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[illegible] and [illegible](t,n)^{8}Be Cross Sections [illegible] Reaction Probability in a Plasma

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^{6}Li(t,n)2α and ^{6}Li(t,n)^{8}Be Cross Sections and Relative Reaction Probability in a Plasma

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^{6}Li(t,n)2α AND ^{6}Li(t,n)^{8}Be CROSS SECTIONS AND RELATIVE REACTION PROBABILITY IN A PLASMA

by

Joseph J. Devaney

ABSTRACT

Because of the high exothermic energy of ^{6}Li(t,n) and consequent high neutron energy therefrom, there is interest in this reaction in thermonuclear processes. We review the cross-section literature readily available. We calculate the comparative ^{6}Li(n,t) reaction probability versus the slowing-down-without-reaction probability for pure lithium for various lithium densities and temperatures, and for tritium energies up to 2.5 MeV.

I. INTRODUCTION

There is interest in the ^{6}Li(t,n) reaction in thermonuclear studies because of the high exothermic energy: $Q = 16.02$ MeV to ^{8}Be and $Q = 16.12$ MeV to 2α; and because the resulting neutron is produced at high energies, which allows, then, energetic triton production through the exothermic reaction ^{6}Li(n,t)^{4}He, $Q = 4.78$ MeV. The question is, can this process repeat in a sustaining way?* The answer appears, at this time, to be no (except thermally at extremely high temperatures).

Although the discrepancies in the MeV (t,n) cross section range to as high as a factor of 10, the cross sections are all much too low (by factors of about 100 to over 10 000) to compete with electronic slowing down of an energetic triton in lithium. Hadronic slowing down will further decrease the nuclear reaction probability with lithium, as will, of course, the presence of other

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*Suggested by Steve Howe, information supplied by Dale Henderson, Los Alamos, X-Division, June 7, 1982.

elements in combination with lithium. For lower energy, i.e., thermal tritons, one is faced with a rather large effective threshold energy in the 100-keV range, i.e., σ^6Li(n,t) is about 12 mb at 150-keV triton energy.[1]

Nevertheless, the potential of the process

$$\begin{array}{l} {}^6\mathrm{Li} + t \rightarrow n + \alpha + \alpha \\ {}^6\mathrm{Li} + n \rightarrow t + \alpha \end{array} \qquad Q_{tot} = 20.90\ \mathrm{MeV} \tag{1}$$

is so great that I herewith document my findings for the edification, criticism, and correction of (and by) others.

II. CROSS-SECTION SEARCH

In pursuit of the ^{6}Li(t,n)2α, ^{6}Li(t,n)^{8}Be cross sections, I have checked: the Nuclear Data Sheets[2] Reaction Lists for 1981 to 1975, inclusive; Fay Ajzenberg-Selove's A = 9 compilation;[3] R. J. Howerton's $\overline{\sigma v}$'s;[4] J. Rand McNally, Jr., Fusion Reactivity Graphs and Tables;[5] Jarmie and Seagrave, Charged Particle Cross-Section compilation;[6] and Gerry Hale's Data for Fusion Reactions.* Further, I consulted with McNally, Selove, Howerton, Jarmie, Hale, and with Norman Holden of Brookhaven National Laboratory. Four sources of MeV cross sections were, thereby, obtained.[1,7-9] A fifth source[10] was not used. The ^{6}Li(t,2n)^{7}Be reaction was ignored because its effective threshold is about 4.5 MeV.[11] Only Ref. 1 (Val'mer et al.) gives angular distributions and total reaction cross sections. Accordingly, its angular distributions were used for all. In addition, Jarmie and Diven[8] give only thick target yields at 0°. We unscramble the thick target yields as follows: the probability, p, that a given triton of energy, E_0, will react during its slowing down in a thick target of lithium is given by

$$p = \int_{E_0}^{0} \left[\frac{n_{Li}\sigma_{tn}(E)}{(dE/dx)}\right] dE \quad . \tag{2}$$

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*Information supplied by G. M. Hale, Los Alamos Group T-2, March 1981.

We use this equation in the approximate form:

$$\sigma_{tn}(E) \approx \frac{\Delta p \cdot (dE/dx)}{\Delta E \cdot n_{Li}} \quad . \tag{3}$$

$\Delta p/\Delta E$ is obtained from the thick target yields of Jarmie and Diven (Ref. 8); n_{Li} for cold solid lithium is 4.598×10^{22} atoms/cc (Ref. 12); and dE/dx is obtained from Andersen and Ziegler (Ref. 12). Then, as noted above, we use the angular distributions of Val'mer et al.[1] to get a total reaction cross section. The results are given in Table I.

