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Abstract

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ON THE QUESTION OF THE RADIATION OF EASILY IONIZABLE IMPURITIES IN A PLASMA UNDER THERMAL EXCITATION

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Until now it has been accepted that the dependence of the intensity of spectral lines emitted by a plasma under a thermal excitation mechanism has one maximum at a temperature T_{m}, whose value is determined by the ionization potential of the emitting atoms V and the excitation energy E. In the work of Larentz ([1]), who considered a one-component plasma, a relation between T_{m}, V, and E was established. This relation is also used for finding T_{m} for lines emitted by impurities, since it is assumed that the action of the other components present in the plasma can introduce only a small correction into the value of T_{m}. However, as was first shown in our work ([2]), the composition of the plasma can have a very strong effect on the radiation of easily ionizable impurities because of the existence of interconnection between the ionization processes of the individual constituents of the plasma. The influence of the plasma composition may manifest itself even through the appearance of a second high-temperature maximum in the dependence $I(T)$ for easily ionizable impurities.

The present work is devoted to clarifying the conditions under which a second high-temperature maximum $I_{T_{\mathrm{m2}}}$ can be observed in the dependence $I(T)$ of an easily ionizable impurity, and to establishing the relation between $T_{\mathrm{m2}}, V, E, V_{\mathrm{eff}}$, and N_{imp}/N. The intensity of an atomic spectral line emitted by a small impurity is written in the form:

$$I_{\mathrm{imp}} = C \frac{N_{\mathrm{imp}}}{N} \frac{1 - x_{\mathrm{imp}}}{1 + x_{\mathrm{res}}} \frac{P}{kT} e^{-E/kT}. \tag{1}$$

Investigation of the dependence $I(T)$ for a maximum leads to an expression for $(T_{\mathrm{m\,imp}})$ in the form

$$\left({}^5/_2 + \frac{V_{\mathrm{imp}}}{kT}\right) x_{\mathrm{imp}} - \frac{1}{2}(1 - x_{\mathrm{res}}) \left({}^5/_2 + \frac{V_{\mathrm{eff}}}{kT} - \frac{1}{k}\frac{\partial V_{\mathrm{eff}}}{\partial T}\right)(x_{\mathrm{imp}} - x_{\mathrm{res}}) = \frac{E}{kT} - 1. \tag{2}$$

Passing to a one-component plasma, putting $x_{\mathrm{imp}} = x_{\mathrm{res}} = x$ and $V_{\mathrm{imp}} = V_{\mathrm{eff}} = V_i$, from (2) we obtain, as a special case, Larentz' s formula ([1]). Solving (2) with respect to T_m for a plasma of complex composition in general form involves great difficulties because of the dependence of V_{eff} on T. It is simpler to consider a two-component plasma consisting of the principal element (V_{bas}, N_{bas}) and the impurity of interest to us (V_{imp}, N_{imp}).

Using the method of calculating $I(T)$ described in ([2]), the dependences $I(T)$ were calculated for the lines of hydrogen, carbon, and some metals for plasmas based on air, nitrogen, argon, and helium and containing the indicated elements as impurities, $\sim 1\%$. Typical dependences are presented in Fig. 1. The calculation shows that, for the temperature region corresponding to the appearance of the second high-temperature maximum in the radiation of easily ionizable impurities, one may take $x_{imp} \cong 1$, $V_{eff} = V_{bas}$ ($x_{bas} \gg N_{imp}/N$, since $V_{imp} < V_{bas}, N_{imp} \ll N$), and rewrite relation (2) in the form

$$({}^5/_2 + V_{imp}/kT_m) - \frac{1}{2}(1 - x_{bas})^3({}^5/_2 + V_{bas}/kT_m) = E/kT_m - 1.$$

