Observation of a nuclear-elastic-scattering effect caused by energetic protons on deuteron slowing-down behaviour on the Large Helical Device

H. Matsuura, S. Sugiyama, K. Kimura, S. Kajimoto, T. Nishitani, K. Ogawa, Y. Kawamoto, M. Isobe, and M. Osakabe

1 Department of Applied Quantum Physics and Nuclear Engineering, Kyushu University, 744 Motooka, Fukuoka 819-0395, Japan
2 National Institute for Fusion Science, National Institutes of Natural Sciences, 322-6 Oroshi-cho, Toki 509-5292, Japan
3 SOKENDAI (The Graduate University for Advanced Studies), 322-6 Oroshi-cho, Toki 509-5292, Japan

E-mail: matsuura@kyudai.jp

Received 1 December 2019, revised 16 February 2020
Accepted for publication 9 March 2020
Published 24 April 2020

Abstract
A first attempt to observe a nuclear-elastic-scattering (NES) effect caused by energetic protons on deuteron slowing-down behaviour was made on the Large Helical Device located at the National Institute for Fusion Science. The NES effect on the slowing-down of fast ions can influence the confinement of fast ions, ion heating, fusion reaction rate coefficient, etc. An intense hydrogen beam was injected into a deuterium plasma to create a knock-on tail, i.e. a non-Maxwellian energetic component in the deuteron velocity distribution function. We conducted two types of experiment: (1) observation of the slowing-down of the knock-on tail and (2) observation of the NES effect on the slowing-down time of fast ions. The phenomena are discussed in terms of the difference in the decay process of the D(d,n)3He neutron generation rate after neutral beam heating is terminated between the cases when the knock-on effect is influential and not influential, and also from the difference in the neutron decay times. The results of a series of experiments indicate that the NES effect caused by energetic protons can have an impact on the slowing-down of fast deuterons.

Keywords: nuclear elastic scattering, NES effect, knock-on tail, neutron decay time, LHD deuterium plasma

(Some figures may appear in colour only in the online journal)

1. Introduction
In a thermonuclear plasma, energetic ions are continuously produced, and they play important roles in sustaining the process of plasma burning. Nuclear elastic scattering (NES) [1] contributes to the deceleration of energetic ions. The cross section of NES is defined by subtracting the Coulomb scattering contribution from the experimentally measured one [1]. NES is a non-Coulombic scattering process, and a large fraction of ion energy is transferred in a single scattering event. NES always occurs in plasma operations and experiments, and it can introduce an additional energy-transfer channel between ions, in some cases bringing this process into competition with the Coulombic scattering process. In deuterium–tritium (DT) plasma, the NES effect on the properties of plasma burning may be small [2, 3]. However, the NES effect will still be
observed during typical plasma operations, for example in the neutron emission spectrum as a result of the T(d,n)4He reactions [4]. Ryutov [5] has indicated that the NES of α particles significantly affects the distribution function of the impurity ions, and this phenomenon may be utilized to perform plasma diagnostics. The formation of a knock-on tail in deuteron and triton distributions by α particles and its effect on the emitted-neutron spectrum were examined by Fisher [6] and Ballabio [4]. Energetic neutron generation due to knock-on deuterons and tritons has been ascertained in the JET experiment [7, 8]. In contrast, in deuterium–helium-3 (D3He) plasma, the NES effects caused by energetic protons (produced by 3He(d,p)4He reactions) can be important physical phenomena that contribute to the feasibility of D3He plasma [9, 10]. Many estimations of D3He plasma have indicated that the transferred power ratio from energetic protons to bulk ions is enhanced by approximately three-fold due to NES compared to the case in which only the energy transfer via Coulomb collisions is considered [9]. In such a situation, the RT confinement parameter can be significantly reduced [10]. At this point, however, no experiments have been carried out to quantitatively exhibit the NES effect on plasma performance as a collective phenomenon that is induced by the energetic ions in high-temperature plasmas. To ensure the development of fusion reactors, it is important to experimentally observe and validate this phenomenon using the relevant numerical models.

As an initial step, this paper reports on an experiment to observe the NES effect caused by externally injected protons on slowing-down behaviours of fast deuterons. The experiment was conducted using the Large Helical Device (LHD) at the National Institute for Fusion Science (NIFS) [11].

