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Ion Channeling by Nuclear Elastic Scattering and Its Effect on Neutral Beam Injection Heating in Thermonuclear Plasmas

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Abstract

Distortion in the fuel-ion (deuteron and triton) velocity distribution functions due to nuclear elastic scattering (NES) by beam ion during neutral-beam-injection (NBI) plasma heating operation is examined by solving the Boltzmann-Fokker-Planck (BFP) equations for deuteron, triton and beam ion, simultaneously with the Fokker-Planck equation for α-particle in the deuterium-tritium (DT) thermonuclear plasmas. Using the obtained distribution functions, enhancement in the T(d,n)^{4}He fusion reaction rate coefficient between background deuteron and triton are evaluated. It is shown that the enhancement becomes appreciable when beam energy is larger than ~700 keV.

Keywords:

nuclear elastic scattering, NBI plasma heating, Boltzmann-Fokker-Planck equation, T(d,n)^{4}He fusion reaction rate coefficient

1. Introduction

It is well known that for suprathermal ions, the Nuclear Elastic Scattering (NES) contributes to the slowing-down process. In conceptual designs of next-generation fusion devices, use of beam energy more than 1 MeV is considered. In this case, the NES effects on slowing down of beam particles may not be ignorant compared with those due to Coulomb collisions. The Coulomb scattering process is characterized by many small-energy-transfer events. On the other hand, the NES is a non-Coulombic, large-energy-transfer (LET) scattering process. Devany & Stein [1] first pointed out the necessity to take into account the nuclear-forces contribution to ion-ion scattering in high-temperature plasmas. In order to investigate the NES effect, many analysis formulations to describe the discrete nature of LET scattering have been developed [2-11].

The global NES effect on plasma burn-characteristics was first estimated by Nakao *et al*. [4] by using the energy loss rate [1]. On the basis of the multi-group analysis method [5], more accurate estimation were made by Galambos *et al*. [6] and Nakao *et al*. [7], accounting for the LET knocking-up of background ions from thermal to higher energy range. A knock-on tail formation in deuteron (triton) distribution functions owing to the NES by α-particles in DT plasmas and its effect on the emitted-neutron spectrum were examined by Fisher [12] and Ballabio [13]. By explicitly separating the continuous slowing-down (Fokker-Planck collision) and the LET scattering (Boltzmann collision) terms, we have developed the Boltzmann-Fokker-Planck (BFP) analysis model [8,9].

We derived the energy loss rate of fast ion due to NES, including thermal motion effect of background ions, and using the derived expression we roughly estimated NES effect on fractional NBI power deposition to ions in DT plasmas [10]. Since the NES is a discrete energy transfer process, however, the NES effect should be examined considering the shape of the velocity distribution function of both beam and background ions. Recently by solving the BFP equation for beam ion on the assumption that background deuteron and triton are Maxwellian, we more accurately examined the fractional NBI power deposition to ions in DT plasmas [11]. In this paper we solve the BFP equation not only for beam ion, but also for background deuteron and triton. Considering the distortion in background deuteron and triton distribution functions, we further investigate the NES effect on the T(d,n)^{4}He fusion reaction rate coefficient between background deuteron and triton during NBI plasma heating operations.

2. Analysis model

To facilitate the analysis we only consider the nu-

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clear elastic collision between beam ion and background fuel ions (D and T). We solve the following BFP equations for D, T and injected beam ion simultaneously with the Fokker-Planck equation for α :

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

where f_a is the velocity distribution function of species a ($a = D, T, beam - ion$). The first term in Eq. (1) represents the effect of the Coulomb collisions with background ions and electron. The second term accounts for the nuclear elastic collision between beam ion and background ions:

$$\left(\frac{\partial f_a}{\partial t}\right)_i^{NES} = \frac{2\pi}{v_a^2}\int_0^\infty v'_a f_a(v'_a)\int_0^\infty v_i f_i(v_i) P(v'_a \to v_a|v_i) \int_{|v'_a - v_i|}^{v'_a+v_i} v_r'^2 \sigma_{NES}(v'_r) \mathrm{d}v'_r \mathrm{d}v_i \mathrm{d}v'_a - \sum_i \frac{2\pi}{v_a} f_a(v_a)\int_0^\infty v_i f_i(v_i) \int_{|v'_a - v_i|}^{v'_a+v_i} v_r^2 \sigma_{NES}(v_r) \mathrm{d}v_r \mathrm{d}v_i, \quad (2)$$

