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Study of impurity behaviour in non-coronal equilibrium state

Cheng Fa-Yin(程发银)[a)] and Shi Bing-Ren(石秉仁)[b)]

[a)] *College of Science, Chongqing Technology and Business University, Chongqing* 400067, *China*

[b)] *Southwest Institute of Physics, Chengdu* 610041, *China*

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A physical model of analysing the behaviour of impurities out of coronal equilibrium in tokamak plasmas has been proposed. Through solving the time-dependent rate equations including the effects of atomic processes and the particle transport losses, the ionization state distribution is obtained for a range of low Z impurities such as helium, carbon, oxygen and argon. By using the ionization state distribution of these impurities, the radiation rate coefficients and the mean charge state changing with plasma temperature are calculated. The results show that the mean charge state $\langle Z \rangle$ is sensitively dependent on the parameter $n_e\tau$, and this is the reason why the radiation power of impurities under non-coronal equilibrium conditions is several orders of magnitude higher than that under coronal equilibrium condition.

Keywords: plasma, impurity, non-coronal equilibrium, radiation
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1. Introduction

The high electron temperature ($1\text{eV} < T_e < 100$ keV) and low density ($n_e \leq 10^{19}\text{m}^{-3}$) of magnetically confined fusion plasma can represent the coronal approximation as the starting point when treating the atomic physics of the impurity ions. First, the plasma is optically thin to atomic line radiation, hence all photoabsorption processes may be neglected. Second, in this low density situation, the electron collision time is much longer than the decay time of most excited atomic states and the plasma-maintaining time is much longer than the ionization time, so the coronal model can be a good approximation when treating the impurity radiation.

The time for an impurity particle to reach its coronal equilibrium state depends on not only the species itself but also the plasma electron temperature and density.[1] Because of the transverse transport in tokamak peripheral plasma, impurities will experience the rapidly varying the plasma conditions. Furthermore, because of the competition between fast transport along field line and the transverse transport which result from a very narrow scrape off layer (SOL) width and a very short residence time of impurity,[2] thus the impurity particles will find that they have not enough time to reach their steady state before they reach the vessel wall or the divertor target plate.

Researches show that the impurity radiation power in tokamak edge plasma is much larger than the calculation results using a coronal equilibrium model, namely, using the steady state coronal model, the radiation loss in edge plasma will be grossly underestimated.[3,4] This happens when the impurities find themselves in lower ionization states than those obtained at steady state. Consequently increase in ion excitation rate usually leads the radiation power to increase.

In the previous work[5] Cheng and Shi calculated the radiation power coefficients of a few typical light impurities using simple 0-dimensional model, and in Ref.[6] Cheng *et al* calculated and analysed the radiation features of impurity carbon through considering the transport loss. In the present work we study the behaviour of a few typical light impurities out of coronal equilibrium including the charge state distribution, the mean charge state and the radiation coefficients as a function of parameter $n_e\tau$.

2. The impurity charge state distribution

The main atomic processes in plasmas are almost all caused by electron collisions. Through collisions with electron, ions are excited and then im-

mediately decay to their ground state. As a consequence, the excitation rate coefficients are fully determined by the electron density and temperature. The radiation power is calculated from the sums of the products of the excitation rates and energies at each charge state which are then weighted according to the charge state distributions of the impurities.[7] The essential problem in the time-dependent treatment of impurities thus consists in determining these charge distributions.

