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Krystyna Maria MAŁUSZYŃSKA

Study of the $^{9}Be(t, n)^{11}B$ and $^{12}C(t, n)^{14}N$ Reactions at Incident Energies of 1.1 to 1.7 MeV

Badanie reakcji $^{9}Be(t, n)^{11}B$ i $^{12}C(t, n)^{14}N$ przy energiach zderzenia od 1,1 do 1,7 MeV

Исследование реакции $^{9}Be(t, n)^{11}B$ и $^{12}C(t, n)^{14}N$ при энергии столкновений от 1,1 до 1,7 Мев

INTRODUCTION

Cross section measurements for (t, n) reactions on light nuclei have not attracted much attention in the literature, particularly at low triton energies.

Neutron spectra have been measured by Serov et al. [1] at triton energy 1.1 MeV for $^{6}Li(t, n)^{8}Be$, $^{7}Li(t, n)^{9}Be$ and $^{9}Be(t, n)^{11}B$ reactions. In the works of Walter et al. the angular distributions of all neutron groups together have been shown for $^{6}Li(t, n)^{8}Be$, $^{7}Li(t, n)^{9}Be$ [4], $^{9}Be(t, n)^{11}B$ [3] and $^{19}F(t, n)^{21}Ne$ [2] reactions at incident particle energy lower than 2.1 MeV. In this energy range also the total cross sections have been measuered for (t, n) reactions on ^{6}Li, ^{7}Li [1, 3, 5], ^{9}Be [3, 6, 7], ^{16}O [8, 9] and ^{27}Al [2].

In the case of $^{9}Be(t, n)^{11}B$, $^{12}C(t, n)^{14}N$ and $^{16}O(t, n)^{18}F$ reactions, and for triton energy range from 1.1 to 1.7 MeV, only Małuszyńska et al. [10, 11, 12, 13, 14] have presented the neutron spectra and angular distributions for various neutron energy intervals.

In the low energy region the cross sections are described quite well by the Breit-Wigner formula. However, if $\Gamma \geqslant D$ the applications of this formula becomes doubtful.

Therefore, it seems to be useful to attempt to apply the Hauser-Feshbach theory for the study of this energy range. Up to now such attempts, paticularly for light nuclei, were only few.

The $^{10}B(d, p)^{11}B$ reaction giving the same residual nucleus as $^{9}Be(t, n)^{11}B$ one, has been analyzed by Arena et al. [23] in incident deuteron energy range from 1 to 2 MeV. The reasonable agreement of the averaged angular distributions of protons corresponding to the ground and first three excited levels of the residual nucleus ^{11}B with Hauser-Feshbach theory was obtained. On the basis of the calculations for one nucleon stripping the authors have proved that at the proton emission corresponding to the ground, second and third levels of the residual nucleus a small direct interraction contribution was observed.

In this work we want to discuss the experimental results for $^{9}Be(t,n)^{11}B$ and $^{12}C(t,n)^{14}N$ reactions at triton energies from 1.1 to 1.7 MeV; to show that for low states of the residual nucleus a differential cross section may be evaluated on the basis of the Hauser-Feshbach theory for the compound nucleus formation, though for higher states one has to consider also the direct interaction.

It is interesting to extend this kind of approach to low energies in order to further test the H-F model in energy region where $\langle\Gamma\rangle/\langle D\rangle \approx 3$ the relative contributions of these two mechanismscan be comparable andonly a few channels are open.

EXPERIMENTAL RESULTS

The tritons were accelerated in the 2 MeV Van de Graff generator of JINR Dubna. The neutron spectra were measu-red by using nuclear emulsions NIKFI Ya-2, with 20 mm X 40 mm dimensions and 200–400 μm thick [16]. The neutron spectra were measured for 10 emission angles. One of the 40 measured neutron spectra for $^{9}Be(t,n)^{11}B$ reaction is shown in Fig. 1.

