Satellites to $\Delta n = 1$ Transitions between High-Lying Levels of Multiply Ionized Atoms

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In a θ pinch discharge satellites to $\Delta n = 1$ transitions between high-lying levels are observed for the ions Si IX, Si X, and Si XI, but not for Si XII. They are identified as $\Delta n = 1$ transitions between the corresponding levels of doubly excited systems. At high densities, the series of Rydberg levels above their respective thermal limit are collisionally coupled to their ionization limit: The intensity ratio of a transition to that of its satellite thus offers the unique possibility of measuring the ratio of the population density in the ground energy level of the next ionization stage to that in the lowest excited levels of this ion.

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The $\Delta n = 1$ transitions between high-lying levels of multiply ionized atoms occur at relatively long wavelengths and thus offer convenient possibilities for the investigation of impurity concentrations and impurity dynamics in plasma devices. At low densities, these transitions are usually weak as excitation from the ground state decreases rapidly with increasing principal quantum number ($\sim n^{-3}$), and charge exchange with neutral hydrogen injected into the plasma is used in order to achieve sufficient population of these levels.[1]

At higher electron densities, however, collisions couple higher excited states to each other and to the ground state of the next ionization stage, the population densities in these levels being governed by the Saha-Boltzmann equation. The principal quantum number n_{th} of the lowest level ("thermal limit") for which this model holds in a quasistationary plasma is given on the basis of the simplified hydrogenic model by[2]

$$n_{\mathrm{th}} \geq 165 Z^{12/17} \left(\frac{n_e}{\mathrm{cm}^{-3}} \right)^{-2/17} \left(\frac{kT_e}{E_H} \right)^{1/17}, \qquad (1)$$

where Z is the ionization stage, n_e is the electron density, kT_e is the electron temperature, and E_H denotes the Rydberg unit of energy.

In a recent publication, Koshelev[3] applied the concept of partial local thermodynamic equilibrium (PLTE) also to doubly excited states which, at low densities, are usually populated by inner-shell excitation or dielectronic capture. In particular, the last process has attracted much interest as radiative decay (radiative "stabilization" in competition with autoionization) leads to effective recombination ("dielectronic recombination"), which is the dominant recombination process in low-density high-temperature plasmas described by the coronal model.[4] The stabilizing transitions occur on the long-wavelength sides of the respective resonance lines of the previous ionization stage: They are known as dielectronic satellites and provide various diagnostic possibilities.[5]

In order for PLTE to hold also for doubly excited states, the rates for collisional transitions between the levels must be larger than the rates for autoionization, which decrease rapidly ($\sim n^{-5}$) with increasing principal quantum number. This leads to a modified estimate for the respective thermal limit [see Ref. 3, Eq. (2a)].

Figure 1 illustrates the model in the case of the berylliumlike ion Si XI. Rydberg levels above n_{th} are collisionally coupled to the $2s$ ground state of the lithiumlike ion Si XII: the respective levels of the doubly excited system to the $2p$ levels of the same ion. Application of the Saha-Boltzmann equation to both systems yields the ratio of the population densities and hence the ratio of the emission coefficients for corresponding $\Delta n = 1$ transitions

$$\frac{\epsilon_{\mathrm{se}}}{\epsilon_{\mathrm{de}}} = \frac{n(2s)}{n(2p)}, \qquad (2)$$

where ϵ_{se} refers to the transition in the singly excited term system of Si XI and ϵ_{de} to that in the doubly excited term system of this ion. All other factors cancel as transition energies, transition probabilities, and energies of the upper levels are practically identical. The transition ϵ_{de} will be shifted slightly in wavelength with respect to the transition ϵ_{se}. The shift will be to the short-wavelength side as the wavelength λ for a $\Delta n = 1$ transition between Rydberg levels is given in terms of the Rydberg

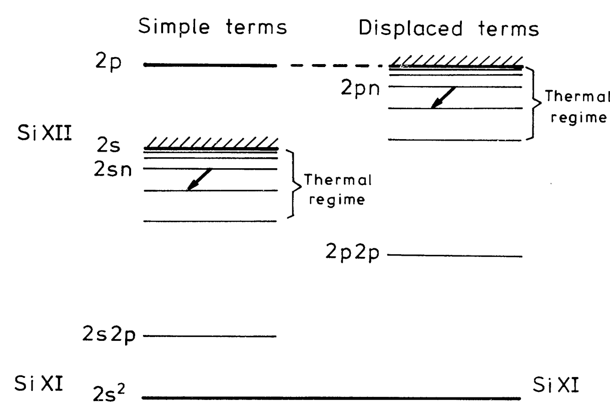

FIG. 1. Schematic level diagram of singly and doubly excited Si XI.