After substituting x_{bas} from the Saha formula, introducing the notations

$$K = (U_0/U^+)_{bas}\frac{P\,(\text{atm})}{V_{bas}^{5/2}\,(\text{eV})}, \quad \alpha = (V_{imp} - E)/V_{bas} \quad \text{and} \quad \xi = V_{bas}/kT_m,$$

we obtain a simple expression for calculating T_m:

$$1.03 \cdot 10^{-4} \cdot Ke^{\xi}\xi^{5/2} = \frac{1}{\left(\sqrt{2\,\frac{7/2+\alpha\xi}{5/2+\xi}} - 1\right)^2} - 1, \tag{3}$$

$$f_1(K, \xi) = f_2(\alpha, \xi). \tag{3'}$$

It is convenient to solve equation (3) graphically, analogously

because this was done in the work of Larenz ([1]). In considering a specific line, knowing K and a, we find at what ξ $\log f_1 = \log f_2$, and hence $T_{m2} = V_{base} \cdot 1.16 \cdot 10^4/\xi$.

Analysis shows that the condition for the appearance of the second high-temperature maximum in the radiation of an easily ionized impurity, at which $x_{imp} \simeq 1$, is $0 < V_{imp}/V_{base} < 0.5$ for $(U^+/U_0)_{imp} = (U^+/U_0)_{base}$. For $(U^+/U_0)_{imp} > (U^+/U_0)_{base}$, the range of variation of V_{imp}/V_{base} may broaden somewhat. The T_{m2} calculated from relation (3) coincide with the T_{m2} found from the complete dependences $I(T)$.

Fig. 1. $I(T)$ of the Cu 5218 Å line for plasma compositions: 1 atm. Cu (1); 0.99 atm. Na + 0.01 atm. Cu (2); 0.99 atm. C + 0.01 atm. Cu (3); 0.99 atm. Ar + 0.01 atm. Cu (4). $I(T)$ of the H_α line for plasma compositions: 1 atm.

Fig. 1

Figure 1: Fig. 1

H_2 (5); 0.99 atm. C + 0.01 atm. H_2 (6). $I(T)$ of the Cu 5218 Å line for plasma compositions: 0.99 atm. He + 0.01 atm. Cu (7); 0.99 atm. Ne + 0.01 atm. Cu_α (8). $I(T)$ of the C 2478 Å line for plasma composition: 0.99 atm. He + 0.01 atm. C (9). $I(T)$ of the H_α line for plasma composition 0.99 atm. He + 0.01 atm. H_2 (10).

As is seen from (3), the position of the second high-temperature maximum of the radiation of an easily ionized impurity depends very sharply on the ionization potential of the plasma base V_{base} and much more weakly on the characteristics of the impurity itself, V_{imp} and E, and moreover does not depend separately on V_{imp}, but only on the difference $V_{\text{imp}} - E$. If V_{imp} and V_{base} are close, then there will be no second maximum in the dependence $I_{\text{imp}}(T)$; and the influence of the main component of the plasma on the radiation of an easily ionized impurity is manifested in a shift and deformation of $I(T)$. The most advantageous for increasing the radiation intensity of an easily ionized impurity is the closeness of V_{imp} and V_{base} (see Fig. 1A).

In the present work a two-component plasma has been considered. In the case of a plasma of complex composition, with an appropriate choice of components, several maxima may appear in the dependence $I(T)$ of an easily ionized impurity, each of which will be associated with a sharp increase in the contribution of ionization of an individual plasma constituent to the resultant ionization. The most advantageous conditions for increasing the intensity will be those under which $V_{\text{imp}} = V_{\text{eff}}$, and $T = T_{\text{imp}}$, calculated by Larenz's formula for the impurity of interest to us.

The established regularities are of a general character and may be extended to the radiation of ionic lines. The sharp influence of the plasma composition on the radiation of its easily ionized impurities must be taken into account when using I_{m} to estimate the local temperature in studying the temperature gradient in an inhomogeneous gas-discharge plasma, in astrophysics, and in selecting excitation conditions in developing methods of spectral analysis for minor impurities.

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Note: Figure translations are in progress. See original paper for figures.