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Research Article

KLL Dielectronic Recombination of Highly Charged Sulfur and Silicon Ions

Safdar Ali

Department of Physics, University of Gujrat, Hafiz Hayat Campus, Gujrat 50 700, Pakistan

Correspondence should be addressed to Safdar Ali; safdar.ali@uog.edu.pk

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Dielectronic recombination measurements for highly charged ions were performed at the Stockholm refrigerated electron beam ion trap. We have obtained KLL DR resonance strengths for highly charged H- and He-like sulfur and silicon ions. The experimental results are compared with the theoretical data obtained from GRASP II code. Both the experimental and calculated results agree well within the experimental error bars. Moreover, the dielectronic recombination resonance strengths are used to obtain the new scaling parameters by incorporating our results with the previous measurements and to check the behaviour of scaling formula for H- and He-like isoelectronic sequences.

1. Introduction

Dielectronic recombination (DR) process has been observed in high-temperature astrophysical and laboratory plasmas and thus affects the charge state distributions of the plasmas. It plays a crucial role in modelling and diagnosing of these plasmas [1]. For example, DR satellite lines from fusion plasma devices are often used to determine plasma temperature for diagnostics [2]. On the other hand, plasma modelling codes such as XSTAR [3], CLOUDY [4], and CHIANTI [5] crucially depend upon the input atomic data such as DR cross sections and rate coefficients to obtain ionization balance and physical conditions of the plasmas [6]. Highly charged sulfur and silicon ions are present in astrophysics and laboratory plasmas [7, 8]. Accurate atomic data for these ions is therefore needed for the identification of the emission lines and to derive ion abundances and plasma temperatures.

Historically, DR process was first suggested as recombination mechanism by Sayers in 1939 [9]. Later, Massy and Bates [10] considered it theoretically to explain atomic processes related to O^+ ions in the upper atmosphere. However, it was Burgess [11] who for the first time pointed that DR had a large recombination rate in high-temperature plasmas and dominates over the radiative recombination in the solar corona. DR is a resonant two-step electron-ion recombination process, in which a free electron is captured into a vacant shell of the ion, while one of the bound electrons is simultaneously excited producing a doubly excited state. The process is completed by stabilization through photon emission, reducing the ion energy below the ionization threshold. This process can be schematically represented as

$$A_i^{q+} + e^- \longrightarrow \left[A_j^{(q-1)+}\right]^{**} \longrightarrow A_k^{(q-1)+} + h\nu, \quad (1)$$

where q is the charge state of ion A, and subscripts i, j, and k denote the initial, doubly excited, and final states, respectively.

In this paper, we present the results for H- and He-like KLL DR resonances of highly charged sulfur and silicon ions obtained from the measurements performed at the Stockholm EBIT.

2. Experimental Details

The measurement for the ions discussed in this paper was performed using Stockholm Refrigrated electron beam ion trap (R-EBIT) [12, 13]. For the measurements, the gas atoms are injected into the EBIT through one of the ports. These atoms make collision with the electrons emitted from the electron gun and trapped in the potential well. The trapping region consists of three drift tubes: bottom, middle, and top starting from electron gun side. The whole drift tubes

