Radiative losses of alpha particles on tungsten impurities in thermonuclear plasmas

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The plasma radiative losses is the long standing subject of research of different chemical elements as plasma impurities. The conventional channel of plasma radiative losses is attributed to electron collisions with impurity ions. However, for the nuclear reactor parameters the essential part of plasma energy becomes concentrated in the fast alpha-particles. As it is shown in the present contribution the account of a new channel of radiative losses due to collisions of fast alpha particles with tungsten impurity ions could become important. Indeed the large tungsten nuclear charge bears the significant number of bound electrons up to high plasma temperature values (20-30 keV for ITER plasma conditions). At the same time due to the high energy of alpha particles their collisional excitation of multielectron tungsten impurity ions could be essential. First of all we suppose that plasma is in corona equilibrium, so that the energy absorbed due to collisional excitation is completely emitted afterwards. For evaluation of energy spent for collisional excitation of tungsten impurities by electrons and alpha-particles we use the Fermi approximation of equivalent photons (see [1]). Then radiation losses are expressed via the photoabsorption cross section $\sigma_{ph}(\omega)$ and the equivalent photons flux - $dN_{e,\alpha}(\omega)$, which includes integration over velocity distribution of incident particles $\mathrm{v}_{e,\alpha}$ (electrons or alpha-particles) with corresponding velocity distribution $f_{e,\alpha}(\mathrm{v}_{e,\alpha})$ (compare with [1])

$$\frac{Q_{e,\alpha}}{N_w} = \int_0^{\omega_{e,\alpha}^{(\max)}} dN_{e,\alpha}(\omega)\cdot\sigma_{ph}(\omega)\cdot\hbar\omega = \frac{1}{2\sqrt{3}}\left(\frac{\hbar^2 c}{e^2}\right)\int_0^{\omega_{e,\alpha}^{(\max)}} d\omega\cdot\sigma_{ph}(\omega)\cdot\int_{\mathrm{v}_{e,\alpha}^{(\min)}}^{\mathrm{v}_{e,\alpha}^{(\max)}} d^3\mathrm{v}_{e,\alpha}\cdot f_{e,\alpha}(\mathrm{v}_{e,\alpha})\cdot\frac{g(\nu_{e,\alpha})}{\mathrm{v}_{e,\alpha}}\cdot \\ \cdot\begin{cases}1 \\ \mathrm{e}^{-2\pi\nu_\alpha}\end{cases}, \quad \nu_{e,\alpha} = \frac{ze^2{}_{e,\alpha} z_{eff}(\omega)\omega}{m_{e,\alpha}\mathrm{v}_{e,\alpha}^3} \tag{1}$$

where e is the electron charge, c speed of light, $\hbar$ is the Planck constant, $m_{e,\alpha}$ and $z_{e,\alpha}$ are the mass and charge of either electron or alpha-particle ($z_e = 1, z_\alpha = 2$), $f_{e,\alpha}(\mathrm{v}_{e,\alpha})$ are the velocity distribution functions either of electrons (e) or alpha-particles (α), $g(\nu)$ is the Gaunt factor, which is defined by the expression [1]

$$g(\nu) = (\pi\sqrt{3}/4)\left\{i\nu\, H_{i\nu}^{(1)\prime}(i\nu) H_{i\nu}^{(1)}(i\nu)\right\} \approx (\sqrt{6}/\pi)\ln\left[\left(2/\gamma\nu\right)^{1/\sqrt{2}} + e^{\pi/\sqrt{6}}\right], \qquad (2)$$

where $H_p^{(1)}(z), H_p^{(1)\prime}(z)$ are Hankel function and its first derivative over argument, $\gamma \approx 1.78$, is Euler's constant. The upper line of (1) corresponds to electrons, whereas lower line to alpha-particles. The electron velocity distribution function is Maxwellian, while the alpha particle velocity distribution function $f_\alpha(\mathrm{v})$ is formed primarily by its deceleration during scattering in the surrounding plasmas [2]. The density of alpha-particles N_α could be determined using the total power in d-t reaction P_{dt} and relaxation time - τ_s, taken for the typical ITER plasma conditions [3], as (compare with [2])

