A Method of Knock-on Tail Observation Accounting Temperature Fluctuation Using ^{6}Li+T/D+T Reaction in Deuterium Plasma

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It is important to understand the phenomena occurring in nuclear burning plasmas in order to operate fusion reactors. Although multiple studies have been conducted on nuclear elastic scattering (NES), only few experiments have focused on the observation of a knock-on tail via NES in nuclear burning plasmas. NES is an important phenomenon because it occurs in various plasmas and affects their energy balance. As for the observation of a knock-on tail, a method using γ-rays/neutrons generated from ^{6}Li + d → ^{7}Li* + p, ^{6}Li + d → ^{7}Be* + n, or D + d → ^{3}He + n reactions in a proton-beam-injected deuterium plasma has been proposed. However, there is a possibility to be unable to distinguish whether the main factor affecting the reaction rates is the plasma temperature or the formation of a knock-on tail. To avoid this confusion, herein, we proposed a method based on ^{6}Li + t → ^{8}Li* + p or D + t → ^{4}He + n reactions. These reactions can reveal the plasma temperature without the influence of a knock-on tail because the triton distribution function in deuterium plasmas is remarkably distorted from Maxwellian. The procedure and utilization possibility of the proposed method are discussed.

Keywords: nuclear burning plasma, nuclear elastic scattering, knock-on tail, γ-ray, neutron, deuterium plasma, ^{6}Li(t, pγ)^{8}Li reaction, T(d, n)^{4}He reaction

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1. Introduction

In nuclear burning plasmas, high-energy particles generated from nuclear reactions or beam injections cause nuclear elastic scattering (NES) with a certain probability [1, 2]. NES is predominated by nuclear force, except the pure Coulomb force. Unlike the case of pure Coulomb scattering, NES, including nuclear interactions, produce a distortion of the fuel-ion distribution function from Maxwellian because NES is a large-angle scattering phenomenon that causes large energy transfer. The non-Maxwellian components in the velocity distribution functions via NES are referred to as a "knock-on tail." A knock-on tail has various effects on plasmas, e.g., reaction rate variations [3], spectrum modification of emission particles due to nuclear reactions [4], and ion-heating enhancement [5, 6]. It is expected that a knock-on tail would be utilized for diagnosing fusion reactors [7]. Furthermore, in D-^{3}He plasmas, NES can significantly reduce the confinement requirements for plasma ignition [5]. Therefore, an accurate experimental analysis of the velocity distribution would provide important information about nuclear burning plasmas in fusion reactors. Several observation methods have been reported for a knock-on tail [3, 4, 8–10]. Fisher *et al.* [10] proposed an observation method for a knock-on tail to measure the DT neutron up to 20.6 MeV. In the deuterium–tritium fusion, a 3.5-MeV alpha (α) particle generated due to the DT reaction can transfer a maximum of 3.4 MeV to the triton in a single collision. The knock-on tail ion can generate DT neutrons with energies up to 20.6 MeV. The presence of a knock-on tail could be proved by measuring the DT neutrons up to 20.6 MeV. To date, experimental verifications of a knock-on tail formation caused by α-particles using the deuterium–tritium fusion have been conducted at JET [11].

To provide further quantitative validations for the NES effects under various experimental conditions, we previously proposed a method to observe the knock-on tail formation [3, 8, 9]. This method employed the γ-ray-generating and neutron-generating nuclear reactions, such as ^{6}Li(d, pγ)^{7}Li, ^{6}Li(d, nγ)^{7}Be, and D(d, n)^{3}He, occurring in a proton-beam-injected deuterium plasma admixed with a small amount of ^{6}Li. By injecting a high-energy proton beam into a deuterium plasma, the NES between protons and deuterons causes the formation of a knock-on tail in the high-energy region of the deuteron distribution function.

In deuterium plasmas, including ^{6}Li, the following reactions, which yield γ-rays, can occur:

$$^6\mathrm{Li} + \mathrm{d} \rightarrow \mathrm{n} + {}^7\mathrm{Be}^* + 2.95\,\mathrm{MeV},$$
$$^7\mathrm{Be}^* \rightarrow {}^7\mathrm{Be} + \gamma\ [0.429\,\mathrm{MeV}], \qquad (1)$$
$$^6\mathrm{Li} + \mathrm{d} \rightarrow \mathrm{p} + {}^7\mathrm{Li}^* + 4.55\,\mathrm{MeV},$$
$$^7\mathrm{Li}^* \rightarrow {}^7\mathrm{Li} + \gamma\ [0.478\,\mathrm{MeV}], \qquad (2)$$

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$$^{6}\mathrm{Li} + \mathrm{t} \rightarrow \mathrm{d} + {}^{7}\mathrm{Li}^{*} + 0.51\,\mathrm{MeV},$$
$$^{7}\mathrm{Li}^{*} \rightarrow {}^{7}\mathrm{Li} + \gamma\ [0.478\,\mathrm{MeV}], \tag{3}$$
$$^{6}\mathrm{Li} + \mathrm{t} \rightarrow \mathrm{p} + {}^{8}\mathrm{Li}^{*} - 0.18\,\mathrm{MeV},$$
$$^{8}\mathrm{Li}^{*} \rightarrow {}^{8}\mathrm{Li} + \gamma\ [0.981\,\mathrm{MeV}]. \tag{4}$$