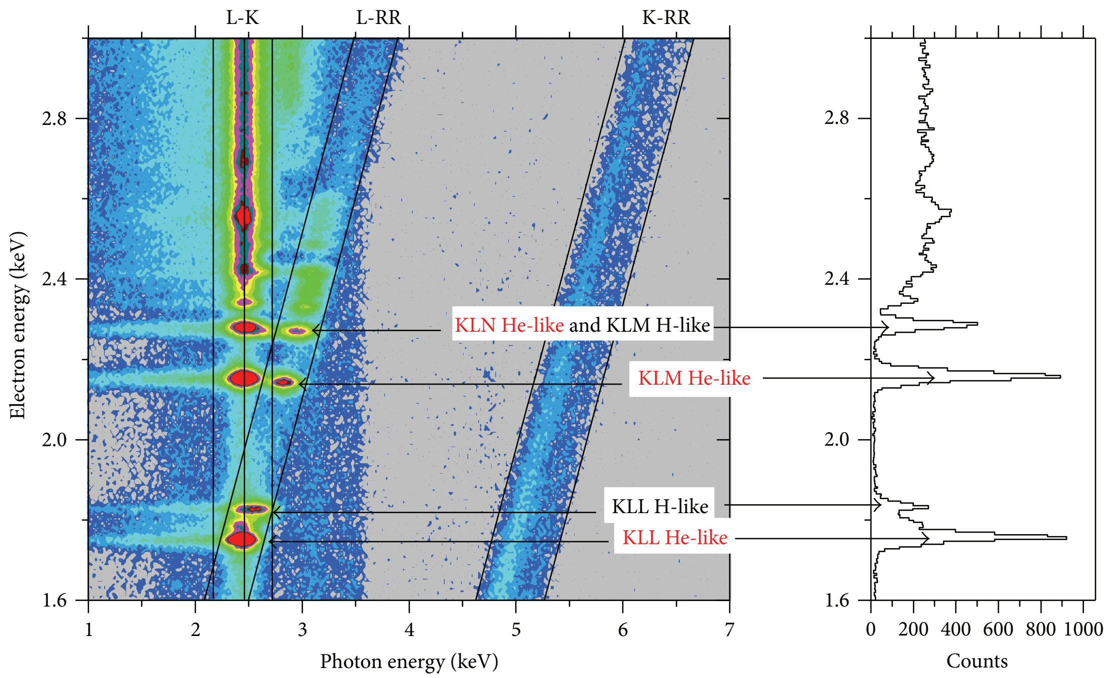

Figure 1: Two-dimensional scatter plot of X-ray energy versus electron beam energy. The dense blobs on the K-L and L-RR ridge are due to DR resonances. The right panel of the figure gives projection of the date under black vertical line onto the electron beam energy axis.

assembly is floating on high positive voltage plate form. The voltage of the middle drift tube determines the energy of the electron beam relative to the trapped ions. The ions are trapped radially by the space charge produced by the electron beam and axially by the positive potential applied on bottom and top drift tubes.

In the first stage of the experiment, the electron beam energy was set to ionization energy of 8 keV to produce a suitable charge state distribution of these ions by collisions for 900 ms with trapped ions/atoms. In order to scan for DR resonances, the electron beam energy was ramped linearly up and down for 300 ms. The electron beam current was kept constant at about 10 mA with the trap depth of 10 V throughout the measurements. At the same time, X-rays emitted from the trapped ions were recorded using a SiLi detector, placed at 90° to the electron beam direction. The signal was taken into computer by using electronics and multiparameter data acquisition system. The X-ray energy, electron energy, and time were recorded in the computer in event mode following the procedure described in [13].

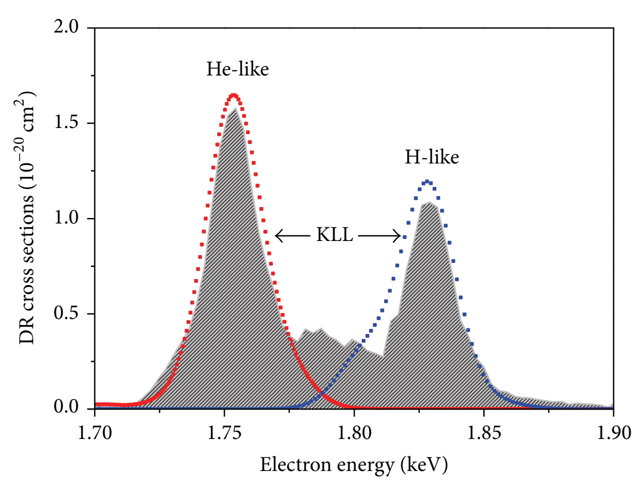

Figure 2: KLL DR spectra of highly charged sulfur ions. The shaded area shows the experimental result, while the red and blue dotted lines are the calculation for He-like and H-like ions, respectively.

