Use of γ-Ray-Generating ^{6}Li+D Reaction for Verification of Boltzmann-Fokker-Planck Simulation and Knock-on Tail Diagnostic in Neutral-Beam-Injected Plasmas

Hideaki MATSUURA, Makoto NAKAMURA and Yasuyuki NAKAO

Department of Applied Quantum Physics and Nuclear Engineering, Kyushu University, Fukuoka 819-0395, Japan

(Received 3 December 2006 / Accepted 11 April 2007)

The γ-ray emission rate by ^{6}Li(d,p)^{7}Li*, ^{7}Li$^{*}\rightarrow^{7}$Li+γ reaction when 50∼250 keV proton beam is injected into ^{6}Li containing deuterium plasmas ($n_e \sim 10^{19}$ m^{-3} and T_e = 1∼10 keV) is evaluated by simultaneously solving the Boltzmann-Fokker-Planck (BFP) equations for deuteron and proton. A possible experiment to verify the BFP simulations, e.g. knock-on tail effect on T(d,n)^{4}He reaction rate coefficient and/or plasma diagnostics which utilize the tail formation in ion distribution function, is proposed.

Keywords: Nuclear elastic scattering, Boltzmann-Fokker-Planck equation, ^{6}Li(d,p)^{7}Li* reaction rate coefficient, γ−ray emission rate

DOI: 10.1585/pfr.2.S1078

1. Inroduction

It is well known that the nuclear elastic scattering (NES) contributes to a certain extent to the slowing-down of suprathermal ions in fusion plasmas. In a conceptual design of next-generation fusion device, 3.52-MeV α-particles are continuously produced and use of beam injection with energy more than 1 MeV is also considered. In such a state, the NES [1, 2] effects on slowing down of energetic ions may not be negligible compared with those due to Coulomb collisions.

In a magnetically-confined deuterium-tritium (DT) thermonuclear plasma, aiming at an application to the plasma diagnostic, knock-on tails in triton, deuteron and impurity ion distribution functions due to NES of energetic α-particle were studied [3–10]. A knock-on tail formation in impurity ions [3, 4], tail effect on the emitted-neutron spectrum [5, 6] and γ-ray emission rate by nuclear reaction between fuel and impurity ions [7, 8] were calculated. The knock-on tail formation (production of suprathermal ion) by NES of fusion-produced α-particle was experimentally ascertained [9, 10]. To know the NES effect on the reaction rate coefficient, an analysis model which can consistently treat the distortion of "bulk" component of fuel-ion velocity distribution function simultaneously with the knock-on tail formation is required. We have previously developed the Boltzmann-Fokker-Planck (BFP) model [11, 12] to examine the NES effect on the fusion reaction rate coefficients in magnetically-confined D^{3}He plasmas. Recently on the basis of the previously developed BFP model, we studied the NES effect on fractional energy deposition to ions [13–15] and T(d, n)^{4}He reaction rate coefficient [7, 8, 16, 17] in ITER-like deuterium-tritium plasmas. For a forthcoming burning plasma experiment, it would be meaningful to perform a verification of the BFP model by comparing the calculations with measured data in currently-existing fusion devices.

Use of γ-ray spectrometry as a burning-plasma diagnostic has been proposed and developed assuming various γ-ray-generating nuclear reactions [18]. The use of ^{6}Li-induced γ-ray-generating reactions was proposed by Voronchev *et al.* [19]. In this paper, we consider the use of ^{6}Li+D reaction in non-reactive (low temperature) and low density plasmas which are often seen in currently-existing devices, for the purpose to verify the BFP simulations. By reasons of (a) the knock-on tail tends to become relatively large in low density plasmas [14–17], (b) to look at the knock-on tail effect clearly, it is desirable that the injected-beam specie is different from the background ion species and (c) the NES cross-section between proton and deuteron is comparably larger than deuteron-deuteron one [2], we consider the proton beam injection into the ^{6}Li containing deuterium plasmas. The knock-on tail formation in deuteron distribution function due to NES of injected proton is examined on the basis of the previously developed BFP model [11, 12]. From the obtained deuteron distribution function, the 0.5 MeV γ-ray emission rate by ^{6}Li(d,p)^{7}Li*, ^{7}Li$^{*}\rightarrow^{7}$Li+γ [19, 20] is evaluated for various plasma states. The experiment to verify the BFP simulations is presented.