In addition to the above reactions, the following reactions can occur:

$$\mathrm{D} + \mathrm{d} \rightarrow \mathrm{n} + {}^{3}\mathrm{He} + 3.27\,\mathrm{MeV}, \tag{5}$$
$$\mathrm{D} + \mathrm{d} \rightarrow \mathrm{p} + \mathrm{T} + 4.04\,\mathrm{MeV}, \tag{6}$$
$$\mathrm{D} + \mathrm{t} \rightarrow \mathrm{n} + {}^{4}\mathrm{He} + 17.58\,\mathrm{MeV}. \tag{7}$$

The following reactions are written as ^{6}Li(d, nγ)^{7}Be, ^{6}Li(d, pγ)^{7}Li, ^{6}Li(t, dγ)^{7}Li, ^{6}Li(t, pγ)^{8}Li, D(d, n)^{3}He, D(d, p)T, and T(d, n)^{4}He respectively. The cross sections of reactions (1), (2), (5), and (6) are shown in Fig. 1 (a). The cross sections of reactions (1), (2), and (5) are employed for observing a knock-on tail. Because the ^{6}Li(d, nγ)^{7}Be reaction, whose γ-ray energy is 0.429 MeV, and the ^{6}Li(d, pγ)^{7}Li reaction, whose γ-ray energy is 0.478 MeV, have a reaction threshold, a rapid increase in the reaction rates can be expected by a knock-on tail formation in the deuteron distribution function. In this manner, the previously proposed method [3, 8, 9] can prove the presence of a knock-on tail by capturing the quantitative changes of these reaction rates. Although the change in neutron generation rate from the D(d, n)^{3}He reaction is smaller than that change in γ-ray generation rate from the ^{6}Li(d, pγ)^{7}Li and ^{6}Li(d, nγ)^{7}Be reactions due to a knock-on tail formation, the higher emission rate from the D(d, n)^{3}He reaction can still be expected than that γ-ray generation rate from the ^{6}Li(d, pγ)^{7}Li and ^{6}Li(d, nγ)^{7}Be reactions. The experiment using the proposed method for observing a knock-on tail has been projected on the Large Helical Device (LHD) at National Institute for Fusion Science.

However, there is a possibility that the plasma temperature is affected by beam injection. It needs to distinguish the γ-ray (neutron) with which a knock-on tail formation is related from the measured γ-ray (neutron). In other words, a method to eliminate the effect of the plasma temperature on the reaction rate is required to derive only the effect of a knock-on tail on the reaction rate. In this study, we consider to use a nuclear reaction as correction of the observation of the knock-on tail. To this end, it is required that i) the reaction is not affected by the knock-on tail, ii) the reaction depend on plasma temperature.

In this paper, we proposed a method to prevent confusing the effect of a knock-on tail formation with the effect of the plasma temperature increase by using ^{6}Li(t, pγ)^{8}Li or T(d, n)^{4}He reaction. We evaluate the utilization possibility of the ^{6}Li(t, pγ)^{8}Li or T(d, n)^{4}He reaction as a diagnostic method of plasma temperature not depending on the knock-on tail formation using the Fokker–Planck model.

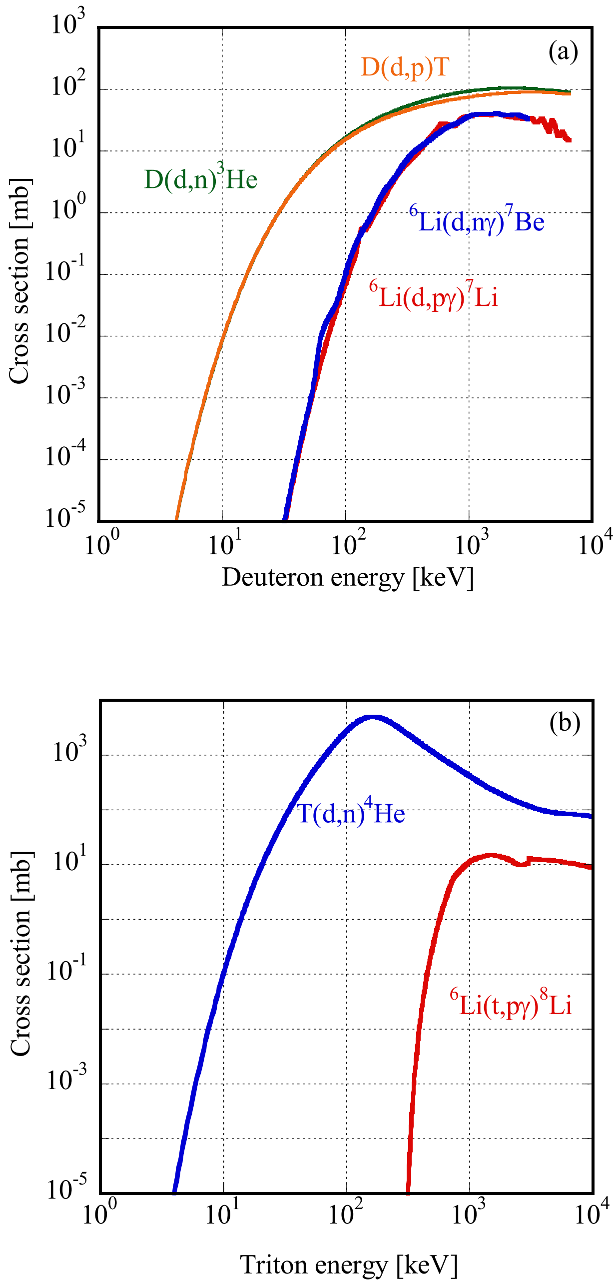


Fig. 1 (a) ^{6}Li(d, nγ)^{7}Be, ^{6}Li(d, pγ)^{7}Li, D(d, p)T, and D(d, n)^{3}He and (b) ^{6}Li(t, pγ)^{8}Li and T(d, n)^{4}He cross sections as a function of deuteron or triton energy in the laboratory system.