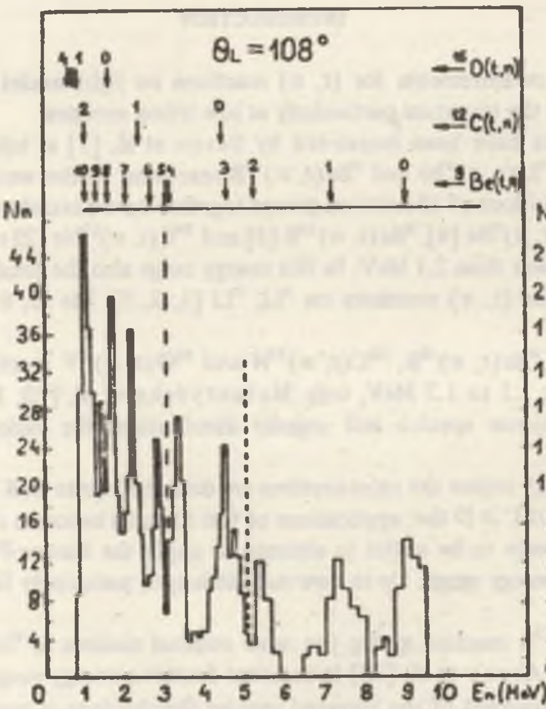

Fig. 1. Neutron spectrum for the $^{9}Be(t,n)^{11}B$ reaction at $\Theta_L = 108°$ for triton energy $E_t = 1.30$ MeV

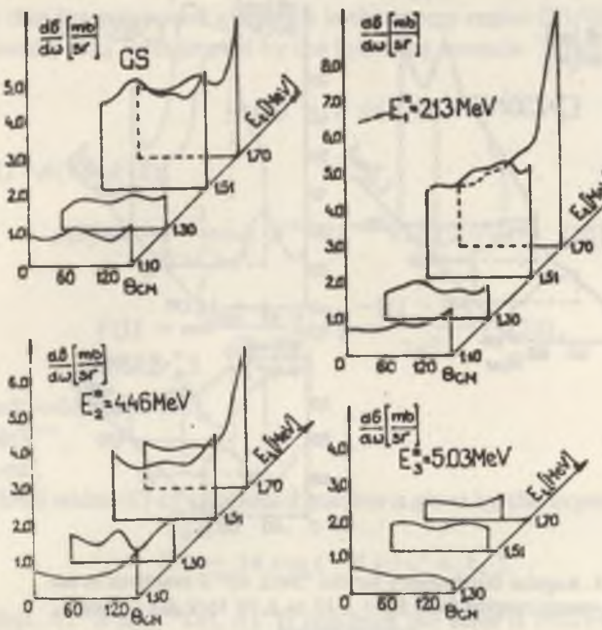

Fig. 2. Angular distributions for the $^9Be(t, n)^{11}B$ reactions at the triton energy range from E_t = 1.10 to 1.70 MeV for n_0, n_1 and n_2 neutron groups and from 1.30 to 1.70 MeV for n_3

The angular distributions for the separate neutron groups from the $^9Be(t, n)^{11}B$ and $^{12}C(t, n)^{14}N$ reactions are presented in Figs.2, 3 and 4. The solid lines are least-square fits of sums of Legendre polynomials to the experimental data. Systematic error, arising mainly from the target thickness measurement, is smaller than 30%.

The total cross sections were measured [11] for all investigated neutron groups in the incident triton energy range from 1.1 to 1.7 MeV.

THEORETICAL ANALYSIS

The shapes and rapid variation of most of the angular distributions with energy gives further support to the assumption that the reaction proceeds first of all through the levels of the compound nucleus. Interference of levels of opposite parity and possible energy fluctuations may cause the asymmetry in the distributions with regard to 90° in the CM system. In order to eliminate these effect, the data must be averaged [15] over energy before they can be compared with Hauser-Feshbach calculations. The relevant criteria are that the averaging interval must be greater than the mean-width $\langle\Gamma\rangle$ of the underlying compound nucleus. Some calculations of Ericson [29] indicate that $\Delta E \geqslant \pi \cdot \langle\Gamma\rangle$

