Use of γ-Ray-Generating ^{6}Li+D Reaction for Fast-Ion Diagnostics in Deuterium Plasmas

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The energy spectrum of γ-ray emitted from ^{6}Li+D nuclear reaction induced by admixing a small amount of ^{6}Li in deuterium plasma and its application to fast-ion diagnostics are studied. It is shown that the monochromatic γ-ray with energies E_γ^0 (0.429 and/or 0.478 MeV) can be used for diagnostics of fast-ion velocity distribution function in non-reactive and thinly-peopled deuterium plasmas. A possible experiment to verify knock-on tail simulations and fast-ion diagnostics based on the γ-ray spectrometry using ^{6}Li+D γ-ray-generating nuclear reaction in currently-existing deuterium plasmas is proposed.

Keywords: γ-ray-generating ^{6}Li+D nuclear reaction, deuterium plasma, γ-ray emission rate, γ-ray energy spectrum, plasma diagnostics, non-Maxwellian tail

1. Introduction

The clarification of energetic-ion behavior in burning plasmas is one of the most important issues for controlled fusion research and so far many deuterium-plasma experiments have been performed. In these experiments, appearance of energetic component in fuel-ion velocity distribution functions by nuclear elastic scattering (NES) [1-5] and/or external heatings, e.g. ion cyclotron range of frequencies (ICRF) heating [6,7] has been ascertained.

So far various ideas for energetic ion diagnostics have been developed, e.g. pellet charge exchange [8], charge exchange recombination spectroscopy [9] and γ-ray spectroscopy. For its simple diagnostic system and utilization of standard technology, the quantitative spectrometry of high energy γ-rays emitted from nuclear reactions induced by fuel and impurity ions has been considered to be applicable for plasma diagnostics and investigations to use the γ-ray- generating nuclear reaction as a diagnostic tool have been made for a number of decades [10-13]. We have previously developed the Boltzmann-Fokker-Planck (BFP) model [14-18] for the purpose to analyze energetic-ion behavior in fusion devices and proposed a possible experiment [19] using γ-ray-generating ^{6}Li+D reaction [20-22] to verify the BFP simulations. We have shown that the knock-on tail formation can be experimentally examined by looking at the γ-ray emission rate by ^{6}Li+D reaction in currently-existing fusion-experiment devices; however, no detailed discussion about γ-ray energy spectrum has been made.

In this paper, the use of 0.478 (0.429) MeV γ-ray-emitting ^{6}Li(d,p)^{7}Li* (^{6}Li(d,n)^{7}Be*), ^{7}Li*→^{7}Li+γ (^{7}Be*→^{7}Be+γ) reaction [20-22] in low-temperature and low-density plasmas which are often seen in the currently-existing devices is considered. In the future fusion reactors with DT burning many different types of γ-ray can occur concurrently, and to measure the specific γ-ray against the background noise, the nuclear reaction emitting γ-ray with several-MeV energy would be required. Although the energies of γ-ray emitted from excited ^{7}Li* and ^{7}Be* from ^{6}Li+D reaction do not satisfy the above requirement (E_γ^0= 0.478 and 0.429 MeV), the cross sections of ^{6}Li+D reactions have quite unique properties, i.e. rapidly increases in more than several hundreds-keV energy range in the centre-of-mass frame (see Fig.1). By using the ^{6}Li+D reaction we can examine the fast-deuteron distribution function from the γ-rays caused by the "energetic" deuterons. By looking at both the γ-ray generation rate and γ-ray energy spectrum at the same time, more precise measurement of energetic-ion velocity distribution function can be expected. Furthermore

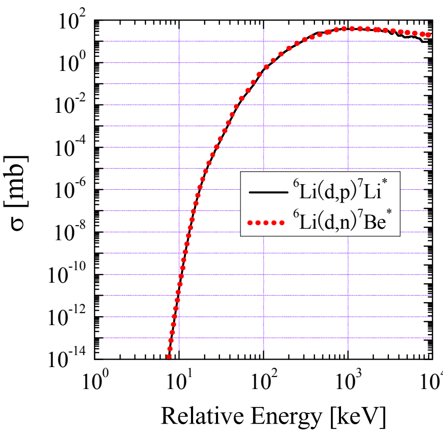

Fig.1 ^{6}Li(d,p)^{7}Li* and ^{6}Li(d,n)^{7}Be* cross sections as a function of center-of-mass energy[18-20].