2. Analysis Model

2.1 Two-temperature Maxwellian model for deuterons

The deuteron distribution function in which a knock-on tail is formed in the proton-beam-injected deuteron plasma is simulated using the following two-temperature Maxwellian model:

$$f_{\text{total}}(v_{\text{D}}) = f_{\text{bulk}}(v_{\text{D}}) + f_{\text{tail}}(v_{\text{D}}),$$
$$f_{\text{bulk(tail)}}(v_{\text{D}}) = 4\pi n_{\text{bulk(tail)}} v_{\text{D}}^2 \times \left(\frac{m_{\text{D}}}{2\pi T_{\text{bulk(tail)}}}\right)^{3/2} \times \exp\left(-\frac{m_{\text{D}} v_{\text{D}}^2}{2T_{\text{bulk(tail)}}}\right). \quad (8)$$

Here, $f(v_{\text{D}})$ is deuteron distribution function as a function of deuteron velocity v_{D}. The subscripts "bulk" and "tail" indicate the Maxwellian and non-Maxwellian components respectively. T_{bulk} represents the bulk temperature, T_{tail} represents the tail deuteron temperature, n_{bulk} is the bulk deuteron density, and n_{tail} is the tail density. In addition, we introduce the α-value, which represents the ratio of a knock-on tail component density to deuteron density, i.e., $\alpha \equiv n_{\text{tail}}/(n_{\text{tail}} + n_{\text{bulk}})$.

2.2 Fokker–Planck model for tritons

In this study, to obtain the triton distribution function, we employed the Fokker–Planck model:

$$\sum_j \left(\frac{\partial f_{\text{T}}(v_{\text{T}})}{\partial t}\right)_j^{\text{Coulomb}} + S(v_{\text{T}}) - \frac{f_{\text{T}}(v_{\text{T}})}{\tau_{\text{p}}(v_{\text{T}})} - \zeta(v_{\text{T}}) f_{\text{T}}(v_{\text{T}}) = 0. \quad (9)$$

The first term on the left-hand side of Eq. (9) represents the Coulomb collision term. Summation is performed over background species, i.e., j = deuteron and electron. The electron distribution function is assumed to be Maxwellian with temperature T_{bulk}. The second term on the left-hand side of Eq. (9) represents the source due to the D(d, p)T reaction whose generative energy is 1.01 MeV. The third and fourth terms on the left-hand side of Eq. (9) represent loss terms. The ratio $f_{\text{T}}/\tau_{\text{p}}(v_{\text{T}})$ indicates the particle loss from the plasma. We assumed that the particle loss time τ_{p} has a velocity dependence that can be expressed using a dimensionless parameter γ (in this study, $\gamma = 4$) [12]:

$$\tau_{\text{p}}(v_{\text{T}}) = \begin{cases} C_{\text{p}}\tau_{\text{p}} & \text{when } v_{\text{T}} < v_{\text{th}} \\ C_{\text{p}}\tau_{\text{p}}(v_{\text{T}}/v_{\text{th}})^{\gamma} & \text{when } v_{\text{T}} \geq v_{\text{th}} \end{cases}, \quad (10)$$

where $v_{\text{th}} = (2T_{\text{bulk}}/m_{\text{T}})^{1/2}$.

The term $\zeta(v_{\text{T}}) f_{\text{T}}$ indicates the particle loss due to the $\text{T}(\text{d, n})^4\text{He}$ reaction, which can be expressed as follows:

$$\zeta(v_{\text{T}}) = \frac{2\pi}{v_{\text{T}}} \int_0^{\infty} \mathrm{d}v_{\text{D}} v_{\text{D}} f_{\text{D}}(v_{\text{D}}) \left[\int_{|v_{\text{D}}-v_{\text{T}}|}^{v_{\text{D}}+v_{\text{T}}} v_{\text{r}}^2 \sigma_{\text{DT}}(v_{\text{r}}) \mathrm{d}v_{\text{r}}\right], \quad (11)$$

where $\sigma_{\text{DT}}(v_{\text{r}})$ is the cross section of the $\text{T}(\text{d, n})^4\text{He}$ reaction and v_{r} is relative velocity between the deuteron and the triton, i.e., $v_{\text{r}} = |\vec{v}_{\text{D}} - \vec{v}_{\text{T}}|$.

