Radiation power losses and opacity of mid-Z impurities

D Benredjem¹, A Calisti², J C Pain³, F Gilleron³

¹ Laboratoire Aimé Cotton, Campus d’Orsay, 91400 Orsay, France
² PIIM, Université de Provence, Marseille, France
³ CEA, DAM, DIF, F-91297 Arpajon Cedex, France

E-mail: djamel.benredjem@lac.u-psud.fr

Abstract. We present results on opacity and radiation losses of mid-Z impurities in ICF conditions. Two approaches were investigated. The first one is based on a detailed calculation where the atomic database is provided by the MCDF code. Then a lineshape code (PPP) based on a fast algorithm was adapted to the calculation of emissivity and opacity profiles. The second approach is a statistical one. It involves high-order moments of the radiative power losses. Atomic calculations were performed with the Cowan code. The Normal Inverse Gaussian and the Generalized Gaussian distributions were then used to calculate the radiation power loss profile.

The knowledge of opacity and radiative power losses (RPL) is very important when one deals with radiative properties of ICF and astrophysical plasmas. Many experiments have been performed in the recent years on iron (see for example Ref. [1]), aluminum (see for example Ref. [2]) and heavier elements such as gold [3]. In Ref. [1], the absorption of the 2p − 3d transition array in Fe V to Fe X has been measured. Concerning aluminum, recent results have been obtained at the LULI facility [2] by irradiating a very thin foil (≈tens of nm) with a subpicosecond laser pulse.

In this work we use a detailed line calculation. Two approaches were investigated. In the first one the PPP line profile code [4, 5] developed at the University of Marseille is adapted to opacity and RPL calculations. This approach is interesting in the sense that it accounts for all major line broadening mechanisms. We have explored a second approach which is based on statistical distributions. This approach involves high-order moments of the RPL. The code based on the second approach is much faster than the PPP-like code.

The line shape of a radiative line results from a competition between homogeneous and inhomogeneous broadening and it can be written as a sum of L Lorentzians (see Ref. [6]):

\[ I(\omega) = \sum_{q=1}^{L} \frac{c_q(\omega - f_q) + a_q \gamma_q}{(\omega - f_q)^2 + \gamma_q^2}, \]

where \((a_q + ic_q)\) are the generalized intensities and \((f_q + i\gamma_q)\) are the generalized frequencies. The profile can then be seen as resulting from the contribution of \(L\) two-level systems. It takes the following form:

\[ I(\omega) = \sum_{q=1}^{L} a_q \Psi_q, \]

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where $\Psi_q$ is the profile of the Stark component $q$ belonging to the E1 radiative line. We have $a_q = S_q/e^2$, where $S_q$ designates the effective line strength, in atomic units.

Considering that each two-level system contributes to the emission and absorption processes, it is possible to define an opacity and RPL for each one of them.

1. Opacity

The opacity of an ion of net charge $i$ is given by

$$k_i(\nu) = \sum_{u-l} L \sum_{q=1} N_{l,q} \frac{(2\pi)^2}{3hc} f_q S_q \Psi_q(\nu),$$

(3)

where the first sum involves all radiative transitions between upper levels labeled $u$ and lower levels labeled $l$. The second sum accounts for all the Stark components associated with the radiative line $u - l$. $N_{l,q}$ is the population density of the lower level of the 2-level system. For each radiative transition there are $L$ Stark transitions, and each one is broadened due to electron-ion collisions and thermal Doppler detuning. To account for the various ionic stages, the opacity is written as

$$k(\nu) = \sum_i p_i k_i(\nu),$$

(4)

where the $p_i$’s are the ionic fractions. We have $\sum_i p_i = 1$. We are interested in the transition array $1s - 2p$. The required atomic data are given by the MCDF code [7]. The atomic basis used for the ion of charge $i$, i.e., Al$^{i+}$, is formed by the following superconfigurations: $(1)^2(2)^R$, $(1)^1(2)^R$, $(1)^1(2)^{R-2}(3)^1$, where $R = Z - i$. The notation $(n)^r$ represents the ensemble of all the configurations $(nl_1)^{r_1}(nl_2)^{r_2} \ldots$ with the condition $\sum_j r_j = r$. For example, $(2)^2$ represents the three configurations $2s^2$, $2s2p$ and $2p^2$. We focus on the spectral range 7.7–8.5 Å which is covered by the Al$^{4+}$ to Al$^{11+}$ inner shell $n = 1$ to 2 transitions and the Al$^{14+}$ $n = 1$ to 3 transitions. The electron density is estimated to be $5 \times 10^{22}$ cm$^{-3}$ and the electron temperature to 50 eV [2].

The transmission is given by the Beer’s law:

$$T(\nu) = \exp \left[ -k(\nu) \frac{\rho_i}{\rho} \right],$$

(5)

where $\rho_i$ and $\rho$ are the areal density and the density of the absorbing sample, respectively. The free-free and free-bound continuum absorptions are neglected.

