Evaluation of Fusion Reactivity Enhancement due to Nuclear Plus Interference Scattering in ^{3}He-Containing Deuterium Plasmas*)

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An effect of nuclear plus interference (NI) scattering on D(d,n)^{3}He, T(d,n)^{4}He and ^{3}He(d,p)^{4}He reaction rate coefficients in ^{3}He-containing deuterium plasma is evaluated on the basis of the Boltzmann-Fokker-Planck (BFP) analysis model. An energetic ^{3}He beam and/or externally-fueled low-energy ^{3}He enhance the ^{3}He(d,p)^{4}He reaction rate from the value for Maxwellian plasma, and increase energetic proton production rate. The energetic protons create the knock-on tail via NI scattering on the fuel-ion velocity distribution functions. It is shown that a recognizable change in the rate coefficients of fusion reactions due to the knock-on tail formation appears.

Keywords: nuclear plus interference scattering, fast-ion velocity distribution function, fusion reaction rate coefficient, ^{3}He-beam injection, Boltzmann-Fokker-Planck model

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1. Introduction

In beam-injected deuterium plasma, energetic beam and fusion-produced ions contribute to the knock-on tail formation in fuel-ion velocity distribution functions [1–4] via nuclear plus interference (NI) scattering[1] [5, 6]. The knock-on tails cause modification of the neutron emission spectrum from the Gaussian distribution [3, 7, 8]. By detecting the non-Gaussian (energetic) component in the neutron emission spectrum, information for energetic ions and NI scattering effect on plasma heating process can be obtained. Ryutov [9] has pointed out that the NI scattering of alpha-particle significantly affects the distribution function of impurity ions and has suggested that the phenomenon can be utilized for diagnostics in thermonuclear plasmas. The hot ion populations created by alpha-particles or RF-heated minority ions were evaluated in DT plasmas [10] and a scenario to measure the fast confined alpha-particle distribution using hot ions produced by NI scattering was also proposed [11]. The measurement using related techniques is planned to be implemented in ITER [12].

So far several calculations have predicted that in D^{3}He plasmas the fraction of transferred power from energetic protons to bulk ions is enhanced almost three times due to the NI scattering [13, 14]. In such a case the confinement parameter can be reduced significantly [15]. Recently we have also shown that the magnitude of the energetic component in proton slowing-down distribution in D^{3}He plasmas is considerably overestimated if the NI scattering was ignored [16]. The contributions of the NI scattering on plasma burning can determine the important physics of thermonuclear fusion especially in the D^{3}He plasmas, and it is important to experimentally ascertain the phenomena and validate the analysis model.

We have presented a scenario to experimentally examine the NI-scattering effects which is expected to appear in reactor-grade plasmas by utilizing the currently existing deuterium plasmas [17, 18]. In deuterium plasmas, proton is intrinsically produced by the D(d,p)T and subsidiary ^{3}He(d,p)^{4}He reactions. If a small amount of ^{3}He is externally included (for example in the minority heating experiments) or intense ^{3}He beam is injected, the proton production rate by the ^{3}He(d,p)^{4}He reaction is enhanced. The fusion-produced energetic protons would contribute to the knock-on tail formation and the spectrum modification processes.

In such a ^{3}He-containing plasma, as a result of the knock-on tail formation, the fusion reactivities for D(d,n)^{3}He, T(d,n)^{4}He and ^{3}He(d,p)^{4}He reactions are also influenced. Since thermonuclear plasma is sustained by fusion reactions caused by small amount of energetic ions that have large fusion cross sections, slight change in the tail component of the fuel-ion velocity distribution function causes significant change in the velocity-averaged reaction rate coefficient. To estimate the magnitude of the knock-on tail from the experimental data, degree of the reactivity enhancement for each reaction should be grasped previously. In this paper, fusion reactivity change due to beam-injection, fusion source and knock-on tail formation via NI scattering are evaluated in ^{3}He-containing (^{3}He beam-injected) deuterium plasma for several plasma conditions on the basis of the Boltzmann-Fokker-Planck sim-

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[1] The NI scattering is defined by subtracting Coulomb contributions from experimental data. It is also referred to as "nuclear elastic scattering (NES)".

ulation.

