On Degenerate Plasma Diagnostics Based on $\gamma$-Ray Measurement

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Abstract. The potentiality of electron degeneracy diagnostics based on $\gamma$-ray measurement is discussed. For this purpose, the nuclear reactions D ($\alpha, \gamma$)$^6$Li and T ($\alpha, \gamma$)$^7$Li are considered. These reactions are induced in DT plasma by fusion-born energetic $\alpha$-particles and proceed through the excited nuclei $^6$Li* and $^7$Li* emitting monochromatic $\gamma$-quanta with 2.186-MeV and 0.478-MeV energies, respectively, in their decay to the ground state. If the plasma is being highly compressed and the electrons are in degenerate state, then the stopping range of the $\alpha$-particles is lengthened compared with the case of non-degenerate electron plasma. As a result, the probability that a fusion-born $\alpha$-particle will undergo D ($\alpha, \gamma$) or T($\alpha, \gamma$) reaction during slowing down would be enhanced. In this paper we will discuss the feasibility of detecting the 2.186-MeV and 0.478-MeV $\gamma$-ray in ICF environment.

1. Introduction

In ICF, the fuel is compressed to more than 1000 times the solid density, so that the electrons in the fuel just after implosion should be in degenerate state. One of the consequences of the electron degeneracy is reduction in the stopping power of the plasma; the range of energetic particles is lengthened than in the case of classical plasma. Using this, the degenerate parameter $\Theta = kT_e / E_F$ ($kT_e$: kinetic electron temperature, $E_F$: Fermi energy) of compressed CD plasma was determined [1]. The above feature, i.e. range lengthening effect, is also applicable to diagnostics of electron degeneracy in compressed DT fuel.

In the present study, we propose to use the following specific $\gamma$-ray modes of the nuclear reactions induced by $\alpha$-particles:

$$\alpha + D \rightarrow ^6\text{Li} + \gamma \ (E_\gamma=2.186\text{MeV}),$$  
$$\alpha + T \rightarrow ^7\text{Li} + \gamma \ (E_\gamma=0.478\text{MeV}).$$  

The modes lead to formation of daughter nuclei $^6\text{Li}^*$, $^7\text{Li}^*$ in the first excited states. The cross-section curves of respective reactions are shown in figure1.
The effect of electron degeneracy appears as a reduction in the stopping power for the $\alpha$-particles, i.e. the stopping range is lengthened. As a result, the probability that a fusion-born $\alpha$-particle will undergo D ($\alpha, \gamma$) or T($\alpha, \gamma$) reaction during slowing down would be enhanced. In terms of the stopping power and reaction cross-sections [2], we can estimate the reaction probabilities $p_{\alpha-D}$ and $p_{\alpha-T}$ as a function of plasma temperature and degeneracy parameter $\Theta$. The probability $p_{\alpha-D}$, for example, can also be expressed as the ratio of 2.186-MeV $\gamma$-ray yield to DT neutron yield, both of which can be measured in principle. Thus, if the plasma temperatures are determined from some other measurements, the degeneracy parameter $\Theta$ could be assessed using the diagnostic $p_{\alpha-D}$-$\Theta$ curve and the experimental $\gamma$-ray and neutron yields.

The purpose of this paper is to examine the possibility of electron degeneracy diagnostics based on $\gamma$-ray measurement. For that purpose, we have estimated 2.186-MeV and 0.478-MeV $\gamma$-ray yields in the case of several $\rho R$ values by using estimated reaction probability.

2. Analysis Model

In this section we describe the probability that a fusion-born $\alpha$-particle undergo D ($\alpha, \gamma$) or T($\alpha, \gamma$) reaction during slowing down. In the present analysis, plasma is assumed to be infinite and spatially uniform. For example, the probability $p_{\alpha-D}$ can be written in the following form:

$$p_{\alpha-D} = \exp \left( - \int_0^{E_b} n_D \sigma_{\alpha-D} dx \right) \approx \int_{E_c}^{E_b} n_D \sigma_{\alpha-D}(E) dE,$$

where $E_b$ is the birth energy of $\alpha$-particles (i.e. $E_b = 3.52$-MeV) and $E_c$ is the thermal cutoff energy. When the background particles $j$ have an unit-normalyzed distribution $\hat{f}_j(v)$, the stopping power for the $\alpha$-particles with energy $E$ is given by [3,4,5]:

$$S(E) = \sum_j \frac{2\pi Z_a^2 Z_j^2 e^4 m_w \ln \Lambda}{m_j E} n_j G_j(v), \quad j = e, d, t,$$

with the functions related to field particle distributions:

$$G_j(v) = J_{j,2} \left[ 1 - \frac{m_j}{3E} \frac{J_{j,4} + J_{j,3} v^3}{J_{j,2}} \right],$$

where

$$J_{j,1} = \int_0^\infty 4\pi v f_j(v) dv, \quad J_{j,2} = \int_0^\infty 4\pi v^2 f_j(v) dv, \quad J_{j,3} = \int_0^\infty 4\pi v^3 f_j(v) dv, \quad J_{j,4} = \int_0^\infty 4\pi v^4 f_j(v) dv.$$

