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Quenching of spontaneous emission coefficients versus dielectronic satellites

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In a dense and cold laser-produced plasma the measured intensity of $\alpha_2 \rightarrow \alpha_1$ transitions in highly ionized atoms may be strongly influenced by dielectronic satellites $\alpha_2 nl \rightarrow \alpha_1 nl$ with a high value of the principal quantum number n of the "spectator" electron. This effect may be partially or fully responsible for the reported [Y. Chung, P. Lemaire, and S. Suckewer, Phys. Rev. Lett. **60**, 1122 (1988); Y. Chung, H. Hirose, and S. Suckewer, Phys. Rev. A **40**, 7142 (1989)] observation that the intensity branching ratio of lines depends on the parameters of the laser-produced plasma.

Recent publications[1,2] reported the observation that the intensity branching ratio of several pairs of lines with a common upper level emitted by multiply charged ions depends on the parameters of the laser-produced plasma. In particular, the relative intensity of the $3p \rightarrow 3s$ ($\lambda = 5801$ and 5812 Å) transitions compared with $3p \rightarrow 2s$ transition ($\lambda = 312$ Å) in the Li-like ion C IV has been analyzed. It was shown that the ratio depends on the plasma density and that this effect is not related to the line absorption; the authors concluded that the experiment can serve as a demonstration of quenching of the Einstein A coefficients in dense plasma. The influence of the surrounding plasma on the values of the A coefficient was found to be essential for transitions with lower radiative decay rates.

Such a revolutionary interpretation of the phenomenon leads to rather serious consequences, a minor one being the radical revision of the traditional methods of plasma spectroscopic diagnostics at high densities. In that sense it seems natural to discuss alternative possible mechanisms of the observed phenomena.

The proposal described below can be briefly expressed in the following way: in the dense (but already cold) plasma in the vicinity of the laser target the measured intensity of the $3p \rightarrow 2s$ vacuum ultraviolet (vuv) transition is strongly influenced by the dielectronic satellite (DS)—transitions in ions of the previous stage of ionization, $3p,nl \rightarrow 2s,nl$—which radiate close to their "parent" $3p \rightarrow 2s$ line. Satellites analogous to the $3p \rightarrow 3s$ visible transition $3p,nl \rightarrow 3s,nl$ do not change the measured intensity of their parent $3p \rightarrow 3s$ line because the density broadening of the satellites can reach tens of angstroms in that spectral region, and superposition of satellites creates in the vicinity of the line a "continuum" with increased intensity towards longer wavelengths.

A similar idea showing the strong influence of DS on the line profile was used[3] for the explanation of the essential line asymmetry (appearance of strong "red" wings) in transitions of Li-like F VII (Ref. 4) and Si XII (Ref. 5).

Possible channels for excitation of dielectronic satellites with a high principal quantum number n of the "spectator electron" are shown in Fig. 1. The ground state of the Li-like ion $1s^2 2s$ as well as all excited states (∗) (e.g., $1s^2 3s$ and $1s^2 3p$) can be treated as ionization limits of corresponding Rydberg series of the Be-like ion: normal series, $1s^2 2snl$ for the Li-like ion ground-state configuration; "shifted" (∗,nl) series, $1s^2 3snl$ or $1s^2 3pnl$ for the $1s^2 3s$ and $1s^2 3p$ levels. The dielectronic satellites are the transitions between levels of two shifted series (e.g., $1s^2 3pnl \rightarrow 1s^2 3snl$) or between shifted and normal series (e.g., $1s^2 3pnl \rightarrow 1s^2 2snl$). The intensities of these satellites in optically thin plasma are determined by the population of the corresponding Rydberg levels. It is well