where $v'_r = |\vec{v'}_a - \vec{v}_i|$ and $v_r = |\vec{v}_a - \vec{v}_i|$, subscript i represents background ion species, i.e. D, T for beam-ion and beam-ion for D and T. We have introduced the probability distribution function P (i.e. probability that the injected beam ion which has the speed v'_a is scattered into the speed region v_a owing to the NES with background ion, i.e. deuteron or triton, which has speed v_i). If we assume that the NES is isotropic in the CM system, then

$$P(v'_a \to v_a|v_i) = \begin{cases} \dfrac{2v_a}{v_{max}^2 - v_{min}^2} & \text{, for } v_{min} \le v_a \le v_{max} \\ 0 & \text{, otherwise} \end{cases}, \quad (3)$$

where

$$v_{max(min)} = \left| \frac{m_i\sqrt{v_a'^2 + v_i^2}}{m_a + m_i} + (-)\frac{\sqrt{m_a^2 v_a'^2 + m_i^2 v_i^2}}{m_a + m_i} \right|. \quad (4)$$

The third term in Eq. (1) represents the diffusion in velocity space due to thermal conduction. The typical energy-loss time due to thermal conduction may be written as $\tau_C^*(v) = C_C\tau_C \mathrm{Max}[1, v/v_{th}]^\gamma$ Here the coefficient C_C is determined so that the velocity-integrated energy loss rate becomes $(3/2)nT/\tau_C$. By adjusting the parameters γ, we can simulate various loss mechanisms due to thermal conduction. For beam ion, particle source ($S_{beam}(v)$) and loss ($L_{beam}(v)$) terms can be written as

$$S_{beam}(v) - L_{beam}(v) = \frac{S_{NBI}}{4\pi v^2}\delta(v - v_{NBI}) - \frac{f_{beam}(v)}{\tau_P^*(v)}, \quad (5)$$

where S_{NBI} is NBI rate per unit volume and v_{NBI} is speed corresponding to injected beam energy E_{NBI}. We express the injection rate by using the beam energy and plasma Q-value, i.e. $S_{NBI} = P_f/(QE_{NBI})$. Here P_f represents fusion power produced by T(d,n)^{4}He reaction, i.e. $P_f = n_D n_T \langle\sigma v\rangle_{DT} E_f (E_f = 17.6\,\mathrm{MeV})$. The confinement time of beam ion may be written as $\tau_P^*(v) = C_P\tau_P\mathrm{Max}[1, v/v_{th}]^\gamma$. The coefficient C_P is determined so that the velocity-integrated particle loss rate becomesn/τ_P. In present calculations we assume that the loss of energetic ions is smaller compared with that of thermal ones, thus large γ value, *e.g.* $\gamma = 6$, is chosen. In this assumption, the influence of the γ values on the fusion reactivity is small. Considering both energy loss mechanisms due to thermal conduction and particle transport, the global energy confinement time is defined as $1/\tau_E = 1/\tau_C + 1/\tau_P$. For background deuteron and triton, we assume that the particle loss is compensated by adequate fuelling method, i.e. $S_{D(T)}(v) - L_{D(T)}(v) = 0$. In this treatment we may overestimate the power supplied by fueling (they are injected to keep the fuel-ion density constant). Since in ∼ 10- keV temperature range, however, both powers supplied by fueling and lost by particle loss are smaller than those by NBI and α-heating, the influence of the fueling and particle loss terms on the fuel-ion distribution functions is negligible.

From the obtained deuteron and triton distribution functions, we can evaluate the T(d,n)^{4}He fusion reactivity as

$$\langle\sigma v\rangle_{T(d,n)^4He} = 8\pi^2 \int \mathrm{d}v_D v_D f_D \int \mathrm{d}v_T v_T f_T \left[\int_{|v_D - v_T|}^{v_D+v_T} \mathrm{d}v_r v_r^2 \sigma_{DT}(v_r)\right]. \quad (6)$$

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

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

where, $\langle\sigma v\rangle^{Maxwell}_{T(d,n)^4He}$ is the T(d,n)^{4}He fusion reaction rate coefficient when both deuteron and triton distribution functions are Maxwellian of temperature T_{bulk}. In this paper the NES cross-sections are taken from the work of Perkins and Cullen [14], and the T(d,n)^{4}He fusion cross sections are taken from the work of Duane [15].

