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(Translated by the IAEA)

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EVALUATION OF NEUTRON-^{6}Li INTERACTION CROSS-SECTIONS FOR CALCULATING KERMA FACTORS

I.M. Bondarenko and Eh.E. Petrov

Many studies have been devoted to the interaction of neutrons with ^{6}Li nuclei [1-24]. This is because lithium is extensively used in practice. Owing to its large neutron absorption cross-section, ^{6}Li is an important component of shielding materials. The cross-section of the reaction $^{6}Li(n,t)\alpha$ is a standard one for neutron energies below 1 MeV, and for this reason ^{6}Li is used in measurement technology. Moreover, it is planned to use lithium in the blankets of thermonuclear reactors for breeding and heat production by means of the $^{6}Li(n,t)\alpha$ reaction (reaction energy $Q = +4.7839$ MeV) [9].

The most important functionals for blanket design are the tritium breeding factor and the thermal yield. For calculating the thermal yield functional it is necessary to have, in addition to data on neutron fields and gamma radiation, an exact knowledge of the conversion factors for the transition from radiation fluxes to thermal yield (kerma factors).

A high-energy neutron spectrum in the blanket enhances the role of the breeding reactions (n,n'd), (n,2n'), as a result of which further neutrons are produced in addition to those arising during fusion - an effect which is important both from the point of view of tritium breeding and from that of thermal yield. However, the cross-sections of these reactions are insufficiently well known [9]. In the energy region above 5 MeV the neutron elastic scattering cross-section of ^{6}Li nuclei is up to 12% higher in the ENDF/B-V evaluation [25] than in Refs [3,6-8]. On the other hand, the deuterium build-up cross-section is lower, since it is obtained by taking the difference between the total cross-section and the cross-sections of all other reactions in this range of neutron energies. In addition, it is pointed out in Ref. [26] that the spectrum of neutrons emitted in the deuterium build-up reaction in the ENDF/B-V evaluation is not in agreement with the measured value. This may lead to serious errors in calculations of neutron attenuation and thermal yield from neutrons. For all these reasons, a new evaluation of neutron-^{6}Li interaction cross-sections has been carried out. The evaluation was performed on the basis of an analysis of experimental data in the most important energy region for neutron slowing-down (0.001-16 MeV). The deuterium build-up reaction was examined in particular detail.

The following reactions are possible in the neutron energy range 0.001-16 MeV:

$^{6}Li(n,n)^{6}Li$,	Q = 0.0 MeV;
$^{6}Li(n,n'\gamma)^{6}Li$,	Q = -3.563 MeV;
$^{6}Li(n,n')^{6}Li^{*}$,	Q = -2.185 MeV; -4.31 MeV...;
$^{6}Li^{*} \rightarrow d + \alpha$	Q = +0.7115 MeV; +2.8365 MeV...;
$^{6}Li(n,t)\alpha$	Q = +4.7839 MeV;
$^{6}Li(n,n'd)\alpha$	Q = -1.4735 MeV;
$^{6}Li(n,p)^{6}He$,	Q = -2.725 MeV;
$^{6}Li(n,2n')^{5}Li$,	Q = -5.66 MeV;
$^{5}Li \rightarrow p + \alpha$	Q = +1.97 MeV;
$^{6}Li(n,\gamma)^{7}Li$,	Q = 7.251 MeV.

The cross-section of the (n,γ) reaction in this neutron energy region is very small and has therefore not been considered in this study; it was taken to be as in the ENDF/B-V evaluation.

Experimental data and recommended cross-sections

Total cross-section

This cross-section has been thoroughly studied in the neutron energy region concerned. The results of various authors agree to within ± 3% [4]. In Ref. [4], for E_n = 0.1-4.8 MeV, a complete analysis is made of experimental results on total cross-sections and a recommended total cross-section with an uncertainty of ± 3% is proposed. These results were used in our own evaluation. In the neutron energy region 0.001-0.1 MeV, the total cross-section is equal to the sum of the (n,t) reaction cross-section, which is standard, and the neutron elastic scattering cross-section, which is almost constant in this neutron energy region and is known to within ± 3%

[2]. For neutron energies above 4.8 MeV, the total cross-section corresponds to the data of Ref. [10] and is systematically lower than the results of the ENDF/B-V evaluation by approximately 1%.

The uncertainty in the total cross-section in the neutron energy range considered is ± 3%. This cross-section - from the evaluations of our study and from and ENDF/B-V - is shown together with experimental results from Ref. [11] in Figs 1-3. The largest discrepancy between the results of the two evaluations is found in the resonance region and does not exceed 5%.

Cross-section of the (n,t) reaction

For neutron energies up to 3 MeV, this is the most important reaction from the point of view of thermal yield from neutrons. Considerable attention is being paid to theoretical and experimental investigation of its cross-section [4,5,12-16]. For neutron energies below 0.1 MeV the cross-section is standard. Discrepancies in the experimental data are found in the resonance region, i.e. in the energy range 0.1-2 MeV. In the rest of the energy region considered, the data of the various authors are in good agreement to within ± 5%. Not all the experimental data are shown in Figs 1-3, but only those

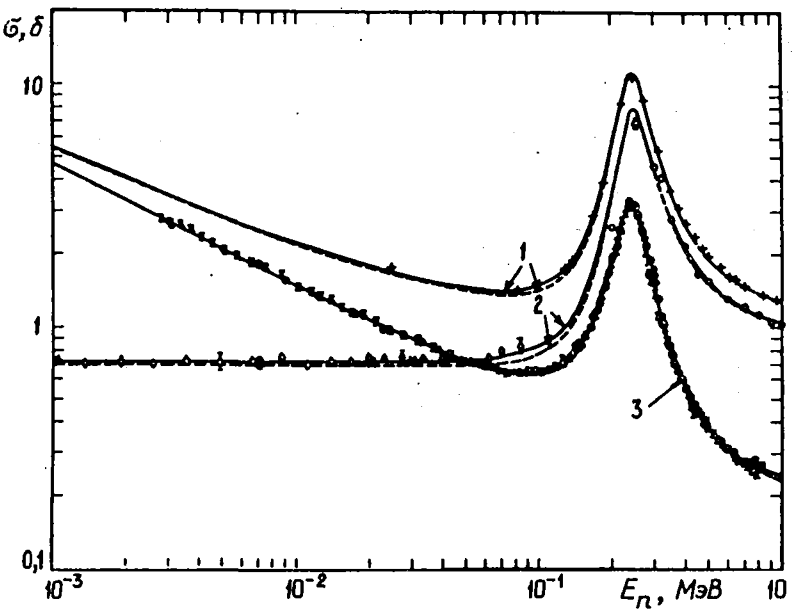

Fig. 1. Cross-sections in the neutron energy region 0.001-1 MeV. (--- = ENDF/B-V evaluation); 1 - total cross-section; 2 - neutron elastic scattering cross-section; 3 - (n,t) reaction cross-section; ◇ = [2]; + = [11]; ⧗ = [13]; ● = [14]; * = [17]; o = [18].
[Vertical axis: σ, b; Horizontal axis: E_n, MeV]

