the probability of obtaining in the final state two nucleons with a small relative momentum $\overline{P}$, within an interval $d\overline{P}$, is proportional to $|\varphi(r)|^2 d\overline{P}$, where $\varphi(r)$ is the wave function of the relative motion of two nucleons in the S state (outside the range of nuclear forces) known from the data on nucleon-nucleon scattering. If we consider only a small range of relative-energy values of the two nucleons ($E \ll E_0$, where E_0 is the total energy of the three nucleons produced in the reaction) then we can neglect the dependence of the remaining factors which determine this probability on the relative nucleon energy. Watson[9] obtained an analogous result.

The relative-energy distribution of a proton and a neutron is given by the expression

$$d\sigma = \text{const}\cdot\sqrt{E}\, dE/(E + \varepsilon),$$

where ϵ = 2.23 for the triplet, and ϵ = 0.07 Mev

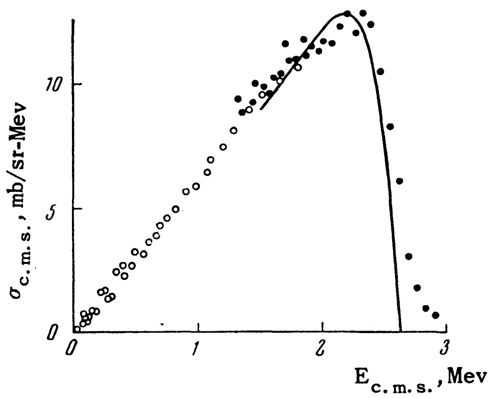

FIG. 4. Neutron spectrum from the d + p → 2p + n reaction in the c.m.s., observed at an angle of 0° to the direction of the deuterons (E_0 = 4.0 Mev).

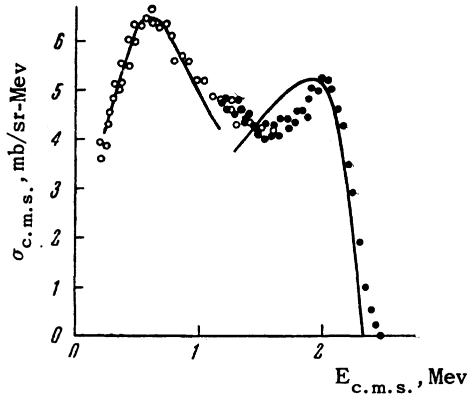

FIG. 5. Neutron spectrum from the d + p → 2p + n reaction in the c.m.s., observed at 180° to the direction of the deuterons (E_0 = 3.5 Mev).

for the singlet state. The distribution has a maximum when E is on the order of ϵ. For our energies (E_0 = 4 and 3.5 Mev) the condition $E \ll E_0$ is satisfactorily fulfilled for the singlet state in the region of the maximum.

The neutron-spectrum curve for ϵ = 0.07 Mev thus obtained is plotted in Fig. 5 in the neutron-energy region of about 0.6 Mev. The apparent larger width of the maximum in the c.m.s. of the three nucleons is due to the superposition of the c.m.s. velocities of the two nucleons on their relative velocity. The theoretical curve is in excellent agreement with the experimental points. Curves with ϵ from 0.03 to 0.15 Mev fit within the experimental errors. The proton-neutron interaction in the triplet state (ϵ = 2.23 Mev) would have yielded a considerably broader maximum.

In the case of two protons with small relative energies only the interaction in the singlet S state need be taken into account. The relative-energy distribution has in this case a more complicated form[8] on account of the Coulomb interaction. The theoretical neutron spectra corresponding to the interaction of protons in the final state are shown in Figs. 4 and 5 (near the upper bound of the spectra). They are in qualitative agreement with the experimental curves but have a somewhat larger "width" of the maximum (especially for $\theta_{n,d}$ = 180° where the precision of the measurements is higher and E_0 is smaller). No better agreement is to be expected, apparently, for the Coulomb repulsion makes the width of the two-proton relative-energy distribution considerably larger than for a neutron and proton in the singlet state, and the condition that the relative energy be small in the region of the maximum is fulfilled to a considerably lesser extent.

Komarov and Popova[10] carried out a detailed neutron-spectrum calculation for the d + p → 2p + n interaction with account of nucleon pair interaction on the basis of data on nucleon-nucleon scattering. The Born approximation was employed to account for the interaction of the pair with a third nucleon. The obtained curves are in good agreement with the experimental results in the entire neutron-energy region. The calculations also explain the variation of the relative height of the maxima with angle. The calculated ratio of the cross section for neutron production at 0° and 180° is in good agreement with the experimental value.

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336