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Abstract

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CROSS SECTION OF THE $(n, 2n)$ REACTION ON C^{12}, N^{14}, O^{16}, AND F^{19} IN THE ENERGY INTERVAL 10-37 MeV

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The $(n, 2n)$ reaction is the principal process of inelastic interaction of neutrons with medium and heavy nuclei at energies of 10-30 MeV. The behavior of the reaction cross section in this region is satisfactorily described by the statistical theory of the nucleus. With regard to the behavior of the cross section of $(n, 2n)$ reactions on light nuclei, the question is much less clear. The statistical theory of the nucleus is doubtful here; there are no calculations of direct processes; reactions with the emission of charged particles are more probable; and therefore there are no theoretical predictions of the behavior of the cross section. Experimental data on $(n, 2n)$ cross sections exist only for an energy of 14 MeV ($^{1-5}$), and only for the reaction $C^{12}(n, 2n)C^{11}$ up to 28 MeV (^{6}). Measurement of cross sections in the energy region 10-35 MeV is associated with great difficulties because of the absence of sources of monoenergetic neutrons. Meanwhile, knowledge of these cross sections is necessary in connection with the use of the $(n, 2n)$ reaction on light nuclei as a threshold neutron detector.

In the present work, measurements have been made of the cross sections of the $(n, 2n)$ reaction on four light nuclei in the energy interval 10-35 MeV.

To obtain neutrons, the reactions $D(d, n)He^3$ and $T(d, n)He^4$ were used, excited by deuterons with an energy of about 20 MeV accelerated on the cyclotron of the Institute of Atomic Energy of the Academy of Sciences of the USSR (^{7}). The neutron energy was varied by slowing the deuterons in platinum foils placed directly in front of the target. In the work a solid $T + Zr$ target and gaseous deuterium were used.

When deuterium or tritium is bombarded by fast deuterons, in addition to the principal monoenergetic neutron groups, neutrons of a continuous spectrum are also formed as a result of the (d, pn) and $(d, 2n)$ reactions. The intensities of the continuous spectra exceed the intensities of the monoenergetic groups by several times, and their limits are located approximately at $E_n \simeq E_d - 4$ MeV (^{8}). The angular distributions of neutrons fall off rather rapidly with angle. Determination of the $(n, 2n)$ reaction cross sections is associated with the need to measure the absolute intensities of the fluxes, spectra, and angular distributions of neutrons formed when deuterium and tritium are bombarded by deuterons. Such measurements were carried out by Rybakov and Sokolov

Fig. 1. Cross section of the reaction C12 (n, 2n) C11. a –data (6)

Figure 1: Fig. 1. Cross section of the reaction C12 (n, 2n) C11. a –data (6)

Fig. 2. Cross section of the reaction N14 (n, 2n) N13. a –data (1), b –(2), c –(3)

Figure 2: Fig. 2. Cross section of the reaction N14 (n, 2n) N13. a –data (1), b –(2), c –(3)

using a time-of-flight neutron spectrometer (^{9}). In the literature there are no data on the spectra and fluxes of neutrons for the reactions $D(d,n)$ and $T(d,n)$ at $E_d > 10.5$ MeV.

To obtain curves of the relative yield of the $(n,2n)$ reactions at different neutron energies, specially prepared samples of carbon, ammonium nitrate (NH_4NO_3), and Teflon (CF_2) were irradiated with neutrons at an angle of 0° under standard conditions, and their activity was measured by β-particles on a Geiger counter. For each sample a decay curve was recorded, by extrapolating which the activity at the moment the irradiation ended was found. When NH_4NO_3 and Teflon were irradiated, the activities of N^{13}, O^{15}, and F^{18} were induced not only by target neutrons but also by neutrons from the backing. The background from the backing neutrons amounted to as much as 30% for O^{15}, up to 80% for N^{13}, and up to 88% for F^{18}. When carbon was irradiated by backing neutrons, the activity of C^{11} was practically not induced.

The absolute value of the cross section of the $(n,2n)$ reaction on carbon was determined at $E_n = 34$ MeV and on fluorine at $E_n = 25$ MeV and $E_n = 14$ MeV. Neutrons with an energy of 14 MeV were obtained in the reaction $T(d,n)He^4$ on an electrostatic–

tube. To determine the absolute value of the cross section, the activity of specially prepared samples of carbon and Teflon was measured with a Geiger counter from the annihilation γ rays under conditions in which all positrons were stopped inside the sample. The absolute sensitivity of the γ-ray counter was determined by measuring the γ activity of an Au^{198} preparation, whose absolute β activity had been measured on an apparatus with a defined solid angle. The sensitivity of the Geiger counter to annihilation γ rays and to the γ rays of Au^{198} (0.411 MeV) was taken to be the same.

