# Use of $\gamma$-ray-generating nuclear reactions for temperature diagnostics of DT fusion plasma

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A diagnostic application of $\gamma$ rays emitted in $^6$Li+D and $^6$Li+T nuclear reactions induced by admixing a small amount of $^6$Li in DT fusion plasma is investigated. It is shown that the reaction-produced monochromatic $\gamma$ quanta with energies $E_\gamma = 0.429$, 0.478, and 0.981 MeV can be used for ion temperature measurements in DT plasma. The proposed measurements are expected to be essentially independent of the plasma density and its local fluctuations. The required reaction cross sections and the Maxwellian rate parameters of the $^6$Li+T $\gamma$-ray production are calculated within a realistic nuclear model.

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## I. INTRODUCTION

Temperature diagnostics of hot plasmas is an important problem in controlled nuclear fusion research. Conventional diagnostic methods based on atomic processes are able to measure the electron temperature while the most significant plasma parameters, such as its reactivity and the energy released, are determined by the temperature of an ionic component. However, any information on ion dynamics obtained by conventional techniques is mainly indirect and is derived, in many cases, under the additional assumption of thermal equilibrium between electron and ion components.

Direct control of the plasma ion temperature can be realized by nuclear-physics diagnostic methods based on detecting products of nuclear reactions between charged particles. These methods should be sensitive and effective in the important temperature range 1–100 keV. Indeed, the yield $Y$ of a nuclear reaction between species 1 and 2 in a plasma is given by

$$Y = \alpha_{12} n_1 n_2 \langle \sigma v \rangle_{12}, \tag{1}$$

where $\alpha_{12}$ equals 0.5 or 1 for reactions between identical or different nuclei, respectively, $n_1$ and $n_2$ are densities of the particles 1 and 2, and $\langle \sigma v \rangle_{12}$ is the reaction rate parameter, which is a function of ion temperature. The value of $\langle \sigma v \rangle_{12}$ is mainly determined by the reaction cross sections at energies close to the Gamow peak energy $E_G$. This peak corresponds to the maximum overlap of the cross section and the product of the relative velocity of the colliding particles and their velocity distribution function. For a Maxwellian plasma at ion temperature $T_i$ the value of $E_G$ equals [1]

$$E_G = 6.254 \left( Z_1^2 Z_2^2 \frac{A_1 A_2}{A_1 + A_2} T_i^2 \right)^{1/3} \text{ keV}, \tag{2}$$

where $Z_1$ ($Z_2$) and $A_1$ ($A_2$) are the charges and atomic numbers of the reacting nuclei, respectively, and $T_i$ is expressed in keV. Simple estimations show that at temperatures of 1 to 100 keV the value of $E_G$ for light nuclei does not exceed a few hundred keV. In such a low-energy region the nuclear cross sections are strongly dependent on energy due to Coulomb suppression and, therefore, the reaction yield $Y$ should be a very sensitive function of ion temperature.

Thus, development of nuclear-physics methods of plasma temperature diagnostics is of particular importance. In the present work we examine the possibility of using $\gamma$-ray-producing nuclear reactions for ion temperature measurements in DT fusion plasma. These reactions seem to be very convenient for practical application. Gamma rays are capable of escaping freely from the plasma burning area and often can be separated from the $\gamma$ background, since the $\gamma$ spectrum of a fusion plasma can be recorded with high resolution.

The $(d,\gamma)$ capture reactions emitting $\gamma$ rays of high energy

$$\mathrm{T}(d,\gamma)\,^5\mathrm{He} + 16.70 \text{ MeV}, \tag{3}$$

$$\mathrm{D}(d,\gamma)\,^4\mathrm{He} + 23.85 \text{ MeV} \tag{4}$$

were proposed previously for diagnostic applications [2–5]. It was suggested that information on ion dynamics could be derived from measurements of the $\gamma$-ray yield [2–4] or from the broadening of the $\mathrm{D}(d,\gamma)\,^4\mathrm{He}$ $\gamma$ line [5]. Here we wish to draw the reader's attention to the other capture process, the $(t,\gamma)$ reaction

$$\mathrm{T}(t,\gamma)\,^6\mathrm{He} + 12.31 \text{ MeV}, \tag{5}$$

which also must accompany burning in the DT plasma. This reaction may give the interesting possibility of density independent temperature measurements in the DT plasma. In fact, the measurements could be carried out by comparing the $\gamma$-ray yields from all three reactions (3)–(5). Using Eq. (1) it is easy to show that the ratio of the $\gamma$-ray yields

$$\frac{Y_\gamma^2(\mathrm{TD})}{Y_\gamma(\mathrm{DD})\, Y_\gamma(\mathrm{TT})} = \frac{4 \langle \sigma v \rangle^2_{\mathrm{T}(d,\gamma)}}{\langle \sigma v \rangle_{\mathrm{D}(d,\gamma)} \langle \sigma v \rangle_{\mathrm{T}(t,\gamma)}} = f(T_i). \tag{6}$$

This ratio does not include any plasma density parameter and is a function of ion temperature only. However, it is difficult to draw a final conclusion about the sensitivity of this technique because the low-energy $\mathrm{T}(t,\gamma)\,^6\mathrm{He}$ reaction has not been well studied yet.

