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by

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(Dated: 21 June 2021)

Abstract

The enhancement of the fusion reaction rate coefficient induced by energetic protons, which is one of the typical nuclear elastic scattering (NES) effects, was observed in the large helical device (LHD) located at the National Institute for Fusion Science. An intense high purity hydrogen beam (the atomic ratio of the contained deuterium was less than 1 ppm) with ~170-keV-energy and ~10-MW-power was injected into a deuterium plasma with the electron temperature ~9 keV and density ~10^{19} m^{-3}. After the hydrogen beam injection, the neutron generation rate by the D(d,n)^{3}He fusion reaction immediately increased, and an increment of over one order of magnitude was observed, even though there was no meaningful ion temperature variation. The reasons for the increment in the neutron generation rate are discussed with reference to the Boltzmann−Fokker−Planck analysis along with LHD experimental data. It is concluded that the increment was induced by the production of energetic deuterons due to the NES of energetic protons.

Prepared for submission to Nuclear Fusion

In thermonuclear plasma, energetic ions exhibiting a non-Maxwellian velocity distribution are always present and, during their slowing-down process, these energetic fuel ions react with thermal ions. Since the fusion cross sections strongly depend on the relative energy between the reactants, the velocity-averaged reaction rate coefficient is influenced by the shape of the fuel ion velocity distribution function. Nuclear elastic scattering (NES) [1,2] contributes to the deceleration of energetic ions. NES is a non-Coulombic scattering process through which a large fraction of ion energy is transferred during a single scattering event. Because of the accumulation of the discrete high energy transfer processes from energetic to thermal ions via NES, energetic ions are continuously produced via the recoil process of thermal fuel ions. The resulting distortion of the distribution function induces a modification in the velocity-averaged reaction rate coefficient.

It is well known that, when a fuel ion velocity distribution function is modified from being Maxwellian, the emission spectrum of the fusion products also changes its shape from that of a Gaussian distribution [3]. A non-Gaussian energetic component in the T(d,n)α neutron emission spectrum was observed in JET [4,5]. This component may be created by the T(d,n)α reactions between the energetic recoil components in both the deuteron and triton distribution functions due to NES. Recently, the NES effect on the fast ion slowing-down process was also observed in the large helical device (LHD) [6], by measuring a delay in the decay (attenuation) time of the $D(d,n)^3He$ neutron generation rate due to NES of beam-injected energetic protons by thermal deuterons. Thus far, several NES effects that will be important for the sustainment of nuclear burning have also been predicted. Several numerical estimations have indicated that the transferred power ratio from energetic to bulk ions can be enhanced due to NES depending on the fast ion energy and species compared with the case in which only the energy transfer via Coulomb collisions is considered [7,8]. The effect of NES on the fusion reaction rate coefficients has also been predicted [9]. Some of the NES effects, i.e., modification of the neutron emission spectrum [4] and slowing down of energetic ions, have already been confirmed [6], however, the experimental confirmations for

other phenomena remain limited. This work reports an experiment to observe the NES effect on the D(d,n)^{3}He fusion reaction rate coefficient induced by the externally injected protons. The experiment was conducted in the LHD [10,11] at the National Institute for Fusion Science (NIFS).

Figure 1 depicts a schematic of the set of neutral beam injectors (NBIs) in the LHD. In the experiment, deuterium plasma was formed, and the plasma was heated via the NBIs and electron cyclotron resonance heating (ECH). Three negative-hydrogen (H) beam (NBI#1, 2, and 3) and two positive-deuterium (D) beam (NBI#4 and 5) injectors were used. Injectors NBI#1, 2, and 3 are directed tangentially toward the axis of the toroidal magnetic field, with the negative-ion sources providing fast hydrogens at an energy of 160–175 keV with powers of ~2.4 MW (NBI#1) and ~3.8 MW (NBI#2, 3). Injectors NBI#4 and 5 are perpendicular to the magnetic axis, with positive-ion sources of deuterium at energy of ~60 keV and with powers of ~8 and ~3.6 MW, respectively. For this experiment, high purity (enriched) H was prepared in three injectors (NBI#1, 2, and 3), where the deuterium atomic ratio contained in the H beam as an impurity was suppressed to less than 1 ppm. Throughout the experiment, a magnetic axis (R_{ax}) of 3.6 m and a toroidal magnetic field (B_t) of 2.75 T (in the counter clockwise direction) were adopted.