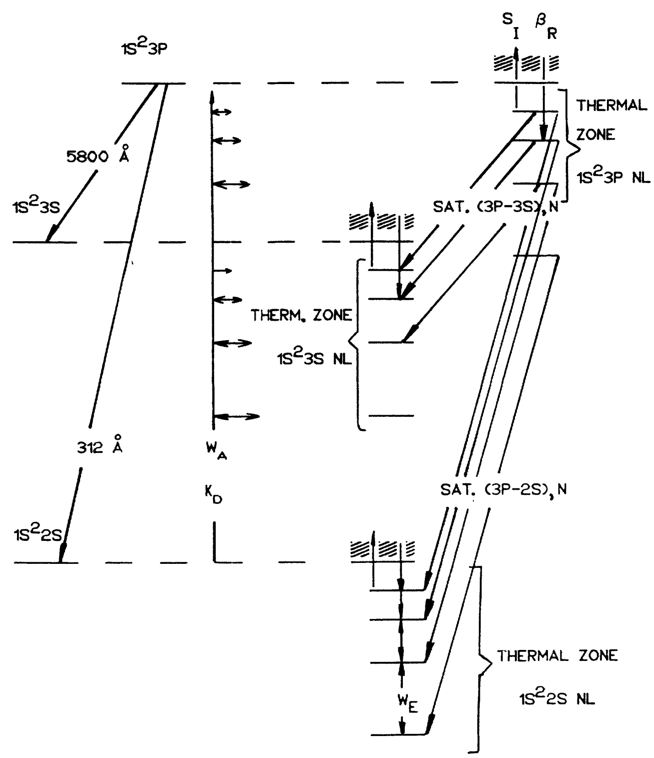

FIG. 1. Ground ($1s^2 2s$) and excited ($1s^2 3s$ and $1s^2 3p$) levels of the Li-like ion C IV and their adjacent "normal" ($1s^2 2s,nl$) and "shifted" ($1s^2 3s,nl$ and $1s^2 3p,nl$) series of the Be-like ion C III. Processes contributing to the level population are designated: W_a, autoionization; K_d, dielectronic capture; W_e, collisional transfer; S_i, ionization; β_r, recombination.

known that in plasmas that are not very dense, dielectronic (two excited electrons) autoionizing levels with low n are mostly populated by dielectronic capture. The high-n levels and adjacent continuum states are coupled to each other due to collisions (W_e). One can also apply here the conventional concept of a "thermal zone"[6] for the shifted series of autoionizing levels taking into account some peculiarities: (i) The $(*,nl)$ states are subject to autoionization (W_a) and can be populated by the inverse process, i.e., by dielectronic capture. (ii) The radiative decay rates for the shifted series have a weak dependence on n:

$$W_r(a_2,nl \rightarrow a_1,nl) \simeq W_r(a_2 \rightarrow a_1) ;$$

for the normal series, $W_r(a_g,nl) \sim n^{-5}$.

These peculiarities lead to the "narrowing" of the thermal zone with the new definition $W_e(*,n) \geq W_a(*,n)+W_r(*,n)$. The population densities of thermal zone levels are governed by the Saha-Boltzman equation

$$N^{z-1}(a,n)=N^z(a)N_e \frac{\omega(a,n)}{\omega(a)} \frac{\exp[I(a,n)/kT]}{AT^{3/2}} , \quad (1)$$

where $A=2(2\pi mk/h^2)^{3/2}=6.06\times10^{21}$ cm^{-3}eV$^{-3/2}$ and ω are statistical weights.

For dense and cold plasmas, the population of $(a,n)^{z-1}$ states can be comparable to or even exceed the population of the $(a)^z$ level. Together with the fact that

$$W_r(a_2,nl \rightarrow a_1,nl) \simeq W_r(a_2 \rightarrow a_1) ,$$

this means that under such conditions the intensity of dielectronic satellites as well can be comparable to or even exceed the intensity of the parent line. Estimation of the thermal-zone limit[3] shows that for plasmas with electron densities $n_e \geq 10^{19}$cm^{-3} and temperatures $T_e < 5$ eV, levels with $n \geq 6$ are coupled in the thermal zone. We estimated the line intensities using the hydrogenlike approximation. It follows that for $n_e = 5\times10^{19}$ cm^{-3} and $T_e = 2$ eV intensities of satellites with $n \geq 6$ are comparable with the intensity of the parent line.