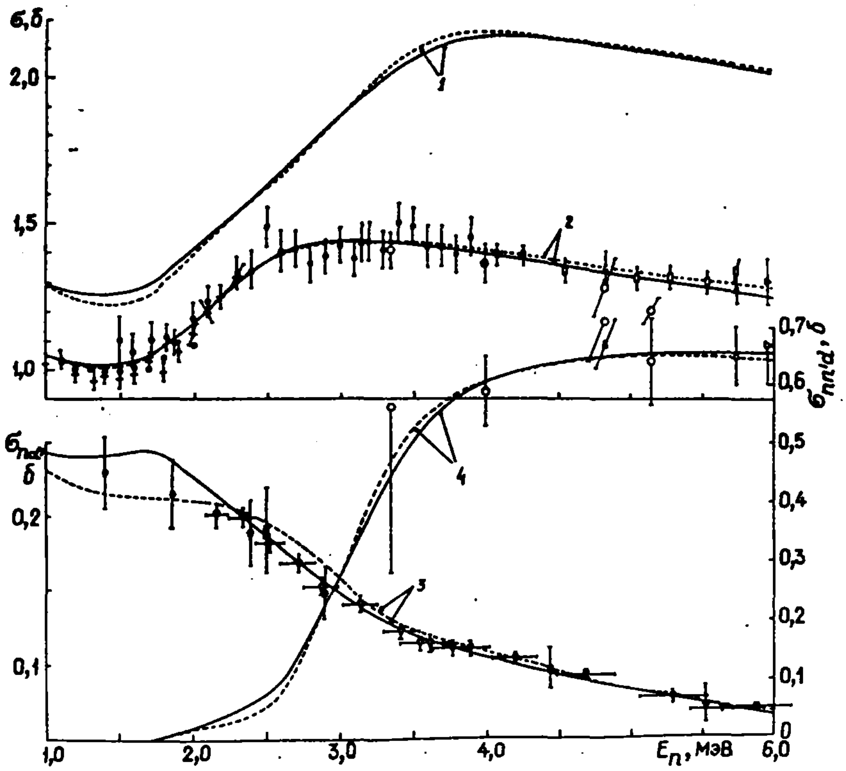

Fig. 2. Cross-sections in the neutron energy region 1-6 MeV (--- = ENDF/B-V evaluation); 1 - total cross-section; 2 - neutron elastic scattering cross-section; 3 - (n,t) reaction cross-section; 4 - deuterium build-up reaction cross-section.
● = [4]; □ = [7]; Δ = [8]; ∇ = [15]; * = [16];
● = [18]; + = [19]; Δ = [20]; o = [23].
[Vertical axes (left): σ, b; σ_{nd}, b; (right): $\sigma_{nn'd}$, b.
Horizontal axis: E_n, MeV]

of Refs [13-16], on which the evaluation was carried out. The most reliable results on this cross-section obtained in recent years are those published by the authors of Refs [12-15].

The evaluation of the cross-section in the 0.1-2 MeV neutron energy region was based on the experimental and theoretical data of Refs [5,12-14]. For neutron energies in the range 0.001-0.6 MeV the recommended cross-section coincides with the ENDF/B-V evaluation, while in the 0.6-2 MeV range the results of the evaluation are higher than the ENDF/B-V results (up to 15%). In the neutron energy region 2-14 MeV the cross-sections correspond to the experimental data of Refs [15,16]. The evaluated cross-section of our study in the neutron energy range 2.3-12.6 MeV is systematically lower than that of ENDF/B-V. The discrepancy is up to 8%. For neutron energies above 12.5 MeV

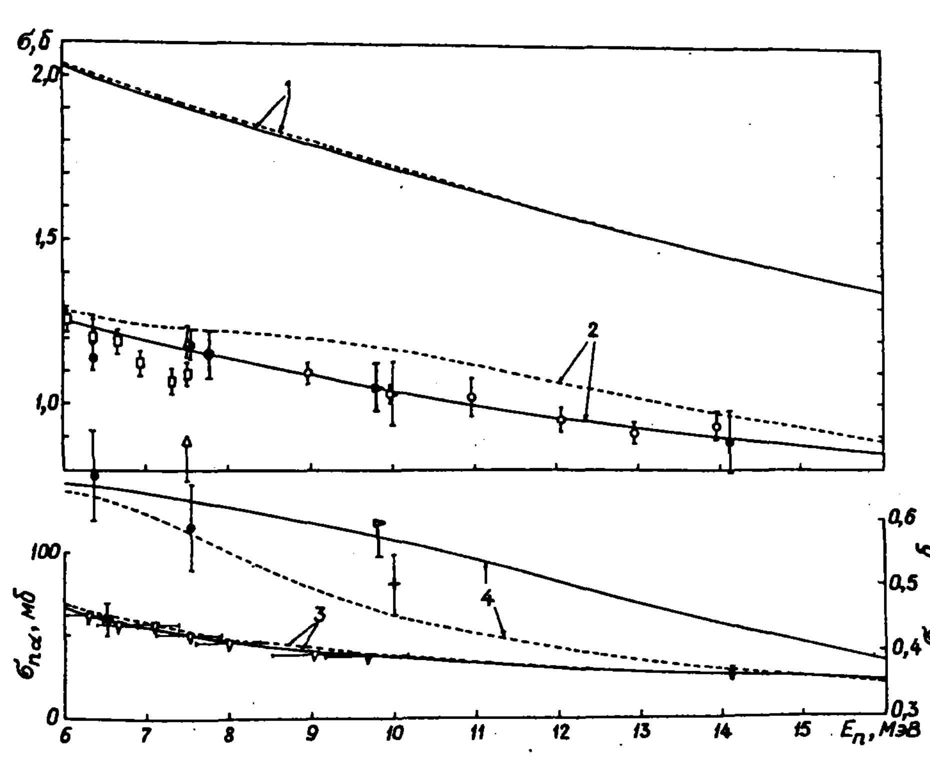

Fig. 3. Cross-sections in the neutron energy region 1-6 MeV (--- = ENDF/B-V evaluation); 1 - total cross-section; 2 - neutron elastic scattering cross-section; 3 - (n,t) reaction cross-section; 4 - deuterium build-up reaction cross-section. ⊙ = [3]; o = [6]; □ = [7]; Δ = [8]; ∇ = [15]; * = [16]; Δ = [20]; + = [21]; ⊗ = [22]; o = [23]. [Vertical axes (left): σ, b; σ_{nd}, mb; (right): $\sigma_{nn'd}$, b. Horizontal axis: E_n, MeV]

the evaluations coincide. The uncertainty in the evaluated cross-section (see Figs 1-3) in the neutron energy range 0.1-16 MeV does not exceed 5%.

Elastic scattering cross-section

In the neutron energy region 0.001-0.1 MeV the cross-section evaluation was carried out on the basis of the experimental data of Refs [2,17]. The uncertainty in these data and in the evaluated cross-section is ± 3%. In the neutron energy region 0.1-1 MeV the cross-section was found by subtracting the (n,t) reaction cross-section from the total cross-section. These results agree well with the experimental data of Ref. [18]. The uncertainty in the cross-section does not exceed 6%.

For neutron energies of 1-4 MeV, the recommended data of Ref. [4] with an uncertainty of ± 4% were used. The evaluated cross-section in the

4-16 MeV range was found by the least-squares method on the basis of the experimental data of Refs [3,6-8,20-23] with an uncertainty of ± 4%. This cross-section, as determined from our evaluations and from ENDF/B-V, is shown in Figs 1-3 together with experimental data. The largest discrepancy between the results of the two evaluations (up to 12%) is found in the neutron energy region above 5 MeV.

Inelastic scattering cross-sections

Inelastic interaction between neutrons and ^6Li nuclei takes place in reactions such as (n,n'γ), (n,2n') and (n,n'd)α.

(1) The (n,n'γ) reaction. This is an inelastic neutron scattering reaction at a discrete level (Q = -3.563 MeV) with the emission of a gamma ray. Neutron inelastic scattering at other levels leads to the emission of two charged particles. This interaction is involved in the deuterium build-up reaction. The cross-section of the (n,n'γ) reaction is small, and there is only one reference [24] containing a systematic study of this cross-section in the neutron energy range from the reaction threshold up to 9 MeV. The evaluated cross-section in this neutron energy region therefore corresponds to the experimental results of Ref. [24]; for E_n > 9 MeV it coincides with the ENDF/B-V evaluation.

(2) The (n,2n') reaction cross-section corresponds to the ENDF/B-V evaluation. The cross-sections of the (n,n'γ) and (n,2n') reactions are shown in Fig. 4.