The charge state distribution of impurities can be obtained by solving the rate equations, which describe the ionization, recombination and transport processes of impurities in plasmas. Considering that a plasma system is comprised of a high temperature region and a low temperature region, this system can be applied to the following cases: (I) core peripheral plasma serves as a hot region and SOL as a cold region; (II) SOL plasma serves as a hot region and divertor plasma serves as a cold region. There exists not only transport loss in each region but also particle exchange process between the two regions. So the rate equations are described as follows:

$$\begin{aligned}
\frac{\mathrm{d}n_k^{(\mathrm{l})}}{\mathrm{d}t} &= n_{\mathrm{e}}^{(\mathrm{l})} n_{k-1}^{(\mathrm{l})} S_{k-1}^{(\mathrm{l})} - n_{\mathrm{e}}^{(\mathrm{l})} n_k^{(\mathrm{l})} (S_k^{(\mathrm{l})} + \alpha_k^{(\mathrm{l})}) + n_{\mathrm{e}}^{(\mathrm{l})} n_{k+1}^{(\mathrm{l})} \alpha_{k+1}^{(\mathrm{l})} - \frac{n_k^{(\mathrm{l})}}{\tau_{k,\mathrm{loss}}^{(\mathrm{l})}} - \frac{n_k^{(\mathrm{l})} - \beta n_k^{(\mathrm{h})}}{\tau_{\mathrm{ex}}}, \\
\frac{\mathrm{d}n_k^{(\mathrm{h})}}{\mathrm{d}t} &= n_{\mathrm{e}}^{(\mathrm{h})} n_{k-1}^{(\mathrm{h})} S_{k-1}^{(\mathrm{h})} - n_{\mathrm{e}}^{(\mathrm{h})} n_k^{(\mathrm{h})} (S_k^{(\mathrm{h})} + \alpha_k^{(\mathrm{h})}) + n_{\mathrm{e}}^{(\mathrm{h})} n_{k+1}^{(\mathrm{h})} \alpha_{k+1}^{(\mathrm{h})} - \frac{n_k^{(\mathrm{h})}}{\tau_{k,\mathrm{loss}}^{(\mathrm{h})}} - \frac{n_k^{(\mathrm{h})} - (1/\beta) n_k^{(\mathrm{l})}}{\tau_{\mathrm{ex}}},
\end{aligned} \tag{1}$$

where n is the impurity density; subscript k represents charge state; superscripts (l) and (h) represent low and high temperature regions respectively; S and α are the ionization and recombination rate coefficients respectively; τ_{ex} is the particle-exchanging time between the two regions; τ_{loss} is the transport loss time which can be defined as $\tau_{k,\mathrm{loss}} = \int n_k(x)\mathrm{d}x/\Gamma_k$ with Γ_k representing the loss flux; parameter $\beta = V^{(\mathrm{h})}/V^{(\mathrm{l})}$ is introduced so that the particle exchange does not change the total number of impurities.

In order to maintain the particle balance, we assume that all the particles lost from the system are recycled and supplied to the low temperature region as neutrals. So for the neutral impurity, we have

$$\begin{aligned}
\frac{\mathrm{d}n_{\mathrm{o}}^{(\mathrm{l})}}{\mathrm{d}t} &= n_{\mathrm{e}}^{(\mathrm{l})} n_1^{(\mathrm{l})} \alpha_1^{(\mathrm{l})} - n_{\mathrm{e}}^{(\mathrm{l})} n_0^{(\mathrm{l})} S_0^{(\mathrm{l})} - \frac{n_0^{(\mathrm{l})} - n_0^{(\mathrm{h})}}{\tau_{\mathrm{ex}}} \\
&\quad + \sum_{k=1}^{z} \frac{n_k^{(\mathrm{l})}}{\tau_{k,\mathrm{loss}}^{(\mathrm{l})}} + \sum_{k=0}^{z} \frac{n_k^{(\mathrm{h})}}{\tau_{k,\mathrm{loss}}^{(\mathrm{h})}}, \\
n_0^{(\mathrm{h})} &= n_{\mathrm{tot}} - \sum_{k=0}^{z} n_k^{(\mathrm{l})} - \sum_{k=1}^{z} n_k^{(\mathrm{h})}.
\end{aligned} \tag{2}$$

The ionization and recombination rate coefficients can be obtained form the Hulse[8] average atom model. By solving Eqs.(1) and (2) we can obtain the charge state distribution of various impurities. The numerical method of solving the rate equations has been described in Ref.[6].