$$N_\alpha = p\tau_s C_\alpha,\;\; f_\alpha(\mathrm{v}) = \frac{1}{C_\alpha}\frac{\mathrm{v}^2}{\mathrm{v}^3 + \mathrm{v}_*^3},\;\; C_\alpha = \int_0^1 dy\frac{y^2}{y^3 + y_*^3},\;\; y = \mathrm{v}/\mathrm{v}_{\max},\;\; \mathrm{y}_* = \mathrm{v}_*/\mathrm{v}_{\max},$$

$$p = \frac{P_{dt}}{\mathrm{E}_\alpha} \approx \frac{0.5\,(\mathrm{MW}/m^3)}{3.5\,(\mathrm{MeV})} \approx 10^{18}(m^{-3}s^{-1}),\quad \tau_s = 0.02\left(\frac{10}{\Lambda_e}\right)\frac{m_\alpha}{m_e}\frac{z_e^2}{z_\alpha^2}\frac{(T,keV)^{3/2}}{N_e(m^{-3})/10^{20}}(s), \qquad (3)$$

where P_{dt} is the power per unit volume released in thermonuclear D-T reaction and E_α is the initial energy of alpha-particles [2], τ_s is the time of elastic Coulomb relaxation in seconds, $v_{\max} = \sqrt{2E_\alpha/m_\alpha}$, m_α, z_α are the alpha particle mass and charge correspondingly, and

$$\mathrm{v}_* = \left[\frac{3\pi^{1/2}}{4}\frac{\Lambda_i}{\Lambda_e}\left(\sum_\beta \frac{m_e}{m_\beta}\cdot\frac{Z_\beta^2 n_\beta}{n_e}\right)\right]^{1/3}\left(\frac{2T_e}{m_e}\right)^{1/2} \qquad (4)$$

$\Lambda_{\mathrm{i},e}$ are the ion and electron Coulomb logarithms, m_β, Z_β are mass and charge of the plasma ion of the β sort. For D-T mixture and electron temperature about 1 keV the value of $y_* \simeq \sqrt{1/15}$ [3]. The total radiative losses of electrons $Q_e = N_e N_w q_e$ and alpha particles $Q_\alpha = N_\alpha N_w q_\alpha$ for a given density of tungsten impurity ions N_w and their ratio $R^{(1)} = Q_\alpha / Q_e$ are expressed in terms of electrons and alpha particles densities as well as reduced losses $q_{e,\alpha}$ per one impurity ion and per one impact particle as the following:

$$R^{(1)} = N_\alpha q_\alpha / N_e q_e \qquad (5)$$

In this formulation the excitation of bound electrons in a multielectron ion is expressed in terms of the photoabsorption cross section, for which the statistical models of multielectron ions could be used [1]. Here we shall use the statistical Thomas-Fermi (TF) distribution of atomic electron density dependent on orbital momentum L of the ion - $n(r,L)$ [4]. In the statistical model [1] the effective oscillator strengths f_{ij} could be determined via the atomic electron density distribution $n(r,L)$ as

$$f_{ij} = 4\pi \cdot n_{TF}(r,L) \cdot r^2 \cdot dr \ , \tag{6}$$

while the atomic frequencies will be defined in the Rost model [5]

$$\omega = \omega_R(r) = \hbar L / \mathrm{m}\, r^2, \tag{7}$$

For $n(r,L)$ and the Rost model the statistical $\sigma_{Rost,L}(s)$ is transformed to

$$\sigma_{Rost,L}(s) = 4\pi a_0^2 \left(\frac{e^2}{\hbar c}\right) \frac{1}{Z} \frac{1}{s} (L+1/2)^2 \sqrt{2\left(\frac{128}{9\pi^2}\right)^{1/3} Z^{1/3} \frac{\chi(\mathrm{q}, x_s)}{s \cdot x_s (L+1/2)} - 1} \ , \tag{8}$$