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from the experiment using the ^{6}Li+D reaction in currently- existing deuterium plasmas, we may obtain the information on the fast-ion behavior and diagnostic method for future fusion reactors.

We consider a few percent of ^{6}Li containing deuterium plasma. By calculating the correlation between the shape of suprathermal deuteron velocity distribution function and the γ-ray emission spectrum for various plasma parameters, a possibility of energetic-ion diagnostics using ^{6}Li+D γ-ray-generating reaction in currently-existing deuterium plasmas is studied. A possible experiment to verify knock-on simulations and γ-ray diagnostics using the ^{6}Li+D γ-ray-generating reaction is proposed.

2. Analysis Model

The emission energy spectrum of species *a* ($a = {}^7Li^*$ or ${}^7Be^*$) is written as

$$\frac{dN_a}{dE}(E) = \iiint f_D(\vec{\upsilon}_D) f_{^6Li}(\vec{\upsilon}_{^6Li}) \times \frac{d\sigma}{d\Omega}\delta(E - E_a)\upsilon_r d\vec{\upsilon}_D d\vec{\upsilon}_{^6Li} d\Omega \quad , \tag{1}$$

where $f_D(\vec{\upsilon}_D)$ and $f_{^6Li}(\vec{\upsilon}_{^6Li})$ are the velocity distribution functions of D and ^{6}Li, $d\sigma/d\Omega$ is the differential cross section of ^{6}Li-d reaction and in this paper which is assumed to be isotropic in the centre-of-mass frame. E_a represents the ion energy in the laboratory system [23];

$$E_a = \frac{1}{2}m_a V_c^2 + \frac{m_b}{m_a + m_b}(Q + E_r) + V_c \cos\theta_c \sqrt{\frac{2m_a m_b}{m_a + m_b}(Q + E_r)} \quad , \tag{2}$$

where the subscript *b* indicates reaction product (*b* =proton or neutron), V_c is the center-of-mass velocity of the colliding particles, θ_c is the angle between the center-of-mass velocity and the $^7Li^*$ ($^7Be^*$) ion velocity in the center-of-mass frame, *Q* is the reaction *Q*-value, and E_r represents the relative energy given by

$$E_r = \frac{1}{2}\frac{m_D m_{^6Li}}{m_D + m_{^6Li}}\left|\vec{\upsilon}_D - \vec{\upsilon}_{^6Li}\right|^2 . \tag{3}$$

In consideration of Doppler effect of γ-ray emitted from the $^7Li^*$ ($^7Be^*$), the energy spectrum of the γ-ray are calculated using the obtained $^7Li^*$ ($^7Be^*$) energy spectrum ;

$$\frac{dE_\gamma}{dE} \cong \sum_{E_a} I(E_\gamma; E_a)$$

$$I(E_\gamma; E_a) = \begin{cases} \dfrac{1}{2}\dfrac{dN_a}{dE}\dfrac{\Delta E_a}{\Delta E_{shift}}, & \left(\left|E_\gamma - E_\gamma^0\right| \le \Delta E_{shift}\right) \\ 0 \quad , & (otherwise) \end{cases} \quad , \tag{4}$$

$$\Delta E_{shift} = \frac{v_a}{c}E_\gamma^0$$

where E_γ^0 is transition energy of γ-ray radiation $\left(E_\gamma^0 = 0.478 \; or \; 0.429 \text{ MeV}\right)$, and c is velocity of light. From the velocity distribution function obtained, we can also evaluate the ^{6}Li+d reaction rate coefficient;