constant R_∞ by

$$\lambda^{-1} \simeq (Z-\sigma)^2 R_\infty \frac{2n-1}{n^2(n-1)^2}, \quad (3)$$

and the screening parameter σ will be smaller for the term system with the "spectator electron" in the $2p$ level than for that with this electron in the $2s$ level. n is the principal quantum number of the upper level. The wavelength shift can be estimated[6]; for the transition $n=10$ to $n'=9$ in Si XI, for example, it was found that $\Delta\lambda \simeq -0.25$ nm. On the other hand, an experimentally obtained shift yields a rather accurate difference of both screening parameters.

The $\Delta n=1$ transitions were observed in the emission from a transient hydrogen plasma seeded with 1% Si as impurity. The plasma was produced in a θ pinch discharge which has been described in detail previously.[7] In such a device, an initially cold plasma is heated rapidly, and the atoms go successively through their various ionization stages.[8]

The plasma was well diagnosed using Thomson scattering; the length of the plasma column was derived from the continuum emission by viewing the discharge volume through small holes of 1-mm diam in the pinch coil along the axis of the discharge tube. Electron temperatures were above 200 eV, electron densities were about 3×10^{16} cm^{-3}, and the lifetime of the plasma was 10 μs.

Spectroscopic observations in the visible and uv were carried out end on employing a 1-m monochromator equipped with a photomultiplier. Total intensities of $\Delta n=1$ transitions originating at levels with principal quantum numbers $n=9$, 10, 11, and 12 were measured as functions of time for the ions Si IX, Si X, Si XI, and Si XII. The following profiles were scanned: the transitions $n=10$ to $n'=9$ of the ions Si IX and Si XI, and the transitions $n=11$ to $n'=10$ of Si X and Si XII. Figure 2 illustrates the results for Si IX, Si XI, and Si XII at different times t during the discharge.

With the aid of a Simplex computational routine,[9] Gaussian profiles were fitted to the experimental points (denoted by open circles). Those of Fig. 2(c) were best fitted by one Gaussian of the relative full half-width $\Delta\lambda/\lambda = 5.5\times10^{-4}$. No satellite is observed during the whole time this ionization stage exists. In contrast, all the observed $\Delta n=1$ transitions of the other ionization stages display a component or "satellite" which we now interpret as a $\Delta n=1$ transition of the corresponding doubly excited system as discussed above. We advance the following arguments in support of this hypothesis.

(i) During the lifetime of the plasma, the plasma column remains centered in the discharge tube, and no mass motion is observed in the direction of observation. Doppler shifts corresponding to the displaced satellites would require directed kinetic energies of the silicon ions larger than 8 keV and no mechanism appears plausible to explain such anomalously large values.

(ii) Si XI and Si XII ions exist simultaneously, and any gross motion of the plasma must produce identical Doppler profiles. Our interpretation yields an explanation of the absence of a satellite in the emission from the Si XII ions [Fig. 2(c)]. The intensities of satellites are given by the population densities of the lowest excited states of the next ionization stage, here the heliumlike ion Si XIII, and because of the high excitation energies of the lowest states of this ion, the relevant population densities remain low. In the case of the ions Si IX to Si XI, the next ionization stages have low-lying excited states which are strongly populated.

(iii) According to Eq. (2), the intensity ratio from Si XI yields directly the ratio $n(2s)/n(2p)$ of the population densities in Si XII if the relevant levels are above

