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Nuclear Elastic Scattering Effect by Energetic Protons on Deuteron Slowing-Down Behavior Observed in the Large Helical Device

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ABSTRACT

- Effects of nuclear elastic scattering (NES) [1] on fast-deuteron slowing-down properties (fusion reaction rate coefficient, energy transfer) were observed in the LHD deuterium plasma.
- Numerical simulations (on the basis of the Boltzmann-Fokker-Planck (BFP) model [2]) could explain the observed results.
- The NES effect would be appreciable in the future reactor-grade plasma.

[1] J. J. Devaney and M. L. Stein, Nucl. Sci. Eng., **46** (1971) 323.
[2] H. Matsuura, et al., Plasma Phys. Contr. Fusion, **53** (2011) 035023.

BACKGROUND

- A large fraction of the energetic-ion energy is transferred to bulk ions in a single NES event, and the energetic-ion slowing-down properties are influenced by NES (*as well as the Coulomb collision*)[3].

  (i) Fractional energy deposition from energetic to bulk ions tends to increase due to NES compared with when we only consider Coulomb collision.

  (ii) NES causes distortion in both energetic and bulk distribution functions, and sometimes fusion reaction rate coefficients are changed compared with the values for the Maxwellian plasma.

- We have developed the BFP model to understand the NES effect [2]. These phenomena could be appreciable in a thermonuclear plasma and the understanding with experimental validation would be important.

[3] J. Källne, et al., Phys. Rev. Lett. **85**, 1246 (2000).

CHALLENGES / METHODS / IMPLEMENTATION

EXPERIMENT

On the large helical device (LHD), we attempted to observe the NES effects by looking at the DD neutrons. We devoted our attention to measure the increment in the DD neutron generation rate ((a) fusion reaction rate coefficient) and increment in the DD neutron decay time ((b) energy transfer process from protons to energetic deuterons).

NUMERICAL SIMULATION

We tried to understand the experimentally observed phenomena by using the Boltzmann-Fokker-Planck model [2].

LHD equipment and D(d,n)³He, ⁶Li(d,γp)⁷Li cross sections

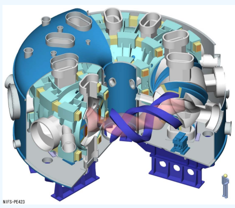

Fig. 1 Schematic view of the LHD .

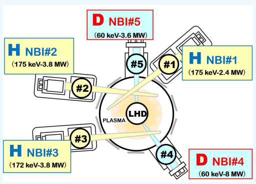

Fig. 2 Schematic of the LHD and the NBI systems.

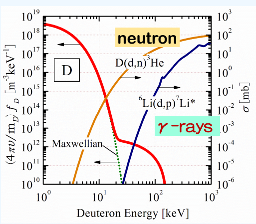

Fig. 3 Knock-on tail and cross sections for the neutron/γ-ray generating reactions.

Nuclear elastic scattering [1]

$$\left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{NES}} = \left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{Total\ (measured)}} - \left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{Coulomb}}$$

Large-angle scattering process

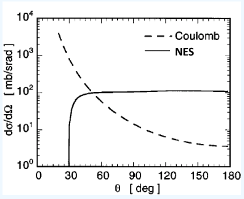

Fig. 4 Example of NES differential cross section. ([4] L. Ballabio, et al., PRE (1997))

Boltzmann-Fokker-Planck Model [2]

$$\left(\frac{\partial f_{\mathrm{f}}}{\partial t}\right)^{\mathrm{C}} + \sum_i \left(\frac{\partial f_{\mathrm{f}}}{\partial t}\right)_i^{\mathrm{NES}} + \frac{1}{v^2}\frac{\partial}{\partial v}\left(\frac{v^3 f_{\mathrm{f}}}{2\tau_C^*(v)}\right) + S_{\mathrm{f}}(v) - L_{\mathrm{f}}(v) = 0$$

FP term; NES term; diffusion in velocity space due to thermal conduction; source; particle loss from plasma

$$S_{\mathrm{f}}(v) - L_{\mathrm{f}}(v) = \frac{S_{\mathrm{f}}}{4\pi v^2}\delta(v - v_0) - \frac{f_{\mathrm{f}}(v)}{\tau_p^*(v)}, \quad \tau_{c(p)}^*(v) = \begin{cases} C_{c(P)}\tau_{c(P)} & \text{when } v < v_{th} \\ C_{c(P)}\tau_{c(P)}(v/v_{th})^{\gamma} & \text{when } v \geq v_{th} \end{cases}$$

OUTCOME

(a) NES EFFECT ON DD FUSION REACTION RATE COEFFICIENT

High-purity H beam (atomic ratio D/H is less than 1 ppm) is injected into deuterium plasma. More than 1 order of the DD neutron production was observed, even though there is no meaningful variations in plasma parameters.