 

A general disadvantage of radiative capture reactions is the small branching ratio of $\gamma$-ray to charged particle channels. For example, the branching ratio for the T+D reaction at thermonuclear energies is about $5\times10^{-5}$ [4]. Fortunately, the dominant reaction channel $\mathrm{T}(d,n)\,^4\mathrm{He}$ is well known to exhibit a strong resonant behavior at low energies, due to which the $\mathrm{T}(d,\gamma)$ cross sections turn out to be quite large enough for experimental measurements. In particular, 16.7-MeV TD $\gamma$ rays were recently reported [6] to have been detected at the Nova Laser Facility and used for a study of burn history. However, the situation with employing the $\mathrm{D}(d,\gamma)\,^4\mathrm{He}$ reaction is less optimistic. The branching ratio of this $\gamma$-ray channel to the $\mathrm{D}(d,p)\mathrm{T}$ reaction is only $10^{-7}$ [4] and values of the $\mathrm{D}(d,\gamma)$ cross sections are rather small. They do not exceed $10^{-5}$ mb at deuteron energies below 1 MeV [7]. Therefore, reliable measurement of the DD $\gamma$ rays from a DT fusion plasma is not a simple problem.

To avoid the specific difficulties of the radiative capture processes other nuclear reactions appropriate for diagnostic applications can be induced in a fusion plasma by admixing some light elements. For example, in nuclear-physics activation methods [8,9] it is suggested to expose $^{14}\mathrm{N}$ and $^{10}\mathrm{B}$ samples to D-containing plasma and subsequently measure the particle yields from $^{14}\mathrm{N}(d,n)\,^{15}\mathrm{O}$ and $^{10}\mathrm{B}(d,n)\,^{11}\mathrm{C}$ nuclear reactions. These yields are expected to be found because of induced radioactivity in the samples by counting annihilation $\gamma$ rays accompanying $\beta^+$ decay of the unstable nuclei $^{15}\mathrm{O}$ and $^{11}\mathrm{C}$. Another reaction channel $^{10}\mathrm{B}(d,n)\,^{11}\mathrm{C}^*$ emitting 4.319-MeV $\gamma$ rays has also been noted to have diagnostic application [10]. The proposed methods, however, have some disadvantages. In particular, the measurement of the $^{11}\mathrm{C}$ isotope yield can involve appreciable errors because a significant fraction of the induced radioactivity may be lost due to rapid evaporation of the sample [8,9]. Besides that, the plasma is seeded with undesirable impurities of $^{14}\mathrm{N}$ and $^{10}\mathrm{B}$ with large charge numbers $Z_{\mathrm{N}}=7$ and $Z_{\mathrm{B}}=5$ that may substantially increase radiation loss.

In the present work we propose an alternative and, in our opinion, preferable diagnostic method capable of avoiding the above disadvantages. This method could be realized by admixing a small amount of $^6\mathrm{Li}$ isotope in DT fuel. We will study here $\gamma$-ray-generating reactions induced by $^6\mathrm{Li}$ in the plasma and show that they can be used for the control or measurement of ion temperature in the DT plasma below 100 keV. Moreover, the measurements are expected to be essentially independent of the plasma density or its local fluctuations.

Among the various nuclear processes initiated by adding $^6\mathrm{Li}$ to the DT fuel the reactions

$$^6\mathrm{Li}(d,n)\,^7\mathrm{Be}^*[0.429\ \mathrm{MeV}] + 2.95\ \mathrm{MeV}, \tag{7a}$$

$$^6\mathrm{Li}(d,p)\,^7\mathrm{Li}^*[0.478\ \mathrm{MeV}] + 4.55\ \mathrm{MeV} \tag{7b}$$

in the $^6\mathrm{Li}$ + D system and

$$^6\mathrm{Li}(t,d)\,^7\mathrm{Li}^*[0.478\ \mathrm{MeV}] + 0.51\ \mathrm{MeV}, \tag{8a}$$

$$^6\mathrm{Li}(t,p)\,^8\mathrm{Li}^*[0.981\ \mathrm{MeV}] - 0.18\ \mathrm{MeV} \tag{8b}$$

in the $^6\mathrm{Li}$+T system must proceed and seem to be convenient for diagnostic application for the following reasons.

(i) The reactions (7) and (8) lead to formation of $^7\mathrm{Be}^*$ and $^{7,8}\mathrm{Li}^*$ excited nuclei which decay by $M1$ electromagnetic transition to the ground states and emit monochromatic $\gamma$ rays of the well-defined energies $E_\gamma(^7\mathrm{Be}^*)=429$ keV, $E_\gamma(^7\mathrm{Li}^*)=478$ keV, and $E_\gamma(^8\mathrm{Li}^*)=981$ keV [11].

(ii) The excited states have appropriate lifetimes of $\sim$10–200 fs, so that the widths of the respective $\gamma$ lines are small [11] and, hence, these lines could be resolved experimentally.