There are three possibilities for the distribution of population among the various ion levels: i. the distribution is assumed in local thermodynamic equilibrium (LTE), ii. it is given by the statistical weights, iii. it is obtained by using a collisional-radiative code (NLTE distribution). Our code is versatile and can treat each possibility without significant difference between computing times.

Figure 1 shows a comparison of the measured and the calculated transmissions of the $1s - 2p$ transition array. Most transmission peaks are attributed to one ionic species. The agreement is good for the peak positions, intensities and widths. The ion Stark broadening is negligible for the $1s - 2p$ transition array. It is worth noting that for transition arrays involving higher configurations such as $1s - 3p$, the ion Stark linewidth is important and can be used to predict the electron density [2].

2. Radiative power losses

In this section, we present the calculated RPL involving all the transitions between states of the ground superconfiguration (SC) of an ion which is generally of the type $(n)^r$. Owing to
Figure 1. Transmission in aluminum as a function of the photon energy. The electron density and temperature are respectively $5 \times 10^{22}$ cm$^{-3}$ and 5 eV.

numerical constraints inherent to detailed line calculations, we restrict ourselves to $n = 3$ and $r = 4$. In fact, we are limited by the atomic data calculations required for the RPL calculations. For higher $r$ values, atomic data calculations are made very complex by the large dimensions of the matrices to be diagonalized.

The radiative power losses of an ion $i$ is given by

$$
\epsilon_i(\nu) = \sum_{u-l} \sum_{q=1}^L N_{u,q} \frac{2}{3} \left( \frac{2\pi}{c} \right)^3 f_q^4 S_q \Psi_q(\nu), \quad (6)
$$

where $N_{u,q}$ is the population density of the upper level of a 2-level system. As in the previous section, the RPL involving all ionic stages are given by

$$
\epsilon(\nu) = \sum_i p_i \epsilon_i(\nu). \quad (7)
$$

We have calculated the RPL profile of Ge$^{18+}$ and Au$^{65+}$ in the $(3)^4$ SC. The non relativistic configurations involved are $3s^23p^2, 3s^23p3d, 3s^23d^2, 3s3p^3, 3s3p^23d, 3s3p3d^2, 3s3d^3, 3p^4, 3p^33d, 3p^23d^2, 3p3d^3, 3d^4$. There are 33,884 E1 lines contributing to the RPL.

For such SCs the precise RPL profile calculated by Eqs. (6) and (7) necessitates long calculation times. We then have explored a statistical approach. This approach is based on the Normal Inverse Gaussian (NIG) and Generalized Gaussian (GG) distributions [8, 9] which require high-order moments of the integrated RPL.

Figure 2.a shows the RPL profile of Ge$^{18+}$ obtained by the two approaches. Due to modest density and $Z$ values, the ion Stark broadening is negligible. The Doppler line broadening overcomes the electron (impact) broadening due to the high temperature value. We have introduced an apparatus width of 1 eV. The NIG distribution, which takes into account the first four moments, only provides an envelope of the precise profile. It is not able to reproduce
Figure 2. Radiative power losses of ions in the superconfiguration $(3)^4$ as a function of the photon energy. The RPL values have to be multiplied by the ground level population density. Full curve: precise profile obtained by using the PPP code. Dashed curve: RPL profile obtained with statistical distributions (NIG or NIG+GG). Figure 2.a: Ge$^{18+}$, $N_e = 10^{20}$ cm$^{-3}$ and $T_e = 1000$ eV, Figure 2.b: Au$^{65+}$, $N_e = 10^{24}$ cm$^{-3}$ and $T_e = 12$ keV.

the individual peaks. The Gram-Charlier expansion series [8] cannot be used since it exhibits negative features, even if very high-order moments are introduced in the distribution.

In Figure 2.b we show the RPL profile of Au$^{65+}$ for the same SC. We have set $N_e = 10^{24}$ cm$^{-3}$ and $T_e = 12$ keV. We have checked that despite a high density, the ion Stark broadening is negligible. For the same reason as above, the Doppler broadening overcomes the electron broadening. The main contribution to the RPL is around 700 eV. A smaller contribution emerges in the 350 eV energy range due to the spin-orbit interaction. In order to account for the entire spectrum, both statistical distributions (NIG and GG) are used.

3. Conclusions and perspectives
We have calculated the transmission of an aluminum plasma created by two femtosecond beams and a picosecond x-ray backlighter source. The agreement between measured and calculated transmission is good for peak positions, widths and magnitudes. All broadening mechanisms are taken into account, but it appears that the ion Stark brodening is very small for the $1s - 2p$ transition array. We have also calculated the RPL of germanium and gold plasma by using the same approach. We concentrated on the $(3)^4$ superconfiguration. Due to long calculation times a statistical approach was explored. The statistical approach provides an appropriate envelope for the germanium case but not for gold.

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