In the experiment, after a period of 3.8 s from the beginning of the plasma discharge, three high purity H beams (NBI#1, 2, and 3) were injected into the deuterium plasma. The total power of the three beams was ~10 MW, and the average energy was ~170 keV. To precisely measure the ion temperature, a spectroscopic measurement method utilizing charge exchange recombination was adopted by providing electrons to thermal deuterons from the deuterium beam. For this purpose, the D beam (NBI#5) was injected before and after the H beam injections, i.e., 3.5 and 4.7 s from the beginning of the plasma discharge, with a short pulse (of 40-ms-duration) modulation. **Figure 2** shows the typical waveform of a deuterium plasma discharge, including the time evolutions of (a) the neutral beam heating powers for injectors NBI#1, 2, 3, and 5, (b) the electron temperature at the radius $r = 0$ and $a/2$ (a is a minor radius

of the LHD plasma), (c) the electron density at the radius r = 0 and a/2, and (d) the neutron generation rate. During the discharge, deuterium plasma was heated by the ECH with 4.1 MW power; the electron temperature increases $\overline{T}_e(0) \approx 9$ keV at the equilibrium state. As a neutron detector, three ^{235}U fission chambers (FCs) alongside ^{10}B and ^{3}He counters were prepared. One of the fission chambers and the ^{10}B counter are placed on the center axis, whereas the remaining two fission chambers are placed on different sides of the LHD vacuum vessel along with the ^{3}He counter (the sensitivity of the ^{3}He and ^{10}B counters is several hundred and ~60 times larger compared with the FC in the 10^{11} n/s range, respectively [11]). It was found that, immediately after the high purity H beam injection at 3.8 s, the neutron generation rate began to increase gradually, almost reaching an equilibrium value at ~2 × 10^{12} s^{-1}; an increment in the neutron generation rate of over one order of magnitude was observed. While the neutron generation rate increased, the electron density and the electron central temperature gradually decreased. The ion temperatures before and after the H beam injection at the radius a/2 were obtained as 2.11 and 2.37 keV, respectively. The ratio of the thermal D(d,n)^{3}He reactivities between 2.11 and 2.37 keV, i.e., $\langle \sigma v \rangle_{2.37\mathrm{keV}}^{DD(n)} / \langle \sigma v \rangle_{2.11\mathrm{keV}}^{DD(n)}$, was ~1.6; thus, the neutron increment cannot be explained from the viewpoint of the thermal fusion. Regarding the shape of the neutron increment curve (**Fig. 2(d)**), the fusion reaction seems to be induced by the energetic ions.

Figure 3 shows the neutron generation rate due to H beam injections in low electron temperature (without ECH) plasma. The waveform of (a) the neutral beam heating powers for injectors NBI#1, 2, or 3 , (b) the electron temperatures at the radius r = 0, (c) the electron densities at the radius r = a/2, and (d) the neutron generation rates are presented for three shots, i.e., #164867, #164868, and #164870. For comparison, we added the electron temperature and neutron production rate from 3.6 to 4.8 s for #164874 (shown in Fig. 2) with the dotted lines in Fig. 3(b) and (d). Because there is no ECH, the electron temperature is lower compared with **Fig. 2**, i.e., $\overline{T}_e(0) = 3$–4 keV. The neutron generation rates measured by the FC, ^{10}B, and ^{3}He counters are almost the same; however, the values obtained by the ^{3}He counters were adopted and indicated as the corresponding count rates were small. For all shots shown in **Fig. 3**, the

neutron generation rate is found to be less than 10^{11} s^{-1}. In general, LHD plasma operation, the neutron generation rate due to negative-deuterium (100% D) beam (NBI#1, 2, or 3) injection in low electron temperature plasma ($T_e(0)$ = ~3 keV) is in the 0.5–1.0 × 10^{15} s^{-1} range. This implies that, even if a small number of deuterons were accelerated and injected into the deuterium plasma unintentionally with the high purity H beams (in **Fig. 2**), the D/H atomic ratio would be 0.02% at most. To examine the correlation between the neutron generation rate and electron temperature, Boltzmann−Fokker−Planck (BFP) simulations [12] were performed. In the BFP simulations we assumed a uniform plasma, and the NES was assumed to be isotropic in the center-of-mass frame. The temporal trends of the neutron generation rate by the D(d,n)^{3}He reaction between energetic and thermal deuterons after D or H beam injection are shown in **Fig. 4(a)** for several electron temperatures. The dotted curves indicate the results when only the 100% D beam is injected into the deuterium plasma, whereas the solid curves denote the case when only the high purity H beam is injected. In all simulations, the D and H beams were assumed to have energy of 170 keV and a power of 10 MW. The BFP equations for protons and deuterons were solved simultaneously considering the non-linear Coulomb scattering and NES processes [9,12]. In the simulations, the ion temperature, electron density, and particle confinement time were assumed to be 2 keV, 10^{19} m^{-3}, and 0.5 s, respectively. When the high purity H beam is injected, the proton distribution is formed gradually; subsequently, because of the continuous energetic deuteron productions via the NES induced by the energetic protons, the energetic component, i.e., so called the knock-on tail, is formed in the deuteron velocity distribution function. Thus, it can be noticed that the time required to reach the equilibrium states is longer when high purity H beams are injected compared with the 100% D injections. The fast deuteron distribution functions at an equilibrium state are shown in **Fig. 4(b)** for the 100% D injections (dotted lines) and high purity H beams are injected (solid lines). Each neutron generation rate at 2 s shown in **Fig. 4(a)** was obtained using the distribution function in the same conditions shown in **Fig. 4(b)**. When the external D beam is adopted, the injection rate is almost constant, whereas, when the