(3) The (n,n'd)α reaction is a deuterium build-up reaction. This channel makes the second largest contribution to the total cross-section after elastic scattering for $E_n \gtrsim 3$ MeV, and from the point of view of neutron stopping and thermal yield, it plays a very important role in the blanket of a thermonuclear reactor. Although the accuracy of individual experimental values for the cross-section is ±(10-15%), the spread in data points is in fact much greater. This is because the available experimental data on the total deuterium build-up cross-section were obtained by direct measurement of neutron inelastic scattering on ^6Li nuclei. This method does not give good results because it is impossible to measure the spectrum of neutrons emitted in the low-energy region experimentally, and any extrapolation leads to considerable errors. The total deuterium build-up cross-section is therefore obtained by subtracting the cross-sections of other reactions from the total

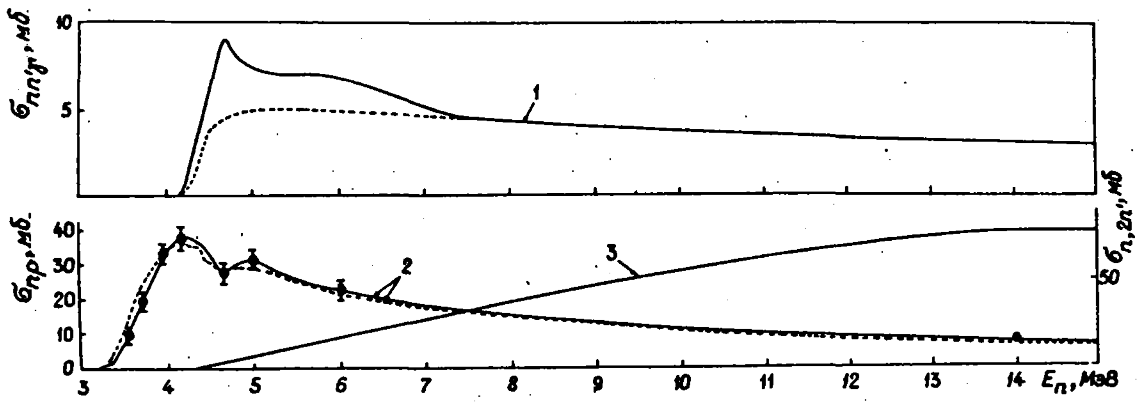

Fig. 4. Reaction cross-sections: 1 - (n,n'γ); 2 - (n,p); 3 - (n,2n'); ● = [24]; ⊙ = [28]; --- = ENDF/B-V evaluation.
[Vertical axes (left): $\sigma_{nn'\gamma}$, mb; σ_{np}, mb;
(right): $\sigma_{n,2n'}$, mb.
Horizontal axis: E_n, MeV]

cross-section. If the total cross-section has an uncertainty of ± 3% and the elastic scattering cross-section one of ± 4%, the deuterium build-up reaction in the neutron energy region 3.5–16 MeV will have an uncertainty of up to 20%.

Figures 2 and 3 show the total deuterium build-up cross-section obtained by subtracting the cross-sections of other reactions from the total cross-sections; these results agree well with experiment [8,20,23] and in the $E_n \geq 5$ MeV range are systematically higher (up to 20%) than the results of the ENDF/B-V evaluation.

Apart from the reaction cross-section, it is also important to know the spectrum of neutrons emitted. For that purpose, all processes occurring in this reaction must be examined. Deuterium build-up can occur through the following channels [27]:

$$^{6}\mathrm{Li}+n \to n+d+\alpha, \qquad Q = -1.4735\ \mathrm{MeV}; \tag{1}$$

$$\to n+{}^{6}\mathrm{Li}^{*}, \qquad Q = -2.185\ \mathrm{MeV};\ -4.31\ \mathrm{MeV}\ldots; \tag{2}$$

$$^{6}\mathrm{Li}^{*} \to d+\alpha, \qquad Q = +0.7115\ \mathrm{MeV};\ 2.8365\ \mathrm{MeV}\ldots;$$

$$\to d+{}^{5}\mathrm{He}, \qquad Q = -2.3635\ \mathrm{MeV} \tag{3}$$

$$^{5}\mathrm{He} \to n+\alpha, \qquad Q = +0.89\ \mathrm{MeV} \tag{4}$$

$$\to d+{}^{5}\mathrm{He}^{*} \to d+n+\alpha.$$

Reaction (1), in which three particles are emitted simultaneously, has been studied only in Ref. [16]. By means of rough measurements at neutron energies of 5.53, 6.52 and 14.1 MeV, a cross-section of approximately 200 mb

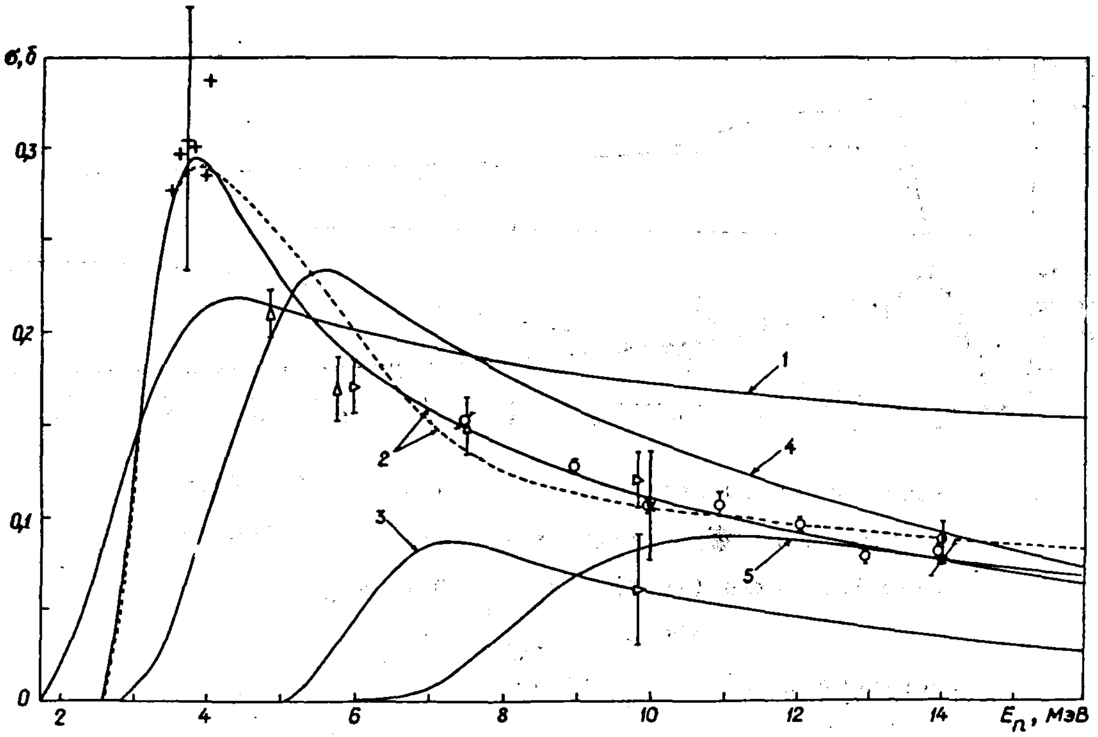

Fig. 5. Partial cross-sections of deuterium build-up reaction:
1 - (n,n'd)α; 2 - ^{6}Li(n,n')^{6}Li* (2.185 MeV);
3 - ^{6}Li(n,n')^{6}Li* (4.31 MeV); 4 - ^{6}Li(n,d)^{5}He;
5 - ^{6}Li(n,d)^{5}He*; + = [4]; o = [16]; Δ = [8];
Δ = [20]; x = [21]; ◑,* = [29]; --- = ENDF/B-V evaluation;
Q = -2.185 MeV.
[Vertical axis: σ, b; Horizontal axis: E_n; MeV]

was obtained. The measurements show that this reaction channel is one of the main ones for the build-up of deuterium. Reaction (2) is a neutron inelastic scattering reaction at discrete levels (Q = -2.185 MeV, -4.31 MeV, etc.) with the emission of two charged particles. The reaction on which the most abundant information is available is the ^{6}Li(n,n')^{6}Li* (2.185 MeV) reaction [3,4,6,8,20,21]. The experimental results of the different authors agree well with each other (Fig. 5). A cross-section evaluation was performed on the basis of these data. In the neutron energy region from the reaction threshold up to 4 MeV, the evaluated cross-section almost coincides with the results of the ENDF/B-V evaluation and is found with an uncertainty of ± 20%. The cross-section in the 4-16 MeV range was obtained by the least-squares method. The uncertainty in this cross-section for neutron energies of 6-16 MeV is ± 5%.