The reaction rate R can be expressed as follows:

$$R = n_i n_k \langle \sigma v \rangle_{ik}, \quad (12)$$

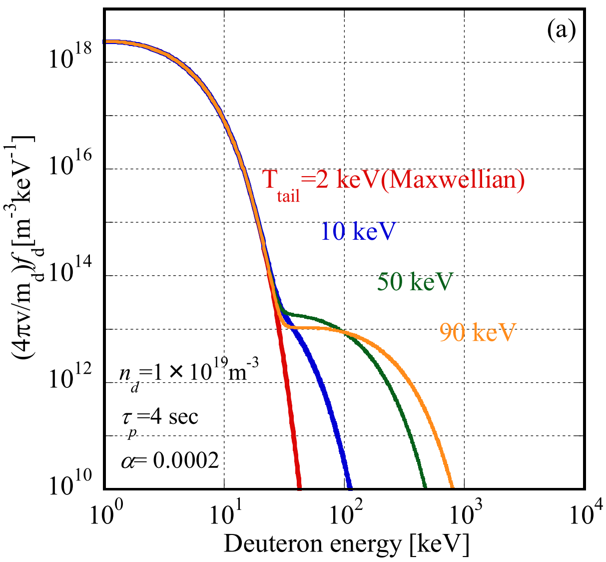
where

$$\langle \sigma v \rangle_{ik} = \int_0^{\infty} \mathrm{d}\vec{v}_i \int_0^{\infty} \mathrm{d}\vec{v}_k \frac{f_i(\vec{v}_i) f_k(\vec{v}_k)}{n_i n_k} \sigma_{ik}(|\vec{v}_i - \vec{v}_k|) |\vec{v}_i - \vec{v}_k|. \quad (13)$$

The subscript i and k represent ion species, i.e., (i, k) = (^{6}Li, d), (^{6}Li, t), (d, d), and (d, t). The ^{6}Li distribution function is assumed to be Maxwellian with temperature T_{bulk}. The ^{6}Li density $n_{6\text{Li}} = 1/100\ n_{\text{D}}$ is assumed. Throughout these the calculations, the cross sections of the fusion reactions were taken from a study by Bosch [13] and the γ-ray-generating reactions were taken from the studies of Voronchev [14, 15].

3. Results and Discussion

Figure 2 (a) shows the deuteron distribution functions simulated by the two-temperature Maxwellian model for



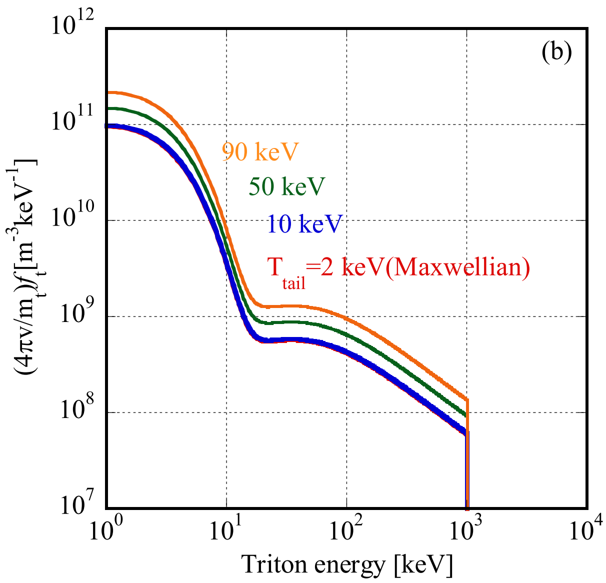


Fig. 2 (a) Deuteron distribution functions simulated by the two-temperature Maxwellian model and (b) triton distribution functions obtained by the Fokker–Planck model for $T_{\text{bulk}} = 2$ keV and several T_{tail}.

several tail temperatures. Here, the bulk temperature is fixed to 2 keV to investigate the effect of the knock-on tail formation. The deuteron distribution function when $T_{\mathrm{bulk}} = 2$ keV, $T_{\mathrm{tail}} = 90$ keV, and $\alpha = 0.0002$ is chosen based on the results of the BFP simulation [16] when a proton beam [power ($P_{\mathrm{NBI}} = 33$ MW) and energy ($E_{\mathrm{NBI}} = 1$ MeV)] is injected into the deuterium plasma. The source term in Eq. (9), i.e., the triton birth rate obtained from the D(d, p)T reaction, is evaluated from the deuteron distribution function shown in Fig. 2 (a), and the triton distribution functions are obtained by solving Eq. (9).

The triton distribution functions obtained for several tail temperatures are shown in Fig. 2 (b). The tritons are generated with a birth energy of 1.01 MeV and form a large burnup component. The burnup component grows large for higher T_{tail} values. This is because the triton generation rate, i.e., the D(d, p)T reaction rate, increases with increasing T_{tail} [Fig. 1 (a)]. Because the birth energy of tritons is invariable and the bulk temperature of the triton does not depend on the T_{tail} value of the deuteron distribution function, the burnup triton distribution function retains in the same shape as the slowing-down distribution [17]. This means that the knock-on tail formation in the deuteron distribution function only affects the absolute amount of triton distribution function.

In Fig. 3 (a) shows the deuteron distribution functions for various bulk temperatures when the tail temperature is fixed $T_{\mathrm{tail}} = 90$ keV. In a manner same as that shown in Fig. 2, the triton distribution function is obtained by solving Eq. (9). When the T_{bulk} value changes, the triton distribution function not only changes its absolute amount but also the $n_{\mathrm{bulk}}/n_{\mathrm{tail}}$ ratio [Fig. 3 (b)]. This is because that the triton birth rate increases (decreases) with increasing (decreasing) T_{bulk} and the slowing down of energetic component is weakened (accelerated) with increasing (decreasing) electron temperature (As described in the analysis model section, electron temperature is assumed as the same value with T_{bulk}).

