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Calculation Method for Alpha-Particle Transport in Degenerate Plasma and Its Application to Degeneracy Diagnostics
縮退プラズマ中でのアルファ粒子輸送計算法の検討と縮退度診断法への応用

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A kinetic model to properly calculate the transport of α-particles in highly compressed plasma is formulated. The effect of electron degeneracy including Pauli blocking is fully incorporated. After showing outline of the model together with some result of test calculation, the code is applied to examine applicability of a method proposed to diagnose electron degeneracy in compressed DT fuel for fast ignition. The method uses the reaction ^{9}Be (α, $n\gamma$)^{12}C governed by fusion-produced energetic α-particles; in the previous proposal, behavior of α-particles was calculated by assuming infinite plasma. We show that the proposed method would be applicable to compressed pellets with areal densities larger than 0.3 g/cm^2.

1. Introduction

In superdense plasmas as realized by laser implosion, the electrons should be in Fermi degenerate state. One of the consequences of electron degeneracy is reduction in the stopping power of plasma for energetic charged particles. Accordingly, their ranges are lengthened than in the case of non-degenerate electron plasma. The electron degeneracy might have influences on the ignition condition in the fast ignition scheme where the implosion is tailored so as to keep the isentrope parameter close to 1.

There have been transport codes for energetic ions in degenerate electron plasmas.[1] However, in these previous codes, an important item was not included. Since transition of the energy state of plasma electrons due to *α-e* scattering collisions, for example, is limited by Pauli's exclusion principle, scattering between an electron and other particles is restricted—Pauli blocking. Thus, recently we have developed transport code for energetic ions in which the effect of electron degeneracy including Pauli blocking is fully incorporated. In the present paper first we show the outline of this model together with some result of test calculation.

The extent of the degree of electron degeneracy in compressed DT fuel for fast ignition is a matter of interest. So, next using the developed code we examine applicability a method previously proposed to diagnose electron degeneracy in compressed for fast ignition.[2] The proposed diagnostics method considers a DT fuel admixed with a small amount of ^{9}Be and uses the following reaction governed by fusion-produced energetic α-particles:

$$\alpha + {}^{9}\mathrm{Be} \rightarrow {}^{12}\mathrm{C}^{*}[2^{+};0] + \mathrm{n}\ ; \qquad {}^{12}\mathrm{C}^{*} \rightarrow {}^{12}\mathrm{C} + \gamma \ \ (E_{\gamma} = 4.44\mathrm{MeV}) \tag{1}$$

The DT/^{9}Be pellet is compressed to high densities by implosions such as tailored for fast ignition, but is not subjected any heating laser. In such a case, the fuel would not be ignited, and most of the nuclear reactions would occur around the maximum compression. Thus, nuclear reaction products are expected to carry information about the compressed state of the fuel such as the degree of electron degeneracy. In [2], however, it was assumed that α-particles slow down in an infinite plasma; leakage from the pellet was not accounted for. In the present study, we calculate the transport of 3.52 MeV α-particles in degenerate plasma, and apply it to the degeneracy diagnostics.

2. Transport Equation

The transport of energetic charged particles in plasmas is described by the Boltzmann-Fokker-Plank (BFP) equation. The BFP equation for the case of non-degenerate electrons was written as follows:

$$\left[\frac{1}{v}\frac{\partial}{\partial t} + \boldsymbol{\Omega}\cdot + \Sigma_{R}\right]\psi(\boldsymbol{r},E,\boldsymbol{\Omega},t)$$
$$= \sum_{j}\frac{\partial}{\partial E}\left[S_{j}(\boldsymbol{r},E)\psi(\boldsymbol{r},E,\boldsymbol{\Omega},t)\right] + \sum_{j}T_{j}(\boldsymbol{r},E)\frac{\partial}{\partial \mu}\left[(1-\mu^{2})\frac{\partial}{\partial \mu}\psi(\boldsymbol{r},E,\boldsymbol{\Omega},t)\right]$$
$$+ \int dE'\int d\boldsymbol{\Omega}'\Sigma_{NES}(E'\rightarrow E,\boldsymbol{\Omega}'\rightarrow\boldsymbol{\Omega},t)\psi(\boldsymbol{r},E',\boldsymbol{\Omega}',t) + Q(\boldsymbol{r},E,\boldsymbol{\Omega},t) \tag{2}$$

where ψ and Q stand for respectively the angular flux and source of energetic particles,; Σ_R and Σ_{NES} are macroscopic removal and macroscopic transfer (differential) cross sections; S and T represent the coulombic stopping power and the angular deflection coefficient, respectively.