3. The radiation power and mean charge of impurities[9]

Many atomic processes of impurity in plasma are frequently accompanied by energy radiation through the electron collision excitation, the radiative recombination process and the dielectronic recombination process etc, so the radiation power of impurities should include the line radiation, radiative recombination radiation, dielectronic recombination radiation and the bremsstrahlung.

3.1. Line radiation

In tokamak experiment, especially for edge plasma, the line radiation is a very important energy loss mechanism.[10] The line radiation coefficient of kth charge state can be obtained by the product of the excitation rate coefficient and the corresponding transition energy

$$L_{kl} = \sum_{n=1}^{N} Q_{kn} \Delta E_{kn}, \tag{3}$$

where N is the number of transitions involved (Typically 1–10), Q_{kn} is the excitation rate coefficient of the nth transition, and ΔE_{kn} is the excitation energy of the nth transition.

3.2. Radiative recombination radiation

In the process of radiative recombination, a free electron in the energy continuum is directly captured by an ion and one or more photons are emitted. The radiation power in this process includes the kinetic energy of the electron and the potential energy of the recombined ion as expressed as

$$L_{kr} = \alpha_k^{\mathrm{rr}}(\varepsilon_{k-1} + \langle E\rangle), \tag{4}$$

where α_k^{rr} is the radiative recombination rate coefficient of kth charge state, ε_{k-1} is the ionization potential of the recombined ion, and $\langle E\rangle$ is the average kinetic energy of the recombined electrons.

3.3. Dielectronic recombination radiation

Dielectronic recombination is a complex process. In this process, a free electron is captured into a highly excited level of an ion during the excitation of a bound electron. This doubly excited state is unstable against autoionization, but it is sometimes stabilized before this occurs by radiative decay of the inner excited electron. The radiation coefficient in this process can be described as follows:

$$L_{kd} = \alpha_k^{\mathrm{dr}}(\varepsilon_{k-1} + E_k), \tag{5}$$

where α_k^{dr} is the dielectronic recombination rate coefficient, and E_k is the excitation energy of the resonant transition.

3.4. Bremsstrahlung

The additional bremsstrahlung power due to the presence of a particular impurity charge state is

$$L_{kbr} = 4.85 \times 10^{-37} k^2 T_{\mathrm{e}}^{1/2}, \tag{6}$$

where T_{e} is the electron temperature in units of keV.

3.5. Total radiation power

The total radiation power produced by a particular impurity species can be written from Eqs.(3)–(6) as

$$P_{\mathrm{rad}} = n_{\mathrm{e}} \sum_k n_k (L_{kl} + L_{kr} + L_{kd} + L_{kcx} + L_{kbr}), \tag{7}$$

where n_{e} is the electron density, and n_k is the density of kth charge state impurity ion.

3.6. Mean charge state

The mean charge state $\langle Z\rangle$ is a useful quantity when calculating the number of additional free electrons produced during impurity ionization, and the enhancement of the plasma resistivity and bremsstrahlung. It can be defined as

$$\langle Z\rangle = \frac{1}{n_{\mathrm{I}}} \sum_k k n_k, \tag{8}$$

where n_{I} is the total impurity density.

4. Calculation results and discussion

Helium, carbon, oxygen and argon are the typical light impurities in tokamak edge plasmas. In the present work we calculate and analyse the behaviour of these impurities under non-coronal condition through solving Eqs.(1) and (2). The rate coefficients are obtained from ADPAK package,[8] which uses an average atom model.