where c-is speed of light, $\chi(x_s, q)$ is the TF universal function for the ion the charge z and the nuclear charge Z and; $q = z/Z$; $s = \omega/(Z\omega_a)$; ω_a is the unit atomic frequency; r_{TF} is TF radius, $x_s = r_s / r_{TF} = \left(128/9\pi^2\right)^{1/3} \sqrt{(L+1/2)/Z^{1/3}s}$ is the solution of (7). The Rost model in fact coincides with the concept of Kramers electrodynamics [6] and is an analogue of Frank-Condon principle for atomic processes. The comparison of electron and alpha-particle radiative losses on tungsten ions, calculated in the statistical model versus electron temperature, is shown in Fig.1. The upper curve is the ratio $R^{(1)}$ of statistical radiative losses due to alpha-particles to those of electrons for the bound-bound transitions. The lower curve is the ratio $R^{(1)}$ of the above alpha-particle radiative losses to the data of detailed calculations of the summary electron radiative losses due the bound-bound transitions, the electron bremsstrahlung (BR), the radiative (RR) and dielectronic (DR) recombination from [7]. It is known that the latter processes amount to the essential part of radiative losses at high temperatures (more than 20 keV). In this region the electron energy losses increase due to BR and RR in contrast with the alpha particle ones where the contributions of itemized radiative channels are suppressed or absent. Fig. 1 shows that the alpha particle losses are comparable with those of electrons at high temperatures being of interest for thermonuclear reactor operation. The values of the ratio $R^{(1)}$ for the different electron temperatures and the ion charges are presented in Table 1. It is worthy to note that in fact the calculations are performed for the mean values of ion charges, corresponding to the ionization equilibrium conditions at given temperatures. Also evidently the account of electron bremsstrahlung will decrease the ratio $R^{(1)}$, especially for high temperatures.

Table 1

T, keV	<Zi>(T)	$R^{(1)}$ (line losses only)	$R^{(1)}$ (line losses +BR+ RR)
2,7	40	0.02	0.015
7	50	0.09	0.065
15	60	0.31	0.186
20	62	0.50	0.257
30	65	0.94	0.352
40	67	1.45	0.391

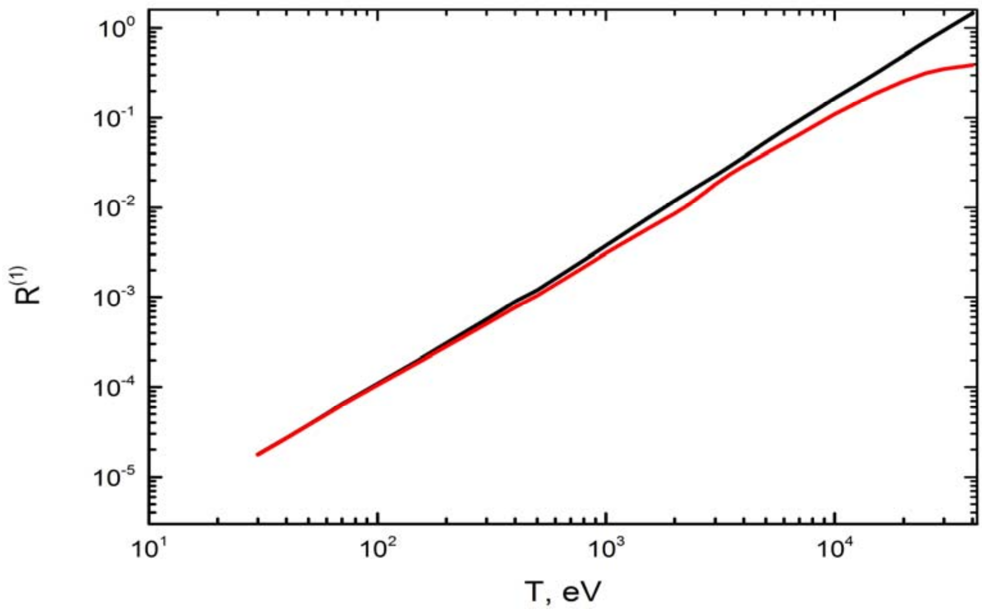

Fig 1. The ratio $R^{(1)}$ of alpha particles radiative losses to electron ones versus electron temperature T_e. The upper curve – ratio of line radiation, the lower curve– ratio of alpha-particle losses to total electron losses

Conclusion

The new channel of radiation losses due to direct excitation of tungsten impurity ions by alpha particles was investigated. The excitation cross sections were calculated in the statistical atomic model for multielectron tungsten ions. It was demonstrated [1] that this model provides good results for electron radiative losses by comparison with more detailed radiative losses calculations [7]. Thus it is justified that the statistical approach provides a reasonable accuracy for the alpha particles radiative losses, which found comparable with electron ones at high temperatures (10-30 keV), typical for thermonuclear reactor operation.

References

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