For high n, the population of the levels in the thermal zone and related DS intensities are proportional to n^2 and the definition of $n_{\max}$, which corresponds to the upper discrete state of the ion adjacent to the real continuum bound in the dense plasma, becomes of principal importance. The latter was assumed to coincide with the extreme of the potential $U=-Ze/r-E_0r$, where E_0 is the Holtsmark ion field, $E_0=2.603eZN_i^{2/3}$. Under these conditions

$$n_{\max}=5400\frac{Z^{1/2}}{N_i^{1/6}}+\Delta_n , \quad (2)$$

where Δ_n is the term which is responsible for the lowering of the level energy because of the deviation of the effective potential from a Coulomb one: $\Delta_n \approx 2$.

For plasmas of the above parameters $n_{\max} \approx 9$; therefore, the sum of the DS intensities for $n=6$, 7, 8, and 9 can much exceed the intensity of the parent line, which can lead to the overestimation of its intensity in the measurements in case these DS fit inside the spectral line.

The problem of high-n DS linewidths is not investigated well in the literature. Evidently, one should not expect essential ($\sim n^2$) broadening of $(a_2,n) \rightarrow (a_1,n)$ transitions in the ion field because the strong compensation of Rydberg levels shift for both series. Estimation of the broadening due to nonelastic electron-ion collisions resulting in $n \rightarrow n+1$ transitions gives the linewidth:[7]

$$\Delta\nu \cong (1-3)\times10^{-19}N_e \frac{n^4}{Z^2T^{1/2}} \text{ cm}^{-1} . \quad (3)$$

For $n=8$ Rydberg levels in a plasma with $N_e=3\times10^{19}$ cm^{-3}, $\Delta\nu \cong 1000$ cm^{-1}, which corresponds to a linewidth of $(3p,n) \rightarrow (2s,n)$ vuv satellites $\Delta\lambda_{\text{vuv}} \cong 1$ Å and $\Delta\lambda_{\text{vis}} \cong 300$ Å for $(3p,n \rightarrow 3s,n)$ visible transitions. Interference effects[8,9] that are especially strong for $\Delta n=0$ collisions can decrease the linewidths, but the broadening of DS could not be smaller than distances between lines with different n.

The estimation above shows that the vuv DS that are shifted less than 1 Å cannot be distinguished from the parent $(3p \rightarrow 2s)$ line. The broadening of visible DS is still larger than the splitting of the $3p \rightarrow 3s$ doublet and their superposition creates the broad background.

Numerical modeling. For an estimate of DS contributions to the line intensities, a computer code calculation of the level populations was carried out for the case of a recombining plasma with constant temperature and density. The set of rate equations included levels of both types: levels with one excited electron for Be-, Li-, and He-like ions, and levels with two excited electrons for Be-like ions (some of them are shown in Fig. 1). The calculations show that the autoionizing Rydberg levels in the thermal zone follow the population of the corresponding ionization limits [according to Eq. (1)] and the relative intensity of high-n DS depends only on the plasma parameters (N_e,T) but not on the prehistory or initial conditions.

It is essential to note that in a dense and cold plasma the supplementary channel of the level deexcitation can play a significant role: three-body recombination to the thermal zone of shifted series with subsequent "stabilization" through DS radiative decay. For the particular case under consideration:

$$(1s^23p)_{\text{Li}}+e+e \rightarrow (1s^23p,n)_{\text{Be}}+e ,$$
$$(1s^23p,n)_{\text{Be}} \rightarrow (1s^22s,n)_{\text{Be}}+h\nu \text{ (DS to } 3p \rightarrow 2s) . \quad (4)$$

The results of the modeling emission spectra in the vicinity of the $3p \rightarrow 3s$ and $3p \rightarrow 2s$ transitions are shown in Fig. 2 for a plasma with electron density $N_e=3\times10^{19}$ cm^{-3} and $T=2$ eV. The recalculation towards the lower densities is very straightforward—the intensities of DS from the thermal zone are proportional to N_e. This means that for plasmas with $N_e < 3\times10^{18}$ cm^{-3} one should not expect essential enhancement of the $3p \rightarrow 2s$ line and additional "background" for the $3p \rightarrow 3s$ doublet.

