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I. M. Podgornyi, G. V. Sholin

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Abstract

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I. M. Podgornyi, G. V. Sholin

On the Question of Measuring the Electron Temperature from the Ratio of the Intensities of Helium Lines

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In recent years a number of experimental works have appeared in which the electron temperature T_e is determined from the ratio of the intensities of spectral lines of singlet and triplet states of neutral helium. At present there are data indicating that by no means all lines whose excitation functions are known can be used for this purpose. In particular, it was shown ([1]) that the excitation function of the line 2^1S—3^1P 5016 Å, other conditions being equal, depends not only on the electron energy but also on the pressure of the neutral gas. Up to now the method of determining the temperature from the ratio of the intensities of the lines 2^1P—4^1D 4922 Å and 2^3P—4^3S 4713 Å has raised no objections. In reality there exist processes that limit the applicability of this method when the plasma concentration n_e is increased above a certain critical value n^*. In this case the population of the levels 4^1D and 4^3S will be determined not only by excitation from the ground state and by spontaneous emission, but also by transitions between states within the given principal quantum number due to collisions with electrons. It should be emphasized that electron collisions lead to such a change in line intensities that it may be erroneously interpreted as evidence of a high electron temperature of the plasma.

Let us first consider the influence of electron collisions on the population of the singlet state 4^1D. At low plasma concentration it does not depend on the population of neighboring levels with principal quantum number $n = 4$, and the intensity of the 4922 Å line is determined by the excitation cross section of this level $\sigma(1^1S \to 4^1D)$ and by the values of the probabilities of spontaneous radiative transitions A_{ik} to lower levels. As the concentration is increased, the role of collisional transitions between levels with the given principal quantum number becomes significant.

Let us consider what results from transitions from the level 4^1P to the level 4^1D, since from the available experimental data on excitation probabilities ([2]) it follows that in the region $T_e < 100$ eV the population of 4^1P exceeds the population of 4^1D by several times. The contribution of the collisional transitions $4^1P \to 4^1D$ becomes substantial if the probability of the stepwise excitation

$1^1S \to 4^1P \to 4^1D$ becomes comparable with the probability of direct excitation of the level $1^1S \to 4^1D$. This condition may be written in the form

$$\langle\sigma(1^1S \to 4^1D) \cdot v\rangle = \langle\sigma(1^1S \to 4^1P) \cdot v\rangle \frac{n_e\langle\sigma(4^1P \to 4^1D) \cdot v\rangle}{A_{4^1P\to1^1S}},$$

where the brackets $\langle\ \rangle$ denote averaging over the electron velocity distribution, and $A_{4^1P\to1^1S}$ is the probability of spontaneous emission of the level 4^1P to the ground state.

Using the available data ([2]) for the excitation cross sections $\sigma(1^1S \to 4^1D)$, $\sigma(1^1S \to 4^1P)$, and $A_{4^1P\to1^1S}$, and calculating $\sigma(4^1P—4^1D)$ under the assumption of classical trajectories of the incident electrons (as this is done—

is used in the theory of spectral-line broadening ([8]), we obtain for n_e^* the value 10^{12} cm^{-3}. This value of the concentration corresponds to the case when the intensity of the 4922 Å line becomes twice as high as it would be at the given temperature if the only de-excitation process were radiative decay, and the population of the 4^1D level arose only from direct excitation from the ground state. At a concentration $n_e = 10^{12}$ cm^{-3} and an electron temperature of the plasma of 5 eV, the method of measuring T_e from the intensity ratio of the 4713 and 4922 Å lines (see Fig. 5 in ([4])), taking account only of transitions between singlet levels, thus gives a value of T_e overestimated by more than a factor of 2.

An analogous limitation follows from consideration of transitions between triplet states. Indeed, here the radiative transition to the ground state is forbidden, while the probability of radiative transitions to levels with principal quantum number $n = 2$ is $3.3 \cdot 10^6$ s^{-1} for 4^3S, and $6.6 \cdot 10^6$ s^{-1} for 4^3P. Therefore, a relative depletion of the population of the 4^3S level should occur when the probability of the transition $4^3S \to 4^3P$ due to collisions with electrons becomes greater than the probability of the radiative transition $4^3S \to 2^3P$. This reasoning is, of course, valid only under conditions in which the cross section $\sigma(1^1S \to 4^3S)$ is not smaller than the cross section $\sigma(1^1S \to 4^3P)$. The theoretical consideration of excitation of triplet states shows ([5]) that the n^3S levels are indeed excited with maximum probability, and this conclusion is confirmed by experiments on measuring the excitation cross sections of the 3^3S, 3^3P, 3^3D, as well as 2^3S and 2^3P levels ([2]). The experimental data available in the literature ([6]) show that, even taking into account cascade transitions from upper levels, $\sigma(1^1S \to 4^3P)$ is 10% smaller than $\sigma(1^1S \to 4^3S)$.

Thus, the electron concentration at which depletion of the population of the 4^3S level due to electron collisions will occur can be determined from the expression

$$n_e\langle\sigma(4^3S \to 4^3P) \cdot v\rangle = A_{4^3S\to2^3P}.$$

Substitution of numerical values of the quantities shows that, at $n_e \sim 10^{12}$ cm^{-3}, determination of T_e from the curve given in ([4]) also leads to an overestimate of the temperature.