2. Experimental apparatus and property of knock-on tail

Figure 1 depicts a schematic of the set of neutral beam injectors (NBIs) in the LHD. The experiment uses deuterium plasma, which was heated by NBIs and electron cyclotron resonance heating. We prepared two types of negative-hydrogen (H) beam injectors (a) NBI#1 and #3, and (b) NBI#2, and positive-deuterium (D) beam injectors (NBI#4 and #5). NBI#1, #2, and #3 are injectors that are directed tangentially toward the axis of the toroidal magnetic field, with the negative-ion sources providing fast particles at an energy of 180 keV. NBI#4 and #5 are perpendicular to the magnetic axis, with positive-ion sources with energies of 60 and 80 keV, respectively. The two tangential NBIs are H beams in which ~1% deuterium is included as an impurity (NBI#1 and #3), and the other tangential H beam includes D at its natural abundance (N/A), i.e. ~0.015% deuterium is included (NBI#2). The properties for NB injectors are summarized in table 1.

The NES cross section is known to be approximately isotropic over the scattering angle in the center-of-mass system. This implies that a large fraction of energy is transferred in a single scattering event, unlike in Coulomb scattering. It is well known that we cannot treat such a discrete (large-angle scattering) energy-transfer process in the usual Fokker–Planck (FP) analysis. In order to consider such a process, we introduce the Boltzmann collision term in the FP analysis [2, 3]. Although the Boltzmann collision term can also treat the small-angle scattering process, we have added this term separately in addition to the FP term. This is because the Coulomb and NES cross sections are defined separately, and to remain an excellent technique for the conventional FP method developed in this field. In this paper we use two types of analysis model, i.e. Boltzmann–Fokker–Planck (BFP) and FP. The BFP simulation implies that we consider the both Coulomb scattering and NES contributions. On the other hand, the FP simulation implies that we only consider the Coulomb scattering, i.e. the NES term is neglected. The BFP simulations [2, 3] for a typical plasma condition (T_i = 3 keV, T_e = 6 keV, and n_e = 0.5 × 10^{19} m^{-3}) predict that when more than ~0.1% of the deuterons are included in the H beam, the knock-on tail is buried under the beam-injected deuterons as shown in figure 2. Further, when a beam with more than ~0.1% deuterium (NBI#1 or #3) is used, the neutrons are produced mainly by the D(d,n)3He reactions between the slowing-down beam component (blue line) and the thermal deuterons. However, when the N/A deuterons are included (NBI#2), a knock-on tail appears in the deuteron distribution function, and the neutrons are mainly produced by the D(d,n)3He reactions between the knock-on component (solid red line) and thermal deuterons. The D(d,n)3He fusion cross section is indicated on the same plane as the function of deuteron energy in a laboratory system. The cross sections for NES and the D(d,n)3He reaction can be found from the results by Perkins and Cullen.

![Figure 1. Schematic of the NBI systems around the LHD.](image)

| Table 1. The beam species, D abundance fraction, normal rated power and energy of NBIs in LHD (see figure 1). |
|-----------------|-----------------|-----------------|-------------------|
| NBI No. | Species | D content | P_{BFI} (MW) | E_{BFI} (keV) |
|-----------------|-----------------|-----------------|-------------------|
| NBI#1 | Hydrogen | ~1% D | 5.0 | 180.0 |
| NBI#2 | Hydrogen | N/A D | 5.0 | 180.0 |
| NBI#3 | Hydrogen | ~1% D | 5.0 | 180.0 |
| NBI#4 | Deuterium | 100% D | 9.0 | 60.0 |
| NBI#5 | Deuterium | 100% D | 9.0 | 80.0 |
Equilibrium deuteron distribution functions with a beam-created (NBI#1 or #3) or knock-on (NBI#2) tail (evaluated on the basis of BFP simulations \[2, 3\]) for \(T_e = 6 \text{ keV}, T_i = 3 \text{ keV}, n_e = 0.5 \times 10^{19} \text{ m}^{-3}\) along with the D(d,n)\(^3\)He fusion cross section.\[12\] and Bosch and Hale \[13\], respectively. In this paper we have neglected the influence of beam–beam fusion \[14\].

