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THE SPECTRAL COEFFICIENTS OF ABSORPTION PROCESSES IN DENSE STRONGLY IONIZED ASTROPHYSICAL PLASMAS

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Abstract. In this contribution we present a new model method of describing atomic photo-absorption processes in dense strongly ionized astrophysical plasmas, which is based on the approximation of cut-off Coulomb potential. By now this approximation has been used in order to describe transport properties of dense plasmas, but it was clear that it could be applied to some absorption processes in non-ideal plasmas. The presented results cover a wide region of the plasma electron densities and temperatures. Such plasmas are of interest from both the laboratory and the astrophysical aspect. Here, we have in mind the plasma of inner layers of the solar atmosphere, as well as of partially ionized layers of other stellar atmospheres, for example the atmospheres of DA white dwarfs with effective temperatures between 4 500 K and 30 000 K.

1. INTRODUCTION

The problems of plasma opacity, energy transport and radiative transfer under moderate and strong non-ideality are of interest in theoretical and experimental research (Fortov et al. 1999, Rogers et al. 1998, Mihajlov et al. 2011a, 2013). The strong coupling and density effects in plasma radiation were the subject of numerous experimental and theoretical studies in the last decades. Here, we keep in mind the plasma of the inner layers of the solar atmosphere, as well as of partially ionized layers of other stellar atmospheres, for example the atmospheres of DA white dwarfs with effective temperatures between 4 500 K and 30 000 K.

In this paper we presented a continuation of work on a model way of describing atomic photo-absorption processes in dense strongly ionized hydrogen plasmas, which is based on the approximation of the cut-off Coulomb potential. By now this approximation has been used to describe transport properties of dense plasmas (see e.g. Fortov et al. 1999, Mihajlov et al. 1989, Ignjatović et al. 2017), but it was clear that it could be applied to some absorption processes in non-ideal plasmas too (Mihajlov et al. 2011a,b, 2015, Sakan et al. 2005).

As a continuation of the previous work, the bound-bound absorption processes, i.e. photo absorption are investigated:

$$\varepsilon_\lambda + \mathrm{H}^*(n_i, l_i) \rightarrow \mathrm{H}^*(n_f, l_f), \tag{1}$$

where n and l are the principal and the orbital quantum number of hydrogen-atom excited states, hydrogen atom in it's initial state $|n_i, l_i>$ is presented by $\mathrm{H}^*(n_i, l_i)$, it's final state $|n_f, l_f>$ by $\mathrm{H}^*(n_f, l_f)$, and ε_λ presents absorbed photon energy.

The absorption processes (1) in astrophysical plasma are considered here as a result of radiative transition in the whole system "electron-ion pair (atom) + the neighborhood", namely: $\varepsilon_\lambda + (\mathrm{H}^+ + e)_i + S_{rest} \rightarrow (\mathrm{H}^+ + e)_f + S'_{rest}$, where S_{rest} and S'_{rest} denote the rest of the considered plasma. However, as it is well known, many-body processes can sometimes be simplified by their transformation to the corresponding single-particle processes in an adequately chosen model potential.

Here the model potential is used in form

$$U_c(r) = \begin{cases} -\dfrac{e^2}{r} + \dfrac{e^2}{r_c}, & 0 < r \leq r_c, \\ 0, & r_c < r < \infty, \end{cases} \tag{2}$$

Within the frame of the presented model the results for the bound-bound transitions are sought. In accordance with that, the behavior of the dipole matrix element is investigated. It is given by

$$\hat{D}(r; r_c; n_i, l_i; n_f, l_f) = < n_f, l_f|\mathbf{r}|n_i, l_i >, \tag{3}$$

where the wave functions $|n_i, l_i>$ and $|n_f, l_f>$ are initial and final state wave functions obtained within the model of cut-off Coulomb potential 2, for calculations of plasma characteristics, or the theoretical hydrogen ones in order to check the model additionally.

For the calculation of oscillator strength we use expressions from (Sobelman 1979, Hoang-Binh, D., 2005).

$$f(n_f, l_f; n_i, l_i; r_c) = \frac{1}{3}\frac{\nu}{Ry}\left[\frac{max(l_f, l_i)}{2l_f + 1}\right]\hat{D}(r; r_c; n_i, l_i; n_f, l_f)^2, \tag{4}$$

where Ry is the Rydberg constant, in the same units as the frequency ν of the transition $|n_i, l_i> \rightarrow |n_f, l_f>$.

The analysis of the results took place in dimensionless units, where the fraction of the calculated osccilator strength value $f(n_f, l_f; n_i, l_i; r_c)$ and the $f_t(n_f, l_f; n_i, l_i)$, the theoretical hydrogen case calculated by code from (Hoang-Binh, D., 2005) is used.

$$f^*(n_f, l_f; n_i, l_i; r_c) = \frac{f(n_f, l_f; n_i, l_i; r_c)}{f_t(n_f, l_f; n_i, l_i)}. \tag{5}$$

The theoretical oscillator strength values. $f_t(n_f, l_f; n_i, l_i)$ for the presented results are calculated by code from (Hoang-Binh, D., 2005).