Figure 4 shows the rates of the reactions expressed in Eqs. (1), (2), (4), (5), and (7) (a) for $T_{\mathrm{bulk}} = 2$ keV as a function of T_{tail} and (b) for $T_{\mathrm{tail}} = 90$ keV as a function of T_{bulk}. The dotted lines represent the reaction rates in absence of a knock-on tail formation [Fig. 4 (b)]. It is desirable to describe the $\mathrm{D(d,n)^3He}$, $\mathrm{^6Li(d,n\gamma)^7Be}$, and $\mathrm{^6Li(d,p\gamma)^7Li}$ reactions, which are employed for observing a knock-on tail, before moving on to the proposed method. When a knock-on tail is formed in deuteron distribution functions [solid line in Fig. 4 (b)], the $\mathrm{D(d,n)^3He}$, $\mathrm{^6Li(d,\gamma n)^7Be}$, and $\mathrm{^6Li(d,\gamma p)^7Li}$ reaction rates are not considerably affected by the bulk temperature. The $\mathrm{^6Li(d,\gamma n)^7Be}$ and $\mathrm{^6Li(d,p\gamma)^7Li}$ reactions show remarkable changes in response to the variations in both the "T_{tail}" and "T_{bulk} values (when a knock-on tail is not created) [dotted lines in Fig. 4 (b)]" because these reactions have a threshold cross section. In contrast, the $\mathrm{D(d,n)^3He}$ reaction has a high reaction rate and is not highly sensitive to both T_{tail}

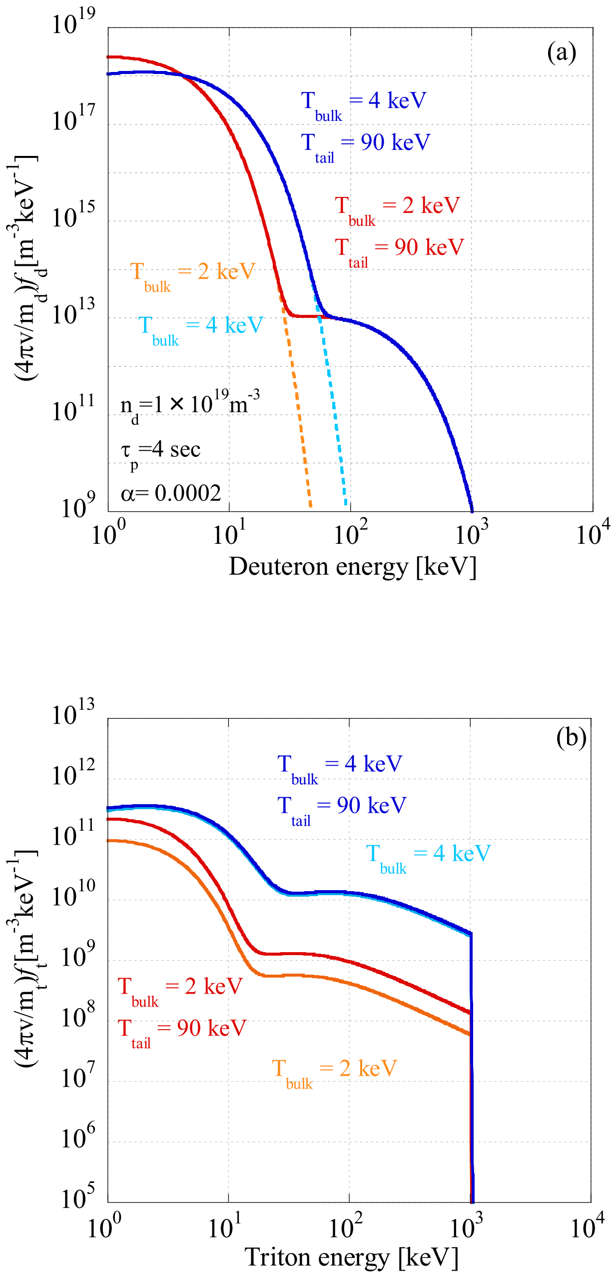


Fig. 3 (a) Deuteron distribution functions simulated by the two-temperature Maxwellian model and (b) triton distribution functions obtained by the Fokker–Planck model for $T_{\mathrm{tail}} = 90$ keV and several T_{bulk}.

and T_{bulk} compared to the $\mathrm{^6Li(d,\gamma n)^7Be}$ and $\mathrm{^6Li(d,p\gamma)^7Li}$ reactions, but the $\mathrm{D(d,n)^3He}$ reaction rate is slightly affected by both T_{bulk} and T_{tail}. From the above discussion, it can be said that there is a possibility of not being able to distinguish whether the increments in the reaction rates of the $\mathrm{D(d,n)^3He}$, $\mathrm{^6Li(d,n\gamma)^7Be}$, and $\mathrm{^6Li(d,p\gamma)^7Li}$ reactions are caused by an increase in T_{bulk} or by a knock-on tail formation.