3. Results and Discussions

A two-dimensional event mode data plot is shown in Figure 1 for highly charged sulfur ions. The horizontal and vertical axes indicate the photon energy and the electron energy, respectively. X-ray signal due to L-RR processes is seen along diagonal line (since in radiative recombination, X-rays energy is the sum of beam energy and the binding energy of the recombined state, so this increases linearly with the electron beam energy). X-rays corresponding to transition from L → K can be seen along the vertical column denoted with L-K ridge. The DR resonances form the intense spots and are labelled as KLL, KLM, and KLN parallel to the electron energy axis. There are two specific decay channels after the production of the doubly excited state. If the inner electron decays to K-shell, the resonances appear on L-K ridge. The resonances observed on L-RR ridge are due to the decay of the outer electron to K-shell. Since both the initial and final states are the same as for nonresonant RR process, the X-rays due to DR and RR are observed on the same position. The 2D spectrum allows projecting the selected regions either onto the photon energy axis or onto electron beam energy axis.

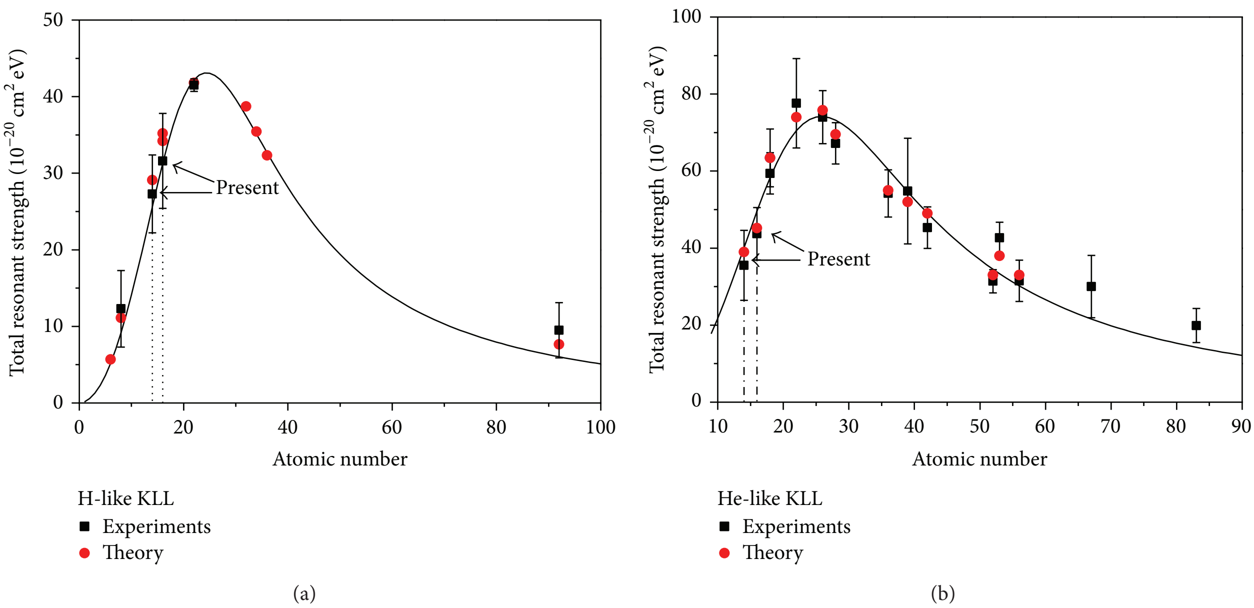

FIGURE 3: DR resonant strength versus atomic number (a) for H-like and (b) for He-like isoelectronic sequence. The data points with vertical dotted lines are our results for sulfur and silicon. The other data points are from Ar^{16+} [19, 20], Ti^{20+} [16], Fe^{24+} [21, 22], Ni^{26+}, Mo^{40+}, and Ba^{54+} [23], Kr^{34+} [24], I^{51+} [25], Xe^{52+} and all He-like calculations [26], Y^{37+}, Ho^{65+}, and Bi^{81+} [27], O^{7+} [28], Ti^{21+} [29], C^{5+}, O^{7+}, Si^{13+}, and S^{15+} [30], Ge^{31+}, Se^{33+}, and Kr^{35+} [31], and U^{91+} [32].