The presented results are easily fitted with the rational functions, but with the order not smaller than of fifth degree,

$$f^{fit}(r_c) = \begin{cases} 0, & r_c < r_c^{min}, \\ \left(1 - \displaystyle\sum_{i=0}^{n} \frac{b_i}{(r_c - x_0)^i}\right), & r_c > r_c^{min}, \quad n \geq 5 \end{cases} . \tag{6}$$

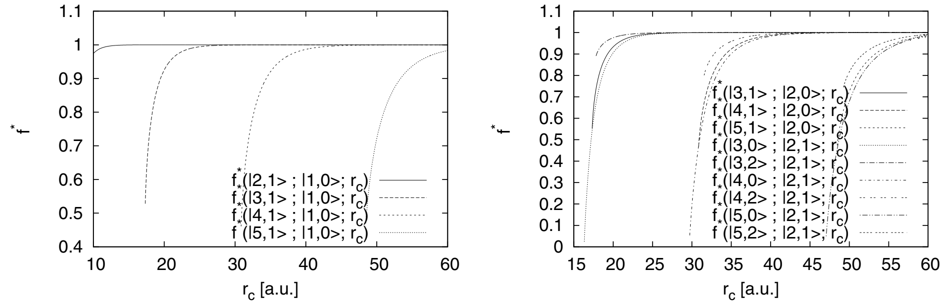

Figure 1: *Left*: The behavior of the $f^*(n_f, l_f; n_i, l_i; r_c)$ for the $n_i = 1$. *Right:* The behavior of the $f^*(n_f, l_f; n_i, l_i; r_c)$ for the $n_i = 2$

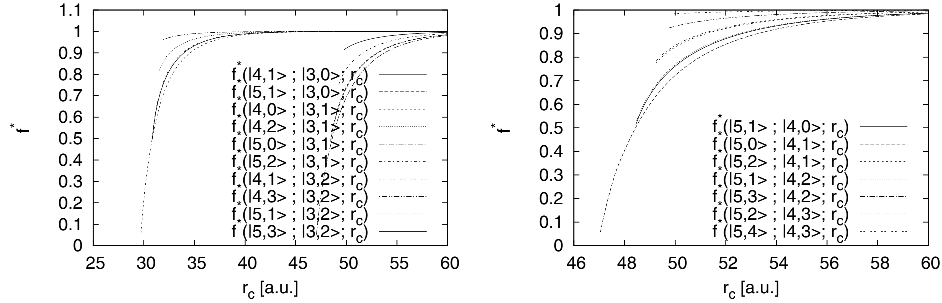

Figure 2: *Left*: The behavior of the $f^*(n_f, l_f; n_i, l_i; r_c)$ for the $n_i = 3$ *Right:* The behavior of the $f^*(n_f, l_f; n_i, l_i; r_c)$ for the $n_i = 4$

Here, r_c^{min} is the cut-off radii on which the upper level appears. Also the rational function is defined in such a matter that the first coefficient b_0 has a meaning of the probing does the fit function posses a usable solution in area of large cut-off radii r_c. Since the asymptotical behavior of the solutions is investigated and the limiting values for the osccilator strength is almost exact to the theoretical one, if the coefficient b_0 differs significantlly from zero, the fit is not usable in area of large r_c.

2. RESULTS AND DISCUSSION

The results in Figs. 1 and 2 show the behavior of the $f^*(n_f, l_f; n_i, l_i; r_c)$ for the $n_i = 1, 2, 3, 4$. It could be seen that there are some numerical effects needed to be analysed and carried out for the transitions from $n_i = 2$ to $n_f = 5$. Also from Fig. 3 it could be seen that such artefacts affects the fit to be usable only in vicinity of the r_c^{min}.

Presented results include the plasma influence into the account, and as such are usable for the hydrogen plasmas of moderate and high non-ideality. Since it was studied before that even for the transitions from $n_i = 2$ to $n_f = 5$ for the huge r_c values the oscillator strengths converge towards the theoretical values from (Hoang-Binh, D., 2005) there is a posibility that the adequate artefacts visible in the Fig. 1

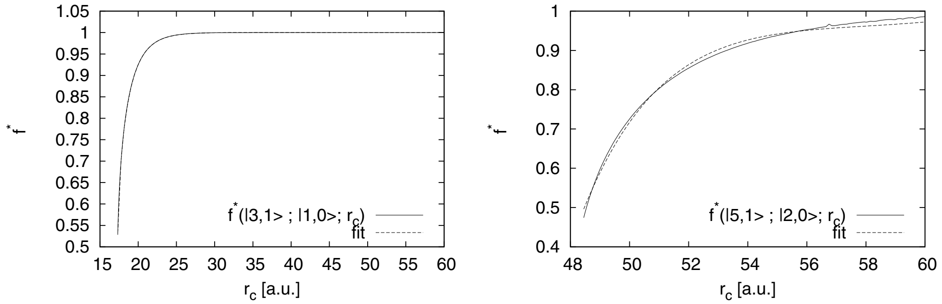

Figure 3: *Left*: The good fit example $f^*(|3,1>;|1,0>;r_c)$ and fit. *Right:* The acceptable fit example $f^*(|5,1>;|2,0>;r_c)$.

right, are of purely numerical form and are avoidable.

The work on obtaining the well defined fitting function for the bound-bound oscillator strengths is still in progress. The goal is to reduce computational time for the absorption coefficients, as well as to produce the usable form of presenting the results for further usage in theoretical and experimental practise.

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