(iii) Unlike the radiative capture reactions governed by electromagnetic force, the reactions (7) and (8) are induced by strong (nuclear) interaction and proceed with sizable cross sections. This suggests that even at a low $^6\mathrm{Li}$ concentration (required to prevent a significant increase of radiation loss from the plasma) the $\gamma$-ray yield may turn out to be high enough for experimental measurements.

(iv) An interesting remark concerns the process (8b). Although this reaction is endothermic, its threshold energy $E_{thr}$ is only 180 keV. Therefore, one may hope that the monochromatic 981-keV $\gamma$ rays could be detected at thermonuclear temperatures due to the contribution of the high-energy part ($E>180$ keV) of the ion distribution function in the plasma. Moreover, the yield of these $\gamma$ quanta should be an extremely sensitive function of ion temperature at a few tens of keV because this range corresponds to the Gamov peak energy close to the reaction threshold $E_{thr}$ where the energy dependence of the cross sections is especially strong. In addition, the threshold behavior completely excludes a contribution of the slow particles ($E<180$ keV) to the reaction yield. This may help in inferring the behavior of the high-energy part of the tritium distribution function, which is somewhat distorted due to scattering of fast 14-MeV DT neutrons by T ions in dense plasma [12].

## II. NUCLEAR REACTION CROSS SECTIONS

To verify the above suggestions and to explore the applicability of the $^6\mathrm{Li}$-induced reactions for DT plasma diagnostics at thermonuclear temperatures below 100 keV, it is necessary to know the $^6\mathrm{Li}$+D and $^6\mathrm{Li}$+T reaction cross sections at energies below $\sim$1 MeV. The $^6\mathrm{Li}$+D reactions (7) have been studied previously in detail and experimental measurements [10,13–16] supplemented by theoretical low-energy extrapolations [17,18] cover the required energy range. The appropriate reaction rate parameters calculated for the Maxwellian ion velocity distribution function are given in [19,20]. However, cross section data on the other $\gamma$-ray-producing reactions $^6\mathrm{Li}$+T (8) are still very scanty. These processes have been measured at center-of-mass energies $E$ above $\sim$2 MeV [21] only, while in the lower-energy region experimental and reliable data are not available.

Therefore, finding the cross sections of the $^6\mathrm{Li}(t,d)\,^7\mathrm{Li}^*$ and $^6\mathrm{Li}(t,p)\,^8\mathrm{Li}^*$ nuclear reactions at energies $E$ below 2 MeV is an objective of the present work. The essential element here is a calculation of the cross sections in the low-energy region, which determine a major part of the reactivity at thermonuclear temperatures. The conventional factorization of the $^{6}$Li+T reaction cross sections $\sigma(E)$

$$\sigma(E)=\frac{S}{E}W(E) \quad (9)$$

is employed to find the sub-barrier energy behavior of $\sigma(E)$. The main energy dependence comes from $W(E)$, describing Coulomb suppression of the $^{6}$Li+T reactions in the low-energy region. The astrophysical $S$ factor in Eq. (9) is generally a smooth function of energy and in certain cases may be assumed to be constant.

In the present study we adopt this assumption but try to reproduce a precise, physically justified, energy dependence of $W(E)$. Since the $^{6}$Li+T nuclear reactions (8a) and (8b) have small positive and negative $Q$ values, respectively, their cross sections are determined, in general, by Coulomb suppression in both the entrance ($\alpha$) and the exit ($\beta$) channels. This means that the $W$ factor is of the form

$$W(E)=P_{\alpha}(E)P_{\beta}(E+Q_{\beta}), \quad (10)$$

where the transmission coefficient (or penetrability) $P_{\alpha(\beta)}$ is defined by the ratio of the particle flux traversing the potential barrier between the participating nuclei in the $\alpha$ ($\beta$) channel to the incident flux. In order to find $P_{\alpha(\beta)}$ we employ a technique developed by us earlier [22,23] and used to calculate low-energy cross sections of the $^{6}$Li$(d,n)^{7}$Be* and $^{6}$Li$(d,p)^{7}$Li* reactions [18]. Very recently it was also applied for the extrapolation of $^{6}$Li$(d,p\alpha)$T and $^{6}$Li$(d,n\alpha)^{3}$He nuclear reaction cross sections down to low energies typical of primordial nucleosynthesis [24]. According to this techique, the transmission coefficient $P(E)$ is determined not for an ideal (Coulomb) but for a realistic (nuclear-Coulomb) form of the potential barrier and is found by an accurate quantum-mechanical calculation. This barrier explicitly includes a nuclear potential tail in the system and allows for the internal cluster structure of the participating particles. The nuclear potential used to establish an exact form of the barrier is determined in terms of a cluster folding model involving no adjustable parameters. It is obtained by folding the microscopic Hamiltonian of the system of the reacting particles over their nuclear wave functions. This folding model was successfully applied earlier to study interaction potentials between $^{6}$Li and the lightest nuclei with $A=1$–4 [22,25].