$$\langle\sigma\upsilon\rangle_{^6Li(d,b)a} = \sqrt{8\pi}\left(\frac{m_{^6Li}}{T_{^6Li}}\right)^{3/2}\int d\upsilon_D \upsilon_D f_D(\upsilon_D) \times \int d\upsilon_{^6Li}\upsilon_{^6Li}\exp\left(-\frac{m_{^6Li}}{2T_{^6Li}}\upsilon_{^6Li}^2\right) \times \left[\int_{\left|\upsilon_D - \upsilon_{^6Li}\right|}^{\upsilon_D + \upsilon_{^6Li}} d\upsilon_r \upsilon_r^2 \sigma_{^6Li(d,b)a}(\upsilon_r)\right] / n_D n_{^6Li} , \tag{5}$$

where υ_r is relative velocity between D and ^{6}Li. Because the excited nuclei rapidly transit to ground state emitting γ-ray in several femto-seconds order, thus the reaction rate coefficient can be obtained directly from the γ-ray emission rate. If the distribution function is given, the 0.478 and 0.429 MeV γ-rays emission rates and energy spectrums are evaluated. The ^{6}Li(*d,p*)^{7}Li* and ^{6}Li(*d,n*)^{7}Be* cross sections are taken from Refs. 20-22. Throughout the calculations, ^{6}Li is assumed to be Maxwellian at the same temperature with bulk ion. Because the mass of ^{6}Li is larger than deuteron, distortion of velocity distribution function, e.g. due to NES, would be negligible.

To calculate the correlation between the shape of non-Maxwellian distribution function and the γ-ray emission spectrum, we roughly simulate the fuel-ion distribution function using the following two-temperature Maxwellian model;

$$f_{total} = f_{bulk} + f_{tail}$$

$$f_{bulk\ (tail)} = 4\pi n_{bulk\ (tail)}\upsilon_D^2 \times \left(\frac{m_D}{2\pi k T_{bulk\ (tail)}}\right)^{3/2} \times \exp\left(\frac{m_D \upsilon_D^2}{2kT_{bulk\ (tail)}}\right) . \tag{6}$$

In above expression, total distribution function f_{total} is expressed as a summation of the bulk f_{bulk} and tail f_{tail} distribution functions.

In Fig.2 we show the distribution functions (Eq.(6)) when tail temperature T_{tail} (=10, 60, 300, 500 and 1000 keV) and bulk temperature T_{bulk} = 5keV, total deuteron density $n_D = 10^{19}$ m^{-3}, tail-ion density $n_{tail} = 10^{17}$ m^{-3}, and bulk ion density $n_{bulk} = n_D - n_{tail}$ are assumed. The bulk T_{bulk} and tail T_{tail} temperatures and tail density n_{tail} are chosen referring to the distribution function experimentally observed in Large Helical Device (LHD) [6,7].

3. Results and Discussion

The emission spectrums of ^{7}Li* and ^{7}Be* are calculated using the deuteron velocity distribution functions of Eq.(6) and presented in Fig.3 and Fig.4 for several tail temperatures. We can observe the broadening of ^{7}Li* (^{7}Be*) energy spectrum due to the energetic tail f_{tail} formation in deuteron distribution function (see Fig.2) and the increment in the emission rate of ^{7}Li* (^{7}Be*) with increasing tail temperature T_{tail}.

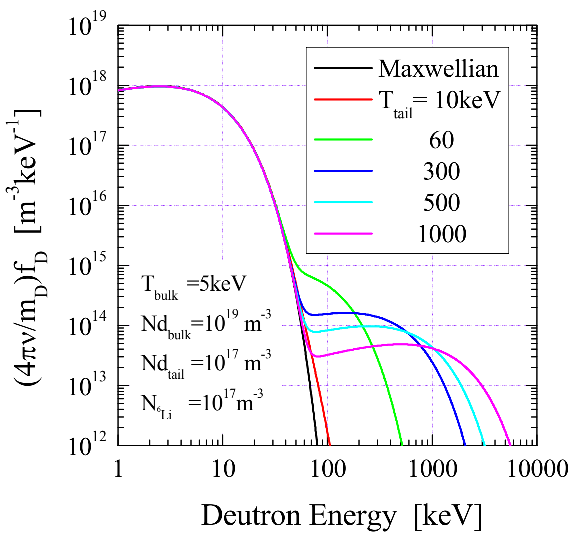

Fig.2 Deuteron distribution function simulated by two-temperature Maxwellian model.