author's e-mail: mat@nucl.kyushu-u.ac.jp

2. Analysis Model

The following BFP equations for deuteron and injected proton are solved simultaneously:

$$\left(\frac{\partial f_a}{\partial t}\right)^{\mathrm{C}} + \sum_i \left(\frac{\partial f_a}{\partial t}\right)_i^{\mathrm{NES}} + \frac{1}{v^2}\frac{\partial}{\partial v}\left(\frac{v^3 f_a}{2\tau_C^*(v)}\right) + S_a(v) - L_a(v) = 0, \quad (1)$$

where f_a is the velocity distribution function of species a ($a = D, p$). The first term in Eq. (1) represents the effect of the Coulomb collision with background ion and electron. The electron is assumed to be Maxwellian with temperature T_e. The second term accounts for NES of particle a with "background" species i; $(a,i) = (D,p)$ and/or (p,D) [7, 11, 12, 14–17]. The third term in Eq. (1) represents the diffusion in velocity space due to thermal conduction. For proton, the particle source ($S_{proton}(v)$) and loss ($L_{proton}(v)$) terms can be written as

$$S_{proton}(v) - L_{proton}(v) = \frac{S_{\mathrm{NBI}}}{4\pi v^2}\delta(v - v_{\mathrm{NBI}}) - \frac{f_P(v)}{\tau_P^*(v)}, \quad (2)$$

where S_{NBI} is neutral beam injection (NBI) rate per unit volume and v_{NBI} is speed corresponding to injected proton energy E_{NBI}. We express the injection rate by using the beam power P_{NBI}, i.e. $S_{\mathrm{NBI}} = P_{NBI}/(E_{\mathrm{NBI}} Vol)$. Here Vol represents the plasma volume, and in this paper we assume $Vol = 100\,\mathrm{m}^3$. To incorporate the unknown loss mechanism of energetic ion into the analysis, following Bittoni's treatment [21], we simulate the velocity dependence of the energy loss due to thermal conduction $\tau_c^*(v)$ and the particle-loss time $\tau_p^*(v)$ by using a dimensionless parameter γ, i.e. $\tau_{c(p)}^*(v) = C_{c(P)}\tau_{c(P)}$ (when $v < v_{th}$), $\tau_{c(p)}^*(v) = C_{c(P)}\tau_{c(P)}(v/v_{th})^\gamma$ (when $v \geq v_{th}$). The high exponent (γ) chosen ensures rapid increment of both confinement times in higher energy range than in thermal energy range, and thus energetic particle itself and its energy are hardly evacuated compared with that of thermal particle. In this paper throughout the calculations $\gamma = 6$ is assumed. As was discussed in Ref. 15, in usual plasma condition, the γ would not be a significant parameter. Considering energy loss mechanisms both due to thermal conduction and particles transport loss from plasma, the global energy confinement time is defined as $1/\tau_E = 1/\tau_C + 1/\tau_P$. For background deuteron, we assume that the particle loss is compensated by adequate fuelling method, i.e. $S_D\delta(v - v_0)/4\pi v^2 - f_D(v)/\tau_p^*(v) = 0$. Here v_0 indicates the speed of the fueled particle, which is much smaller than the thermal speed (nearly equal to zero) and $S_0 = n_D/\tau_p$. Because of the small concentration of ^{6}Li, loss of deuteron and generation of proton due to $^6\mathrm{Li}(d,p)^7\mathrm{Li}^*$ reaction are ignored.

From the obtained deuteron distribution function, we can evaluate the $^6\mathrm{Li}(d,p)^7\mathrm{Li}^*$ reacton rate coefficient as

$$\langle\sigma v\rangle_{^6\mathrm{Li}(d,p)^7\mathrm{Li}} = \sqrt{8\pi}\left(\frac{m_{Li}}{T}\right)^{3/2}\int dv_{\mathrm{D}} v_{\mathrm{D}} f_D \times \int dv_{\mathrm{Li}} v_{\mathrm{Li}} \exp\left(-\frac{m_{Li}}{2T}v_{Li}^2\right) \times \left[\int_{|v_{\mathrm{D}}-v_{\mathrm{Li}}|}^{v_{\mathrm{D}}+v_{\mathrm{Li}}} dv_r v_r^2 \sigma^6_{\mathrm{Li}(d,p)^7\mathrm{Li}}(v_r)\right]. \quad (3)$$

In this paper, to facilitate the analysis, ^{6}Li is assumed to be Maxwellian at the same temperature with electron. Because ^{6}Li has a large mass compared with deuteron, the knock-on tail in ^{6}Li distribution function would appear in smaller velocity (smaller $^6\mathrm{Li}(d,p)^7\mathrm{Li}^*$ cross section) range than that in deuteron distribution function. Since the charge number of Li is 3, the contribution of p-^{6}Li NES would also be smaller than that of p-D one.

