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非平衡プラズマの温度に関する統計力学的検討

Statistical-Mechanical Discussion on Temperatures of Non-Equilibrium Plasma

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It is well known that the electron energy distribution function (EEDF) F becomes far from a Maxwellian one in a weakly-ionized plasma [1]. However, chemical kinetics of counterparts of electron collisions are not often included in such calculations. We discussed the dissociation degree of oxygen molecule, with simultaneous solution of the two-term approximated Boltzmann equation [2]. Here, the definition of the "temperature" should be reconsidered from the statistical thermodynamic viewpoint, which has seldom been discussed. Let the internal energy U and the entropy S for electron gas in a weakly-ionized plasma. Then, the first law of thermodynamics leads:

$$\left(\frac{\partial S}{\partial U}\right)_{V,N_i} = \frac{1}{T}. \qquad (1)$$

Here, we neglect change in its volume or electric potential. Hereafter, T in Eq. (1) is referred to as the thermodynamic electron temperature T_e^{th}. Meanwhile,

$$U = \langle \epsilon \rangle = \int_0^\infty \epsilon F(\epsilon) \mathrm{d}\epsilon. \qquad (2)$$

We can also calculate the Gibbs electron entropy as

$$S = -k \int_0^\infty F(\epsilon) \ln \left[F(\epsilon)\right] \mathrm{d}\epsilon. \qquad (3)$$

In the present study, we chose microwave discharge oxygen plasma in a cylindrical tube of 2.6 cm^ϕ with its discharge pressure 1 Torr. We fixed the electron density $N_e = 2 \times 10^{11} \mathrm{cm}^{-3}$ and the gas temperature 1000 K.

Meanwhile, many researchers define the electron kinetic temperature T_e^k from U of Eq. (2) as follows [3]:

$$T_e^k = \frac{2}{3k} U, \qquad (4)$$

since the kinetic temperature agrees with the equilibrium electron temperature for the plasmas with the Maxwellian EEDF. Although Alvarez *et al.* concluded that $T_e^{th} = T_e^k$ [3], they never solved chemical kinetics of discharge gases of the plasmas. We found the bulk ($\epsilon \leq 8.4$ eV) and tail regions ($\epsilon > 8.4$ eV), which has different slopes with their temperatures T_1 and T_2 ($< T_1$), respectively. This is due to the electron-impact oxygen dissociation, which causes non-equilibrium for the EEPF.

Fig. shows a comparison between various temperatures defined to the oxygen plasma. It should be remarked that $T_e^{th} \neq T_e^k$, which does not agree with Alvarez *et al.*'s result [3]. It should be noted that the thermodynamic temperature T_e^{th} is more close to T_1, the electron temperature of the bulk component than T_e^k is. Further thermodynamic discussion is necessary to understand the physical meaning of each temperature, particularly for the relevance to Tsallis entropy.

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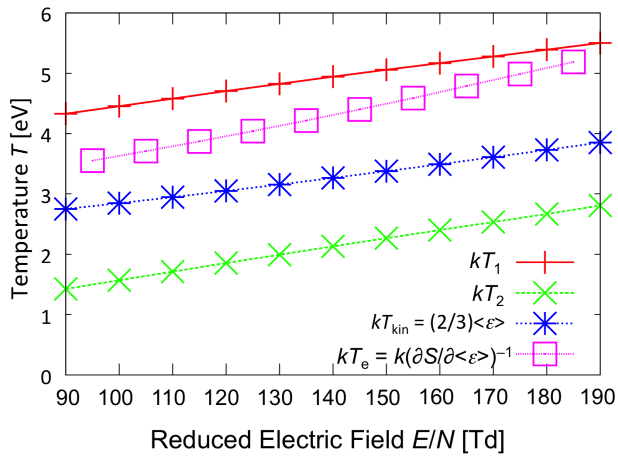

Fig. 1. Comparison between various electron temperatures defined in the present study for the oxygen plasma.

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