H beam is injected, the deuteron recoil rate itself, which corresponds to the beam injection rate, is also influenced by the electron temperature. This is because the formation process of the proton distribution function depends on the electron temperature strongly. This is the reason why the neutron generation rate via NES is more sensitive to the electron temperature in this case compared with the situation with external D beam injections. From **Fig. 4(a)**, it can be seen that the neutron generation rate increases almost by a factor of two at most due to the electron temperature increment from 3 to 9 keV; thus, the increment in the neutron generation rate illustrated in **Fig. 2** still cannot be explained through the small amount of D containment. However, the increment in the neutron generation rate can be quantitatively explained by considering that the neutron generation is caused by the energetic recoil deuteron component created by NES.

Similar neutron generations due to high purity H beam injection have been observed in several plasma conditions. As an example, **Fig. 5(a)** displays the increment in the number of neutrons due to a H beam injection when plasma with a lower electron density (0.8×10^{19} m^{-3}) and a higher electron temperature (13.6 keV) is observed. As discussed in **Fig. 4**, the knock-on tail tends to grow in high electron temperature plasma. From **Fig. 5(a)**, it can be seen that the degree of increase in the neutron generation rate becomes larger by a factor of 20–50 compared with that illustrated in **Fig. 4**. The ion temperature before and after the high purity H beam injection is 2.73 and 2.39 keV, respectively, and the ratio of the thermal $D(d,n)^3He$ reactivities is ~0.6. **Figure 5(b)** shows the increment in the neutron generation rate in an even higher electron density (2.4×10^{19} m^{-3}) and lower electron temperature (5.7 keV) plasma. In this case, only NBI#3 is injected. The increment in the neutron generation rate is less than one order of magnitude. The ion temperature before and after the high purity H beam injection is 1.53 and 1.42 keV, respectively, and the ratio of the thermal $D(d,n)^3He$ reactivities is ~0.7. In both cases, the reactivity enhancement can be attributed to the energetic deuteron productions via the NES caused by the energetic protons. In the experiment, we measured the ion temperature at $r/a = 0.5$. This is because most of the $D(d,n)^3He$ neutrons are

produced around this region. Since a volume of layer between flux surfaces decreases as approaching the magnetic axis, the ion temperature variation at the center plasma region would not be a crucial factor in our experimental condition.

In this work, the NES effect on the $D(d,n)^3He$ reaction rate coefficient was observed in the LHD. It was found that the degree of increment is consistent with BFP simulations [12]. In the experiment, we used the hydrogen beam (~170 keV) to distinguish the recoil deuterons from beam-injected protons. In our LHD experimental condition, the recoil component is very small compared with the beam component [6]. Thus, if we used a deuterium beam instead of hydrogen beam, the recoil component would be buried under the beam component (we could not observe the NES effect). To observe the NES effect for deuterium beam (which would be used in the future fusion reactor), much higher beam-injection energy is required. The NES effect essentially becomes important not only for beam-injected ions but also for fusion-born energetic ions. To grasp the NES effects induced by fusion-born energetic ions in the future reactor, a further confirmation using such large beam injection energies will be necessary.

The authors would like to thank the cooperative program of NIFS20KLPH047 and the LHD experimental team for their contribution. The first author is grateful to Emer. Prof. Y. Nakao for long years of discussion and encouragement.