Figures 1 to 4 show the results of helium, carbon, oxygen and argon respectively. We usually use time-integrated electron density or $n_{\mathrm{e}}\tau$ to represent the non-coronal equilibrium state, because the quality of plasma confinement is often judged in terms of $n_{\mathrm{e}}\tau_{\mathrm{E}}$ and $n_{\mathrm{e}}\tau_{\mathrm{p}}$ where τ_{E} and τ_{p} are the energy and particle confinement times respectively. According to the calculation in Ref.[1], when parameter $n_{\mathrm{e}}\tau = 10^{18}\,\mathrm{m}^{-3}\cdot\mathrm{s}$, the above impurities are approximately all in coronal equilibrium and $n_{\mathrm{e}}\tau = 10^{13}\,\mathrm{m}^{-3}\cdot\mathrm{s}$ is in a typical non-coronal equilibrium state, thus we use these two values to represent the coronal and non-coronal equilibrium state respectively when calculating the charge state distribution. For each impurity, in Figs.1–4, subfigures (a) and (b), respectively, show the charge state distribution under coronal and non-coronal equilibrium states, subfigure (c) shows the mean charge state $\langle Z\rangle$ as a function of parameter $n_{\mathrm{e}}\tau$ changing with temperature, and subfigure (d) shows the radiation power coefficient $L = P_{\mathrm{rad}}/(n_{\mathrm{e}}n_{\mathrm{I}})$, where P_{rad} can be obtained from expression (7).

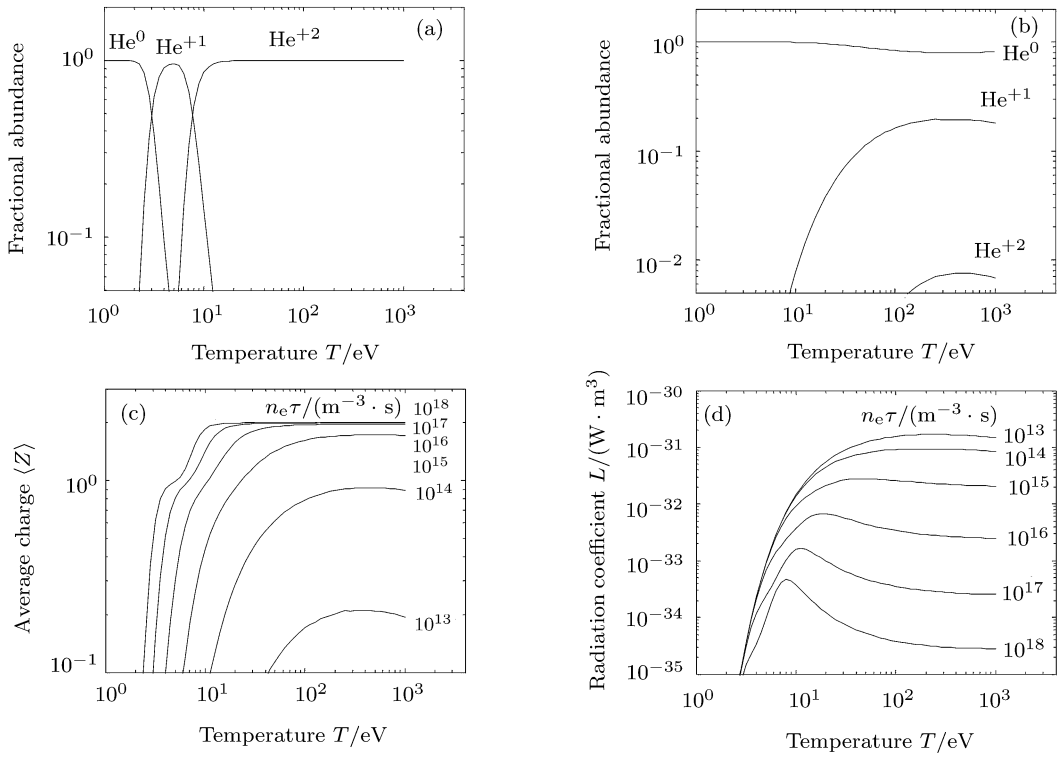


Fig.1. The various parameters of helium changing with temperature: (a) charge state distribution under coronal equilibrium condition, (b) charge state distribution when $n_e\tau_0 = 10^{13}\,s\cdot m^{-3}$, (c) mean charge state, (d) radiation coefficient.