The decay curve of fusion-produced neutron rate is strongly dependent on the energy range of the dominant deuterons that are involved in neutron production, i.e. the D(d,n)\(^3\)He reaction. As depicted in figure 2, when NBI#1 or #3 was used, the 180 keV deuterons that are injected into the plasma are observed to dominate the D(d,n)\(^3\)He reaction (DD neutron generation). On the other hand, if NBI#2 is used, approximately 40–100 keV deuterons produced by the knock-on of thermal deuterons via NES are dominant for the D(d,n)\(^3\)He reaction. The FP simulation assuming a 1D velocity space in a uniform plasma predicts that the decay of the neutron production rate is faster for a low-energy beam than for a high-energy beam. The difference occurs because the Coulombic scattering frequency increases with decreasing relative velocity \(v_r\) between the beam and bulk deuterons (with \(\propto 1/v_r^4\) scaling as shown in the Rutherford differential cross section), and also the gradient of the D(d,n)\(^3\)He cross section, i.e. \(d\sigma_{DD}/dE\), is larger in the \(\sim 60 \text{ keV}\) energy range than in the \(\sim 180 \text{ keV}\) range (see figure 2). When the beam energy is lower, the distribution function reaches a quasi-thermal equilibrium state faster, and the decay speed rapidly decreases. As an example, in figure 3, the decay processes of the normalized neutron generation rates after 4.3 s (neutrons produced by the D(d,n)\(^3\)He reactions between the \(\sim 180 \text{ keV}\) deuterium component contained in the hydrogen beam (NBI#1, #2 or #3) and bulk deuterons). Based on the neutron generation rates that could be observed from more than 20 LHD shots, we estimated that approximately 1% of the deuterons were contained in the NBI#1 and #3 hydrogen beams. In figure 4, the time variations of the measured neutron generation rates with NBI#1 (#136131(a)) and NBI#2 (#136113(b)) are presented (comparison with the case when no additional beam was injected is made later). In this figure, the neutron generation rates are measured using the

\[3.1. \text{Observation of slowing-down feature of the knock-on tail}\]

From the above discussion it is found that we can produce two plasma situations in experiments, i.e. where a knock-on tail appears or does not appear, by using the NBI#1 or #3 and NBI#2. By comparing the neutron decay curves between the two situations, we can examine the slowing-down property of the knock-on tail. In the experiment, deuterium beam injection (NBI#5) was terminated after a period of 3.8 s from the beginning of the plasma discharge, whereas the hydrogen beam containing a small amount of deuterium (NBI1, #2 or #3) was terminated at 4.3 s. To exclude the influence of the DT neutrons caused by triton burning on the decay curve, we chose a 0.5 s interval between the deuterium and hydrogen beam terminations. Because the knock-on tail is completely buried under the beam deuterons supplied by NBI#5 (100% deuterium beam) from 3.8 to 4.3 s, we focused our attention on the decay processes of the neutron generation rates that are observed after 4.3 s (neutrons produced by the D(d,n)\(^3\)He reactions between the \(\sim 180 \text{ keV}\) deuterium component contained in the hydrogen beam (NBI#1, #2 or #3) and bulk deuterons). Based on the neutron generation rates that could be observed from more than 20 LHD shots, we estimated that approximately 1% of the deuterons were contained in the NBI#1 and #3 hydrogen beams.
Figure 4. Decay process of the neutron generation rate after the NBIs were terminated (NBI#5 was terminated at 3.8 s, and (a) NBI#1 or (b) NBI#2 was terminated at 4.3 s from the beginning of plasma discharge).

Figure 5. Decay processes of the normalized neutron generation rates after 4.3 s for NBI#1 (containing 1% deuterium: #136144) and NBI#2 (containing N/A deuterium: #136113).

fission chamber [15]. Firstly, we notice that the gradient of the neutron generation rates gradually relaxes after 3.8 s toward each stagnation point, which indicates that a detectable number of deuterons is included in NBI#1 and #2 beams. At this point, i.e. right after the NBI#5 termination, the knock-on tail is completely buried under the beam deuterons. After 4.3 s, a difference is observed in the gradient of the decay process between the NBI#1 and #2 cases. In figure 5, the normalized neutron generation rates for #136131 (NBI#1) and #136113 (NBI#2) after 4.3 s are presented and compared. The normalization was made by using the neutron generation rate at 4.3 s, thus initial values of both curves are unity. The neutron generation rates as measured by the $^{10}$B counter are presented for NBI#2 because the count rates are small (sensitivity of the $^{10}$B counter is $\sim 60$ times larger than that of the fission chamber in the region of $10^{11}$ neutron s$^{-1}$ [15]). The normalized neutron generation rate for NBI#2 gradually decreases and intersects the neutron generation rate for NBI#1 at $\sim 4.8$ s. The solid lines obtained by the moving average fitting are marked on the same plane. Here the moving average is the method in which we plot a graph by choosing the mean of an equal number of data on either side of a central value.