2. Analysis Model

2.1 Evaluation of ion distribution functions

In this paper uniform deuterium plasma is assumed. The BFP equation for ion species i (i = D, T, alpha-particle, proton and ^{3}He) is written as

$$\sum_j \left(\frac{\partial f_i}{\partial t}\right)_j^{\text{Coulomb}} + \sum_n \left(\frac{\partial f_i}{\partial t}\right)_n^{\text{NI}} + \frac{1}{v^2}\frac{\partial}{\partial v}\left(\frac{v^3 f_i}{2\tau_c^*(v)}\right) + S_i(v) - L_i(v) = 0, \quad (1)$$

where $f_i(v)$ is the velocity distribution function of the species i. The first term on the left-hand side of Eq. (1) represents the Coulomb collision term. The summation is taken over all background species, i.e. j = D, T, alpha-particle, proton, ^{3}He and electron. The collision term is hence non-linear, retaining collisions between ions of the same species. The electron distribution function is assumed to be Maxwellian with temperature T_e. The second term on the left-hand side of Eq. (1) accounts for the NI scattering [19] of species i by background ion n. We consider the NI scattering between 1) alpha-particle and D, 2) alpha and T, 3) alpha and ^{3}He, 4) proton and D, 5) proton and T and 6) proton and ^{3}He, i.e. (i,n) = (D,α), (T,α), (^{3}He,α), (α,D), (α,T), (α,^{3}He), (D,p), (T,p), (^{3}He,p), (p,D), (p,T) and (p,^{3}He). The cross-sections for NI scattering are taken from the work of Perkins and Cullen [6].

The third term in the left-hand side of Eq. (1) represents the diffusion in velocity space due to thermal conduction. To incorporate the unknown loss mechanism of energetic ions into the analysis, we simulate the velocity-dependence of the energy-loss due to thermal conduction and the particle-loss time [20]. The source ($S_i(v)$) and loss ($L_i(v)$) terms take different form for every ion species [19]. By using computational iterative method, BFP equations for deuterons, tritons, alpha-particles, protons and ^{3}He are simultaneously solved for given electron temperature, fuel-ion densities and confinement times, so that global power balance and particle conservation for each ion species are satisfied. By means of iterative computational method, we can obtain the velocity distribution functions at equilibrium state. Throughout the calculations, the cross sections for the D(d,p)T, D(d,n)^{3}He, T(d,n)^{4}He and ^{3}He(d,p)^{4}He reactions are taken from the work of Bosch [21].

3. Results and Discussion

3.1 Reactivity enhancement by beam injection

A ^{3}He-beam-injected deuterium plasma is considered. Energy distribution functions for ^{3}He are presented in Fig. 1 for several beam-injection energies, i.e., E_{NBI} = 100, 300 and 500 keV, together with the one when no beam-injection is made. The dotted line represents Maxwellin distribution. In the calculation, the fuel-ion density n_{D} = 6×10^{19} m^{-3}, energy and particle confinement times $\tau_{\text{E}} = \tau_{\text{p}}$ = 1 sec, beam-injection power P_{NBI} = 20 MW into a 100 m^3 volume plasma are assumed. In this paper the evaluation is made assuming currently existing devices, i.e. the maximum beam injection energy is taken as 500 keV. The electron distribution function is assumed to be Maxwellian with 10 keV temperature. We can find energetic non-Maxwellian components created in the ^{3}He distribution functions due to external beam injection. It should be noted that in the calculation without external ^{3}He-beam injection, a non-Maxwellian component is still exist as a result of the ^{3}He production (with 0.82 MeV birth energy) by the D(d,n)^{3}He fusion reaction. We can also find non-Maxwellian components beyond ~0.9 MeV energy range. These components are created by the NI scattering of energetic protons produced by the D(d,p)T and ^{3}He(d,p)^{4}He reactions.