We now discuss the $\mathrm{^6Li(t,p\gamma)^8Li}$ and $\mathrm{T(d,n)^4He}$ reactions that are employed in the proposed method. These reaction rates are increasing similarly each other with in-

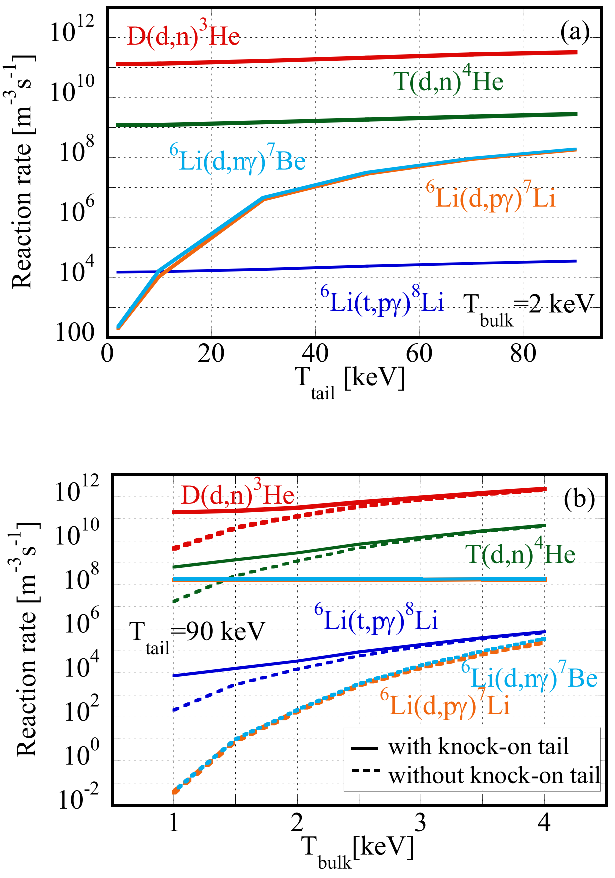


Fig. 4 Reaction rate of D(d, n)^{3}He, T(d, n)^{4}He, ^{6}Li(t, pγ)^{8}Li, ^{6}Li(d, nγ)^{7}Be, and ^{6}Li(d, pγ)^{7}Li for (a) $T_{\mathrm{bulk}} = 2$ keV as a function of T_{tail} and for (b) $T_{\mathrm{tail}} = 90$ keV as a function of T_{bulk}.

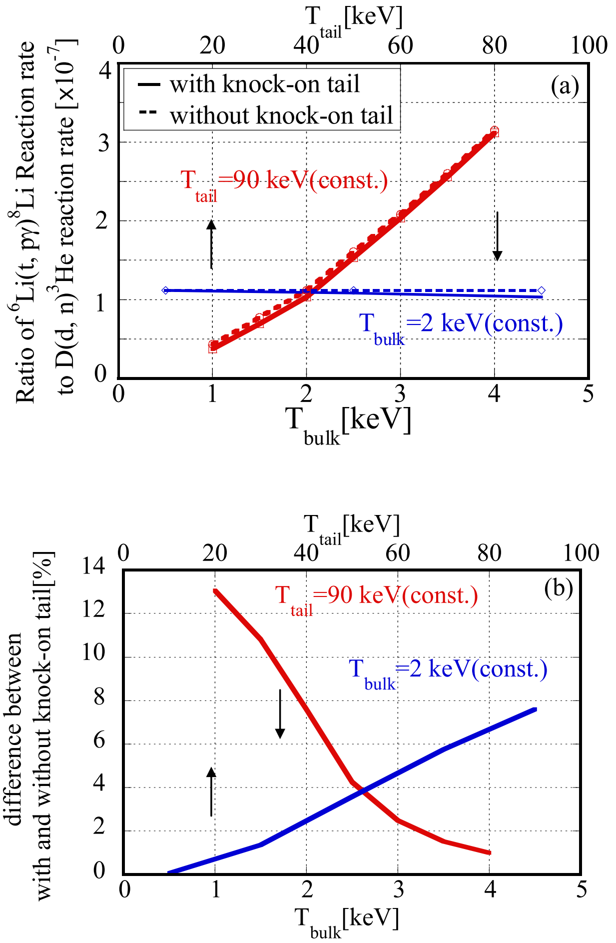


Fig. 5 (a) The ratio of the reaction rate of ^{6}Li(t, pγ)^{8}Li to that of D(d, n)^{3}He and (b) the relative difference between the with and without knock-on tail cases.

creasing T_{tail} (T_{bulk}) in Fig. 4 (a) (Fig. 4 (b)). This is because these reaction rates are almost the same as the triton emission rate. Certainly, the triton emission rate is almost the same as the D(d, n)^{3}He reaction rate, since the cross section of the D(d, p)T reaction (which decides triton emission rates) has almost the same value as the D(d, n)^{3}He reaction. Thus, the triton emission rate can be predicted by measuring the neutrons produced by the D(d, n)^{3}He reaction. It is worth noting that the difference between the dotted and solid lines becomes large in Fig. 4 (b) when T_{bulk} is low because the contribution of bulk component to the reaction rate is relatively small compared to that of energetic component.

Figure 5 (a) shows the ratio of the reaction rate of ^{6}Li(t, pγ)^{8}Li to that of D(d, n)^{3}He as a function of T_{bulk} when $T_{\mathrm{tail}} = 90$ keV (red lines) and as a function of T_{tail} when $T_{\mathrm{bulk}} = 2$ keV (blue lines) both with and without a knock-on tail formation. From this ratio, it is possible to identify the effect of the bulk and tail temperatures on the ^{6}Li(t, pγ)^{8}Li reaction rate, excluding the influence of the triton emission rate. As indicated by the blue lines, the ratio is nearly constant in the entire range of T_{tail}. The trend indicated by the blue line implies that the ratio is not affected by the knock-on tail formation. In contrast, the ratio strongly depends on the bulk temperature, as indicated by the red lines. When $T_{\mathrm{bulk}} = 4$ keV, the ratio is almost six times larger than the value when $T_{\mathrm{bulk}} = 1$ keV. This is because the ^{6}Li(t, pγ)^{8}Li reaction rate is increased when the bulk temperature is high. It can be concluded that the ratio of the reaction rate of ^{6}Li(t, pγ)^{8}Li to that of D(d, n)^{3}He is not influenced by a knock-on tail; however, while it strongly depends on T_{bulk}.