Using a three-body $\alpha+n+p$ model to describe $^{6}$Li one can find the $t+^{6}$Li nuclear potential in the entrance channel of the reactions (8) from

$$V_{t^{6}\mathrm{Li}}(R)=\langle\Psi_{^{6}\mathrm{Li}}(\alpha np)\chi_{t}(\xi)|V_{\alpha t}+V_{nt}+V_{pt}|\Psi_{^{6}\mathrm{Li}}(\alpha np)\chi_{t}(\xi)\rangle. \quad (11)$$

Here, $\Psi_{^{6}\mathrm{Li}}(\alpha np)$ is an accurate wave function of $^{6}$Li found by numerical solution of the three-body Schrödinger equation [26,27] and $\chi_{t}(\xi)$ is an internal triton wave function whose form is not specified in the given case as the triton is treated as a cluster. The pair $\alpha t$ and $Nt$ interactions in Eq. (11) were taken from [28,29] (see details in [25]). The calculated potential (11) has been found to lead to a good description of experimental data for $t+^{6}$Li elastic scattering in the forward hemisphere. This means that the potential $V_{t^{6}\mathrm{Li}}(R)$ reproduces properly the peripheral part of the true interaction in the system and, hence, the $t+^{6}$Li potential barrier should be of a realistic form. It is shown in Fig. 1 together with its nuclear and Coulomb components. The attractive tail of the nuclear potential is seen to strongly affect the barrier shape and reduces the barrier height down to 480 keV. The calculated transmission coefficients $P_{t+^{6}\mathrm{Li}}(E)$ of the realistic $t+^{6}$Li barrier in the entrance reaction channel are given in Fig. 2.

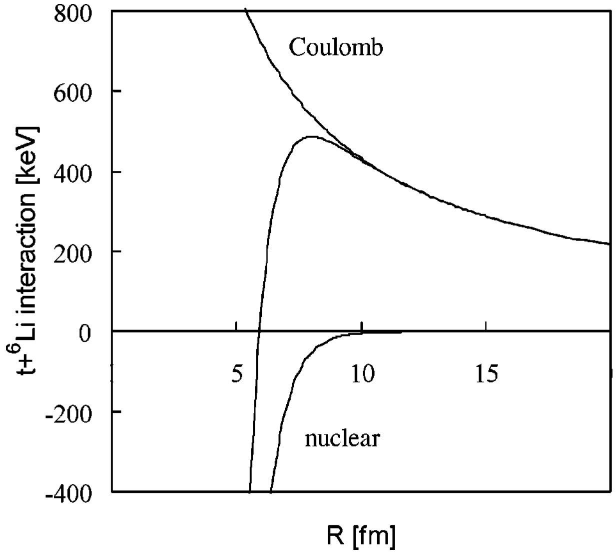


FIG. 1. The realistic potential barrier in the $t+^{6}$Li system and its nuclear and Coulomb components.

The penetrabilities $P_{\beta}(E+Q_{\beta})$ in the exit channels of the

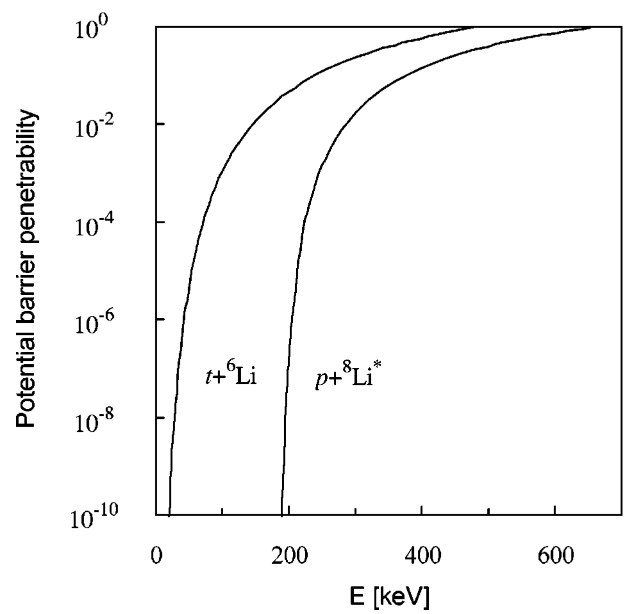


FIG. 2. The penetrabilities $P_{t+^{6}\mathrm{Li}}(E)$ and $P_{p+^{8}\mathrm{Li}*}(E-E_{thr})$ of the entrance and the exit potential barriers, respectively, for the $^{6}$Li+T reactions. $E$ is the center-of-mass energy in the entrance reaction channel.