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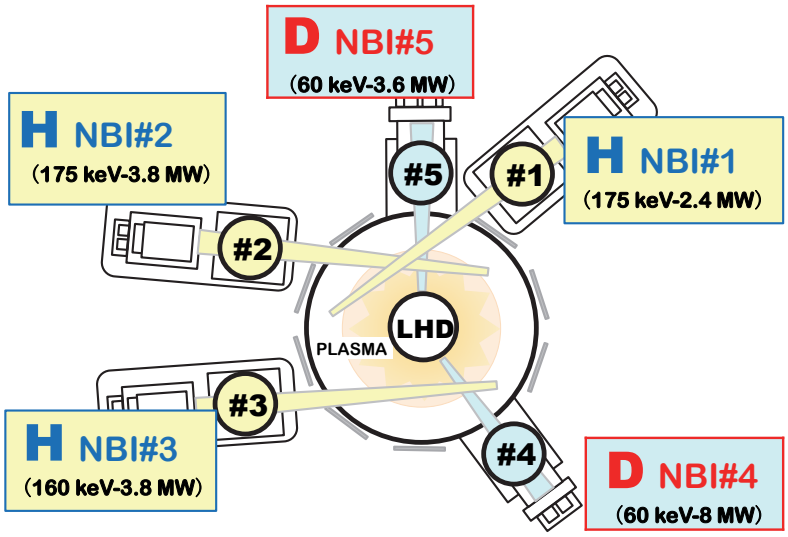

Fig. 1 Schematic of the NBI systems around the LHD.

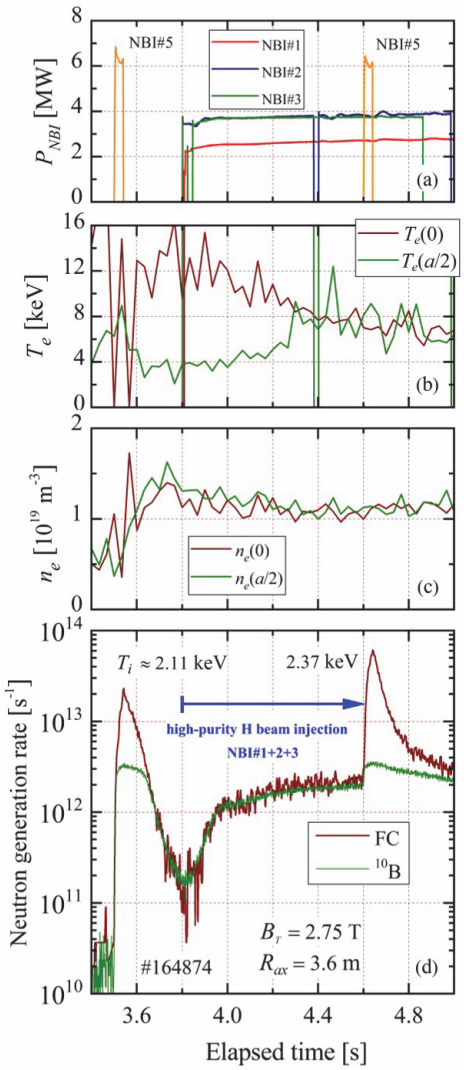

Fig. 2 Time evolution of the deuterium plasma discharge (shot no. #164874). (a) neutral beam heating powers for injectors NBI#1, 2, 3, and 5; (b) electron temperatures at $r = 0$ and $a/2$; (c) electron density at $r = 0$ and $a/2$; (d) neutron generation rate detected by the FC and ^{10}B counters.

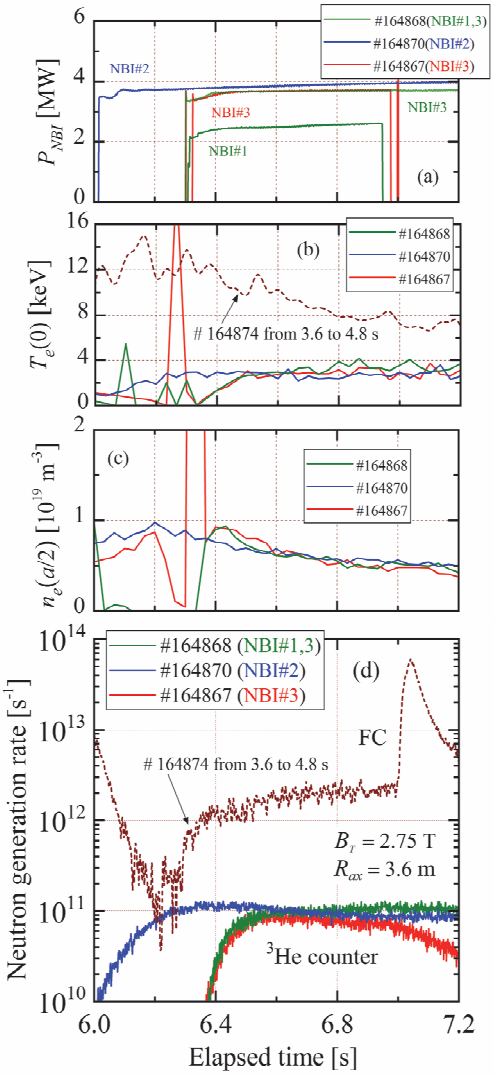

Fig. 3 Time evolution of the deuterium plasma discharges without ECH (shot no. #164867, #164868, and #164870). (a) neutral beam heating powers for injectors NBI#1, 2, 3; (b) electron temperatures at r = 0; (c) electron densities at r = a/2; (d) neutron generation rates detected by the ^{3}He counter.