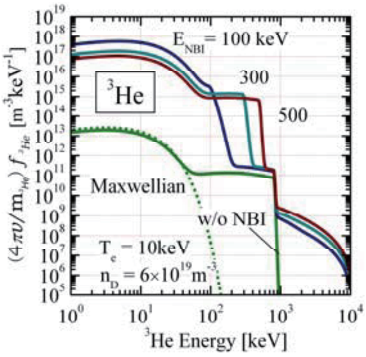

Fig. 1 The ^{3}He Distribution functions in a typical deuterium plasma with ^{3}He-beam injection. The electron temperature is 10 keV, deuteron density $n_{\text{D}} = 6 \times 10^{19}$m^{-3}, energy and particle confinement times $\tau_{\text{E}} = \tau_{\text{p}}$ = 1 sec and beam-injection power P_{NBI} = 20 MW are assumed.

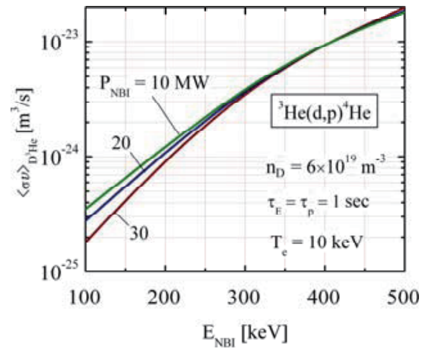

Fig. 2 The ^{3}He(d,p)^{4}He reaction rate coefficient as a function of beam-injection energy E_{NBI} for several beam-injection power P_{NBI}.

The reaction rate coefficients for the ^{3}He(d,p)^{4}He reaction are presented in Fig. 2 as a function of beam-injection energy E_{NBI} for several beam-injection powers, i.e., P_{NBI} = 10, 20 and 30 MW. The calculation conditions are the same as those in Fig. 1. The reaction rate co-

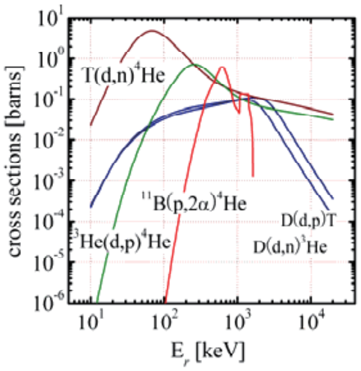

Fig. 3 Cross sections for D(d,p)T, D(d,n)^{3}He, T(d,n)^{4}He, ^{3}He(d,p)^{4}He and ^{11}B(p,2α)^{4}He fusion reactions as a function of relative energy.

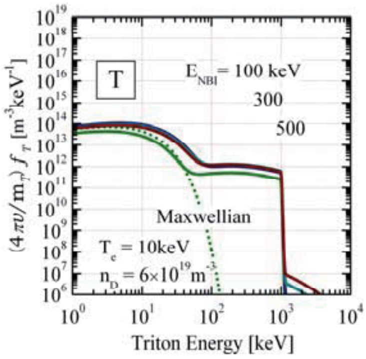

Fig. 4 Triton distribution functions in a typical deuterium plasma with ^{3}He-beam injection. The electron temperature is 10 keV, deuteron density $n_D = 6 \times 10^{19} m^{-3}$, energy and particle confinement times $\tau_E = \tau_p = 1$ sec and beam-injection power $P_{NBI} = 20$ MW are assumed.