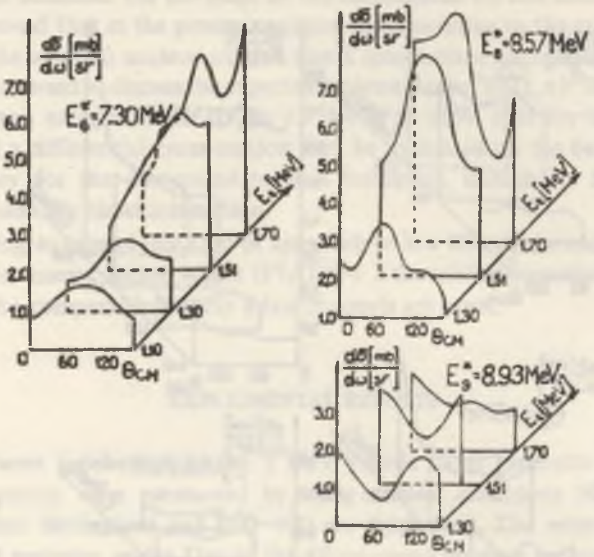

Fig. 3. Angular distributions for the $^{9}Be(t, n)^{11}B$ reactions in the triton energy ranging from E_t = 1.10 to 1.70 MeV for n_6 and n_9 neutron groups

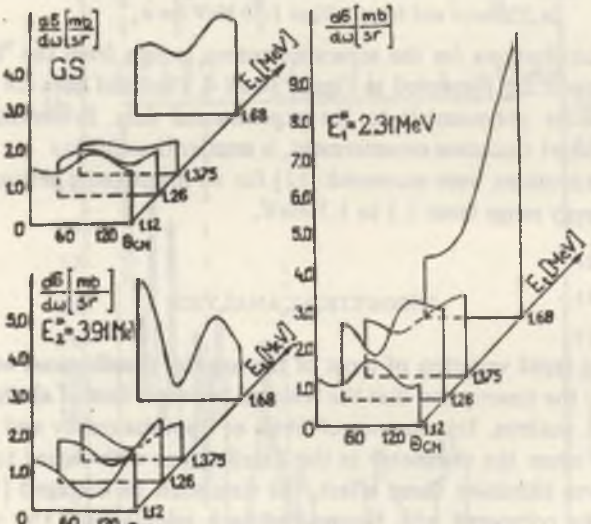

Fig. 4. Angular distributions for the $^{12}C(t, n)^{14}N$ reactions in the triton energy range from E_t = 1.10 to 1.68 MeV

is sufficient. The second important criterion of application of the H-F model is the ascertainment that the compound nucleus is in the energy region $\langle\Gamma\rangle/\langle D\rangle > 1$.

The level density may be estimated by the following formula:

$$\rho_T(E) = \sum_I \rho(E, I) \tag{1}$$

where: $\rho(E, I) = \rho(E) \cdot F(I)$,

$$\rho(E) = \frac{1}{12\sqrt{2\sigma^2}} a^{-1/3} U^{-5/4} \exp(2\sqrt{aU}) \quad [20],$$

$$F(I) = \frac{2I + 1}{\sigma^2} \exp\left(\frac{-I(I + 1)}{2\sigma^2}\right) \quad [31],$$

$U = E_{exc}$ for odd-odd nuclei [32],
$a = A/7.5\ MeV^{-1}$,
σ^2 – spin cut-off.

The mean level width $\langle\Gamma\rangle$ of compound nucleus is given by the expression [33]:

$$\langle\Gamma\rangle = 14 \exp(-4.69\sqrt{A/E_c}). \tag{2}$$

For the $^9Be(t, n)^{11}B$ and $^{12}C(t, n)^{14}N$ reactions the value $\langle\Gamma\rangle/\langle D\rangle \approx 3$ and ΔE is equal to 400–600 KeV.

