

## Use of a $\gamma$ -ray-generating nuclear reaction for detecting the $\alpha$ -particle knock-on effect

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In recent fusion plasma research great attention is paid to clarification of physical properties of energetic ions in hot plasmas. However, it is very difficult to detect the energetic ions in a tokamak configuration since such properties have to be determined while they are in the plasma. Therefore, it is reasonable to use photons or particles freely escaping from the plasma for this purpose. Especially, use of  $\gamma$ -rays emitted in threshold nuclear reactions induced by the energetic ions can be advantageous. In fact, in JET experiments several  $\gamma$ -ray-generating threshold reactions between the energetic ions and impurities have been vigorously used for fast ion diagnostics [1].

An alternative method to diagnose energetic ions has been proposed in recent years [2]. This method is based on using a small amount of  ${}^6\text{Li}$  as low- $Z$  admixture in DT plasma to induce  ${}^6\text{Li}+\text{D}$  and  ${}^6\text{Li}+\text{T}$  nuclear reactions capable of providing information on energetic ions. Here we consider a specific  $\gamma$ -ray mode of the reactions, *i.e.*



which proceeds through the excited nucleus  ${}^8\text{Li}^*$  emitting monochromatic  $\gamma$ -quanta with energy  $E_\gamma = 0.981$  MeV in its decay to the ground state. A remarkable feature of this reaction is strong energy dependence of its cross section [3], because this process is essentially suppressed at thermal energies and forbidden below the reaction threshold at 181 keV. In self-sustained DT fusion plasmas energetic tritons can be created by close elastic (knock-on) collisions of fusion-born energetic  $\alpha$ -particles. Therefore, one could obtain information on energy distributions of both  $\alpha$ -particles and energetic tritons by comparing the 0.981-MeV  $\gamma$ -ray measurement with kinetic model prediction incorporating the knock-on collision processes appropriately [2]. The objective of the present work is to verify the above qualitative discussion. On the basis of simple theoretical models, we estimate diagnostic information the 0.981-MeV  $\gamma$ -rays possess.

We begin with considering the slowing-down behavior of energetic ions. The distribution function  $f_i$  of energetic ions can be obtained by solving the Fokker-Planck equation with an appropriate source term:

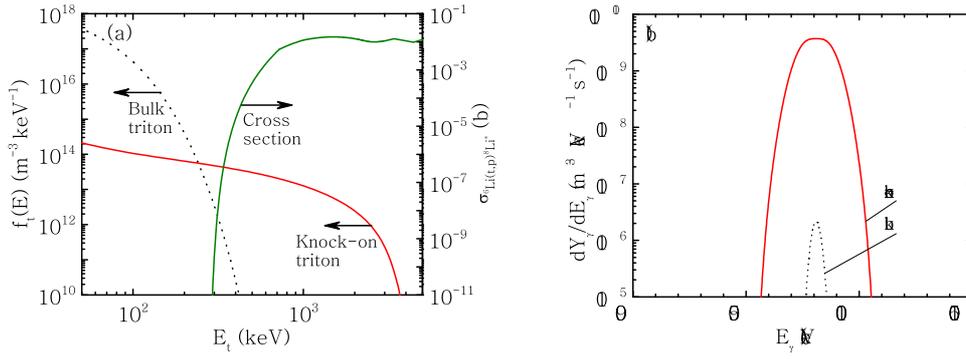


Figure 1: (a) The triton population (bulk and knock-on components) and the cross section of the  ${}^6\text{Li}(t, p){}^8\text{Li}^*$  reaction as functions of triton energy, where  ${}^6\text{Li}$ 's are assumed to be at rest. (b) The 0.981-MeV  $\gamma$ -ray spectra owing to both knock-on and bulk tritons.

$$\frac{1}{v^2} \frac{\partial}{\partial v} [Q_i(v) f_i(v)] = -S_i(v), \quad (2)$$