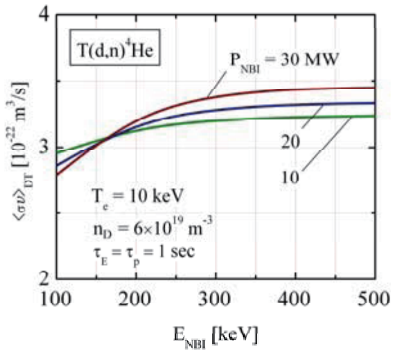

Fig. 5 The T(d,n)^{4}He reaction rate coefficient as a function of beam-injection energy E_{NBI} for several beam-injection power P_{NBI}.

efficient increases with increasing beam-injection energy. This is because the cross section of ^{3}He(d,p)^{4}He reaction has a peak around ~ 250 keV relative energy (see Fig. 3). In Fig. 2 we notice that in low beam-injection energy range, the reaction rate coefficient becomes small as beam-injection power increases. This is because that fraction of ~ 100 keV energy component in ^{3}He distribution function (less-reactive compared with 0.82 MeV birth component) increases as the beam-injection power increases.

It should be noted that if beam injection was not made (only 0.82 MeV fusion source), the ^{3}He(d,p)^{4}He reaction rate coefficient is almost 5.6×10^{-23} m^3/s, i.e., the rate coefficient is reduced almost two orders for 100 keV beam injection by the distortion of ^{3}He velocity distribution function due to external beam injection (the ^{3}He(d,p)^{4}He reaction rate itself may increase depending on the ^{3}He density). As shown in Fig. 1 relative intensity of normalized ^{3}He distribution function beyond 200-keV energy range reduces almost 4 orders for 100 keV ^{3}He beam injection. It should be noted that if the ^{3}He(d,p)^{4}He reaction rate coefficient is estimated assuming Maxwellian plasma with 10 keV temperature, the rate coefficient is almost 2×10^{-25}m^3/s.

3.2 Reactivity enhancement by fusion product

In deuterium plasmas energetic fuel ions are produced by fusion reactions. Tritons are produced by the D(d,p)T reaction and form large non-Maxwellian component in their distribution function. In Fig. 4 we next show the triton distribution functions for several beam-injection energies, i.e., E_{NBI} = 100, 300 and 500 keV. The calculation conditions are the same as those in Figs. 1 and 2. The large non-Maxwellian components appear owing to the energetic triton production (with 1.01-MeV birth energy) by the D(d,p)T reactions. We can also find that the knock-on tails created by NI scattering of energetic fusion-produced protons beyond 1.0 MeV energy range. The reaction rate coefficients for the T(d,n)^{4}He reaction are presented in Fig. 5 as a function of beam-injection energy E_{NBI} for several beam-injection powers, i.e., P_{NBI} = 10, 20 and 30 MW. The reaction rate coefficient slightly increases with increasing beam- injection energy. This is because that the low-energy (~ 10 keV) tritons are knocked up to the reactive energy region (~ 100 keV) as a result of NI scattering of energetic protons. As was shown in Fig. 2, in low beam-injection energy range the proton production due to ^{3}He(d,p)^{4}He reaction is decreased as the beam-injection power increases, thus the T(d,n)^{4}He reaction rate coefficient also becomes small as beam-injection power increases.

It should be noted that if the T(d,n)^{4}He reaction rate coefficient is estimated assuming Maxwellian plasma with 10 keV temperature, the rate coefficient is almost 10^{-22} m^3/s, i.e., as a result of non-Maxwellian tail formation the rate coefficient is increased.

3.3 Reactivity enhancement due to knock-on tail formation via NI scattering

Now let's look at the reactivity enhancement due to knock-on tail formation via NI scattering. The deuteron

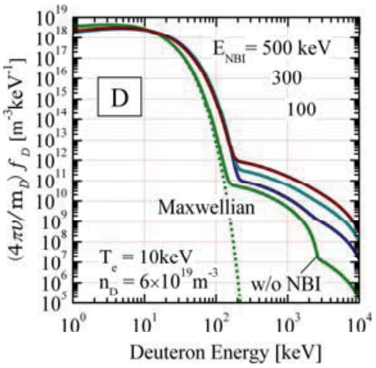

Fig. 6 Deuteron distribution functions in a typical deuterium plasma with ^{3}He-beam injection. The electron temperature is 10 keV, deuteron density $n_D = 6 \times 10^{19} m^{-3}$, energy and particle confinement times $\tau_E = \tau_p = 1$ sec and beam-injection power P_{NBI} = 20 MW are assumed.