According to the Hauser-Feshbach theory [15, 19, 20], the differential cross section averaged over compound nucleus fluctuations may be written as

$$\left\langle \frac{d\sigma_{\alpha,\alpha'}}{d\Omega} \right\rangle = \frac{1}{4k_\alpha^2} \sum_{LJ\pi} \frac{1}{(2I+1)(2i+1)} \left\{ \sum_{s,l} T_l(\alpha) \right\} \left\{ \frac{\sum_{s'l'} T_{l'}(\alpha')}{\sum_{s''l''\alpha''} T_{l''}(\alpha'')} \right\}$$

$$\times Z(lJlJ; sL) \sum (l'J'l'J; s'L)(-1)^{s-s'} P_L(\cos\theta), \tag{3}$$

where unprimed quantities refer to the incoming channel, primed quantities refer to the exit channel, and the sum in the denominator runs over all possible outgoing channels. In expression (3) α labels the pair of particles and their state of excitation, I and i are their intrinsic spins, s is the channel spin ($s = I + i$), l the orbital angular momentum, J the total angular momentum ($J = l + s$), π the channel parity and k_α is the wave number of the incident channel. The Z, so-called Z – coefficients, have been tabulated in the ref. [21]. $P_L(\cos\theta)$ are the Legendre polynomi-als, and $T_L(\alpha)$ are transmission coefficients [30].

In the low energy range, where the contribution of compound nucleus and direct interaction mechanism may be comparable and the open channels are few, the Hauser-Feshbach calculations overestimate the compound nucleus contribution to the cross section, as the incident flux at deposit al is substantially reduced by absorption. Thus, it is possible to define a reduction factor as

$$R = \frac{\sigma_T(E) - \sigma_D(E)}{\sigma_T(E)}, \tag{4}$$

where $\sigma_T(E)$ is the total reaction cross section and $\sigma_D(E)$ the total direct cross section at energy E.

The reduction factor R depends on the incident particle energy, but it is independent of reaction channel [22, 23, 24].

The relation between the measured value of differential cross section and one calculated on the basis of the Hauser-Feshbach theory is the following:

$$\frac{d\sigma}{d\Omega} = R\left(\frac{d\sigma}{d\Omega}\right)_{H\text{-}F}. \tag{5}$$

Reaction $^9Be(t, n)^{11}B$

In consequence of the triton interaction with ^9Be nucleus in the energy region 1.10 to 1.70 MeV, the compound nucleus $^{12}B^*$ has been formed with mean excitation energy about $E_c \cong 14$ MeV. The mean level width in this region is equal to

$$\langle\Gamma\rangle = 0.182 \text{ MeV} \tag{6}$$

and

$$\langle\Gamma\rangle/\langle D\rangle = 2.85. \tag{7}$$

This indicates, that $^{12}B^*$ is in the excitation energy region, where the levels are overlapping. Simultaneously the condition $\Delta E > \pi \cdot \langle\Gamma\rangle$ is satisfied.

The averaged angular distributions are shown is Fig. 5 along with their theoretical fits. The compound nucleus cross sections have been evaluated on the basis of the Hauser-Feshbach theory by the STATIS program [25]. The calculations have been performed with the optical model parameters of ref. [17, 26]. Their values are listed in Tab. 1.

Tab. 1. Optical model parameters

	V(MeV)	r_V(fm)	a_V(fm)	W(MeV)	r_V(fm)	a_W(fm)
$^9Be + t$ [17]	145	0.85	0.704	1.91	2.06	0.722
$^{11}B + n$ [26]	45	1.25	0.65	6.5	1.23	0.47

The averaged angular distributions of n_0 and n_3 neutron groups indicate only a small deviation from isotropy. The averaged angular distributions of n_6, n_8 and n_9 neutron groups are asymmetrical to the 90°_{CM}. The experimental data have been fitted using R = 0.27. The R value was evaluated at the assumption that n_0, n_2 and n_3 neutron group emission occurs by the compound nucleus mechanisms. It is possible that the value of R evaluated

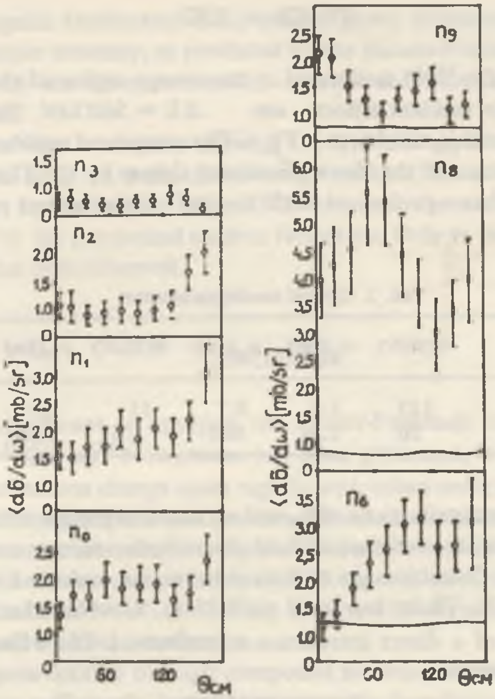

Fig. 5. Energy-averaged angular distributions for the $^{9}Be(t, n)^{11}B$ reactions; the solid curve evaluated on the basis of Hauser-Feshbach theory