The consideration given above shows that the widely used method of measuring the electron temperature from the intensity ratio of the 4713 and 4922 Å lines is applicable only at concentrations below $3 \cdot 10^{11}$ cm^{-3}. At higher concentrations it is necessary to take into account collisional processes leading to transitions between states with the given principal quantum number and the given multiplicity, and to use the following expressions for the line intensities:

$$I_{4713} = \frac{\hbar\omega_{4^3S\to 2^3P} A_{4^3S\to 2^3P} n_0 n_e}{A^3_{4^3S} + \nu^3_{SP}(1-\alpha^3_{PS})} \{\langle\sigma(1^1S \to 4^3S)\cdot v\rangle +$$

$$+\langle\sigma(1^1S \to 4^3P)\cdot v\rangle\alpha^3_{SP} + \langle\sigma(1^1S \to 4^3D)\cdot v\rangle\alpha^3_{DP}\alpha^3_{PS} +$$

$$+\langle\sigma(1^1S \to 4^3F)\cdot v\rangle\alpha^3_{FD}\alpha^3_{DP}\alpha^3_{PS}\};$$

$$I_{4922} = \frac{\hbar\omega_{4^1D\to 2^1P} A_{4^1D\to 2^1P} n_0 n_e}{A^1_{4^1D} + \nu^1_{DP}[1-\alpha^1_{PD}] + \nu^1_{DF}(1-\alpha^1_{FD})} \{\langle\sigma(1^1S \to 4^1D)\cdot v\rangle +$$

$$+\langle\sigma(1^1S \to 4^1S)\cdot v\rangle\alpha^1_{SP}\alpha^1_{PD} + \langle\sigma(1^1S \to 4^1P)\cdot v\rangle\alpha^1_{PD} + \langle\sigma(1^1S \to 4^1F)\cdot v\rangle\alpha^1_{FD}\}.$$

Here $\nu^{2j+1}_{MN} = n_e\langle\sigma(4^{2j+1}M \to 4^{2j+1}N)\cdot v\rangle$ is the collision frequency of plasma electrons with an atom, leading to transitions from the state $4^{2j+1}M$ to the state $4^{2j+1}N$. The index $2j+1$ denotes the multiplicity. The quantities α^{2j+1}_{MN} determine the relative probabilities of collisional

transitions:

$$\alpha^{2j+1}_{FD} = \frac{\nu^{2j+1}_{FD}}{A^{2j+1}_{4F} + \nu^{2j+1}_{FD}};$$

$$\alpha^{2j+1}_{SP} = \frac{\nu^{2j+1}_{SP}}{A^{2j+1}_{4S} + \nu^{2j+1}_{SP}};$$

$$\alpha^{2j+1}_{DP} = \frac{\nu^{2j+1}_{DP}}{A^{2j+1}_{4D} + \nu^{2j+1}_{DP} + \nu^{2j+1}_{DF}\left[1-\alpha^{2j+1}_{FD}\right]};$$

$$\alpha^{2j+1}_{PD} = \frac{\nu^{2j+1}_{PD}}{A^{2j+1}_{4P} + \nu^{2j+1}_{PD} + \nu^{2j+1}_{PS}\left[1-\alpha^{2j+1}_{SP}\right]};$$

$$\alpha_{PS}^{2j+1} = \frac{\nu_{PS}^{2j+1}}{A_{4P}^{2j+1} + \nu_{PS}^{2j+1} + \nu_{PD}^{2j+1}\left[1 - \alpha_{DP}^{2j+1}\right]};$$

A_{4N}^{2j+1} is the total probability of radiative transitions from the level $4^{2j+1}N$. If the concentration of neutral atoms and the dimensions of the system are such that resonance radiation is trapped, then, following work ([6]), the quantity A_{4P}^1 must be replaced by $g_{4P}(\rho)A_{4P\to 1S}^1 + A_{4P\to 2S}^1$, where the function $g_{4P}(\rho)$ denotes the fraction of resonance quanta that are not absorbed within the volume of the system, and depends on the pressure of the neutral gas and on the dimensions of the system. In this case the critical plasma concentration n^* decreases still further, and, as is clear from the formulas given above, a nonlinear dependence of the population of a level on the pressure of the neutral gas appears not only for the n^1P states, but for all the others as well.

In deriving these formulas, the possibility of transitions between states with different multiplicity and different principal quantum numbers was not taken into account. Therefore their applicability is limited to the region of not too high concentrations, where the rates of such processes still do not exceed the probabilities of radiative decays. As the plasma concentration increases, a Boltzmann distribution will be established for levels with a given principal quantum number, and the ratio of the intensities of the spectral lines will be determined only by the ratio of the Einstein coefficients A_{ik} and the statistical weights of the levels.

In conclusion, we note that, when determining the temperature from the ratio of the intensities of HeI lines in the concentration range 10^{11} cm^{-3} $< N_e \lesssim 10^{13}$ cm^{-3}, the error is minimal if, as a result of collisions with electrons, the population of the upper levels of both lines either increases simultaneously or decreases simultaneously. Without allowance for transitions involving a change in multiplicity, such a situation occurs for the pair of lines 2^1P—4^1S 5048 Å and 2^3P—4^3S 4713 Å, the intensity ratio of which as a function of temperature is given in work ([7]).

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