distribution functions are shown in Fig. 6 for several beam-injection energies, i.e., E_{NBI} = 100, 300 and 500 keV together with the one when no beam-injection is made. The calculation conditions are the same as those in Figs. 1 and 2. We can observe that the knock-on tails are created above ∼ 200 keV energy range as a result of NI scattering of energetic protons by bulk deuterons. The first knock-on tail (between ∼ 200 keV to ∼ 2 MeV energy range) is created by the protons produced by D(d,p)T reactions, and the second knock-on tail (above ∼ 2 MeV energy range) is mainly created by the protons by ^{3}He(d,p)^{4}He reactions. The energetic component in proton distribution function above 2.5 MeV energy range glows large as the ^{3}He beam-injection energy increases. This is because the both D(d,p)T and ^{3}He(d,p)^{4}He reaction rate coefficients increase with increasing beam-injection energies.

To quantitatively estimate the degree of the enhancement of the D(d,n)^{3}He reaction rate coefficient due to the knock-on tail formation via NI scattering, we introduce the reactivity enhancement parameter η, i.e., $\eta = \left(\langle\sigma v\rangle_{D(d,n)^3He} / \langle\sigma v\rangle^{Maxwell}_{D(d,n)^3He} - 1\right) \times 100[\%]$. Here, $\langle\sigma v\rangle^{Maxwell}_{D(d,n)^3He}$ is the D(d,n)^{3}He fusion reaction rate coefficient when deuteron distribution function is Maxwellian with temperature T_{bulk}. The bulk temperature of deuterons T_{bulk} is determined by comparing the bulk component of the obtained deuteron distribution function with Maxwellian by mean of the least squares fitting. The enhancement parameter η is presented in Fig. 7 as a function of beam-injection energies. The reactivity is enhanced from the value for Maxwellian with increasing beam-injection energies. This is because the knock-on tail glows large with increasing beam-injection energies. Since in a high temperature plasma the slowing-down effect due to Coulomb scattering tends to be reduced, the fraction of knock-on tail component to total distribution function becomes large. The enhancement parameter thus increases for high-temperature range.

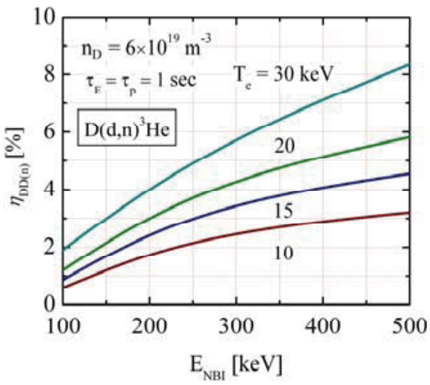

Fig. 7 Reactivity enhancement parameter η as a function of beam-injection energy.

4. Conclusion

The degree of the enhancement of the D(d,n)^{3}He, T(d,n)^{4}He and ^{3}He(d,p)^{4}He fusion reaction rate coefficient caused by (a) external beam-injection, (b) production of energetic fuel ions due to fusion reactions, and (c) the knock-on tail formation via NI scattering is evaluated. When ^{3}He beam is injected, the rate coefficient of the ^{3}He(d,p)^{4}He reaction decreases compared with the case for no beam injection due to distortion of ^{3}He distribution function. The rate coefficient of the T(d,n)^{4}He reaction is enhanced compared with the Maxwellian plasma. The degree of the enhancement in neutron production rate by the D(d,n)^{3}He reaction due to knock-on tail formation is less than 10 percent. In the experiment using ^{3}He-containing deuterium plasma [17, 18], consideration of the reactivity enhancement would be important to evaluate the transferred power via NI scattering.

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