# Anomalous intensities of satellites of resonance lines of hydrogen-like ions

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We investigate the effect of the anomalous increase of the intensities of the components of the satellite structure of resonance lines of hydrogen-like ions in the emission of a dense laser plasma, present its interpretation, and propose a new procedure for measuring the electron density of a plasma in the range $N_e \sim 10^{20}$–$10^{23}$ cm$^{-3}$.

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The use of a laser plasma has made it possible to investigate systematically the spectra of multiply-charged ions in the x-ray band.[1,2] The greatest interest for the diagnostics of laboratory and astrophysical hot plasma are the resonant lines of hydrogen-like and helium-like ions and their satellites. An analysis of the intensities of satellites of the type $1s^2 2l - 1s2l2l'$ for the case of He-like ions, based on relativistic calculations[3,4] of the probabilities of

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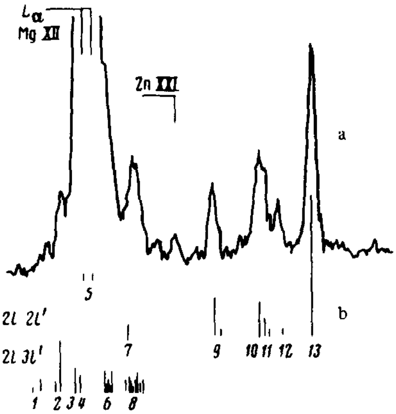

FIG. 1. $Ly_\alpha$ sattellite structure of the Mg XII ion: a—density pattern of laser-plasma spectrum; b—theoretical spectrum when the upper levels of the $2l2l'$ and $2l3l'$ are populated by dielectron recombination (for details see[2]).

radiative ($A$) and nonradiative ($\Gamma$) decays of doubly excited levels has demonstrated not only qualitative but also quantitative agreement between theory and experiment.[2,5]

The intensities of the satellites of the resonance lines of H-like ions have remained practically uninvestigated to this day. The detailed analysis presented here of the emission spectra of a laser plasma has shown that for the greater part of satellites of the type $1snl' - 2lnl'$ (where $n = 2, 3$) just as in the case of He-like ions, there is also agreement between the experimental intensities and those calculated in the corona approximation (see Fig. 1).[1)]

A strong discrepancy is observed, however, for the transitions $1s2p\,^3P_{0,1,2} - 2p^2\,^3P_{1,2}$ and $1s2s\,^3S_2 - 2s2p\,^3P_{0,1,2}$ (marked in Fig. 1 by the numbers 12 and 10—11, respectively). The theoretical intensity ratio for Mg XI is $\kappa = 0.17$ if the autoionization levels are populated only on account of dielectron recombination, as is assumed in the corona model. At the same time, the experimentally measured value is 3—5 times larger. Experiments performed with different installations for a wide range of parameters of the plasma-heating laser radiation have confirmed this discrepancy (see the table). The low calculated intensity of the $1s2p\,^3P - 2p^2\,^3P$ line is attributed to the low probability of the dielectron capture into the $2p^2\,^3P$ state, a capture completely forbidden in the $LS$-coupling approximation. Another possible mechanism of excitation of the dielectron satellites is excitation by electron impact from the ground configuration of the ion with the preceding ionization multiplicity, which is very important for He-like ions,[2,5] does not play any role for He-like ions, since the excitation cross sections of the two-electron transitions are very low. The excitation of satellites from the metastable states of He-like ions, which the authors of[10] attempted to attribute to the discussed anomalous intensity of the satellites, is also insignificant if the concentration ratio of the He-like and H-like ions $\eta$ is not too large: $\eta < 50$. In our case, as follows from the intensity ratio of the resonance lines, $\eta \sim 1$.

TABLE I.

| Laser-radiation parameters | | | | | Measured $Ne$, $cm^{-3}$ | | | |
|---|---|---|---|---|---|---|---|---|
| Wavelength, $\lambda$, $\mu$ | Energy, J | Duration, nsec | Flux density, W/cm | Reference | By satellites | | By Stark broadening | |
| | | | | | $\kappa$ | $N_e$ 1) | Transition | $N_e$ |
| 1.06 | 80 | 1.8 | $5 \cdot 10^{14}$ | [6] | 0.5 | $1 \cdot 10^{21}$ | 1s – 6p | $(1 - 2) \cdot 10^{21}$ |
| 1.06 | 10 | 2.0 | $2 - 5 \cdot 10^{13}$ | [7] | 0.5 | $0.9 \cdot 10^{21}$ | 1s – 5p | $1.5 \cdot 10^{21}$ |
| 1.06 | 20 | 0.1 | $5 \cdot 10^{15}$ | [8] | 0.8 | $2 \cdot 10^{21}$ | 1s – 5p | $2 \cdot 10^{21}$ |
| 1.315 | 190 | 1.0 | $5 \cdot 10^{13}$ | [9] | 0.5 | $0.7 \cdot 10^{21}$ | 1s – 5p | $1.6 \cdot 10^{21}$ |

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[a] The temperature dependence of $\kappa$ is taken into account.