The cross-section of the ^{6}Li(n,n')^{6}Li* reaction (4.31 MeV) has been measured for only one neutron energy (9.83 MeV) and the result is 61 ± 30 mb [8]. On the basis of experimental data and analysis of the measurements of

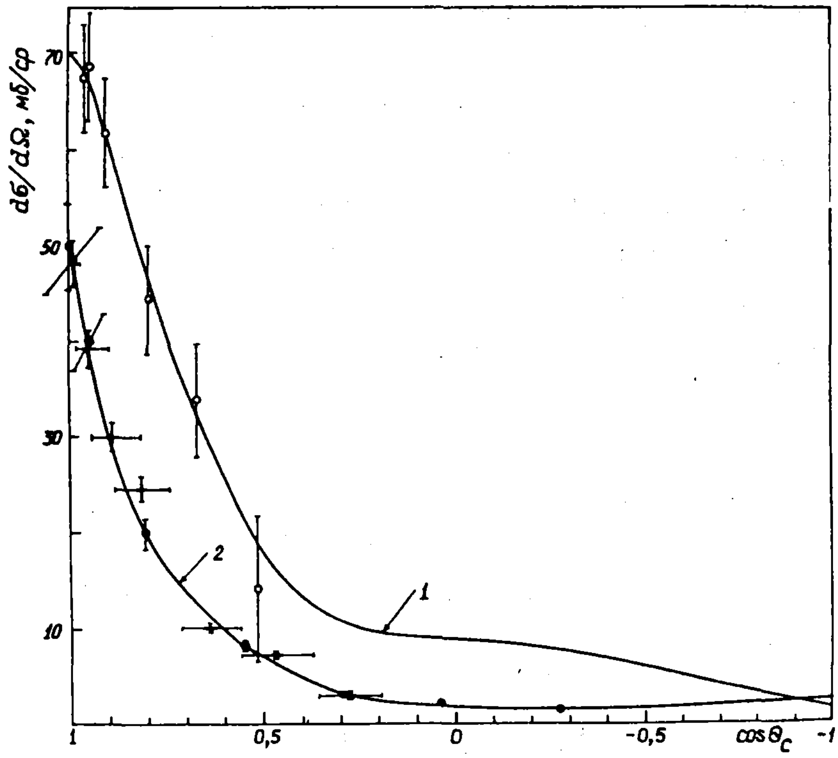

Fig. 6. Differential cross-section of the ^{6}Li(n,d)^{5}He reaction from the data of different authors: 1 - [30] with E_n = 6.77 MeV; 2 - [31, 32] with E_n = 14.1 MeV; o = [30]; + = [31]; ● = [32].

[Vertical axis: dσ/dΩ, mb/sr]

Ref. [29], a recommended cross-section with an uncertainty of not more than 50% has been obtained.

Reaction (3) has been studied at a neutron energy of 6.77 MeV [30] and in the region 14-14.4 MeV [29,31-34]. The differential cross-sections of this reaction are shown in Fig. 6. The data of Refs [31,32] agree well; on the basis of their analysis a cross-section with an uncertainty of ± 10% was obtained.

Reaction (4) has been studied only in the neutron energy region 14-14.4 MeV [29,34]. The cross-sections for reactions (1) and (4) were obtained by subtracting all other partial cross-sections from the total deuterium build-up cross-section, but with allowance for the experimental data of Refs [16,29,34]. The uncertainty in the cross-sections obtained is ± 20%. The partial cross-sections of the deuterium build-up reaction are shown in Fig. 5.

Cross-section of the (n, p) reaction

Ref. [24] contains a systematic study of the cross-section in the neturon energy region from the reaction threshold up to 9 MeV. On the basis of the data of Refs [24,28], the cross-section of this reaction has been obtained with an uncertainty equal to the uncertainty in the experimental data ($\pm$ 10%). The cross-section based on an evaluation and ENDF/B-V is shown together with experimental results in Fig. 4. The discrepancy between the results of the two evaluations is up to 50%.

Calculation of the kerma factor

For interactions between neutrons and ^{6}Li nuclei, the microscopic kerma factor is determined as follows:

$$k(E_n) = \sum \sigma_i(E_n)\bar{E}_{H_i}(E_n),$$

where $\sigma_i(E_n)$ is the cross-section of the i-th reaction, $\bar{E}_{H_i}(E_n)$ is the mean locally produced energy in the i-th reaction and E_n is the energy of interacting neutrons. Reference [1] is devoted to calculation of the mean locally produced energy in reactions of all types. Because of the complexity of determining the spectrum of neutrons emitted, the deuterium build-up reaction must be examined in addition. It is pointed out in Ref. [26] that the spectrum of neutrons emitted in this reaction according to the ENDF/B-V evaluation does not correspond to the experimental spectrum. This could seriously affect the accuracy of the calculated kerma factor and the calculation of thermal yield. The mean locally produced energy in the deuterium build-up reaction is equal to $\bar{E}_H = E_n - Q - \bar{E}_n'$, where $Q = -1.4735$ MeV and $\bar{E}_n'$ is the mean energy of the neutron emitted in this reaction, determined from the spectrum of neutrons emitted (the spectrum is governed by the deuterium build-up reaction channel).

Reaction (1) is a reaction in which three particles are emitted simultaneously. In Ref. [35] it is shown that the spectrum of neutrons emitted in the centre-of-mass system for this reaction has the form $N(E_m') = \text{const}\sqrt{E_m'}\,(E_{max} - E_m')$, where E_m' is the energy of the neutrons emitted and E_{max} is the maximum possible energy of the neutrons emitted. In order to determine the velocity of a neutron emitted in the laboratory system of co-ordinates, $(L)\vec{U}_n'$, we must add to the neutron velocity in the centre-of-mass system, $(C)\vec{U}_m'$, the vector $\vec{V}_c$ velocity of the centre of mass in the L system, i.e. $\vec{U}_n' = \vec{V}_c + \vec{U}_m'$ or $U'^2_n = V^2_c + U'^2_m + 2V_c U'_m \cos\theta_c$:

$$E_n' = \frac{E_n}{(1+A)^2} + E_m' + 2\mu_c \sqrt{E_m' \frac{E_n}{(1+A)^2}} ,$$

where $\mu_c = \cos\theta_c$ is the cosine of the neutron emission angle in the C system, E'_n is the energy of the neutron emitted in the L system, and A is the ratio of the mass of the nucleus to that of the neutron. If we assume that the neutron is emitted isotropically (this has been confirmed experimentally) in system C, then the mean neutron energy in system L will be:

$$\bar{E}_n' = \frac{E_n}{(1+A)^2} + \bar{E}_m' , \tag{5}$$

where $\bar{E}_m' = \frac{\int_0^{E_{max}} E_m' N(E_m') dE_m'}{\int_0^{E_{max}} N(E_m') dE_m'} = \frac{E_{max} \int_0^1 x \sqrt{x(1-x)}\, dx}{\int_0^1 \sqrt{x(1-x)}\, dx} = \frac{E_{max}}{2} ; \; x = E_m'/E_{max}$.

Reaction (2) is a neutron inelastic scattering reaction at a discrete level and thus, as follows from Ref. [1], the mean energy of the neutron emitted is equal to:

$$\bar{E}_n' = \frac{2AE_n}{(1+A)^2} \left[\frac{A^2+1}{2A} - \frac{(A+1)E_\lambda}{2E_n} + \left(1 - \frac{A+1}{A} \frac{E_\lambda}{E_n}\right)^{1/2} \overline{\cos\theta_c} \right] , \tag{6}$$

where E_λ is the energy of the excited level and $\overline{\cos\theta_e}$ is the mean cosine of the neutron scattering angle in the centre-of-mass system. Ref. [36] examines a two-stage reaction (3) and obtains the following expression:

$$E_{He} = \left[\frac{1}{1+\gamma} + \frac{m_{He} m_n}{m_L^2} \beta \right] \beta E_n + \frac{Q_1}{1+\gamma} - 2\mu_{c_1} \frac{\beta E_n}{m_L} \left[\left(1 + \frac{Q_1}{\beta E_n}\right) \frac{m_{He} m_r}{1+\gamma} \right]^{1/2} ; \tag{7}$$

$$E_n' = \frac{Q_2}{\left(1 + \frac{m_n}{m_\alpha}\right)} + E_{He}\left(\frac{m_n}{m_{He}}\right) + 2\mu_{c_2} \left[\frac{Q_2 m_n E_{He}}{\left(1 + \frac{m_n}{m_\alpha}\right) m_{He}} \right]^{1/2} , \tag{8}$$

where $\gamma = m_{He}/m_D$, $\beta = m_L/(m_n + m_L)$, $m_r = m_n m_L/(m_n + m_L)$, E_{He} is the energy of ^{5}He in the laboratory system of co-ordinates, μ_{c_1} is the cosine of the deuterium scattering angle in the centre-of-mass system (n + ^{6}Li), μ_{c_2} is the cosine of the neutron scattering angle in the centre-of-mass system (^{5}He), and m_n, m_L, m_{He}, m_p and m_α are the masses of the neutron, ^{6}Li, ^{5}He, deuterium and an alpha particle respectively. Figure 6 shows differential deuterium emission cross-sections in the first centre-of-mass system.