As predicted theoretically (see figure 3), the decay of the neutron generation rate is observed to be faster and to reach a quasi-thermal equilibrium state in a shorter time for NBI#2 than for NBI#1, which indicates that the neutron generation is dominated by the lower energy deuterons, consistent with a knock-on tail. The decay behaviour in the shot example shown in figure 5 is typical.

In the general slowing-down process of fast ions, the peak of the fast-ion distribution function slows down less at first. When the lower energy side of the distribution function approaches the thermal energy range of background particles, the bulk component of the distribution function immediately increases, and the peak slows down more. When the major part of the distribution function approaches the thermal energy range, the influence of up-scattering begins to be appreciable, and the slowing-down is further relaxed. So, the neutron decay time (slowing-down speed) is not constant during the slowing-down process (in actual plasma the effect of particle loss may further complicate the phenomenon). It should be noted that the neutron decay process does not depend on the intensity of the beam tails, and the shape of the decay line does not depend on the fraction of the deuterium impurity. Thus, if the decay property was different, it would indicate that the shape of the distribution function is different. In simulations, the intersection point of the two curves in figure 3 can change depending on the plasma parameter. For example, if the density increases (decreases), the slowing-down of fast ions is enhanced (delayed) and the two curves intersect sooner (later). Nevertheless, the relative tendency between two curves does
Figure 6. Decay processes of the normalized neutron generation rates with (red) and without (black) NBI#1 heating.

not change regardless of the plasma parameters. It should be noted that we do not examine the neutron decay time directly, but instead focus on the difference in the shape of the decay curves by extending the relevant time duration. The observed tendency is robust, because a similar tendency was observed in all the shots in the LHD experiments, even if NBI#3 was used instead of NBI#1.

3.2. Observation of NES effect on the neutron decay time

We further ascertain the knock-on effect due to NES. For this purpose, the neutron decay times of the neutrons that were produced by the D(d,n)$^3$He reactions between the injected beam and the bulk deuterons were measured just after NBI#4 and #5 (100% deuterium) were terminated. The neutron decay times were compared for cases in which any one of the tangential beams NBI#1, #2 or #3 was continuously injected during the slowing-down process and in which no tangential beams were injected. In this case, since NBI#4 and #5 (100% deuterium) are used, the knock-on tail itself is completely buried under the beam deuterons. However, we expect that if NBI#1, #2 or #3 were continuously injected during the neutron decay process, then that process would be delayed since the bulk and beam deuterons are scattered into a higher energy range via NES.