In the case of DT plasma,  $i = \alpha$ -particle ( $\alpha$ ), knock-on deuteron ( $d'$ ) or knock-on triton ( $t'$ ). The  $\alpha$ -particle source strength  $S_\alpha$  can be described in Gaussian form. The source strength of knock-on ions  $S_{j'}$  can be written in the following form [4]:

$$S_{j'}(v) = \frac{8\pi\gamma^2 n_j}{v} \int_{\gamma v}^{\infty} v_i f_i(v_i) \frac{d\sigma}{d\Omega} dv_i, \quad \gamma \equiv \frac{m_i + m_j}{2m_i}, \quad (3)$$

where  $d\sigma/d\Omega$  and  $n_j$  represent the differential scattering cross section and the number density of bulk ion species  $j$  ( $j = \text{bulk-deuteron } (d) \text{ or bulk-triton } (t)$ ). The calculations are performed for DT plasma with parameters typical of the ITER tokamak plasma, *i.e.* background electron and ion temperatures of  $T_B = 20$  keV and densities of  $n_d = n_t = n_e/2 = 0.5 \times 10^{20} \text{ m}^{-3}$ . The population of knock-on tritons together with the cross section of the  ${}^6\text{Li}(t, p){}^8\text{Li}^*$  reaction is shown in Fig. 1. The estimated 0.981-MeV  $\gamma$ -ray spectra due to both knock-on and bulk tritons are also shown in Fig. 1, where the  ${}^6\text{Li}$  concentration  $n_{\text{Li}}/n_t$  is assumed to be 1 %. The important feature is that the yield and energy spectrum of 0.981MeV  $\gamma$ -rays is solely governed by the population of knock-on tritons.

To examine the specific diagnostic information on energetic ions obtained from the  $\gamma$ -ray yield and spectrum, we introduce the quantity  $Y_{k,g}$  which is defined as

$$Y_{k,g} = \int_{E_{k,g}}^{E_{k,g-1}} y_k(E_k) dE_k; \quad \sum_g Y_{k,g} = Y_\gamma \quad (4)$$

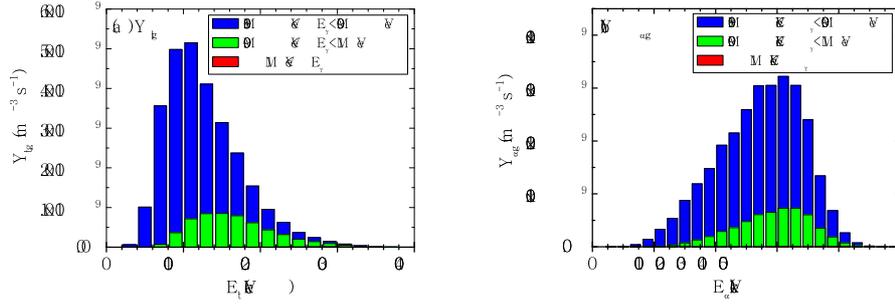


Figure 2: The calculated  $Y_{t',g}$  as a function of triton energy (a) and  $Y_{\alpha,g}$  as a function of  $\alpha$ -particle energy (b).

where  $k =$  knock-on triton ( $t'$ ) or  $\alpha$ -particle ( $\alpha$ ). This quantity expresses the  $\gamma$ -ray yield  $Y_\gamma$  to which knock-on tritons or  $\alpha$ -particles with energy  $E_{k,g} \leq E_k \leq E_{k,g-1}$  contribute. The quantity  $y_k(E_k)$  is the differential  $\gamma$ -ray yield  $dY_\gamma/dE_k$ , being a function of energy  $E_k$  of ion species  $k$ . The calculated  $Y_{k,g}$ 's are shown in Fig. 2, where they are decomposed for several energy regions  $E_\gamma$  of the  $\gamma$ -ray spectrum. Figure 2 shows that the emission of 0.981 MeV  $\gamma$ -rays reflects the presence of knock-on tritons with energy  $0.6 \text{ MeV} \leq E_{t'} \leq 1.8 \text{ MeV}$  and  $\alpha$ -particles with energy  $2.0 \text{ MeV} \leq E_\alpha \leq 3.5 \text{ MeV}$ .

Next, we consider a situation where the confinement is affected by a specific loss mechanism such as where energetic ions with energy  $E_i < E_{i,crit}$  are partially or entirely lost. The corresponding population of energetic ions takes the following form:

$$\tilde{f}_i(E_i) = f_i(E_i) \times \begin{cases} C_i, & (E_i < E_{i,crit}) \\ 1, & (\text{otherwise}) \end{cases} \quad (5)$$