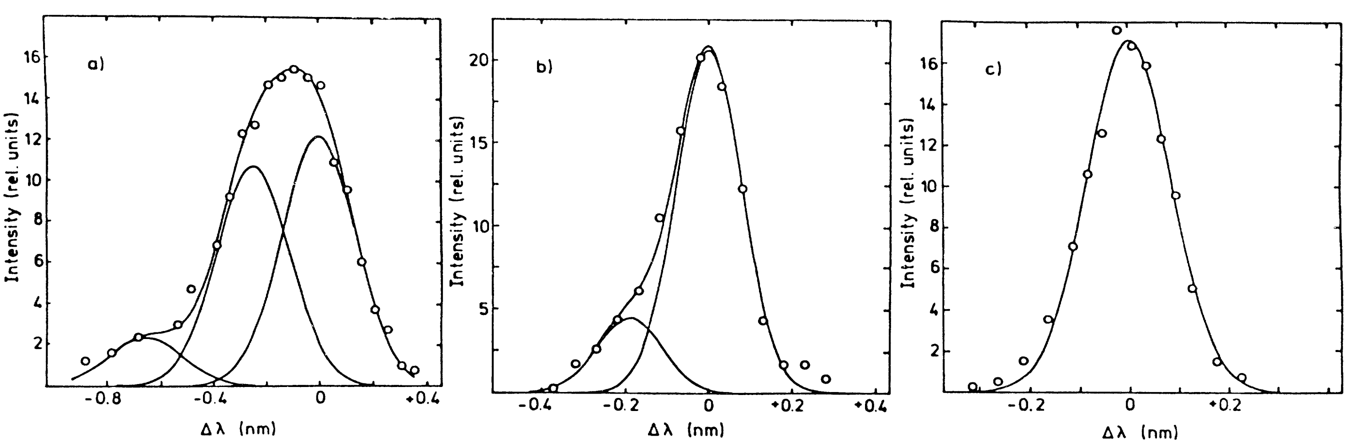

FIG. 2. Profiles of $\Delta n=1$ transitions as functions of wavelength. The abscissa is in nm, the y axis is in arbitrary units. (a) Si IX, $n=10$ to $n'=9$, $\lambda=479.49$ nm, and $t=2.8$ μs. (b) Si XI, $n=10$ to $n'=9$, $\lambda=320.98$ nm, and $t=7.3$ μs. (c) Si XII, $n=11$ to $n'=10$, $\lambda=364.53$ nm, and $t=6.3$ μs.

their respective thermal limit. We obtain

$$\frac{n(2s)}{n(2p)}=4.7\pm0.7$$

from the profile of Fig. 2(b).

This ratio can also be calculated as

$$\frac{n(2s)}{n(2p)}=\frac{n_eX(2p\rightarrow 2s)+A(2p\rightarrow 2s)}{n_eX(2s\rightarrow 2p)}, \qquad (4)$$

where $A(2p\rightarrow 2s)$ is the probability for the spontaneous transition from the $2p$ level to the ground state,[10] and the X's are collisional rate coefficients. We obtain

$$\frac{n(2s)}{n(2p)}=6.1\pm1.2,$$

when using the average Gaunt-factor fit formula proposed by Cochrane and McWhirter[11] for the rate coefficients. The net uncertainty is about 20%, comprising a 10% uncertainty in the excitation rate coefficient and a 10% uncertainty in the experimental electron density. Within the error limits, the theoretical ratio therefore supports our interpretation, although the condition of the levels being above the thermal limit is only marginally fulfilled because of the large autoionization rates [see the modified version of Eq. (1) in Ref. 3]. The agreement should improve if cascading contributions are included in Eq. (4).

(iv) The displacement of the satellite relative to the parent line is of the estimated magnitude and has the correct sign as discussed above.

(v) The widths of the Doppler profiles of the Si XI and Si XII transitions are consistent with each other, but, by comparison, the apparent widths of the $\Delta n=1$ transitions in Si IX and Si X are obviously too large by nearly a factor of 2. However, both ions have a low-lying metastable level which is strongly populated. For Si XI, for example, we estimate for our conditions that 41% of the ions would be in the ground state and 58% in the metastable level. Parent transition of Si X and satellite are thus of about equal intensity and merge into apparently one line, and indeed, the observed profile can be represented as the sum of two Gaussians of the expected width. Figure 2(a) shows the respective transitions in Si IX. We now interpret the weak component as a corresponding $\Delta n=1$ transition in a second doubly excited term system, the ionization limit of which is the $2s2p^2\,{}^2D$ term of Si X.

We have demonstrated that the investigation of the detailed structure of the $\Delta n=1$ transitions between high-lying levels of an ion offers unique possibilities of deriving the population densities of the ground state and strongly populated levels of the next ionization stage. Direct measurements on the higher ionization stage are usually hampered by several difficulties: The respective transitions are in a wavelength region (vacuum uv) where absolute intensity calibration poses a problem, they are influenced by optical depth effects, or they are too weak to be observed because of low transition probabilities as in the case of transitions from metastable levels.

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