When the degeneracy parameter $\Theta$ is smaller than 5, the Fermi-Dirac distribution is used for the electron distribution function. On the other hand, the Maxwell distribution is used for the distribution functions of both
ion and electron component when electrons are non-degenerate \( (i.e. \Theta > 5) \). In equation (4), \( \ln \Lambda \) is the Coulomb logarithm derived on the basis of the quantum-mechanical analysis [6]. In order to allow for the electron degeneracy in the Coulomb logarithm, we adopt a simple approximation made by Brysk [7], \( i.e. \) we replace \( T_e \) in \( \ln \Lambda \) with \( T_e^2 + T^2 \).

We are interested in detecting the \( \gamma \)-ray and DT neutron signals within a short time interval \( \tau \) (~10ps) during which most of the electron components are in degenerate state. The \( \gamma \)-ray yield \( N_\gamma \) per shot may be calculated by

\[
N_\gamma = 2.2 \times 10^9 \times V \times p_{\alpha-D(\alpha,T)},
\]

where \( V \) is the volume of the fuel pellet and \( S_\alpha \) is the \( \alpha \)-particle generation rate;

\[
S_\alpha = n_p n_T <\sigma v>_{DT}.
\]

3. Results and Discussion

We show in figure 2 the reaction probabilities \( p_{\alpha-D} \) and \( p_{\alpha-T} \) calculated as a function of degeneracy parameter \( \Theta \) and plasma temperature. It is seen that \( p_{\alpha-D} \) and \( p_{\alpha-T} \) are enhanced with decreasing \( \Theta \) and increasing temperature. The effect of electron degeneracy is seen to be remarkable in the case that \( \Theta < 5 \). Experimentally, the reaction probability \( p_{\alpha-D} \) (and also \( p_{\alpha-T} \)) is determined as the ratio of the \( \gamma \)-ray yield to the DT neutron yield. Thus, if the \( \gamma \)-rays and DT neutrons are measured and the plasma temperature is known, then we can assess the degeneracy parameter \( \Theta \) using the diagnostic \( p-\Theta \) curve.

Table 1 summarizes the \( \gamma \)-ray yields emitted from the compressed pellets with areal densities of \( \rho R=1.0g/cm^2 \) \( (\rho=200g/cm^3) \) and \( \rho R=2.0g/cm^2 \) \( (\rho=300g/cm^3) \). Although each of the \( \gamma \)-ray yields increases with increasing plasma temperature and \( \rho R \), the values of the yields estimated may be too small to be detected.

If we consider use of a resonant nuclear reaction between \( \alpha \)-particle and \( ^9\text{Be} \) admixture, \( i.e. ^9\text{Be}(\alpha,\gamma)^{12}\text{C} \), which has been used in JET experiments to detect \( \alpha \)-particles emitted in DT fusion [8], we can expect the reaction probability 4 order of magnitude larger than \( p_{\alpha-T} \); the \( \gamma \)-ray yield would be enough to be detected.

![Figure 2. The reaction probabilities \( p_{\alpha-D} \) and \( p_{\alpha-T} \) calculated as a function of degeneracy parameter \( \Theta \) and plasma temperature.](image-url)
4. Concluding Remarks

We have examined the probability that a fusion-born $\alpha$-particle undergoes $\alpha$ ($\alpha$, $\gamma$) $^6$Li or $\alpha$ ($\alpha$, $\gamma$) $^7$Li reaction during slowing down by assuming DT plasma to be the infinite and spatially uniform. It is confirmed that these probabilities are enhanced as the degeneracy parameter decreases. The reaction probabilities and also the $\gamma$-ray yields, however, seem too small to be detected. If some resonant nuclear reactions between $\alpha$-particles and admixture light element, e.g. $^9$Be($\alpha$, $n\gamma$)$^{12}$C, then we can expect enough reaction probabilities and $\gamma$-ray yields.

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