Figure 5 (b) shows the difference between the ratios of the two reactions with and without considering the knock-on tail formation. When $T_{\mathrm{tail}} = 90$ keV and $T_{\mathrm{bulk}} = 1$ keV [red line in Fig. 5 (a)], the difference is approximately 13%, while when $T_{\mathrm{bulk}} = 2$ keV and $T_{\mathrm{tail}} = 90$ keV [blue line in Fig. 5 (a)], the difference is approximately 8%. The differences indicated by the blue line are mainly caused by the differences between the D(d, n)^{3}He and D(d, p)T reaction rates. Thus, the ratio can be accurately tuned using these cross sections. On the other hand, as shown in red line, the ratio is affected by T_{tail} sensitivity when T_{bulk} is small. However, the differences are negligibly small compared with the change in the ^{6}Li(t, pγ)^{8}Li reaction rate it-

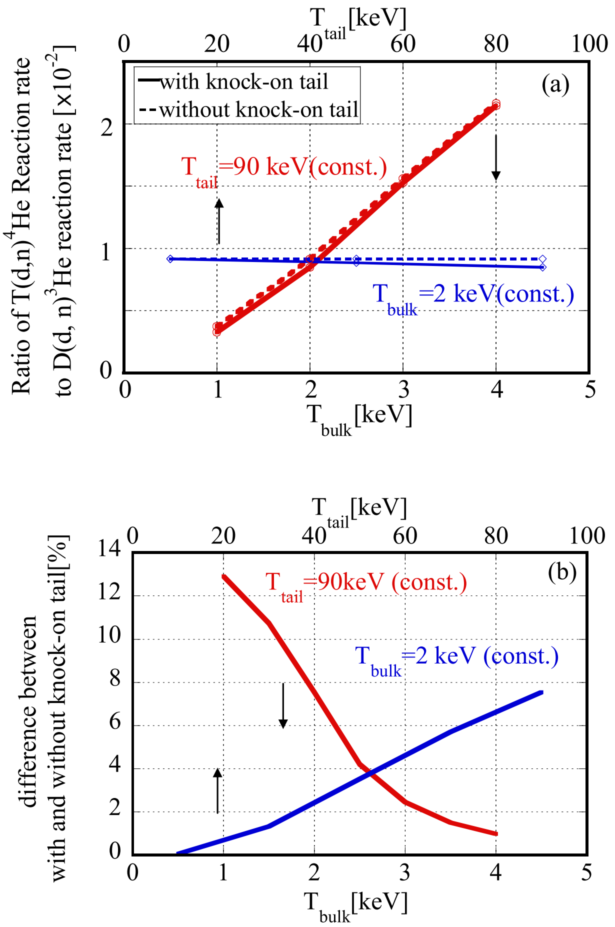


Fig. 6 (a) The ratio of the reaction rate of T(d, n)^{4}He to that of D(d, n)^{3}He and (b) the relative difference between the with and without knock-on tail cases.

self. Thus, it can be ascertained that $T_{\rm bulk}$ does not depend on the knock-on tail formation.

Figure 6 (a) shows the ratio of the reaction of T(d, n)^{4}He to that of D(d, n)^{3}He. The differences between their ratios with and without considering the knock-on tail formation are shown in Fig. 6 (b). In the same reason shown in Fig. 5, a similar tendency with the ^{6}Li(t, pγ)^{8}Li reaction can be observed. In addition, because the T(d, n)^{4}He reaction rate is dominated by a reaction between the bulk component of the deuteron and the non-Maxwellian component of the triton, a knock-on tail component in the deuteron distribution does not affect the reaction rate. Thus, it can be concluded that using the ^{6}Li(t, pγ)^{8}Li and T(d, n)^{4}He reactions, $T_{\rm bulk}$ would not depend on the knock-on tail formation.

The emission rates of the γ-ray from the ^{6}Li(d, pγ)^{7}Li and ^{6}Li(d, pγ)^{7}Li reactions or the neutron from the D(d, n)^{3}He and D(d, p)T reactions are affected not only by a knock-on tail formation but also by changes in the bulk temperature. The procedure presented herein enables us to determine whether a knock-on tail is created in an observation experiment. The ratio of the reaction rate of