in this way may be overestimated, because in these cases a small contribution of direct interaction cannot be neglected. However, in spite of this effect, the solid lines corresponding to the Hauser-Feshbach theory indicate distincly the disagreement with experimental results. This allows to conclude that beside the compound nucleus formation, the direct interaction contribution is considerable for n_6, n_8 and n_9 neutron groups. The comparison of the theoretical and experimental results for n_3 neutron group indicates only an insignificant difference. Then if the direct interaction occurred in this case, it would be rather small.

Reaction $^{12}C(t, n)^{14}N$

As a result of the triton interaction with ^{12}C nucleus at the energy region from 1.12 to 1.68 MeV, the compound nucleus $^{15}N^*$ has been formed with mean excitation energy about $E_c \cong 16$ MeV. The mean level width in this energy region is equal to

$$\langle\Gamma\rangle = 0.146 \text{ MeV} \quad (8)$$

and $$\langle\Gamma\rangle/\langle D\rangle = 3.87. \tag{9}$$

This indicates that the $^{15}N^*$ is situated in the energy region of the overlapping levels. The energy range of the incident tritons was $\Delta E = 560$ keV. The averaged angular distributions for n_0, n_1 and n_2 are shown in Fig. 6. The compound nucleus cross sections have been evaluated on the basis of the Hauser-Feshbach theory by the STATIS program [25]. The calculations have been performed with the use of the optical parameters [27, 18] listed in Tab. 2.

Tab. 2. Optical model parameters

	V(MeV)	r_V(fm)	a_V(fm)	W(MeV)	r_V(fm)	a_W(fm)
$^{12}C + t$ [27]	153	1.4	0.7	15	1.4	0.7
$^{14}N + n$ [18]	50	1.34	0.65	5.3	1.34	0.47

The averaged angular distributions of n_0 and n_1 neutron groups indicate the symmetry to 90°_{CM}. Thus it may be assumed that in these channels the reaction mechanism is entirely the compound nucleus formation. At this assumption the evaluated value of the reduction factors is R = 0.21. There is a small probability, however, that this value may be overstimated in result of a direct interaction contribution. This effect is porabably the reason of a R value dispersion.

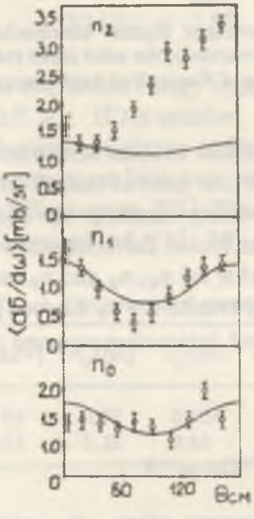

Fig. 6. Energy-averaged angular distributions for the $^{12}C(t, n)^{14}N$ reactions; the solid curve evaluated on the basis of Hauser-Feshbach theory

The averaged angular distribution of n_2 neutron group indicates clearly the asymmetry to the 90°_{CM} and larger intensity, as predicted by the Hauser-Feshbach theory. This effect may be explained by the direct interaction contribution simultaneously with the compound nucleus input.

The character of the excitation curves [11] and the rapid changes of the angular distributions shapes (Fig. 5) with triton energy confirm the above conclusion. In the investigated energy region in the $^{12}C(t, n)^{14}N$ reaction, the neutrons has been emitted entirely or mainly by the compound nucleus formation. Only in the n_2 neutron group the direct interaction has been observed.