Fig. 1. Cross section of the reaction C$^{12}(n,2n)$C^{11}.
a –data of (^{6})

Fig. 2. Cross section of the reaction N$^{14}(n,2n)$N^{13}.
a –data of (^{1}), *b* –(^{2}), *c* –(^{3})

was the same. The absolute value of the cross section for nitrogen and oxygen was determined by comparison, on a scintillation counter, of the annihilation

Fig. 3. Cross section of the reaction O16(n, 2n)O15

Figure 3: Fig. 3. Cross section of the reaction O16(n, 2n)O15

γ activity of samples of NH_4NO_3 and water with the γ activity of a carbon sample of the same geometry. Irradiation and measurement of the activity of the samples were carried out under identical conditions.

The results obtained are shown in Figs. 1-4. The absolute scale of the cross sections was established with an accuracy of ±30%. The relative course of the curves was obtained by averaging several irradiation series. The vertical segments at the points show the root-mean-square deviations of the results of individual series. Arrows indicate the thresholds of the $(n, 2n)$ reactions. The vertical dashed line on the abscissa marks the region of transition from neutrons obtained from the reaction $\mathrm{D}(d, n)\mathrm{He}^3$ to neutrons from the reaction $\mathrm{T}(d, n)\mathrm{He}^4$. The curves for carbon and oxygen were obtained practically with neutrons of a single reaction, $\mathrm{T}(d, n)\mathrm{He}^4$. The $(n, 2n)$ reactions on nitrogen and fluorine have a lower threshold, and in the relative course of their cross sections an additional error is possible, associated with the transition from the $\mathrm{D} + \mathrm{D}$ reaction to the D+T reaction and with the correction for the effect of neutrons of the continuous spectrum. The data for N^{14} are noticeably coarser than the others, since the activity of N^{13}, which has a small yield, was measured in the presence of O^{15} activity and against the level of a high background from the backing. Individual points obtained in previous works (see Figs. 1-4) agree satisfactorily with our results.

The energy spread of the neutrons increases with the thickness of the platinum foil stopping the deuterons and reaches a maximum value of 0.7 MeV. Owing to the difficulties of measuring absolute neutron fluxes and the high level of background from backing neutrons, as well as the need to take into account the effect of neutrons of the continuous spectrum, the results obtained contain a rather large error. It may be stated, however, that the general character of the dependence of the cross section on energy, shown in Figs. 1-4 by the solid curves, is universal. In particular, the decrease of the cross section after the maximum in the case of C^{12}, N^{14}, and O^{16} may be regarded as unquestionable. For the reaction $\mathrm{C}^{12}(n, 2n)\mathrm{C}^{11}$, a cross-section value at $E_n = 90$ MeV is known (^{10}), equal to 22 ± 4 mb. On the basis of measurements of the course of the cross section of the reaction $\mathrm{C}^{12}(p, pn)$

it was assumed that the cross section of the reaction $\mathrm{C}^{12}(n, 2n)$ practically does not change in the energy interval 60-90 MeV. The tendency toward a decrease of the cross section observed by us at $E_n > 30$ MeV is not in very good agreement with the assumption that the cross section reaches a plateau and with the value 22 mb at $E_n = 90$ MeV, unless a very complicated dependence $\sigma(E_n)$ is assumed.

The most characteristic feature of the cross sections on the nuclei C^{12}, N^{14}, and O^{16}

Fig. 4. Cross section of the reaction F19(n, 2n)F18

Figure 4: Fig. 4. Cross section of the reaction F19(n, 2n)F18

Fig. 3. Cross section of the reaction $O^{16}(n, 2n)O^{15}$

Fig. 4. Cross section of the reaction $F^{19}(n, 2n)F^{18}$;
a—data of (1), *b*—(4), *c*—(3)

is their smallness in comparison with the total inelastic-scattering cross sections and the approximate equality of the maxima for all three nuclei. To a considerable extent the smallness of the cross sections can be explained, first, by competition from reactions with emission of charged particles, and, second, by the fact that in inelastic collision with a light nucleus a neutron loses, on the average, a considerably smaller fraction of its energy than in a heavy or medium nucleus, and the excitation of the nucleus proves insufficient for emission of a second neutron. The latter consideration is confirmed by experimental data (11–13) on the relatively high probability of excitation of the lower levels of the nucleus in inelastic scattering of neutrons with energy 14 MeV and protons with energy up to 40 MeV. The most probable mechanism of the $(n, 2n)$ reaction on light nuclei is direct knockout of a neutron by a neutron in a pair collision, as well as tearing out of a neutron by a neutron by means of pickup, analogous to the (n, d) reaction. Although a stable dineutron apparently does not exist, the process of pickup of a neutron by a neutron should occur, since attractive forces act between two neutrons. The process of direct knockout of a proton by a proton with energy 40 MeV was clearly observed (14) even on such a nucleus as Cu. For more accurate measurements of the cross sections of $(n, 2n)$ reactions it is necessary to improve the methods for measuring absolute neutron fluxes and to increase their intensity, in order to irradiate samples under cleaner geometrical conditions.

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