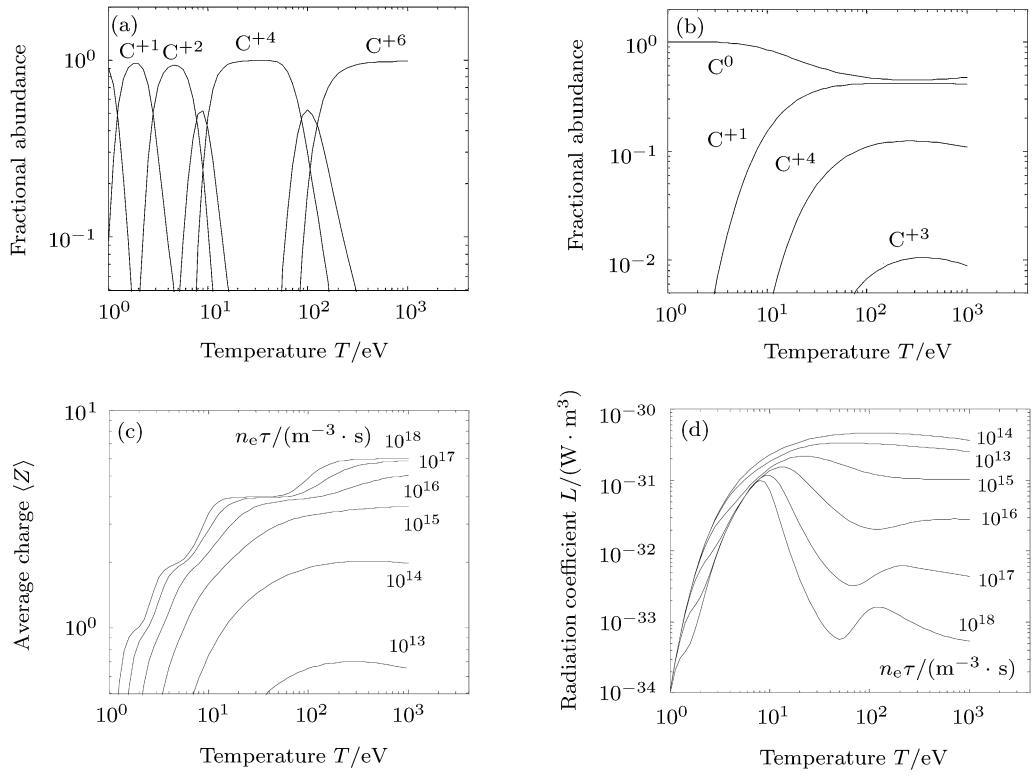


Fig.2. The various parameters of carbon changing with temperature: (a) charge state distribution under coronal equilibrium condition, (b) charge state distribution when $n_e\tau_0 = 10^{13}\,s\cdot m^{-3}$, (c) mean charge state, (d) radiation coefficient.