To estimate the degree of the enhancement of the reaction rate coefficient due to knock-on tail (non-Maxwellian component) formation by NES, we compare the obtained fusion reaction rate coefficient with the one in the case that both deuteron and ^{6}Li distributions are Maxwellian. For this purpose, we must identify the temperature of bulk component in deuteron distribution function. We determine the bulk temperature T_{bulk} of deuteron by comparing the bulk component of the obtained distribution function with Maxwellian by mean of the least squares fitting. To quantitatively estimate the reactivity enhancement, we introduce the enhancement parameter;

$$\eta = \left(\frac{\langle\sigma v\rangle_{^6\mathrm{Li}(d,p)^7\mathrm{Li}}}{\langle\sigma v\rangle^{\mathrm{Maxwell}}_{^6\mathrm{Li}(d,p)^7\mathrm{Li}}} - 1\right) \times 100 \quad [\%], \quad (4)$$

where, $\langle\sigma v\rangle^{\mathrm{Maxwell}}_{^6\mathrm{Li}(d,p)^7\mathrm{Li}}$ is the $^6\mathrm{Li}(d,p)^7\mathrm{Li}^*$ reaction rate coefficient in the case that both deuteron and ^{6}Li distribution functions are Maxwellian at temperature T_{bulk}. In this paper the NES cross-sections are taken from the work of Perkins and Cullen [2], the $^6\mathrm{Li}(d,p)^7\mathrm{Li}^*$ cross sections are taken from Refs. 20, 22 and 23.

3. Results and Discussion

In Fig. 1 we first show the steady-state deuteron distribution function in the case that mono-energetic proton beam is injected into deuterium plasmas. The solid lines indicate the present calculations while the dotted lines denote Maxwellian at temperature T_{bulk}. In this calculation, the electron temperature $T_e = 2\,\mathrm{keV}$, fuel-ion and electron densities $n_{\mathrm{D}} = n_{\mathrm{e}} = 10^{19}\,\mathrm{m}^{-3}$, confinement times $\tau_{\mathrm{E}} = (1/2)\tau_{\mathrm{P}} = 1.0\,\mathrm{sec}$ and $P_{NBI} = 10\,\mathrm{MW}$ are assumed. We can see that knock-on (non-Maxwellian) component appear in deuteron distribution function, owing to the recoils of thermal deuteron due to NES of injected beam proton. The suprathermal component is extended toward high-energy range, with increasing beam-injection energies.

In Fig. 2 the $^6\mathrm{Li}(d,p)^7\mathrm{Li}^*$ cross section is presented as a function of center-of-mass energy. The cross section

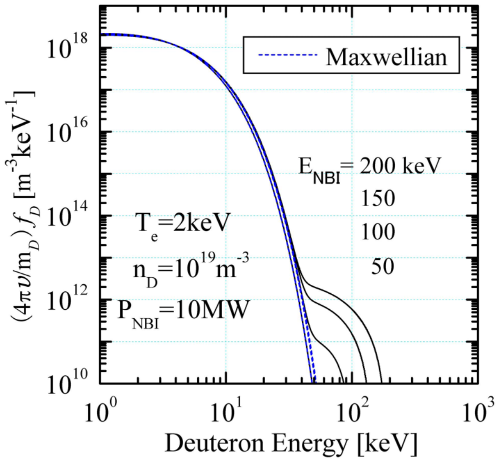

Fig. 1 Deuteron distribution function under mono-energetic proton beam injection.

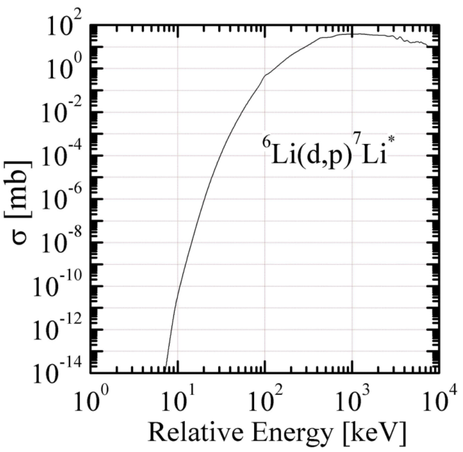

Fig. 2 ^{6}Li(d,p)^{7}Li* cross section as a function of center-of-mass energy.

rapidly decreases with decreasing relative energy. It is expected that owing to the existence of small fraction of knock-on tail component, velocity-averaged ^{6}Li(d,p)^{7}Li* reaction rate coefficient is significantly influenced.