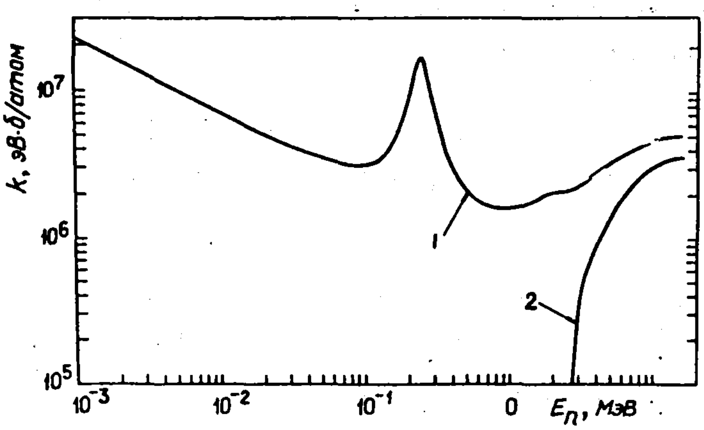

Fig. 7. Kerma factors in the neutron energy region 0.001-16 MeV: 1 - total kerma factor; 2 - kerma factor from deuterium build-up reaction.
[Vertical axis: κ, eV•b/atom; horizontal axis: E_n, MeV]

The mean neutron energy is determined by the mean cosines in the equations shown above. As follows from Ref. [36], $\bar{\mu}_{c_2} = 0$. The value of $\bar{\mu}_{c_1}$ = was found from the experimental data of Refs [29-34]. For reaction (4), the mean energy of the neutron emitted is determined from Eqs (7) and (8) with $Q_1 = -2.3635 - \varepsilon$, $Q_2 = 0.89 + \varepsilon$, $\bar{\mu}_{c_2} = 0$, where ε is the excitation energy of the ^{5}He nucleus for which a broad excitation level of 4 ± 1 MeV is characteristic [27], and Q_1 and Q_2 are in MeV. The value of $\bar{\mu}_{c_1}$ was found from the experimental data of Ref. [29].

Figure 7 shows microscopic kerma factors calculated from the deuterium build-up reaction and from all reactions. With E_n = 14 MeV the contribution of the deuterium build-up reaction to the total kerma factor is approximately 70%. A comparison between the results of this paper and those of Ref. [1] shows that, in the neutron energy region 3-16 MeV, the kerma factor calculated in our study is systematically higher (up to 20%). In other words, the contribution of the deuterium build-up reaction to the total kerma factor has become larger. The uncertainty in the calculated kerma factor for $E_n \leqslant 0.1$ MeV is $\pm 1\%$, for neutron energies of 0.1-4 MeV it is not more than 5%, and for $E_n > 4$ MeV it is not more than 10%.

The authors believe that the present evaluation based on analysis of available experimental data satisfies the accuracy requirements specified in Ref. [9] and that the evaluated cross-sections and calculated kerma factor can therefore be recommended for practical use.

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EVALUATION OF NEUTRON-^{7}Li INTERACTION CROSS-SECTIONS FOR CALCULATING KERMA FACTORS

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In the last few years, considerable attention has been paid to the interaction of neutrons with ^{7}Li nuclei [1-15]. The reason for this is that lithium is expected to be used in the blankets of fusion reactors with tritium-deuterium plasma for tritium breeding via the ^{7}Li(n,n't) and ^{6}Li(n,t)α reactions and additional energy yield through the ^{6}Li(n,t)α reaction (reaction energy Q = +4.7839 MeV). This means that comprehensive and reliable information will be needed on all reactions resulting from the interaction of neutrons with ^{7}Li nuclei in order to calculate neutron attenuation, breeding factors and thermal yield in the blanket with acceptable accuracy. So far the accuracy of the evaluated cross-sections for neutron-^{7}Li interactions has been inadequate [4, 5]. Integral and differential measurements have indicated [4-7] that the cross-section of the tritium build-up reaction for E_n = 6-14 MeV is between 10 and 35% too high in the ENDF/B-V evaluation [16].

Beynon and co-workers [8] analyse the neutron spectrum from the (n,n't)α reaction and demonstrate the discrepancy between the evaporation model used in present evaluations and the measured spectrum. From the analysis of the ^{7}Li(n,n'γ) reaction cross-section in Refs [11, 13, 14], it follows that in the ENDF/B-V evaluation this cross-section is too high for neutron energies above 4 MeV. All this can lead to serious errors in calculations.

Our present paper, which is a continuation of Ref. [1], sets out to evaluate neutron-^{7}Li interaction cross-sections on the basis of an analysis of the experimental data. The authors examine the 0.001-16 MeV region, the most important for neutron moderation. A detailed study is made of the tritium build-up reaction. The following reactions are possible [17] in the

0.001-16 MeV energy range:

$^7Li(n,n)^7Li$,	$Q = 0.0$ MeV	$^7Li(n,2n')^6Li$,	$Q = -7.251$ MeV
$^7Li(n,\gamma)^8Li$,	$Q = 2.033$ MeV	$^7Li(n,2n')d\alpha$,	$Q = -8.725$ MeV
$^7Li(n,n'\gamma)^7Li$,	$Q = -0.478$ MeV	$^7Li(n,p)^7He$,	$Q = -10.42$ MeV
$^7Li(n,n't)\alpha$,	$Q = -2.467$ MeV	$^7Li(n,d)^6He$,	$Q = -7.751$ MeV

The (n,p) reaction cross-section measured in Ref. [18] for $E_n = 14.8$ MeV is very small and therefore is not considered in this paper.

Experimental data and recommended cross-sections

Total cross-section: This cross-section has been studied unevenly in the neutron energy region considered. Four regions can be identified:

1. For the region $1 \leq E_n < 100$ keV, new data are given only in Ref. [3]; these data agree well with the results of measurements made in 1972, an analysis of which is given in Ref. [19]. Therefore, the total cross-section in this region corresponds to the data in Ref. [3] and the uncertainty in the cross-section is not greater than 3%.

2. For the region $0.1 \leq E_n \leq 1$ MeV (resonance region), there is still a shortage of experimental data. The data of the various authors have accuracies to within 10% [19]. There seems to be a disagreement in the determination of the resonance energy. In this paper, we take the resonance energy to be 255 keV, which corresponds to the measured energy of 254 ± 3 keV in Ref. [20]. In accordance with the recommendation in Ref. [19], the evaluation of the total cross-section in this neutron energy region is obtained from the experimental data in Ref. [21], with an energy shift of −6 keV. The error in the cross-section is not more than 5%.

3. In the region $1 < E_n < 2$ MeV, the cross-section corresponds to the data in Ref. [19], the accuracy of which is ±3%.

4. In the region $2 \leq E_n \leq 16$ MeV, the cross-section corresponds to the evaluation in Ref. [4]. The accuracy of the cross-section in this neutron energy region is ±3%. In their measurements of the total cross-section the authors of Ref. [22] isolated, with good

resolution, a resonance at 5.1 MeV. Their results were used to evaluate the total cross-section in this resonance region. The evaluated total cross-sections obtained in this paper and those from the ENDF/B-V evaluation are shown in Figs 1-3. The discrepancy over the whole neutron energy region considered does not exceed ±5%.