CONCLUSION

In this paper an attempt at applying the Hauser-Feshbach theory to the analysis of $^9Be(t, n)^{11}B$ and $^{12}C(t, n)^{14}N$ reactions has been presented. In many cases the shapes of the angular distributions change quite rapidly with triton energy. This effect suggests the occurrence of the compound nucleus formation. Simultaneously the observed asymmetry of the differential cross sections may be explained as a result of interference of levels with oppositie parity, this effect exists probably at the compound nucleus energy, where $\Gamma \gg D$. It was estimated that $\langle\Gamma\rangle/\langle D\rangle \cong 3$. This confirms the hypotethis that the observed a-symmetry is caused by level interference.

If the reaction goes entirely through compound nucleus formation after averaging angular distributions over sufficiently large energy range, the interference effects are eliminated and the averaged distributions are symmetrical in relation to 90°_{CM} angle. When analysing the averaged angular distributions the conclusion was obtained that the compound mechanism is responsible mainly for the emission of the neutron groups to the first four levels of the residual nucleus ^{11}B and two neutron groups n_0 and n_1, corresponding to the ground and first excited levels of the ^{14}N.

The averaged angular distributions of the n_6, n_8 and n_9 neutron groups from $^9Be(t, n)^{11}B$ reaction and the n_3 group from $^{12}C(t, n)^{14}N$ reaction show the distinct asymmetry to the angle 90°_{CM} and the experimental values are much higher than those evaluated by the Hauser-Feshbach theory. The reason of these effect may by the direct interaction contribution. This conclusion for the ^{11}B nucleus is in agreement with the one obtained for ^{11}B by Arena et al [23]. Van der Zwan et al. [28], on the basis of the analysis of excitation function and unaveraged angular distributions, asserted that n_0, n_1 and n_2 neutron groups are emitted entirely by the compound nucleus ^{15}N. This result agrees with the one presented in this paper for the n_0 and n_1 neutrons groups. It seems that our results a the n_2 group are ore accurate because the application of the Hauser-Feshbach theory has allowed for better estimation of the contributions of both mechnisms.

As the obove discussions has shown, the Hause-Feshbach theory may be successfully used for the analysis of the nuclear reaction in the compound nucleus region of overlapping levels, where $\Gamma \gg D$.

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STRESZCZENIE

Badano reakcje jądrowe $^{9}Be(t, n)^{11}B$ i $^{12}C(t, n)^{14}N$ przy energii 1,1; 1,3; 1,5 i 1,7 MeV. Widma neutronów i rozkład kątowy w obszarze od 3° do 162° w układzie środka mas mierzono metodą emulsji jądrowej. Dla zbadania mechanizmu reakcji były uśrednione rozkłady kątowe całego przedziału energii trytonów. Uzyskane wyniki wskazują, że dla kanałów reakcji $^{9}Be(t, n)^{11}B$ z przejściem do czterech niższych poziomów ^{11}B i reakcji $^{12}C(t, n)^{14}N$ z przejściem do dwóch niższych poziomów ^{11}N istotną rolę odgrywa mechanizm jądra złożonego.

Grupy neutronów n_6, n_8 i n_9 z reakcji $^{9}Be(t, n)^{11}B$ i n_3 z reakcji $^{12}C(t, n)^{14}N$ zawierają istotny udział oddziaływania bezpośredniego.

РЕЗЮМЕ

Исследовано ядерные реакции $^{9}Be(t, n)^{11}B$ и $^{12}C(t, n)^{14}N$ при энергии тритонов 1,1; 1,3; 1,5 и 1,7 МеВ. Спектры нейтронов и угловые распределения в области от 3° до 162° в системе центра масс измерялись при помощи ядерных фотоэмульсий. Для исследования механизма реакции усреднено угловые распределения всего интервала энергии тритонов.

Полученные результаты свидетельствуют о том, что для каналов реакции $^{9}Be(t, n)^{11}B$ с переходом до двух нижних уровней ^{11}B и реакции $^{12}C(t, n)^{14}N$ с переходом до двух нижних уровней ^{11}N существенную роль играет механизм составного ядра. В группе нейтронов n_6, n_8 и n_9 в реакции $^{9}Be(t, n)^{11}B$, а также n_3 в реакции $^{12}C(t, n)^{14}N$ существенный вклад вносит механизм прямых реакции.

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