The enhancement parameter of reaction rate coefficient η is presented in Fig. 3 as a function of proton injection energies, together with the reaction rate coefficients when knock-on tail is created and both deuteron and ^{6}Li are Maxwellian at temperature T_{bulk}. In this calculation, the electron temperature $T_e = 2$ keV, confinement times $\tau_E = (1/2)\tau_P = 1.0$ sec and $P_{NBI} = 10$ MW are assumed. Owing to the tail formations in deuteron distribution function, the ^{6}Li(d,p)^{7}Li* reaction rate coefficient increases from the values when the NES is neglected. When $E_{NBI} = 230$ keV, the η parameter reaches almost $\sim 10^4$. If we consider a deuterium plasma containing 1 percent of ^{6}Li to deuteron, the 0.5 MeV γ-ray generation rate is

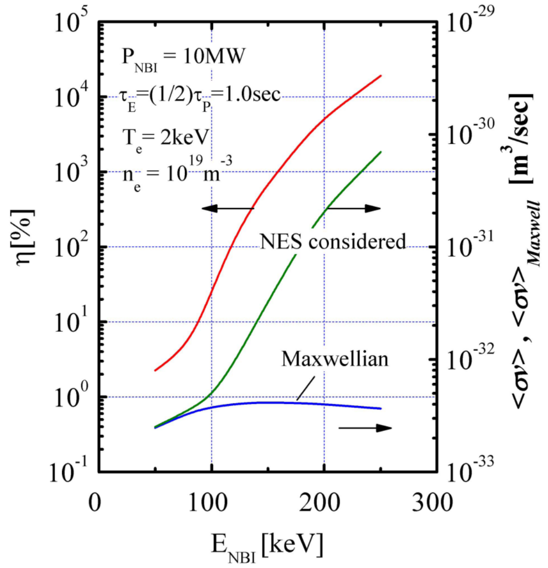

Fig. 3 ^{6}Li(d,p)^{7}Li* reaction rate coefficients and the enhancement parameter η as a function of incident proton energy.

roughly estimated as $\sim 5 \times 10^7$ sec^{-1}. The η parameter becomes large with increasing proton injection energies. This is because the knock-on tail reaches higher energy (large ^{6}Li(d,p)^{7}Li* cross section) range with increasing proton energies (as was shown in Fig. 1). It should be noted that owing to the knock-on tail formation, the rate coefficient (0.5 MeV γ-ray emission rate) is significantly changed.

In Fig. 4, we show the enhancement parameter η as a function of electron temperature for several incident proton energies. In this calculation, confinement times $\tau_E = (1/2)\tau_P = 1.0$ sec and $P_{NBI} = 10$ MW are assumed. With decreasing bulk-ion (electron) temperature, the absolute values of ^{6}Li(d,p)^{7}Li* reaction rate coefficient $\langle\sigma v\rangle^{Maxwell}_{^6Li(d,p)^7Li}$ when both deuteron and ^{6}Li are assumed to be Maxwellian rapidly decreases, which relatively enhances the contribution of knock-on tail component. It is found again that the plasma temperature is a crucial factor which significantly changes the 0.5 MeV γ-ray emission rate, i.e. the knock-on tail formation.

By comparing the measured γ-ray emission rate (absolute value of the γ-ray flux and its enhancement from the value for Maxwellian plasma, i.e. parameter η) with the result of the BFP simulation for various plasma parameters, it is expected that we can verify the BFP calculations. It is also desirable that the spectrum broadening of the γ-ray flux can be measured using a γ-ray detector having high-energy resolution. Comparing the measured spectrum with the result of the simulation we can more directly examine the shape of the knock-on tail component and its effective temperature.

On the basis of the BFP model [11, 12], the enhancement of the ^{6}Li(d,p)^{7}Li* reaction rate coefficient,

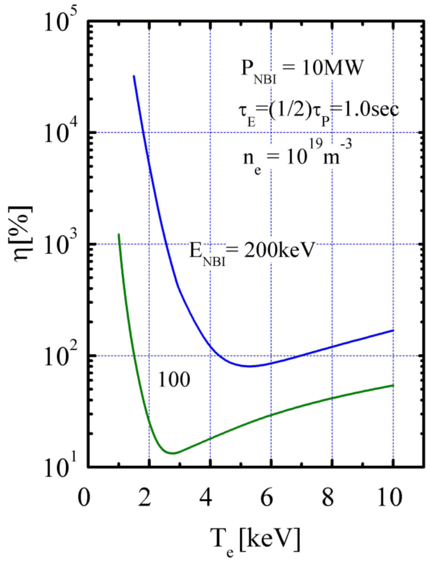

Fig. 4 ^{6}Li(d,p)^{7}Li* reactivity enhancement parameter η as a function of electron temperatures.

i.e. enhancement of the 0.5 MeV γ-ray emission rate by Li$^*\rightarrow{}^7$Li+γ reaction, due to knock-on tail formation in deuteron distribution function when proton beam is injected into ^{6}Li containing plasma has been evaluated. A possible experiment to verify the BFP simulations on currently-existing fusion devices is presented.

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