TABLE I

^{6}Li(t,n) CROSS SECTIONS
(millibarns)

E_t(MeV)	σ_{tn}(mb)			
	Jarmie, Diven[a] (1963)	Val'mer et al. (1961)	Crews[b] (1952)	Serov, Guzhovskii[c] (1962)
0.9	48.6	89.8	7.9	56.8
1.5	44.8	155.9	22.6	77.0
2.1	65.6	324.5	28.2	
2.5	67.2			

[a] Based on thick target, 0° yields (Ref. 8).
[b] Estimated from 90° cross sections for ^{6}Li(t,α)^{5}He (Ref. 9).
[c] From 0° cross sections.

Note: a, b, and c all use Val'mer et al.[1] angular distributions.

III. LOW ENERGY ^{6}Li(t,n)2α CROSS SECTIONS

Because the (t,n) mirror reaction ^{6}Li(^{3}He,p)2α cross section is apparently known at low energies,[5] it is possible to use part of the Dodder-Hale R-matrix theory* to generate the ^{6}Li(t,n)2α cross section at low energies. Estimates of time required run to a few weeks.

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*Information supplied by G. M. Hale, Los Alamos Group T-2, June 1982.

IV. PROBABILITY OF AN MeV (t,n) REACTION IN A HOT LITHIUM PLASMA

When a charged particle enters matter, two broad classes of interaction compete for the fate of the particle: (1) slow down of the particle and (2) nuclear reactions. [In our energy regime, atomic and molecular interactions are part of (1).]

For MeV tritons into lithium, the former wins hands down, even at very hot temperatures. We will substantiate this conclusion by comparing the nuclear reaction probability (essentially σ_{nt}) with only part of the stopping power, the electronic slowing down. There is also hadronic and hadronic-electronic interference stopping.[13] Moreover, we need only include the slowing down in the lithium itself. Lithium, in a compound or mixture, will give a yet greater advantage to the slowing down versus nuclear reaction of the triton. We use the theory of Longmire[14] to calculate the electronic stopping power for the triton by the electrons of ^{6}Li:

$$\frac{dE}{dx} \approx -n_2 \frac{4\sqrt{\pi}\, Z_1^2 Z_2^2 e^4}{\sqrt{EkT}} \cdot \ln\left(\frac{2}{\theta_m}\right) \cdot \sqrt{\frac{m_2}{m_1}} \cdot \left[\frac{E}{(3/2)kT} - 1\right] \tag{4}$$

and by the nuclei ^{6}Li:

$$\frac{dE}{dx} \approx n_2 \frac{2\pi Z_1^2 Z_2^2 e^4}{E} \cdot \ln\left(\frac{2}{\theta_m}\right) \cdot \frac{m_1}{m_2} \quad . \tag{5}$$

Here 2, the target, refers to ^{6}Li, namely to electrons in Eq. (4) and to the ^{6}Li nucleus in Eq. (5), and 1 refers to the projectile, the triton. Therefore, n is either the electron or the ^{6}Li density. Z refers to the charge number ($Z_1 = 1$, $Z_2 = 1$ or 3). E is the projectile (triton) energy, x is the triton path length, e is the electron charge, kT is the temperature in energy units, and m is mass. θ_m is the minimum scattering angle, which we give below.

If the test quantity q

$$q \equiv \frac{2Z_1Z_2e^2}{\hbar v} \quad , \tag{6}$$

where $\hbar$ is Planck's constant divided by 2π, and v is the relative velocity of particle 1 to 2, satisfies:

$$q \gtrsim 1 \quad ; \tag{7}$$

then the scattering is classical and[14]

$$\theta_m = \frac{2Z_1Z_2e^2}{\lambda_D \mu v^2} \text{ (classical)} \quad . \tag{8}$$

However, if

$$q < 1 \quad , \tag{9}$$

then the minimum scattering angle is given by the uncertainty,[14]

$$\theta_m = \frac{\hbar}{\mu v \lambda_D} \text{ (quantum)} \quad , \tag{10}$$

where λ_D is the Debye length of the plasma:

$$\lambda_D = \sqrt{\frac{kT}{4\pi n_e e^2}} \quad , \tag{11}$$

where n_e is the electron density and μ is the reduced mass $\mu \equiv m_1m_2/(m_1 + m_2)$. We find that for electrons, $q < 1$; so we use the quantum result Eq. (11) into Eq. (10) into Eq. (4). For the nucleus ^{6}Li, we find $q \gtrsim 1$; so we use the classical result Eq. (11) into Eq. (8) into Eq. (5). The sum of Eqs. (4) and (5) gives us the total electronic stopping power.

$$\left(\frac{dE}{dx}\right)_{\mathrm{electronic}} = \left(\frac{dE}{dx}\right)_{\mathrm{electrons}} + \left(\frac{dE}{dx}\right)_{\mathrm{nuclei}} \quad . \tag{12}$$

We calculate the stopping power for the ^{6}Li densities of 74.92 g/cc (corresponds to 100 g/cc of D^{6}Li) and 0.62 g/cc (corresponds to the standard temperature and pressure density of lithium-6 in D^{6}Li).