Cross-sections for inelastic scattering: Inelastic interaction of neutrons with ^7Li nuclei in the energy range considered occurs via three basic reactions: (n,n'γ), (n,n't) and (n,2n').

1. The (n,n'γ) reaction - inelastic scattering of neutrons at a discrete level (Q = -0.478 MeV) with emission of a γ-ray. Inelastic scattering of neutrons at higher levels leads to the emission of two charged particles. This interaction is related to the tritium build-up reaction. Figs 1-3 show experimental data from Refs [13, 14, 24-26], which were used to evaluate the (n,n'γ) reaction cross-section. An analysis and comparison of all the

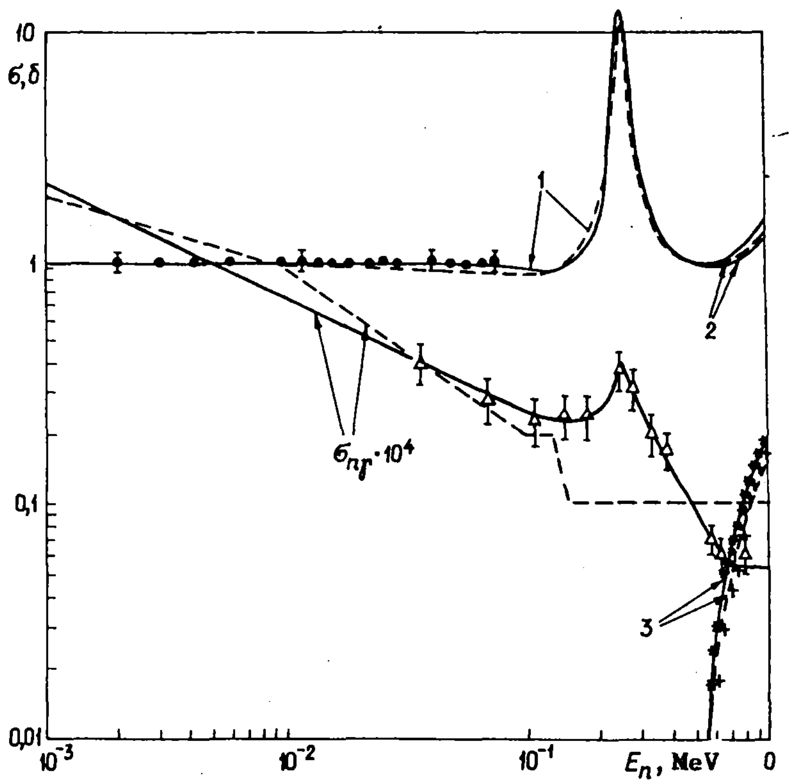

Fig. 1. Cross-section for the 0.001-1 MeV neutron energy region: ---- ENDF/B-V evaluation; ——— - evaluation of the present paper; 1 - total cross-section; 2 - cross-section for elastic neutron scattering; 3 - cross-section for the (n,n'γ) reaction; • - [3]; Δ - [23]; * - [13]; + - [14].

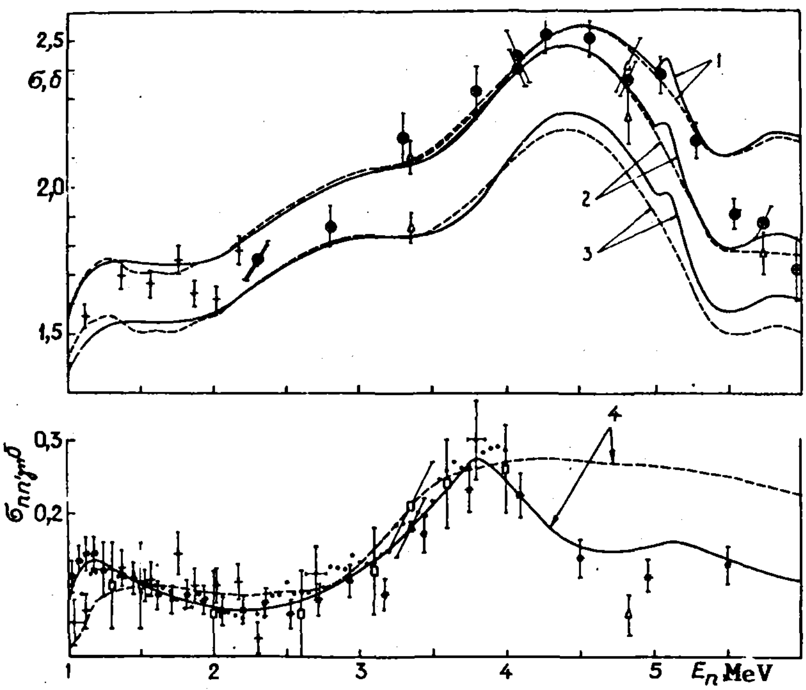

Fig. 2. Cross-sections in the 1-6 MeV neutron energy region: ---- ENDF/B-V evaluation; —— – evaluation of this paper; 1 - total cross-section; 2 - cross-section for elastic neutron scattering and the (n,n'γ) reaction; 3 - cross-section for elastic neutron scattering; 4 - cross-section for the (n^+,n'γ) reaction; ◉ - [10]; ⊕ - [12]; + - [24]; Δ - [25]; * - [13]; o - [14]; □ - [26].

experimental data are given in Refs [11, 13, 14]. There is a divergence in the data for neutron energies from the reaction threshold to 1.2 MeV. As is shown in Refs [13, 14], this is due to poor energy resolution. In this neutron energy region, the data from Refs [13, 14] which show discrepancies of around 15%, were used for the evaluation. There is good agreement between the data in Refs [13, 14, 25, 26] for the 1.2-4 MeV neutron energy region. The cross-section from the reaction threshold to 4 MeV was obtained by the least squares method. The accuracy of the cross-section is ±5%.

For our analysis in the 4-16 MeV region, the data contained in Refs [9, 11] were used. The accuracy of the cross-section in this range is governed by the accuracy of these data and amounts to ±10%. Our cross-sections for the (n,n'γ) reaction are shown together with the ENDF/B-V results in Figs 1-3. The discrepancy goes up to 30% and is particularly significant for E_n > 4 MeV.

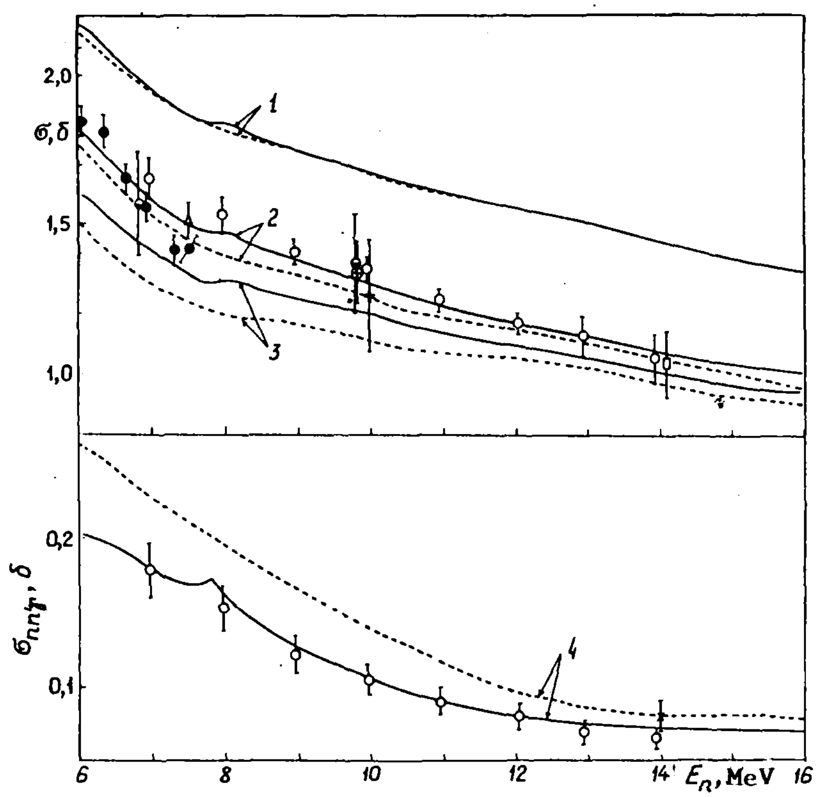

Fig. 3. Cross-sections in the 6-16 MeV neutron energy region: ---- ENDF/B-V evaluation; ——— - evaluation of this paper; 1 - total cross-section; 2 - cross-section for elastic neutron scattering and the (n,n'γ) reaction; 3 - cross-section for inelastic neutron scattering; 4 - cross-section for the (n,n'γ) reaction; ● - [10]; o - [9]; ⊕ - [12]; ◓ - [2] + - [27]; □ - [28]; - [29].