where  $0 \leq C_i \leq 1$ , and  $f_i(E_i)$  is the unchanged population derived by solving Eq. 2. We estimate the dependence of the  $\gamma$ -ray yield  $Y_\gamma$  and the FWHM of  $\gamma$ -ray spectrum  $w_\gamma$  on the loss of energetic ions. For simplicity, the  $\alpha$ -particle population is assumed to be unchanged in examining the influence of the knock-on triton loss, and vice versa. Figures 3 and 4 show changes in the  $\gamma$ -ray yield  $\Delta Y_\gamma/Y_\gamma$  and the FWHM  $\Delta w_\gamma/w_\gamma$  due to perturbation  $C_i$ . One can observe that losses of both knock-on tritons with energy  $E_{t'} > 0.6 \text{ MeV}$  and  $\alpha$ -particles with energy  $E_\alpha > 2 \text{ MeV}$  affect the 0.981 MeV  $\gamma$ -ray yield. It can be also observed that the profiles of  $\Delta Y_\gamma/Y_\gamma$  in Figs. 3(a) and 3(b) are quite similar and contrarily that the profiles of  $\Delta w_\gamma/w_\gamma$  in Figs. 4(a) and 4(b) are quite different. This infers that, by measuring  $Y_\gamma$  and  $w_\gamma$ , one can diagnose the confinement properties of energetic ions and well discriminate the property of knock-on tritons from that of  $\alpha$ -particles.

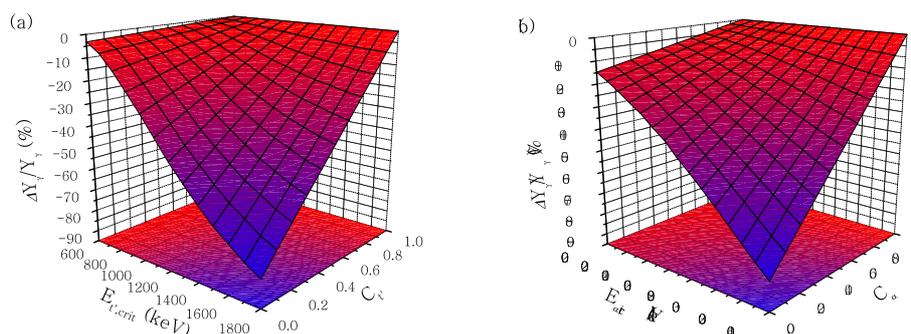


Figure 3: The change in the  $\gamma$ -ray yield,  $\Delta Y_\gamma/Y_\gamma$ , due to losses of knock-on tritons (a) and  $\alpha$ -particles (b).

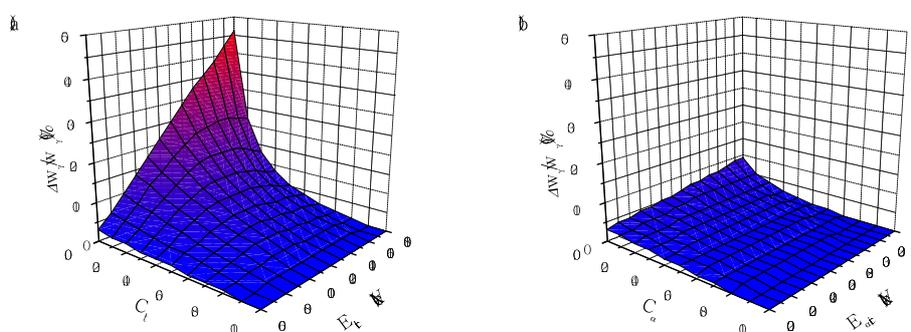


Figure 4: The change in the  $\gamma$ -ray spectrum FWHM,  $\Delta w_\gamma/w_\gamma$ , due to losses of knock-on tritons (a) and  $\alpha$ -particles (b).

The authors would like to thank Dr. V.T. Voronchev, Dr. H. Matsuura and Prof. O. Mitarai for fruitful discussions. The financial support of Research Fellowship of the Japan Society for the Promotion of Science for Young Scientists is acknowledged by M.N.

## References

- [1] V.G. Kiptily *et al.*, Nucl. Fusion **42**, 999 (2002); M.J. Mantsinen *et al.*, Phys. Rev. Lett. **88**, 105002 (2002); V.G. Kiptily *et al.*, Phys. Rev. Lett. **93**, 115001 (2004); V.G. Kiptily *et al.*, Nucl. Fusion **45**, L21 (2005).
- [2] M. Nakamura, Y. Nakao, V.T. Voronchev *et al.*, J. Phys. Soc. Jpn. **75**, 026413 (2006).
- [3] V.T. Voronchev, V.I. Kukulín, Y. Nakao, Phys. Rev. E **63**, 026413 (2001)
- [4] D. Ryutov, Phys. Scr. **45**, 153 (1992); P. Helander, M. Lisak, D.D. Ryutov, Plasma Phys. Control. Fusion **35**, 1246 (1993).