During the experiment, deuterium plasma is prepared by electron cyclotron resonance and neutral-beam (100% deuterium NBI#4 and #5) heating. After 4.01 s from initiating the plasma discharge, deuterium beam injections (NBI#4 and #5) were terminated. We then focused on the investigation of the neutron decay processes produced by the D(d,n)$^3$He reactions with the $\sim$60 keV deuterium beams (NBI#4 and #5) and bulk deuterons after 4.01 s. In figure 6, the time variations of the neutron generation rates with and without additional H-beam heating (NBI#1) are plotted. Without H-beam heating, the plasma density (temperature) was approximately 30% (20%) lower (higher) than in the beam-injected case. If the fast-ion slowing-down time $\tau_s$ obeys the theoretical scaling, i.e. $\tau_s \propto T_e^{3/2}/n_e$, the neutron decay can be faster in low-temperature and high-density plasma. The decay curves show that the neutron decay time becomes shorter when the H beam is not injected, contrary to the plasma condition. The energetic protons might weaken the deuterons’ slowing-down process via NES. For 17 shots, the neutron decay times $\tau_n$ observed experimentally (defined as the time after which the neutron generation rate falls to 1/e after NBI#4 and #5 are terminated) are plotted as a function of the neutron decay time predicted by the FP simulations $\tau_{FP}$ (evaluated as the time after which the beam-thermal D(d,n)$^3$He reaction rate is reduced to 1/e in the simulation). The results are presented in figure 7 and are compared with the simulations using the BFP model [2, 3]. In the simulations we assumed uniform plasma, and the temperature and density were measured for each of the shots. We chose the temperature and density at $a/2$ (where $a$ is the minor radius), because the most of the neutrons are carried around this region. In the FP and BFP simulations the beam injection energy and power are chosen as 180 (60) keV and 6 (4) MW for the hydrogen (deuterium) beam. The confinement times for protons and deuterons are taken from the work of Nuga et al [16, 17] as 0.5 and 0.03 s respectively. The squares represent the experimental results with (red) and without (black) H
beams (NBI#1, #2 or #3), whereas the circles represent the BFP simulations with (red) and without (black) H beams. The green circles represent the FP simulation when we only consider the Coulomb scattering process (the green circles are on the diagonal line). In that case, the neutron decay times increase compared with the cases when no H beam is injected (black circles and squares). This is due to the energy transfer from protons to deuterons via many small-angle scatterings. We further observe that the neutron decay times when additional H-beam injection is made (red circles and squares) are larger than those when only the Coulomb scattering is considered. The NBI powers were 20%–30% smaller and the confinements were deteriorated for five experimental shots represented by red squares within a large dotted circle (counter injection to the toroidal magnetic field) than for the upper seven red squares (co injection to the toroidal magnetic field). It is possible that if the NBI powers and the confinements for the five shots were at the same level as for the other seven, the knock-on effect would be enhanced, and the neutron decay times would approach those for the other seven shots with H-beam heating. This result indicates that the H beam adds energy to the slowing-down component via another process, i.e. NES, in addition to the Coulomb scattering, so that the decay process of the neutrons is further delayed.

4. Conclusion

It has been shown that the deuteron slowing-down behaviour in a fusion plasma is likely to be affected by the NES caused by energetic protons. NES increases the amount of energy passed from fast ions to plasma background ions, with respect to the Coulomb-only case, which also heats plasma background electrons. The NES effect would further increase as the ion energy increases [2, 3]. The observations reported in this paper show an experimental technique that can be used in future experiments to probe directly the slowing-down of deuterons in burning plasmas. In our FP and BFP simulations, several parameters are necessary to reproduce experimentally obtained data, e.g. confinement times; however, the analysis would still be useful for understanding the property of the NES effect. For more detailed qualitative analysis, more sophisticated simulation code that can consistently determine the plasma parameters would be required.

Acknowledgment

The authors would like to thank the cooperative program of NIFS 17KLPH029 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.

ORCID IDs

H. Matsuura  https://orcid.org/0000-0002-7498-4191
S. Sugiyama  https://orcid.org/0000-0002-0010-6310

References

[1] Devany J. J. and Stein M. L. 1971 Nucl. Sci. Eng. 46 323
[2] Matsuura H. and Nakao Y. 2006 Phys. Plasmas 13 062507
[3] Matsuura H. and Nakao Y. 2011 Plasma Phys. Control. Fusion 53 035023
[4] Ballabio L., Gorini G. and Källne J. 1997 Phys. Rev. E 55 335
[5] Ryutov D. 1992 Phys. Scr. 45 153
[6] Fisher R. K. 2004 Rev. Sci. Instrum. 10 3556
[7] Källne J., Ballabio L., Frenje J. et al 2000 Phys. Rev. Lett. 85 1246
[8] Korotkov A. A., Gondhalekar A. and Akers R. J. 2000 Phys. Plasmas 7 957
[9] Galambos J., Gilligan J., Greenspan E. et al 1984 Nucl. Fusion 24 739
[10] Nakao Y., Hori H., Hanada T. et al 1988 Nucl. Fusion 28 1029
[11] Osakabe M., Isobe M., Tanaka M. et al 2018 IEEE Trans. Plasma Sci. 46 2324
[12] Perkins S. T. and Cullen D.E. 1981 Nucl. Sci. Eng. 77 20
[13] Bosch H.S. and Hale G. M. 1992 Nucl. Fusion 32 611
[14] Honma M., Murakami S., Nuga H. et al 2016 Plasma Fusion Res. 11 2403109
[15] Isobe M., Ogawa K., Nishitani T. et al 2018 Nucl. Fusion 58 082004
[16] Nuga H., Seki R., Ogawa K. et al 2019 Plasma Fusion Res. 14 3402075
[17] Nuga H., Seki R., Kamio S. et al 2019 Nucl. Fusion 59 016007