$^6$Li$(t,d)^7$Li* and $^6$Li$(t,p)^8$Li* reactions were evaluated under the assumption that the exit potential barriers are close to those for the $d+{}^7\mathrm{Li}_{\mathrm{gr.st.}}$ and $p+{}^7\mathrm{Li}_{\mathrm{gr.st.}}$ systems, respectively. A cluster folding procedure similar to (11) was used to find the barriers needed. It employs a reliable deuteron wave function obtained with a realistic *NN* potential (RSC) [30] and a two-body wave function of $^7$Li. The latter is calculated in the $\alpha+t$ cluster model and reproduces well the nucleus binding energy in the $\alpha+t$ channel and the rms charge radius. The height of the $d+{}^7$Li barrier has been found to be $\sim$400 keV and thus smaller than the *Q* value of the $^6$Li$(t,d)^7$Li* reaction (8a). Therefore, this reaction does not undergo Coulomb suppression in the exit channel and the penetrability $P_\beta(E+Q_\beta)$ in Eq. (10) should be taken as unity. However, the other endothermic reaction $^6$Li$(t,p)^8$Li*, having the threshold energy $E_{thr}=180$ keV, is still of a tunnel nature in the exit channel. The calculated transmission coefficients $P_{p+{}^8\mathrm{Li}*}(E-E_{thr})$ for the exit reaction channel are shown in Fig. 2 as a function of the entrance center-of-mass energy *E*. Thus, the energy dependence (9),(10) of the reaction cross sections in the sub-barrier region can be established.

At higher energies the $^6$Li$(t,d)^7$Li* and $^6$Li$(t,p)^8$Li* cross section behavior was assumed to be similar to that for the respective reactions with transitions to the ground states, i.e., for $^6\mathrm{Li}(t,d)^7\mathrm{Li}_{\mathrm{gr.st.}}$ and $^6\mathrm{Li}(t,p)^8\mathrm{Li}_{\mathrm{gr.st.}}$. This assumption is realistic at *E* well above the potential barrier where the reaction modes leading to the excited and the ground state of the final nucleus $^7$Li (or $^8$Li) have the same mechanism. Nuclear data for the ground-state reaction modes taken from [31] were employed to extrapolate the energy dependence of the cross sections up to $E\sim2$ MeV where experimental data become available [21]. Finally, the full curves of $\sigma(E)$ over the 0–2 MeV energy range were properly scaled by combining with the lowest experimental point at $E\sim2$ MeV. The calculated cross sections of the $^6$Li-induced reactions (8) are given in Fig. 3. The observed rapid drop in $\sigma(E)$ of the endothermic reaction $^6$Li$(t,p)^8$Li* with decreasing energy in the region of $\sim$200 keV close to the reaction threshold $E_{thr}$ is caused by extremely strong suppression in the exit reaction channel.

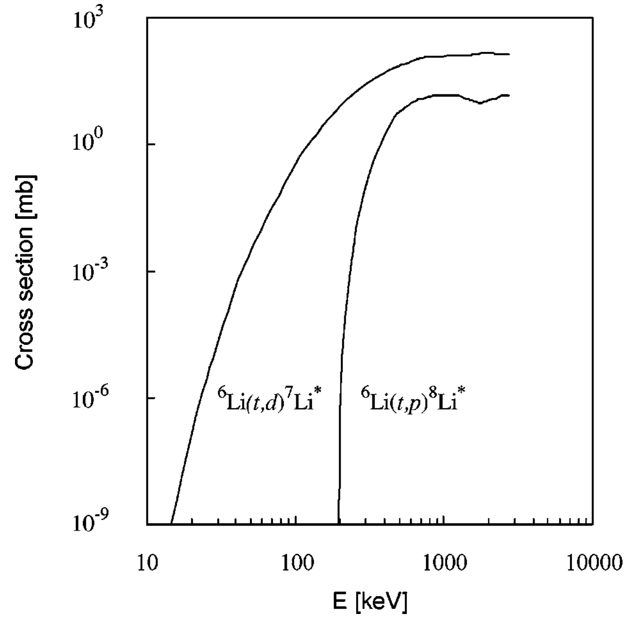


FIG. 3. The cross sections of the $\gamma$-ray-producing $^6$Li+T nuclear reactions as a function of center-of-mass energy *E*.

## III. DIAGNOSTIC APPLICATION

The next step in evaluating the $\gamma$-ray yields in the fusion plasma should be finding the $^6$Li+T reaction rate parameters $\langle\sigma v\rangle$. For a Maxwellian ion velocity distribution function the rate parameters are given by

$$\langle\sigma v\rangle=\left(\frac{8}{\mu\pi}\right)^{1/2}(kT)^{-3/2}\int_0^\infty E\sigma(E)e^{-E/kT}dE, \qquad (12)$$

where $\mu$ is the reduced mass of the $^6$Li+T system and $kT$ is the plasma temperature. The calculated values of $\langle\sigma v\rangle$ are given in Table I and in Fig. 4 together with the rate parameters of the $^6$Li+D $\gamma$-ray-producing reactions (7) [19,20]. For comparison, the reactivity of the D$(d,\gamma)^4$He radiative capture reaction [4] is also shown there. The $^6$Li$(d,n)$ and $^6$Li$(d,p)$ channels are not resolved well in Fig. 4 due to the small difference of their cross sections [15,16]. The $^6$Li-induced reactions (7) and (8a) are seen to have rather high values of $\langle\sigma v\rangle$ which considerably exceed those for the D$(d,\gamma)$ reaction. The reactivity of the endothermic reaction $^6$Li$(t,p)$ is also larger than the D$(d,\gamma)$ reactivity at ion temperatures $T_i>20$ keV. Figure 4 also confirms the suggestion