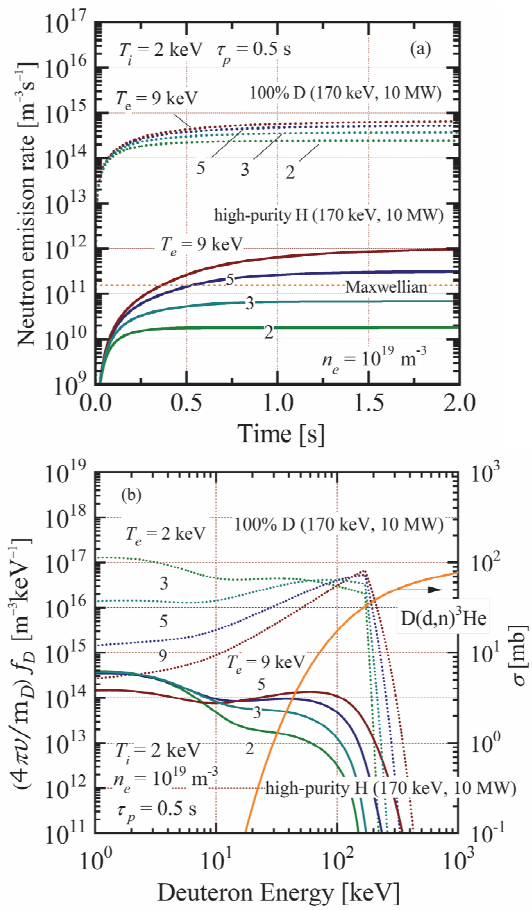

Fig. 4 Numerical BFP simulations for (a) the time evolution of the neutron generation rate and (b) the equilibrium fast deuteron distribution functions when 100% D and high purity H beams with 170 keV energy and 10 MW power are injected for several electron temperatures along with the D(d,n)^{3}He fusion cross section. In the simulations, T_i = 2 keV, n_e = 10^{19} m^{-3}, and τ_p = 0.5 s are assumed.

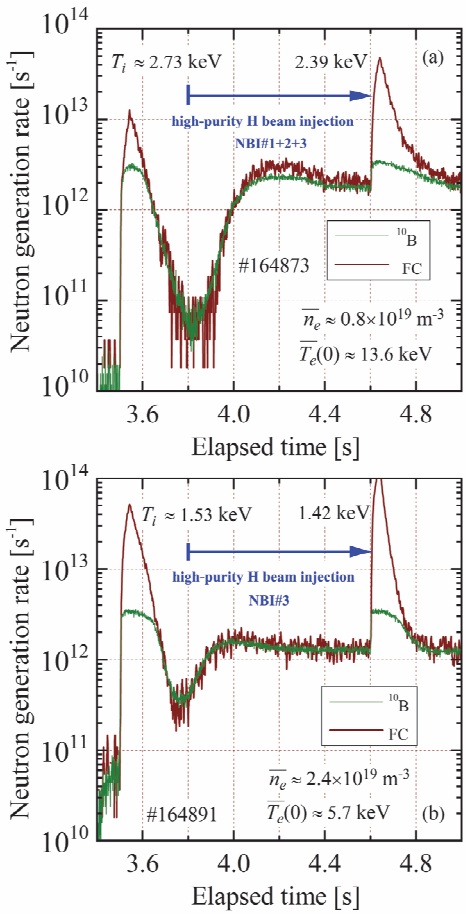

Fig. 5 Time evolution of the neutron generation rates (a) after high purity H beams NBI#1, 2, and 3 are injected (shot no. #164873, time averaged electron density $\overline{n}_e = 0.8\times10^{19}\ \mathrm{m}^{-3}$, and temperature $\overline{T}_e(0) = 13.6\ \mathrm{keV}$) and (b) after the high purity H beam NBI#3 is injected (shot no. #164891, time averaged electron density $\overline{n}_e = 2.4\times10^{19}\ \mathrm{m}^{-3}$, and temperature $\overline{T}_e(0) = 5.7\ \mathrm{keV}$).