3. Results and discussion

We consider the DT plasma in which mono-energetic deuterium beam is injected. In Fig. 1 we first show the steady-state (a) deuteron and (b) triton distribution functions when 1 MeV (2 MeV) mono-energetic beam is injected. The solid lines indicate the present calculations and the dotted lines denote Maxwellian of temperature T_{bulk}. In this calculation, the electron temperature $T_e = 10\,\mathrm{keV}$, fuel-ion and electron densities $n_D = n_T = (1/2)n_e = 10^{19}\,\mathrm{m}^{-3}$, confinement times $\tau_E = (1/2)\tau_P = 3.0\,\mathrm{sec}$ and $Q = 1$ are assumed. We can find that suprathermal (non-Maxwellian) components appear in both deuteron and triton distribution functions, owing to the recoils of thermal deuterons and tritons via NES by injected beam ions. The suprathermal component in deuteron distribution function is somewhat larger than that in the triton distribution function. This is because that the D-D NES cross-sections are larger than those of D-T ones.

In Fig. 2 (a) the enhancement parameter η is presented as a function of beam-injection energies for several background densities. In this calculation, the electron temperature $T_e = 10\,\mathrm{keV}$, confinement times $\tau_E = (1/2)\tau_P = 3.0\,\mathrm{sec}$ and $Q = 1$ are assumed. According to the tail formation in both deuteron and triton distribution functions, the T(d,n)^{4}He fusion reaction rate coefficient between background deuteron and triton increases from the values when the NES is neglected. In Fig. 2 (b), the deuteron distribution functions when $n_D = n_T = (1/2)n_e = 0.5 \times 10^{19}$ and $5 \times 10^{19}\,\mathrm{m}^{-3}$ are exhibited. For large background densities, the bulk temperature is more easily increases, thus the degree of the increment in the high-energy component in the velocity region where fusion cross-sections have a peak ($\sim$ 100 keV deuterium energy) becomes relatively small.

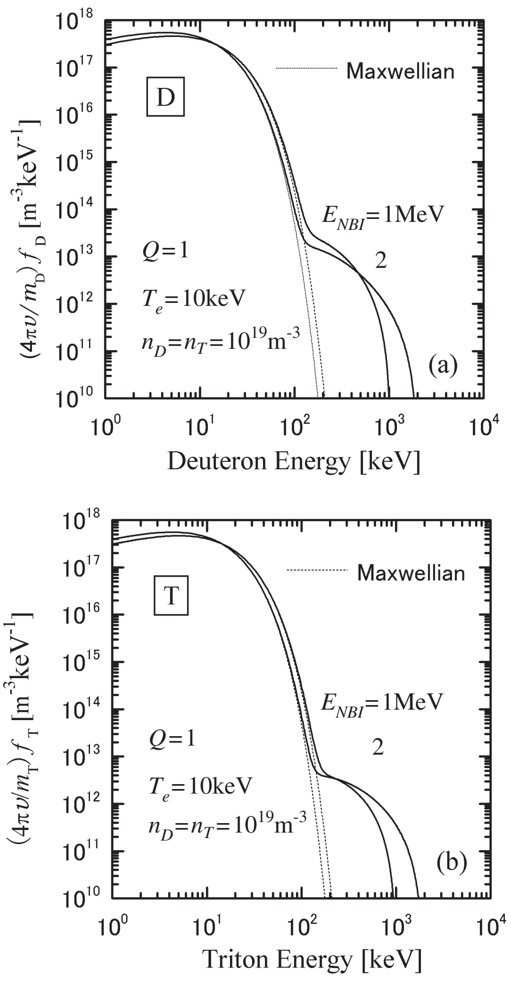


Fig. 1 (a) Deuteron and (b) Triton distribution functions when 1 MeV and 2 MeV mono-energetic deuterium beam is injected into DT plasmas.