TABLE I. Maxwellian rate parameters $\langle\sigma v\rangle$ of the $^6$Li$(t,d)^7$Li*[0.478] and $^6$Li$(t,p)^8$Li*[0.981] nuclear reactions as a function of ion temperature $T_i$. Numbers in square brackets indicate powers of 10.

| Ion temperature (keV) | Rate parameter (cm$^3$ s$^{-1}$) $^6$Li$(t,d)^7$Li* | $^6$Li$(t,p)^8$Li* |
|---|---|---|
| 1 | 2.73 [−33] | <1.00 [−50] |
| 2 | 4.38 [−29] | <1.00 [−50] |
| 3 | 4.64 [−27] | <1.00 [−50] |
| 4 | 8.63 [−26] | 4.36 [−45] |
| 5 | 6.84 [−25] | 1.87 [−40] |
| 6 | 3.29 [−24] | 2.72 [−37] |
| 7 | 1.15 [−23] | 5.55 [−35] |
| 8 | 3.21 [−23] | 3.26 [−33] |
| 9 | 7.63 [−23] | 8.25 [−32] |
| 10 | 1.60 [−22] | 1.15 [−30] |
| 20 | 1.08 [−20] | 4.00 [−25] |
| 30 | 7.86 [−20] | 5.38 [−23] |
| 40 | 2.65 [−19] | 8.09 [−22] |
| 50 | 6.17 [−19] | 4.62 [−21] |
| 60 | 1.16 [−18] | 1.57 [−20] |
| 70 | 1.90 [−18] | 3.88 [−20] |
| 80 | 2.83 [−18] | 7.80 [−20] |
| 90 | 3.94 [−18] | 1.36 [−19] |
| 100 | 5.21 [−18] | 2.15 [−19] |

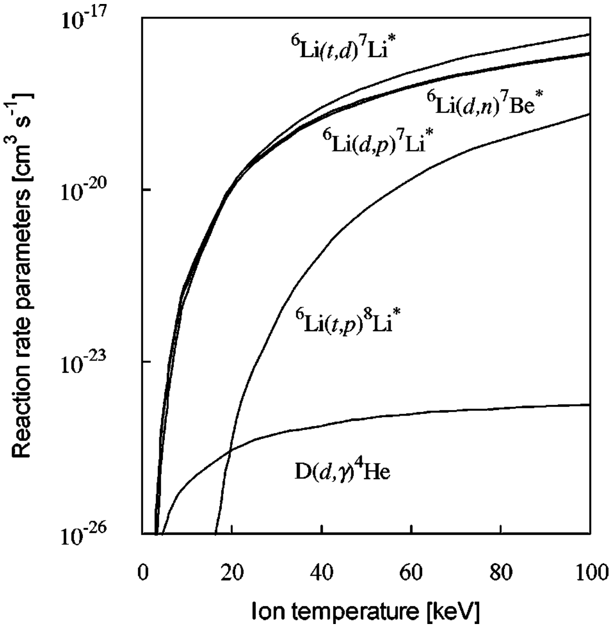


FIG. 4. The Maxwellian rate parameters of the $\gamma$-ray-producing $^6$Li+D, $^6$Li+T, and D+D nuclear reactions as a function of ion temperature.

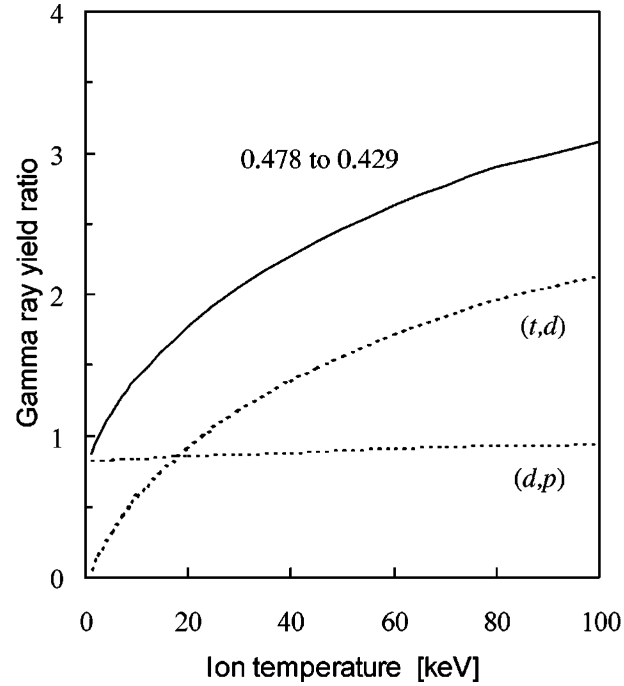


FIG. 5. Temperature dependence of the ratio of the 0.478- to 0.429-MeV monochromatic $\gamma$ quanta yields in DT plasma with admixture of $^6$Li isotope (solid line). The dotted lines represent the separate contribution of the $^6$Li$(d,p)$ and $^6$Li$(t,d)$ reactions. The fuel density ratio $\eta = n_T/n_D = 1$.

that the 0.981-MeV $\gamma$ ray yield $Y_\gamma(0.981)$ from the $^6$Li$(t,p)^8$Li* reaction should be a very sensitive function of $T_i$ in a region of a few tens of keV and this may greatly improve the accuracy of plasma temperature measurements. The $^6$Li$(t,p)^8$Li* reactivity rapidly increases with rising temperature and is fully determined by the contribution of the particles with energy $E > E_{thr}$. Therefore, detection of the 0.981-MeV $\gamma$ rays may help to get valuable information on the high-energy part of the tritium distribution function.