Referring to Eq. (2) or (3), we see that if the quantity $(1/n_{Li})(dE/dx)$ is large compared to the quantity $\sigma_{tn}\Delta E$, then the probability Δp of the (t,n) reaction in that energy interval, ΔE, is low. Accordingly, so that the reader may judge for himself, these quantities are given in Table II for two densities, four energies, and five temperatures. The second-order effect of temperature on σ_{tn} is ignored in Table II.

It can be seen from Table II that in every case, even at 20 keV, the ratio $n_{Li}\sigma_{tn}\Delta E_t/(dE_t/dx)$ is less than 0.004 (and is as low as 0.00008) so that the probability of an ^{6}Li(n,t) reaction given by Eq. (2) is less than 1% at 20 keV and much less than 1% at lower temperatures, even just including electronic slowing down of lithium alone. Therefore, we conclude that, except in an extremely high temperature thermonuclear reaction, say for temperatures, $T \sim\sim 150$ keV roughly, the process of Eq. (1) cannot be sustained because the overwhelming probable fate of the energetic triton from ^{6}Li(n,t)^{4}He is to be slowed down to thermal energies without nuclear reaction.

TABLE II

Comparison of $\sigma_{tn}\Delta E_{triton}$ Versus n_{Li}^{-1} $(dE_{triton}/dx)_{electronic\ total}$ in Pure ^{6}Li (in MeV^{2}- cm)(σ_{tn} are the Jarmie and Diven derived values in Table I)

ρ_{6-Li} = 74.92g/cc

E_t = 0.9 MeV, ΔE_t = 0.9 MeV, $\sigma_{tn}\Delta E_t$ = 4.4(-26)MeV - cm^2

T(keV)	1	2	5	10	20
$n^{-1}(dE_t/dx)$(MeV - cm^2)	1.24(-22)	5.8(-23)	2.3(-23)	1.36(-23)	9.8(-24)

E_t = 1.5 MeV, ΔE_t = 0.6 MeV, $\sigma_{tn}\Delta E_t$ = 2.7(-26)MeV - cm^2

T(keV)	1	2	5	10	20
$n^{-1}(dE_t/dx)$(MeV - cm^2)	1.56(-22)	6.7(-22)	2.5(-23)	1.29(-23)	7.9(-24)

E_t = 2.1 MeV, ΔE_t = 0.6 MeV, $\sigma_{tn}\Delta E_t$ = 3.9(-26)MeV - cm^2

T(keV)	1	2	5	10	20
$n^{-1}(dE_t/dx)$(MeV - cm^2)	1.83(-22)	8.2(-23)	2.8(-23)	1.33(-23)	7.4(-24)

E_t = 2.5 Mev, ΔE_t = 0.4 MeV, $\sigma_{tn}\Delta E_t$ = 2.7(-26)MeV - cm^2

T(keV)	1	2	5	10	20
$n^{-1}(dE_t/dx)$(MeV - cm^2)	1.99(-22)	8.8(-23)	3.0(-23)	1.38(-23)	7.2(-24)

ρ_{6-Li} = 0.62g/cc

E_t = 0.9 MeV, ΔE_t = 0.9 MeV, $\sigma_{tn}\Delta E_t$ = 4.4(-26)MeV - cm^2

T(keV)	1	2	5	10	20
$n^{-1}(dE_t/dx)$(MeV - cm^2)	2.2(-22)	9.3(-23)	3.3(-23)	1.81(-23)	1.2(-23)

E_t = 1.5 MeV, ΔE_t = 1.5 MeV, $\sigma_{tn}\Delta E_t$ = 2.7(-26)MeV - cm^2

T(keV)	1	2	5	10	20
$n^{-1}(dE_t/dx)$(MeV - cm^2)	2.8(-22)	1.15(-22)	3.7(-23)	1.77(-23)	1.0(-23)