The emission spectrums of 0.478- and 0.429-MeV γ-rays are presented in Fig.5. In order to compare the shapes of γ-ray energy spectrums for different emission rates (T_{tail}), normalized 0.478-MeV γ-ray emission spectrums are also presented in Fig.6. They are normalized at the peak value of each spectrum. It is found that the width of the γ-ray emission spectrum is broadened due to the energetic tail formation. Because of the small cross section in thermal energy range, the γ-ray emission spectrum is not affected by the shape of the bulk component in deuteron distribution function, i.e. n_{bulk} and T_{bulk}. Furthermore density of the tail component n_{tail} influences only the magnitude of γ-ray emission rate(the shape of γ-ray energy spectrum is not affected by n_{tail}). By looking at the normalized 0.478-MeV γ-ray emission spectrum from D+^{6}Li reaction, we can directly estimate the energetic-deuteron distribution function, i.e. T_{tail} when two-temperature Maxwellian model is assumed.

In Fig.7, correlation between 0.478-MeV γ-ray emission rate from ^{6}Li(*d,p*)^{7}Li* reaction and n_{tail} is shown for various tail temperatures T_{tail}. If we have previously known the tail temperature by looking at the emission spectrum, we can also determine the magnitude (density) of the tail component, i.e. n_{tail}, by measuring the γ-ray emission rate.

A possibility of diagnostics of fast-ion distribution function using ^{6}Li+D γ-ray-generating reactions has been shown. The spectrometry of γ-ray emitted by ^{6}Li+D reaction can not be used for DT-burning-plasma diagnostics because of the background noise; however similar diagnostic approaches using other γ-ray generating reactions, e.g. ^{9}Be(*α,n*)^{12}C*, ^{12}C*→^{12}C+γ, may have a prospect for fast-ion diagnostics using the presented method. Further investigation using other γ-ray-generating reaction would also be necessary. A measurement method of γ-ray is basically a line-integrated measurement. The γ-ray emission spectrum is not affected by the energy distribution of bulk ions. The energetic ions are locally produced by external heating. If the spatial distribution of the γ-ray emission

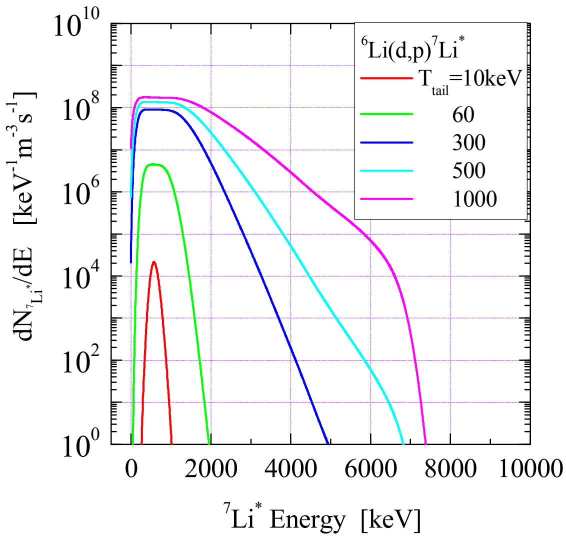

Fig.3 ^{7}Li* energy spectrum (calculated using the deuteron distribution function of Eq.(6)).