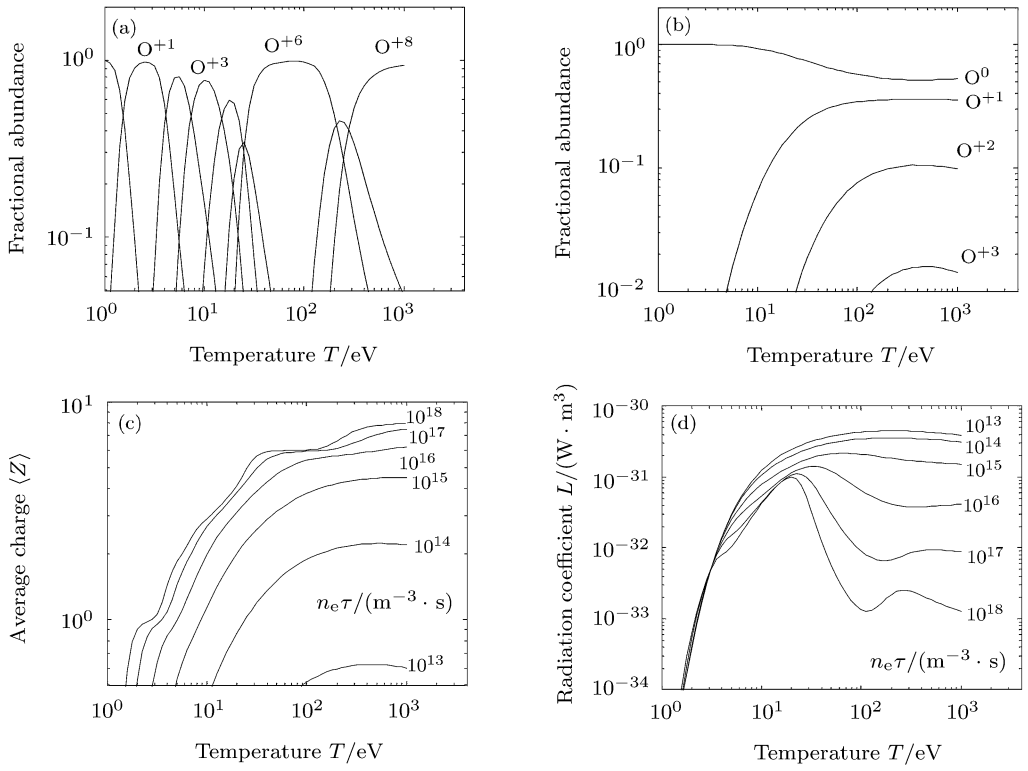


Fig.3. The various parameters of oxygen changing with temperature: (a) charge state distribution under coronal equilibrium condition, (b) charge state distribution when $n_e\tau_0 = 10^{13}\,s\cdot m^{-3}$, (c) mean charge state, (d) radiation coefficient.