The electron degeneracy effect should be incorporated in FP terms, *i.e.* the terms including S and T. To do this, we get the FP terms back to the Boltzmann integral form. After incorporating Pauli blocking, we recover the FP form suitable to treat small-angle scattering.

3. Energy Deposition

We solved the BFP equation for a spherically symmetric case where 3.5-MeV source α-particles are injected into the central region ($r/R < 0.05$) of a compressed 'stationary' DT plasma sphere. Figure 1 shows profile of deposited energy by α-particles per unit path length. It is confirmed that the width of the energy deposition region becomes broader than in the case of non-degenerate background.

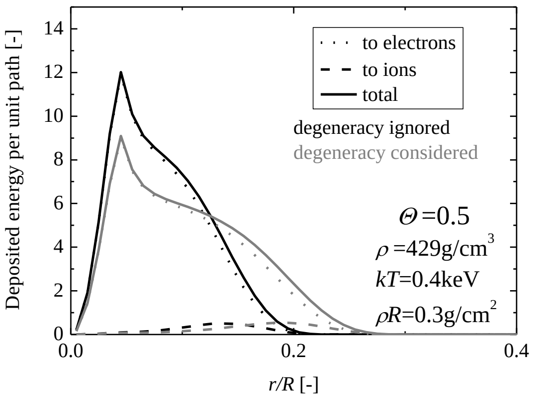

Fig.1. Energy deposited per unit path

4. Reaction Probability

Assuming DT/ ^{9}Be pellets compressed to various areal densities, we calculated the probability $P_{\alpha\text{-}Be}$ that $\alpha + {}^9$Be reaction occurs during the transport of fusion-born α-particles as a function of the degeneracy parameter Θ ($\equiv kT_e / E_{Fermi}$). The probability is calculated using $\psi(r, E)$, the α-particle flux integrated over the angular space:

$$P_{\alpha-Be} = \frac{\iint n_{Be}(r)\sigma_{\alpha-Be}(E)\psi(r,E)dEdV}{\int n_D(r)n_T(r) < \sigma v > dV} \tag{3}$$

Figure 2 shows the calculated probability. The fractional number density of ^{9}Be admixture was fixed to $n_{Be}/n_i = 0.1$. We can see that $P_{\alpha\text{-}Be}$ strongly depends on Θ. The more the range of α- particles is lengthened, the more they leak from the pellet. Therefore, when the pellet is small, the probability $P_{\alpha\text{-}Be}$ is reduced.

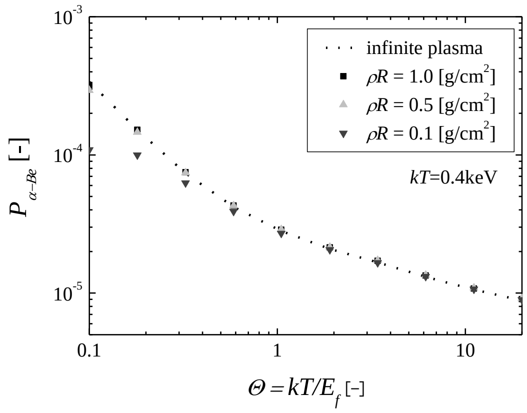

Fig.2. Reaction probability

Experimentally $P_{\alpha\text{-}Be}$ is determined as the ratio of 4.44-MeV γ-ray yield to the DT neutron yield. Thus, if these yields are measured and the plasma temperatures are given by another measurement, we can assess the degeneracy using the $P_{\alpha\text{-}Be}$-Θ curve.

We also estimated the yield of 4.44-MeV γ-rays emitted from compressed DT/ ^{9}Be pellets. In the case that $\rho R = 0.5$ g/cm^2, $\rho = 200$ g/cm^3, $kT = 0.4$,～1.0 keV and $n_{Be}/n_i = 0.1$, for example, the yield was estimated to be 10^5～10^8, which seems enough to be detected.

5. Concluding Remarks

We have calculated the transport of energetic α-particles in degenerate plasma and confirmed the effect such as range lengthening due to electron degeneracy.

Using the transport code, we also examined the applicability of previously proposed method to diagnose electron degeneracy in compressed DT fuel. It was shown that the method would be applicable if the areal density of compressed pellet is larger than 0.3 g/cm^3.

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