We realize that our choice of plasma parameters is somewhat arbitrary. According to Ref. 1, even close to the target, the plasma density does not exceed the value of 10^{19} cm^{-3}. We would like to indicate that the electron-density measurements were done in Ref. 1 with a spatial resolution at least twice worse than 200 μm (the width of a used slit) because of Fresnel diffraction of visible radiation, which has not been taken into account. The critical

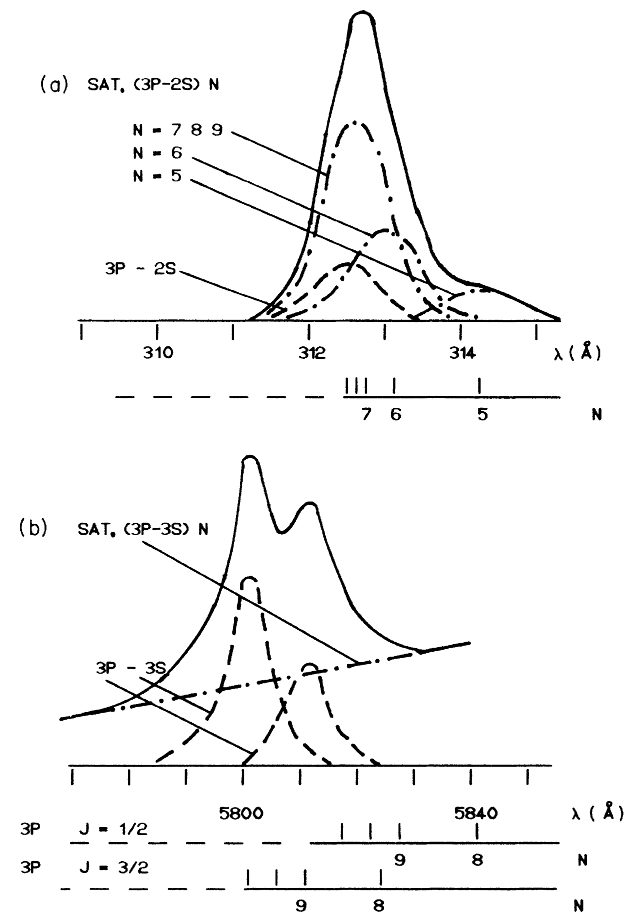

FIG. 2. Calculated line profiles of (a) $3p \rightarrow 3s$ ($\lambda \cong 312$ Å) and (b) $3p \rightarrow 2s$ ($\lambda \cong 5801-5812$ Å) transitions in Li-like ions C IV in a recombining laser-produced plasma with $n_e = 3\times10^{19}$ cm^{-3} and $T_e = 2$ eV. Dashed curves, parent lines; dash-dotted curves, corresponding satellites; solid curves, observed spectra.

point of the proposed mechanism of "quenching" of Einstein A coefficients—the possibility of cooling laser-produced plasma to a temperature of few eV rather close to the target—needs special investigations.

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APPENDIX

For the calculation of DS positions a model potential Eq. (A1) was used for the interaction of the optical electron n_1l_1 ($3p$, $3s$, or $2s$ in our case) with the "spectator" electron n_2l_2:

$$\mathcal{V}(r/n_2) = \frac{1}{Zr}[1-(1+r/n^2)\exp(-2r/n^2)] \;. \quad \text{(A1)}$$

It has the correct asymptotic behavior for $r \rightarrow 0$ and $r \rightarrow \infty$ and the correct (exponential) transition from one asymptotic form to the other. Using radial wave functions for optical electron n_1l_1 in the form

$$\mathcal{R}_{n_1l_1} = \mathcal{N}\exp(-r/n_1)r^{l_1} \;, \quad \text{(A2)}$$

where

$$\mathcal{N}^2 = \left(\frac{2}{n_1}\right)^{2l_1+3} \frac{1}{(2l_1+2)!} \;, \quad \text{(A3)}$$

one obtains an expression for the shift of the "two-electron" state $n_1l_1n_2l_2$ compared to the "one-electron" n_1l_1 for the conditions $n_2 \gg n_1$ and $Z \gg 1$:

$$\Delta E(n_1l_1/n_2) = \frac{2Z\Re}{n_2^2}\left[1-\frac{n_1^2(2l_1+3)(2l_1+4)}{6n_2^4}\right] \;, \quad \text{(A4)}$$

where $\Re$ is the Rydberg constant.

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