2. The (n,n't)α tritium build-up reaction is very important for calculating the tritium breeding factor, neutron transport and thermal yield. Tritium is formed via the following channels [27]:

$^{7}Li + n$	$\rightarrow n + t + \alpha,$	$Q = 2.467$ Mev	(1)
	$\rightarrow n + {}^{7}Li^{*},$	$Q = 4.63$ and 6.68 MeV	(2)
$^{7}Li^{*}$	$\rightarrow t + \alpha,$	$Q = +2.163$ and $+4.213$ MeV;	
	$\rightarrow t + {}^{5}He,$	$Q = -3.357$ MeV	(3)
^{5}He	$\rightarrow n + \alpha,$	$Q = +0.89$ MeV	(4)
	$\rightarrow t + {}^{5}He^{*}.$		

In the last few years, considerable attention has been focused on the (n,n't)α reaction because of the planned use of lithium in the blankets of fusion reactors [4-8]. The cross-section has been measured by different methods, the analysis of which, as well as the data obtained from them, are

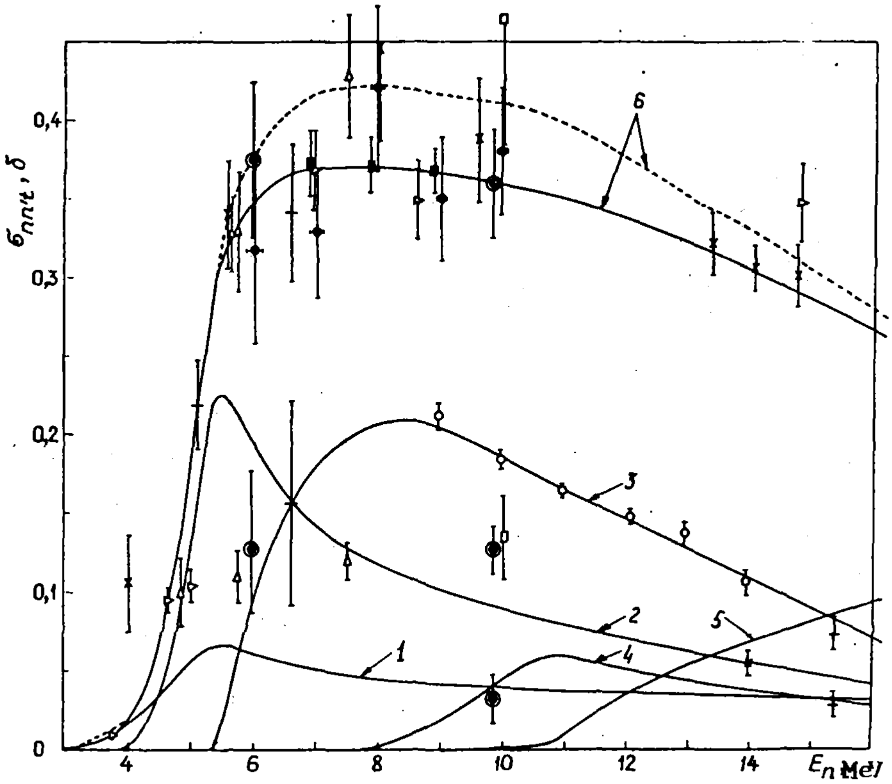

Fig. 4. Partial cross-sections for the tritium build-up reaction: 1 - (n,n't)α; 2 - $^7Li(n,t)^5He$; 3 - $^7Li(n,n')^7Li^*$ (4.63 MeV); 4 - $^7Li(n,n')^7Li^*$ (6.68 MeV); 5 - $^7Li(n,t)^5He^*$; 6 - total tritium build-up cross-section; ⊠ - [6]; • - [7]; o - [9]; ⊕ - [12]; + - [15]; □ - [27]; Δ - [25]; ▷ - [30]; × - [31]; * - [32]

given in Ref. [7]. The most reliable results on the total cross-section are those obtained by the activation method. These data are shown in Fig. 4. Note should be taken of Ref. [6], in which the mean total tritium build-up cross-section was measured in the 7-9 MeV neutron energy region with an accuracy of 3.8%. The cross-section is 372 mb. The total tritium build-up cross-section for neutron energies from the reaction threshold to 5.3 MeV coincides with the ENDF/B-V evaluation and for E_n = 6-16 MeV with the evaluation of Ref. [4]. In the first neutron energy range, the accuracy of the total tritium build-up cross-section is ± 10% and in the second ±5%. Figure 4 shows the tritium build-up cross-sections from the evaluation in this paper (continuous line) and from the ENDF/B-V evaluation (broken line). The discrepancy goes up to 14% for neutron energies above 5.3 MeV. In order to calculate the kerma factor, it is necessary to have information on each channel.

Reaction (1) - involving simultaneous emission of three particles - was studied in the 14-14.4 MeV range [33-35], but the cross-section results are not given. The cross-section, as in Ref. [8], is taken to be equal to 10-15% of the total tritium build-up cross-section.

Reaction (2) - this involves inelastic scattering of neutrons at discrete levels (Q is equal to -4.63 and 6.68 MeV). The most abundant data are for the $^{7}Li(n,n')^{7}Li^{*}$ reaction (4.63 MeV). However, the results of the integral cross-section measurements performed by the authors of Refs [9, 12, 15, 25, 27] diverge by 10 to as much as 60%. It seems that the discrepancy in the experimental data stems from incorrect allowance for the contribution of this reaction to the continuous part of the neutron emission spectrum. Only one paper [9] makes a systematic study of this cross-section in the 9-14 MeV neutron energy region, and the results are higher than in other papers [12, 27]. In studying this reaction, Refs [32, 33] note that it makes a significant contribution to the total tritium build-up reaction. Therefore, the evaluation of the reaction cross-section is based on the data in Refs [9, 15]. The accuracy and reliability of the evaluated cross-section will depend on the accuracy and reliability of these experimental data. On the basis of the $^{7}Li(n,n')^{7}Li^{*}$ reaction (6.68 MeV) studied by the authors of Refs [12, 15, 33], a cross-section is obtained with an accuracy of $\pm$20%.

Reactions (3) and (4) were studied only for the 14-14.4 MeV neutron energy region [32-35]; for the rest of the energy region studied there is no information. The recommended cross-sections for reactions (3) and (4) were obtained by subtracting the remaining partial cross-sections of the tritium build-up reaction from the total cross-section for this reaction, but with allowance for the data from Refs [32-35]. The uncertainty in the cross-sections obtained is not greater than 20%. Figure 5 shows differential cross-sections for the $^{7}Li(n,t)^{5}He$ reaction measured in Refs [32, 34 and 35]. These data were used to calculate the kerma factor.

3. For the (n,2n') reaction there is still a shortage of experimental data. There exists only one paper [36] in which the total cross-section for this reaction was measured at two neutron energies, and these data were used to evaluate the total cross-section for the (n,2n') reaction. However, the reaction can take place via two channels: $^{7}Li(n,2n')^{6}Li$ and $^{7}Li(n,2n')d\alpha$. The correlation between the cross-sections for these two channels, in our evaluation and in the ENDF/B-V evaluation, is maintained for E_n = 14 MeV. The cross-sections are shown in Fig. 6.