E_t = 2.1 MeV, ΔE_t = 0.6 MeV, $\sigma_{tn}\Delta E_t$ = 3.9(-26)MeV - cm^2

T(keV)	1	2	5	10	20
$n^{-1}(dE_t/dx)$(MeV - cm^2)	3.3(-22)	1.34(-22)	4.2(-23)	1.86(-23)	9.6(-24)

E_t = 2.5 MeV, ΔE_t = 0.4 MeV, $\sigma_{tn}\Delta E_t$ = 2.7(-26)MeV - cm^2

T(keV)	1	2	5	10	20
$n^{-1}(dE_t/dx)$(MeV - cm^2)	3.6(-22)	1.45(-22)	4.5(-23)	1.94(-23)	9.6(-24)

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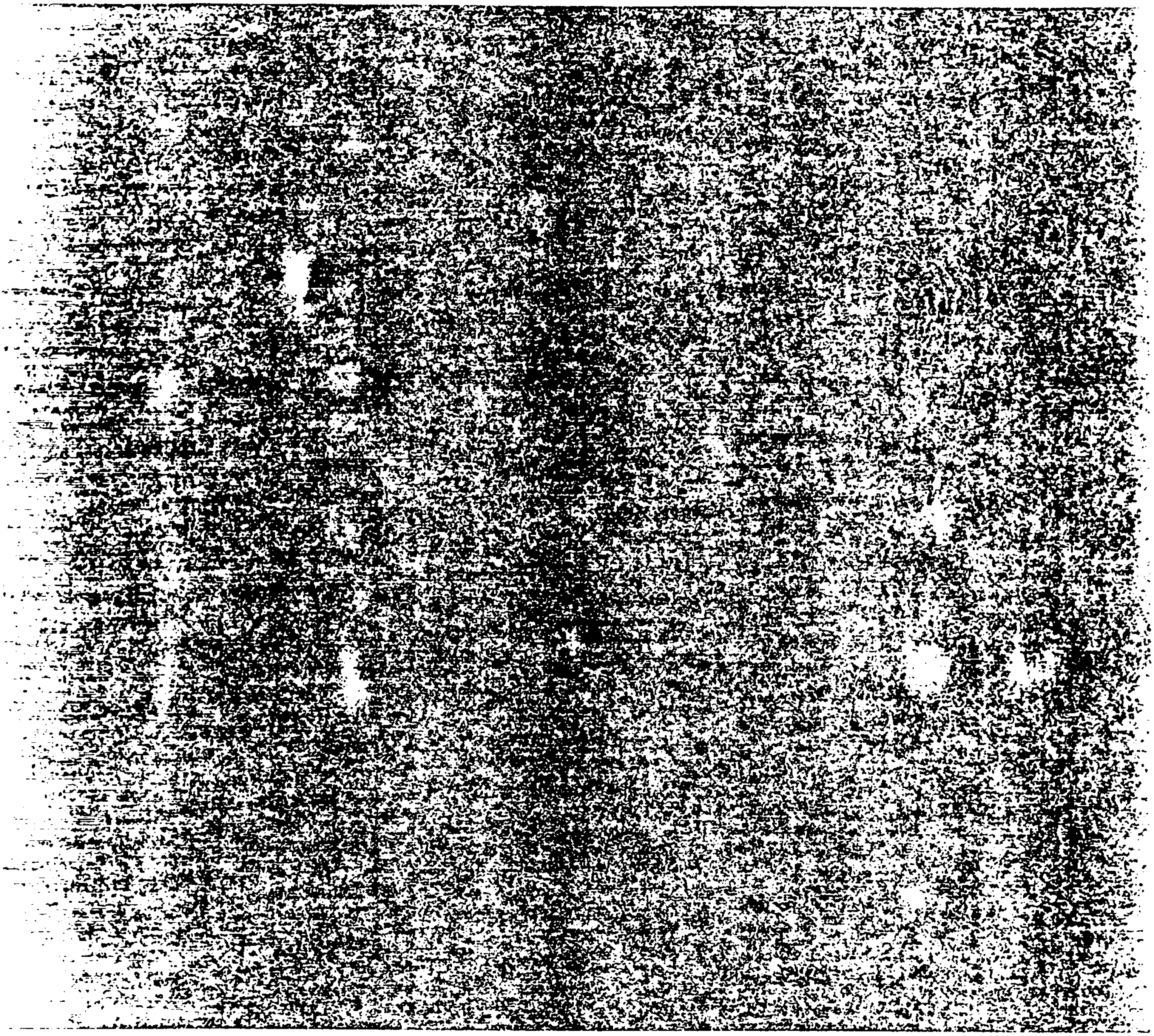

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