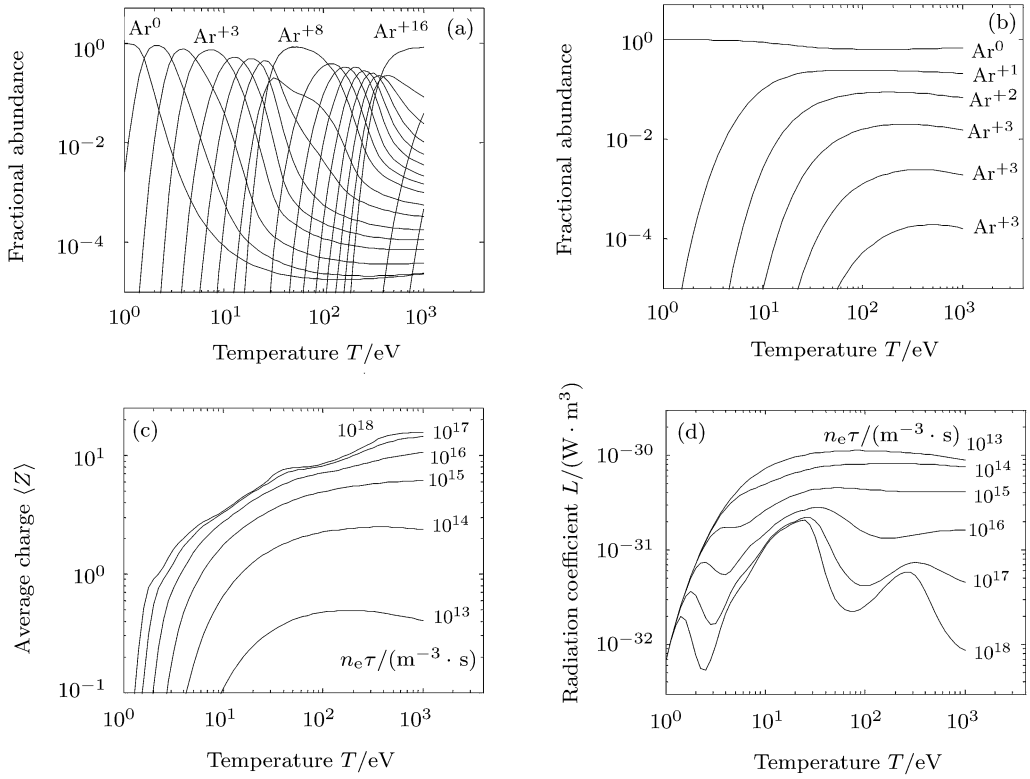


Fig.4. The various parameters of argon changing with temperature: (a) charge state distribution under coronal equilibrium condition, (b) charge state distribution when $n_e\tau_0 = 10^{13}\,s\cdot m^{-3}$, (c) mean charge state, (d) radiation coefficient.

From these figures we can see that the temperature, at which the impurity can be fully stripped (the fractional abundance of the highest charge state greater than 90%), strongly depends on the nuclear charge number. The temperature values for helium, carbon and oxygen in coronal equilibrium are 10, 200 and 500 eV respectively, but their fractional abundances at these temperatures are about 1.5×10^{-6}, 4.5×10^{-10} and 2.3×10^{-12} respectively when $n_e\tau = 10^{13}\,\mathrm{m}^{-3}\cdot\mathrm{s}$, namely the impurity ions have more bound electrons in a non-coronal equilibrium state than in coronal equilibrium state thus they will have more radiation losses. This can also be seen from Figs.1(c)–4(c), the mean charge state of impurities decreases with the decrease of parameter $n_e\tau$ (farther from coronal equilibrium), at a temperature of 1000 eV, the mean charge states of helium, carbon, oxygen and argon decrease from 2.00, 5.99, 7.96 and 15.90 of coronal equilibrium state ($n_e\tau = 10^{18}\,\mathrm{m}^{-3}\cdot\mathrm{s}$) to 0.25, 0.87, 0.84 and 0.64 of non-coronal equilibrium state ($n_e\tau = 10^{13}\,\mathrm{m}^{-3}\cdot\mathrm{s}$) respectively.

From Figs.1(b)–4(b) we can see that in a non-coronal equilibrium state it is the neutral impurities or lower charge state ions that dominate the charge state distribution in our calculated temperature ranges (i.e. 1–1000 eV). In this situation, the radiation power coefficient is affected mainly by the radiation feature of neutral atoms or lower charge state ions, which include mainly the line radiation, and the line radiation itself is usually very strong and has a weak correlation with temperature especially when temperature is sufficiently high, thus we can see from Figs.1(d)–4(d) that the curves of radiation power coefficients become flat under non-coronal equilibrium condition far from coronal equilibrium (i.e. $n_e\tau = 10^{13}\ \mathrm{m}^{-3}\cdot\mathrm{s}$).

It can be seen from the corresponding radiation power coefficient figures (Figs.1(d)–4(d)) that there exists a strong correlation between minima in radiation power and closed shell configurations such as C^{+4}, O^{+6}, Ar^{+8} and Ar^{+16}, which is because that the impurity ions with closed shell configurations have a higher ionization potential energy thus their ionization is more difficult than their neighbouring charge state ions and can dominate the charge state distribution in a large temperature range (see Figs.1(a)–4(a)). It can also be seen that for each impurity there exists a threshold temperature, only when temperature exceeds this value will the radiation power coefficient become sensitive to parameter $n_e\tau$, namely, when plasma temperature is lower than this threshold, using coronal radiation model can obtain sufficiently accurate results.

The physical model used in the present work is simple to some extent, and the behaviour of ion transport in plasma is not completely described. However, the simple calculation like the present work is significative both for the understanding of the behaviour of impurities in a non-coronal equilibrium state and for the experimental analysis.

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