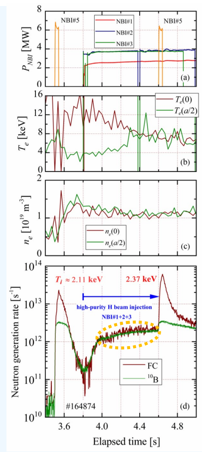

Fig. 5 Enhancement in the neutron production rate after high-purity H beam injection.

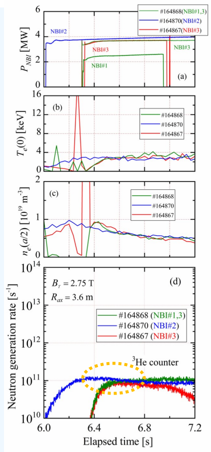

Fig. 6 The neutron production rate in plasma discharge without ECH.

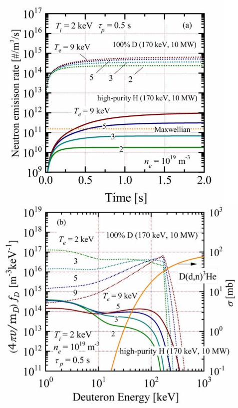

Fig. 7 Numerical BFP simulations for (a) time evolution of the neutron generation rate, and (b) equilibrium deuteron distribution functions.

⇨ The NES effect on D(d,n)³He reaction rate coefficient was observed.

(b) NES EFFECT ON FAST-ION SLOWING-DOWN PROPERTIES

We had expected that the neutron decay process would be disturbed by the NES effect caused by energetic protons. The delay in the neutron decay time due to H beam injection was observed, and we tried to understand the phenomena quantitatively using the BFP model. [5] H. Matsuura, et al., Nucl. Fusion **60** (2020).

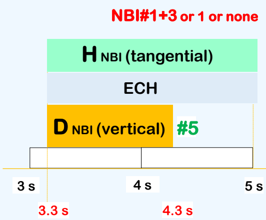

Fig. 8 Beam injection and plasma heating pattern.

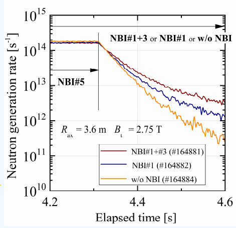

Fig. 9 Delay of the neutron decay times due to H beam injections.

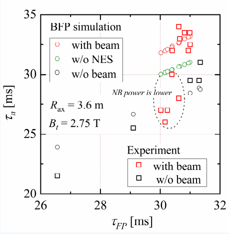

Fig. 10 Delay in the neutron decay times due to H beam injections.

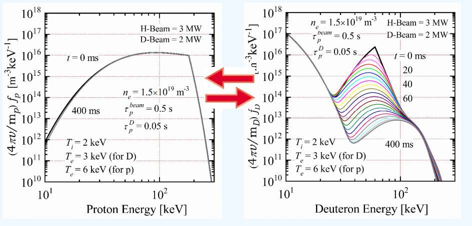

Fig. 11 Time evolutions of proton and deuteron distribution functions.

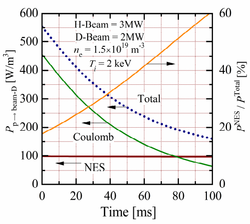

Fig. 12 Transferred power from protons to energetic deuterons via Coulomb and NES processes.

⇨ The energy transfer process due to NES from protons to energetic deuterons are observed.

CONCLUSION

- More than one order of the DD reaction rate coefficient enhancement due to high-purity H beam injection was observed.
- Delay in the DD neutron decay time due to high-purity H beam injection was observed.
- The above results were analyzed by using the BFP model.
- The observed results can be explained quantitatively by considering the NES effect in addition to the Coulombic collisional interaction between energetic ions.

ACKNOWLEDGEMENTS

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