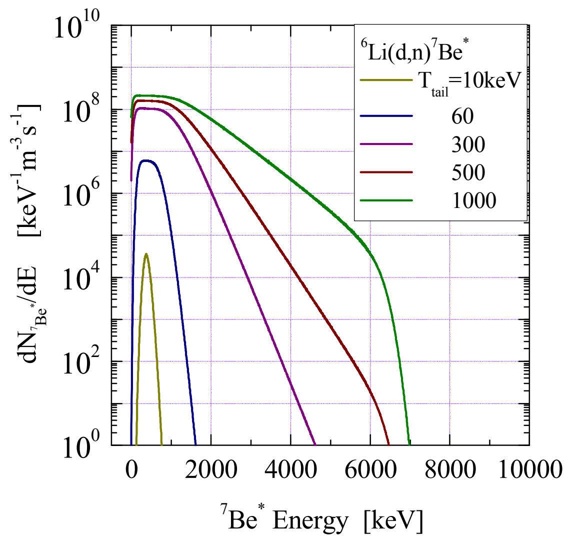

Fig.4 ^{7}Be* energy spectrum (calculated using the deuteron distribution function of Eq.(6)).

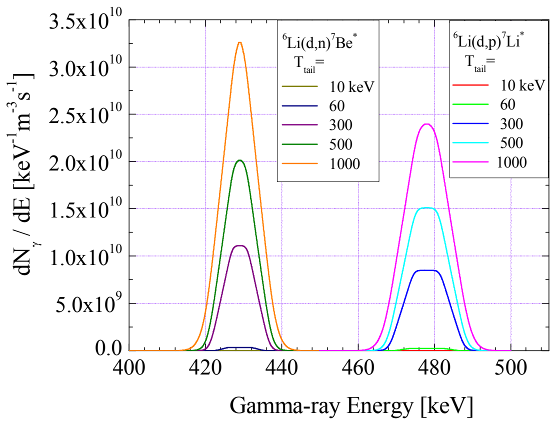

Fig.5 ^{6}Li(d,p)^{7}Li* and ^{6}Li(d,n)^{7}Be* γ-ray energy spectrums for various tail temperatures T_{tail}.

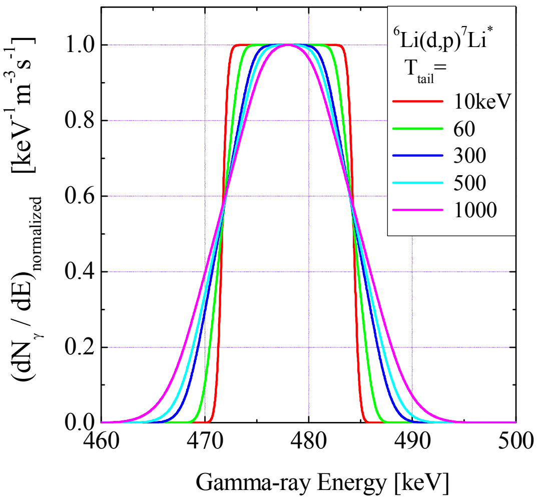

Fig.6 Normalized 0.478 MeV γ-ray energy spectrums for ^{6}Li(d,p)^{7}Li* reactions.

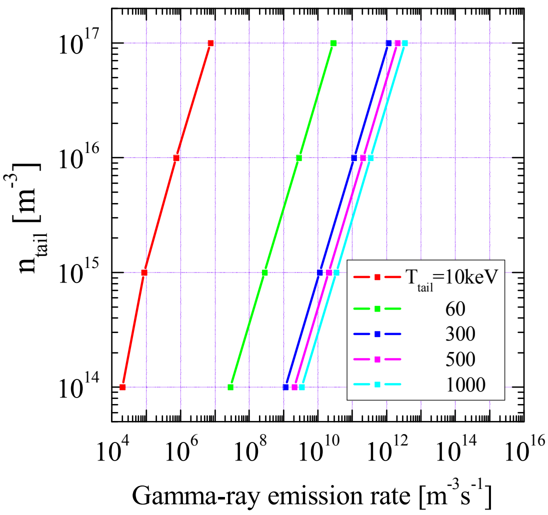

Fig.7 Tail density n_{tail} as a function of γ-ray emission rate from ^{6}Li(d,p)^{7}Li* reactions for several tail temperatures T_{tail}.

sources could be assessed using the techniques like tomography [11], the locally-averaged emission spectrum could be measured by selecting appropriate line of sight. In this paper, we have expressed the deuteron velocity distribution function using the two-temperature Maxwellian model. The analysis using more realistic distribution would be required.

4. References

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