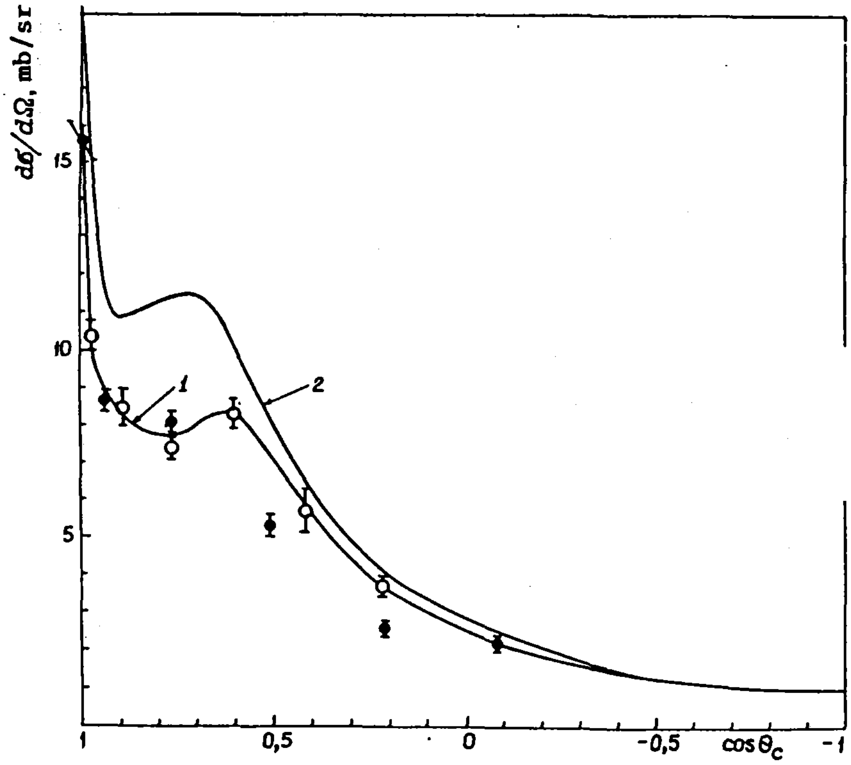

Fig. 5. Differential cross-section for the $^{7}Li(n,t)^{5}He$ reaction from the data of Refs: 1 - [34, 35]; (O - [34]; • - [35]); 2 - [32].

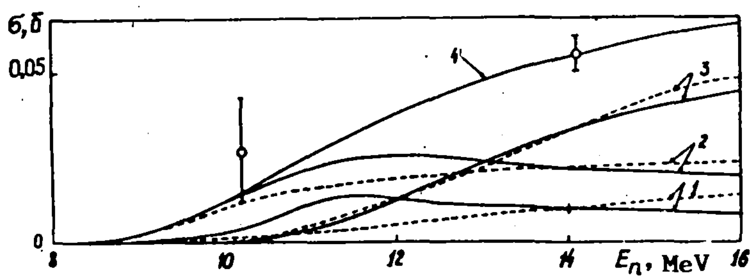

Fig. 6. Cross-sections for the reactions: 1 - (n,d); 2 - $^{7}Li(n,2n')^{6}Li$; 3 - $^{7}Li(n,2n')d\alpha$; 4 - (n,2n'); o - [36]; + - [37]; ---- ENDF/B-V evaluation.

Elastic scattering cross-section: In the energy range from 1 keV to the (n,n'γ) reaction threshold (around 0.55 MeV), this interaction takes place via two channels: elastic scattering and radiative capture. However, the latter can be disregarded in view of the insignificance of the cross-section (less than 0.23 mb) [23]. Consequently, the elastic scattering cross-section in this neutron energy region coincides with the total cross-section. For neutron energies from 0.55 MeV to the tritium-formation reaction threshold (about 2.8 MeV), the interaction also takes place via a third channel - inelastic scattering at a discrete level (Q = -0.478 MeV). It should be noted that, owing to the poor energy resolution of the spectrometers used, it has not yet been possible to isolate this channel from elastic scattering. For this reason, the experimental data are presented for only two channels, the elastic scattering cross-section being determined by subtraction of the cross-section for the $(n,n'\gamma)$ reaction from the total cross-section. For the 0.55-2.8 MeV range, the elastic scattering cross-section is obtained by subtracting the $(n,n'\gamma)$ reaction cross-section from the total cross-section. The accuracy of the cross-section is $\pm 4\%$.

The cross-section for the two channels in the 2.8-16 MeV neutron energy range was obtained by an analysis of the experimental data in Refs [2, 9-12, 25, 26-28] and coincides with the evaluation in Ref. [4]. In this paper, two resonances are identified at neutron energies of 5.1 and 8 MeV. The neutron elastic scattering cross-section is obtained by subtracting the $(n,n'\gamma)$ reaction cross-section from the cross-section for the two channels (accuracy $\pm 5\%$).

Capture cross-section: For neutron interactions with ^7Li nuclei at low energies, only radiative capture is possible and at high energies only the (n,d) reaction need be considered. Other neutron capture reactions with emission of charged particles are possible at high neutron energies [18], but their cross-sections are insignificant and they can therefore be disregarded. The evaluation of the radiative capture cross-section for fast neutrons was done from an analysis of the experimental data in Ref. [23]. For neutron energies below 100 keV, the cross-section (in mb) is $\sigma_{nj} = (7.22095/\sqrt{E_n}) + 0.00227$, where E_n is in electronvolts. This cross-section is shown in Fig. 1. The (n,d) reaction has been studied in many papers in the neutron energy range 14–14.4 MeV, but the evaluation of the cross-section for this reaction, like the ENDF/B-V evaluation, was done on the basis of the results of Ref. [37]. The cross-section is shown in Fig. 6.

Calculation of the kerma factor

The microscopic kerma factor for neutron-^7Li interactions is determined in the following way: $k(E_n) = \sum_i \sigma_i(E_n)\bar{E}_{H_i}(E_n)$, where $\sigma_i(E_n)$ is the cross-section of the i-th reaction and $\bar{E}_{H_i}(E_n)$ is the mean locally released energy in the i-th reaction. Ref. [1] is devoted to calculating the mean locally released energy for all types of reaction. In the tritium build-up reaction, this energy is $\bar{E}_H = E_n + Q - \bar{E}_n'$, where $Q = -2.467$ MeV. Refs [8 and 38] contain an algorithm for calculating the mean

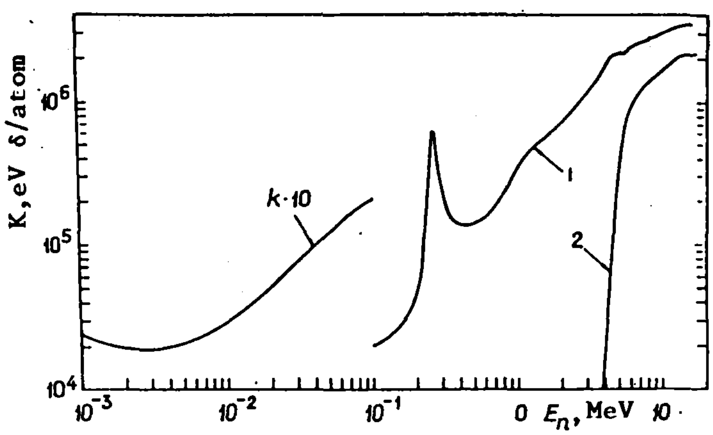

Fig. 7. Kerma factors in the 0.001-16 MeV neutron energy region: 1 - total; 2 - tritium build-up reaction.

energy of the emitted neutron for all channels of the tritium build-up reaction. From this algorithm, with due allowance for the evaluation made of the cross-sections, the microscopic kerma factor is calculated from the tritium build-up reaction. The kerma factor from the other reactions is calculated from the algorithm in Ref. [1].

Figure 7 shows kerma factors from the tritium build-up reaction and from all other reactions. For E_n = 14 MeV, the kerma factor from the tritium build-up reaction is about 60% of the total. Comparison of results shows that for neutron energies in the 4-16 MeV range, the kerma factor in our work is systematically higher (up to 20%) than the results of Ref. [1], i.e. the contribution of the tritium build-up reaction to the total kerma factor has increased. The accuracy of the calculated kerma factor in the 0.001-4 MeV energy range is ±5% and for E_n > 4 MeV not worse than 10%. The authors consider that this evaluation of the cross-sections examined above for the interaction of neutrons with ^{7}Li nuclei corresponds better with the available experimental data than others. The calculated kerma factor can accordingly be recommended for practical application.

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