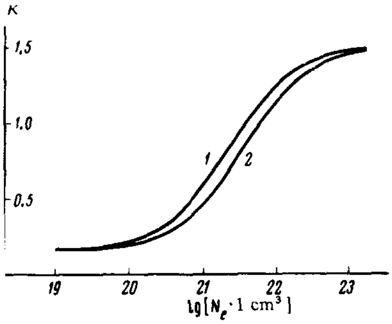

FIG. 2. Dependence of the intensity ratio $\kappa = I(2p^2\ {}^3P - 1s2p\,{}^3P)/I(2s2p\,{}^3P - 1s2s\,{}^3S)$ of the satellites of the $Ly_\alpha$ line of the Mg XII ion on the electron density $N_e$ at different values of the electron temperature ($1$—$kT_e = 200$ eV; $2$—$kT_e = 390$ eV).

To explain the indicated anomaly it is necessary to take into account the possibility of transitions between doubly excited levels on account of electron collisions. It can be shown that when these processes are taken into account$^{2)}$ the ratio κ of interest to us is equal to

$$\kappa = a\alpha + \frac{x^2[a(1-\alpha)+b] + x[a(1-\alpha+\beta)+b]}{(1+x)^2}$$

$$a = \frac{5}{9}\,\frac{A(2p^2\,{}^3P_2 - 1s\,2p\,{}^3P_2) + A(2p^2\,{}^3P_2 - 1s\,2p\,{}^3P_1)}{A(2s\,2p\,{}^3P_1 - 1s\,2s\,{}^3S_1)},$$

$$b = \frac{1}{3}\,\frac{A(2p^2\,{}^3P_1 - 1s\,2p\,{}^3P_1) + A(2p^2\,{}^3P_1 - 1s\,2p\,{}^3P_0)}{A(2s\,2p\,{}^3P_1 - 1s\,2s\,{}^3S_1)},$$

$$\beta = \frac{\Gamma(2p^2\,{}^3P_2)}{\Gamma(2s\,2p\,{}^3P_0)};\quad \alpha = \beta\,\frac{\Gamma(2s\,2p\,{}^3P_0) + A(2s\,2p\,{}^3P_0)}{\Gamma(2p^2\,{}^3P_2) + A(2p^2\,{}^3P_2)}, \qquad (1)$$

/here

$$x = \frac{N_e C}{A(2p^2\,{}^3P_2) + \Gamma(2p^2\,{}^3P_2)}$$

nd $C = \langle v\sigma\rangle$ is the rate of the electronic excitation of the transition $2s2p\,{}^3P_1$ $\cdot 2p^2\,{}^3P_1$. In a tenuous plasma ($x \ll 1$) the ratio κ does not depend on $N_e$ and is etermined by the values of $A$ and Γ. With increasing $N_e$, excitation from the s $2p\,{}^3P$ level due to the electron collisions is transferred to the $2p^2\,{}^3P$ level, nd κ increases to a value $a+b$, which corresponds to a Boltzmann population etween the levels (see Fig. 2).

Table I lists the experimental values of for the case of magnesium tar-ets, for plasma regions with dimensions ~100 μ near the target surface, the alues of $N_e$ determined from κ (see Fig. 2), and also the result of the determination of $N_e$ by measuring the Stark broadening[11] of the Lyman lines of Mg XII that are present on the same films. When complicated targets are used, the determination of $N_e$ by measuring the ratio of the intensities of the resonant and intercombination lines of He-like ions near the target also yield values $N_e \sim 10^{21}$ cm$^{-3}$.[12] We note that $\kappa$ and $N_e$ increase with increasing flux density of the laser radiation.

The mechanism considered in this paper, in addition to dielectron recombination, makes it possible to bring into full agreement the experimentally observed and recalculated intensities. We note the advantages of the method of determining $N_e$ from the satellite intensities: 1) In contrast to the resonance line, the satellites are not subjected to radiation-dragging effects, which generally speaking can distort the integrated intensity and the shapes of the spectral lines (cf.[13]); 2) The sattellite wavelengths are close to each other, so that one can dispense with calibration of the spectrographs (cf.[14]).

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[1)] The authors are grateful to X.U.I. Safronova for supplying the calculated values of $A$ and $\Gamma$ for the satellites of the resonance lines of H-like ions.

[2)] A detailed description of the calculation will be published in a separate paper.

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