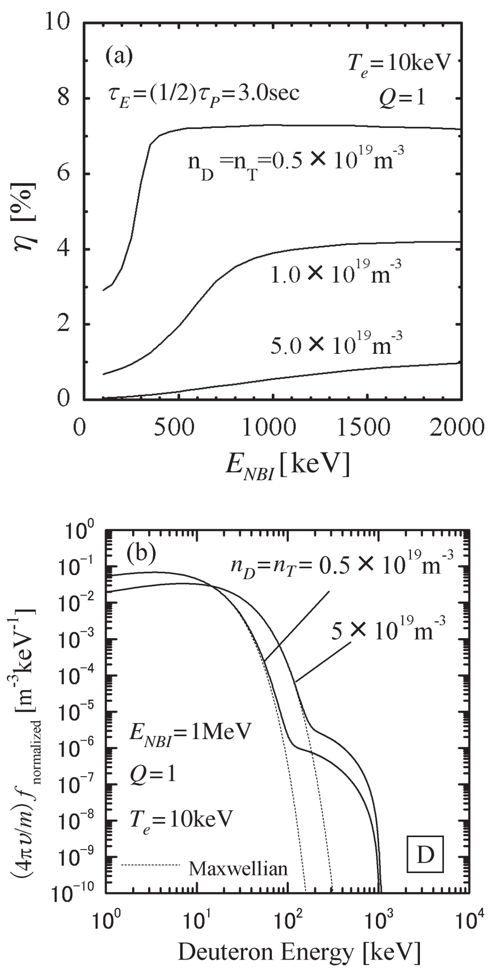
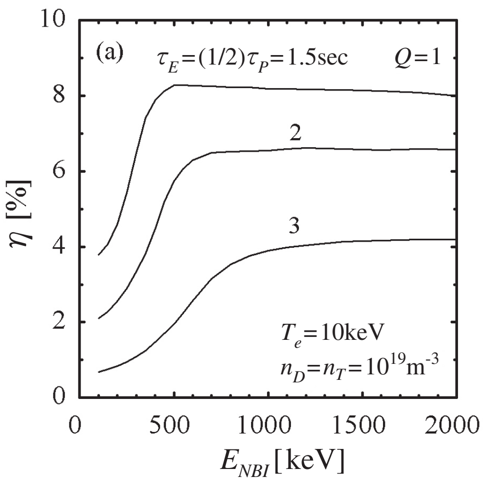


Fig. 2 (a) Enhancement parameters and (b) deuteron distribution functions for several background densities.

This is the reason why the enhancement parameter is small for large background densities.

We next show the enhancement parameter η for several confinement times in Fig. 3 (a). The electron temperature $T_e = 10$ keV, densities $n_D = n_T = (1/2)n_e = 10^{19}$ m^{-3} and $Q = 1$ are assumed. In Fig. 3 (b), the deuteron distribution functions when $\tau_E = (1/2)\tau_P = 3.0$ and 1.5 sec are presented. When the confinement times are small, the bulk temperature does not so easily increase, thus the degree of the increment in the high-energy component in the velocity region where fusion cross-sections have a peak (~100 keV deuterium energy) becomes relatively large. The enhancement in T(d,n)^{4}He reaction rate coefficient becomes large for small confinement times.

We have shown that the enhancement in the T(d,n)^{4}He fusion reaction rate coefficient due to NES becomes appreciable when beam energy is larger than ~700 keV, and the degree of the enhancement is influenced by the plasma parameters. In this paper we only consider the T(d,n)^{4}He reaction rate coefficient between *background* deuteron and triton. When the tail is created in the background triton distribution function, the fusion reaction between injected beam and background triton would also be influenced. Throughout the calculations $Q = 1$ has been assumed. The NES effect becomes smaller for large Q values. If we consider the NBI heating during plasma startup operation for small Q values, however, more significant NES effect on the fusion reaction rate coefficient may appear. To clarify the NES effect in startup operations, time-dependent startup simulation considering electron power-balance would be necessary.



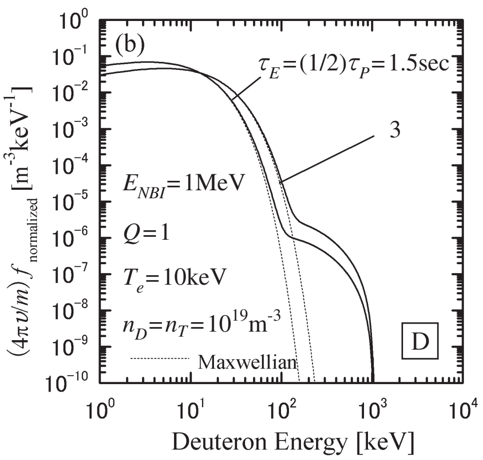


Fig. 3 (a) Enhancement parameters and (b) deuteron distribution functions for several confinement times.

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