Although the rate parameters (and, hence, the respective $\gamma$-ray yields $Y_\gamma$) obtained are strongly dependent on $T_i$, the direct use of absolute values of $Y_\gamma$ for finding ion temperature is not an obvious matter as they include unknown values of the plasma current density. Fortunately, one can avoid this difficulty by comparative measurements of any pair of monochromatic $\gamma$ lines with $E_\gamma = 0.429$, 0.478, and 0.981 MeV accompanying the $^6$Li+D and $^6$Li+T reactions (7) and (8). It follows from Eq. (1) that

$$\frac{Y_\gamma(0.478)}{Y_\gamma(0.429)} = \frac{\langle\sigma v\rangle_{^6\mathrm{Li}(d,p)^7\mathrm{Li}*} + \eta\langle\sigma v\rangle_{^6\mathrm{Li}(t,d)^7\mathrm{Li}*}}{\langle\sigma v\rangle_{^6\mathrm{Li}(d,n)^7\mathrm{Be}*}}, \quad (13a)$$

$$\frac{Y_\gamma(0.981)}{Y_\gamma(0.478)} = \frac{\eta\langle\sigma v\rangle_{^6\mathrm{Li}(t,p)^8\mathrm{Li}*}}{\langle\sigma v\rangle_{^6\mathrm{Li}(d,p)^7\mathrm{Li}*} + \eta\langle\sigma v\rangle_{^6\mathrm{Li}(t,d)^7\mathrm{Li}*}}, \quad (13b)$$

$$\frac{Y_\gamma(0.981)}{Y_\gamma(0.429)} = \eta\frac{\langle\sigma v\rangle_{^6\mathrm{Li}(t,p)^8\mathrm{Li}*}}{\langle\sigma v\rangle_{^6\mathrm{Li}(d,n)^7\mathrm{Be}*}}, \quad (13c)$$

where $\eta$ is the fuel density ratio $n_T/n_D$. Since at thermonuclear temperatures below 100 keV the reaction T$(d,n)^4$He strongly dominates among all nuclear reactions proceeding in the DT+$^6$Li plasma, the rates of T and D burning are almost equal to each other. Therefore, within good accuracy the density parameter $\eta$ can be assumed to be constant and thus all the combined measurements (13) are determined by plasma ion temperature only. The ratio of the monochromatic $\gamma$-ray yields (13a) denoted by "0.478 to 0.429" for $\eta = 1$ is shown in Fig. 5. The dotted lines represent the separate contributions of the 0.478-MeV $\gamma$ quanta from the $(d,p)$ and $(t,d)$ reactions. The former leads to a weak temperature dependence of the yield ratio ranging within $\sim$0.8–0.9. The contribution of the $(t,d)$ reaction is seen to be masked near the origin but it rapidly increases and makes the total ratio (13a) (solid line) a quite sensitive function of $T_i$. The value of $Y_\gamma(0.478)/Y_\gamma(0.429)$ increases by 3.5 times when the ion temperature rises from 1 to 100 keV. This technique of temperature measurements seems to be productive for a tritium-rich DT fuel with the density parameter $\eta \sim 1$. If $\eta < 1$ the contribution of the important $(t,d)$ component in Eq. (13a) becomes smaller and the necessary sensitivity of the method may be lost.

The diagnostic application of the other $\gamma$-ray measurements (13b,c) for $\eta = 1$ is well illustrated in Fig. 6. The ratios "0.981 to 0.478" and "0.981 to 0.429" are clearly seen to reveal the extremely strong temperature dependence resulting from the rapid rise of the reactivity for the $^6$Li$(t,p)^8$Li* reaction. In particular, the values of $Y_\gamma(0.981)/Y_\gamma(0.478)$ and $Y_\gamma(0.981)/Y_\gamma(0.429)$ increase by a few orders of magnitude when the temperature rises from 20 to 100 keV. Therefore, it seems reasonable to employ such a counting technique for DT plasma temperature mea-