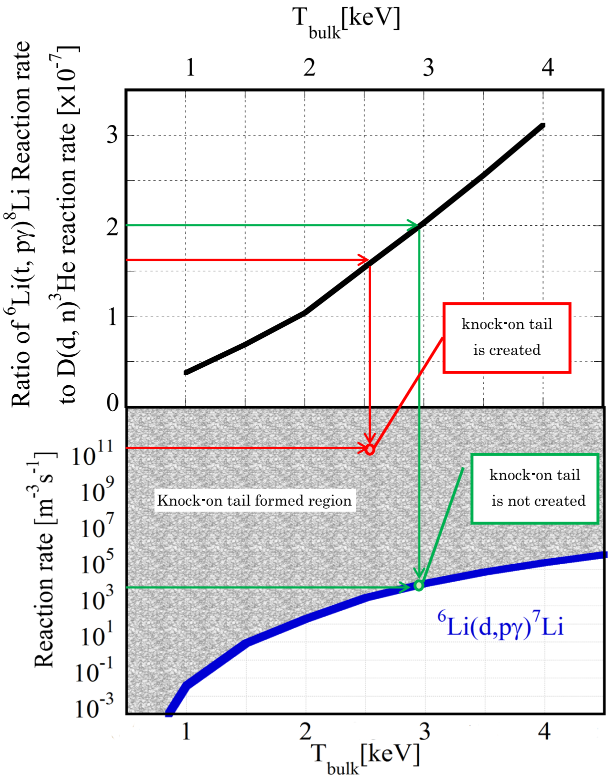


Fig. 7 The procedure to determine whether a knock-on tail is created using the ratio of the reaction rate of ^{6}Li(t, pγ)^{8}Li to that of D(d, n)^{3}He and the ^{6}Li(d, pγ)^{7}Li reaction rate.

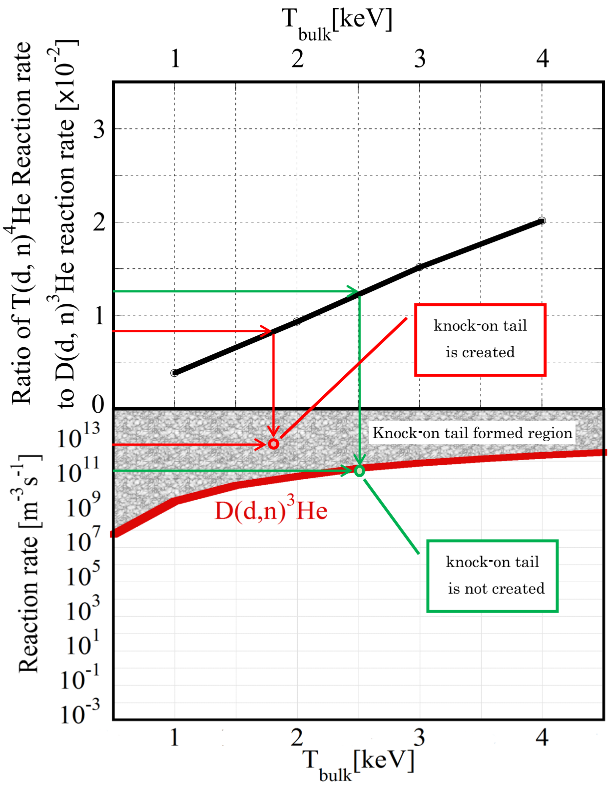


Fig. 8 The procedure to determine whether a knock-on tail is created using the ratio of the reaction rate of T(d, n)^{4}He to that of D(d, n)^{3}He and the D(d, n)^{3}He reaction rate.

^{6}Li(t, pγ)^{8}Li to that of D(d, n)^{3}He and the reaction rate of ^{6}Li(d, pγ)^{7}Li when a knock-on tail is not created are shown in Fig. 7. The ratio of the reaction rate of ^{6}Li(t, pγ)^{8}Li to that of D(d, n)^{3}He, which is obtained from the observation experiment of the knock-on tail formation, can determine the bulk temperature because the ratio does not depend on the knock-on tail component. Then, the shaded region in Fig. 7 indicates that a knock-on tail is created in the deuteron distribution function; however, the rate at which γ-rays are emitted by ^{6}Li(d, pγ)^{7}Li reactions on the blue line indicates that a knock-on tail is not created. Similarly, the ratio of the reaction rate of T(d, n)^{4}He to that of D(d, n)^{3}He and the reaction rate of D(d, n)^{3}He when a knock-on tail is not created are shown in Fig. 8. Thus, the information from the proposed method can be used to determine whether a knock-on tail is created in the observation experiment.

4. Concluding Remarks

This research showed that the use of the ^{6}Li(t, pγ)^{8}Li and T(d, n)^{4}He reactions enabled us to distinguish the change in the reaction rate caused by an increase in the plasma temperature from the change in the reaction rate caused by a knock-on tail formation. This will be utilized in an observation experiment of a knock-on tail using the γ-rays of the ^{6}Li(d, pγ)^{7}Li and ^{6}Li(d, nγ)^{7}Be reactions and the neutron of the D(d, n)^{3}He reaction. It was shown that based on the ^{6}Li(t, pγ)^{8}Li and T(d, n)^{4}He reaction rates, the plasma temperature can be derived without the influence of a knock-on tail formation because the effects of the knock-on tail on the reactions were eliminated by using the D(d, n)^{3}He reaction rate. For the proposed method, there is no need to install a new apparatus. Moreover, there is an advantage that the plasma temperature at the observation area can be measured.

In this study, several assumptions have been made. First, a two-temperature Maxwellian model was used for the deuteron distribution function containing a knock-on tail. Second, the knock-on tails in triton distribution functions were not considered. Third, the distribution functions were spatially uniform and isotropic in the plasma. A two-temperature Maxwellian distribution function was not able to represent a deuteron distribution function formed knock-on tail when relative energy between bulk and beam components is small. However, as was discussed previously, the proposed method is not affected by the shape of energetic component in the two-temperature Maxwellian model. For the same reason, a knock-on tail of the triton distribution function does not need to be considered. The beam-injected plasma is non-uniform. The influence of the assumption of uniform plasma would be small because anisotropic component appears in the high-energy region. It needs to be examined if these assumptions affect the utilization of the proposed method.

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