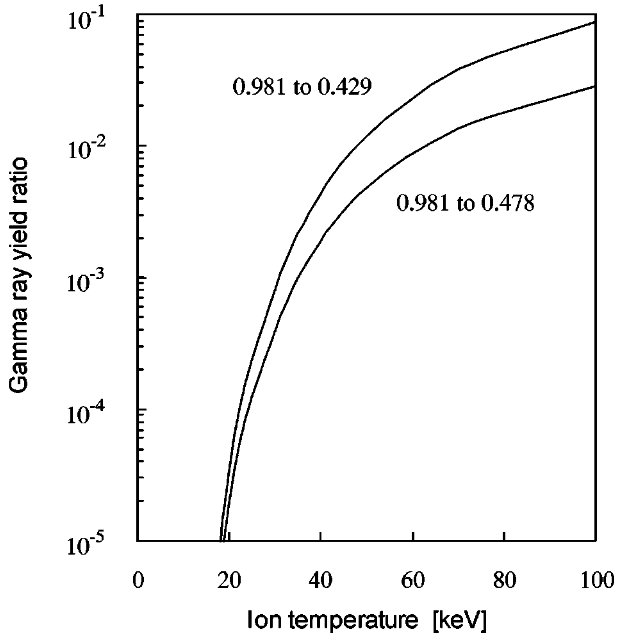


FIG. 6. The ratio of the 0.981- to 0.429- (and 0.478-)MeV monochromatic $\gamma$ quanta yields in DT plasma with admixture of $^6$Li isotope for $\eta=1$.

surements at $T_i > 20$ keV and, probably, for deriving information on the high-energy part of the ion distribution function.

We estimate now the $^6$Li concentration in the DT plasma needed to produce the necessary flux of monochromatic $\gamma$ rays. This flux must be counted experimentally in the presence of a strong $\gamma$-ray background. Since the latter may differ significantly for various nuclear fusion devices, we restrict our estimation to the particular example of Princeton's Tokamak Fusion Test Reactor (TFTR). For the background typical of the TFTR the so-called delayed counting technique has been shown [32] to be able to observe 4.825-MeV $\gamma$ rays with $Y_\gamma \sim 900$ cm$^{-3}$ s$^{-1}$ (released in a $^7$Li-$\alpha$ capture reaction proposed to study $\alpha$-particle confinement). The same conclusion is likely to be valid also for the $^6$Li+D and $^6$Li+T $\gamma$ rays since the background is roughly constant with energy below 10 MeV [32]. It is easy to show that, at the fuel density $n_{\mathrm{T}} = n_{\mathrm{D}} = 10^{14}$ cm$^{-3}$, a $^6$Li concentration of 1% provides the required values of $Y_\gamma(0.429)$ and $Y_\gamma(0.478)$ at an ion temperature of $\sim 6$ keV, and $Y_\gamma(0.981)$ at $T_i \sim 22$ keV.

Although the presence of $^6$Li with charge number $Z_{\mathrm{Li}} = 3$ in the hydrogen DT plasma increases radiation loss, 1% $^6$Li concentration is rather small to drastically worsen burning conditions. The specific power of bremsstrahlung loss $P_B$ due to electron-ion scattering in the DT+$^6$Li plasma can be estimated as follows:

$$P_B = \mathrm{const} \times n_e T_e^{1/2} (n_{\mathrm{T}} Z_{\mathrm{T}}^2 + n_{\mathrm{D}} Z_{\mathrm{D}}^2 + n_{\mathrm{Li}} Z_{\mathrm{Li}}^2), \qquad (14)$$

where $n_e$ and $T_e$ are the electron density and the electron temperature, respectively. Simple estimations show that the 1% $^6$Li concentration increases $P_B$ by only 6%. Moreover, this value may be partly compensated by additional nuclear energy released due to several exothermic reactions in the $^6$Li+D system with the total $Q$ value of 43 MeV [17]. The major part of this energy ($\sim$84%) is carried by charged particles and, therefore, remains in the plasma [33].

## IV. CONCLUSIONS

Summarizing the results of the present work, we conclude that the $^6$Li+D and $^6$Li+T reactions (7) and (8) induced by admixing a small amount of $^6$Li in DT plasma have an important diagnostic application. The reaction-produced monochromatic $\gamma$ rays can be used for measurements of the plasma ion temperature. The measurements are expected to be essentially independent of the plasma density and its local fluctuations.

The study carried out did not take into consideration $^9$Be* excited states near the $^6$Li+$t$ threshold at $E^* \sim 17.5$–$18.5$ MeV, which may affect the $^6$Li+T reaction cross section behavior at low energies. Some of these states have not been investigated with sufficient care, so their role in the low-energy $^6$Li+T reactions is still unclear. Therefore, further experimental study of the $^6$Li$(t,d)^7$Li*[0.478] and $^6$Li$(t,p)^8$Li*[0.981] reactions at energies below 1 MeV is desirable.

It would also be important to consider some other processes that may contribute to production of the diagnostic $\gamma$ rays. The first one is the suprathermal $^6$Li+D and $^6$Li+T nuclear reactions induced by fast D and T ions. These energetic ions are mainly created by recoil in 14-MeV neutron scattering and they have been shown to play a certain role in fusion plasmas (see, for example, [34]). The other process appears due to the buildup of $^7$Be$_{\mathrm{gr.st.}}$ in the DT+$^6$Li plasma. Although the half-life of this nucleus is rather long ($\tau_{1/2} = 53$ days) it is capable of producing 0.478-MeV $\gamma$ rays in its decay by electron capture to $^7$Li*[0.478] [11]. Therefore, the background buildup of $^7$Be$_{\mathrm{gr.st.}}$ is worth studying further.

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