The natural width of the DR cross section is smaller than the beam energy width of 25 eV FWHM. Thus, instead of working with the theoretical narrow profiled DR cross section, DR resonance strength is normally used, which is cross section integrated over all energies. The resonance strength S^{KLj} is defined by

$$\sigma_{\mathrm{DR}}^{\mathrm{KLj}}(E) = S_{\mathrm{DR}}^{\mathrm{KLj}} \frac{1}{\Delta\sqrt{\pi}} \exp\left[-\frac{(E-E_{\mathrm{DR}})^2}{\Delta^2}\right], \qquad (2)$$

where $\Delta = \omega/2\sqrt{ln2}$ and $\omega = 25$ are the electron beam energy spread, obtained by using the KLM resonance peak of He-like sulfur. The experimental DR resonance strength can be obtained using the relation

$$S^{\mathrm{KLj}} = \frac{I^{\mathrm{KLj}}}{I^{\mathrm{RR}}}\left(\sigma^{\mathrm{RR}}\Delta E\right)\frac{3-P^{\mathrm{KLj}}}{3-P^{\mathrm{RR}}}\frac{N_{\mathrm{H}}}{N_{\mathrm{He}}}, \qquad (3)$$

where I^{RR} and I^{KLj} are the total count rates of the photons over an energy spread ΔE, σ^{RR} is the theoretical RR cross section of H-like ions, $N_{\mathrm{H}}/N_{\mathrm{He}}$ is the ratio of H- to He-like ions, and $3-P^{\mathrm{KLj}}/3-P^{\mathrm{RR}}$ is a correction factor to the photon intensity due to the anisotropy of DR and RR photon emission.

The experimental results obtained for KLL resonances of H- and He-like sulfur are compared with the calculations as shown in Figure 2. A distorted wave approximation method was used for the calculations of the continuum wave functions of the incident electrons. Atomic structures of the target and recombined ions were calculated with the GRASP II code [14]. The Auger decay rates and resonant strengths were calculated by using a code developed by Y. M. Li et al. [15]. These codes were already used successfully for the calculations of DR resonance strengths and energy position of different atomic ions [6, 16, 17]. The generalized Breit interactions (GBI) and the decay through forbidden radiation are very weak; therefore such effects were not taken into account. In the calculations, all possible decay paths were taken into account, including radiative decay to lower doubly excited states and autoionizing decay to excited states.

TABLE 1: Fitting parameters m_1 and m_2 used in (4) obtained by incorporating present results with previous measurements.

Charge state	m_1 (10^{15} cm^{-2}eV^{-1})	m_1 (10^{15} cm^{-2}eV^{-1})
H-like	1.95	6.91
He-like	1.01	4.51

Previously, an empirical formula was given by Watanabe et al. [18] to estimate the DR resonant strength of He-like isoelectronic sequence by defining the radiative transition rate $A^r(Z)$, the autoionization rate $A^a(Z)$, and the resonance energy $E(Z)$ in terms of their Z dependence:

$$S^{\mathrm{KLj}} = \sum_d \sum_f \frac{\pi^2}{E_{di}} \frac{g}{2g_i} \frac{A_{di}^a A_{df}^r}{\sum A^a + \sum A^r} = \frac{1}{m_1 Z^2 + m_2 Z^2}, \qquad (4)$$

where Z is the atomic number and m_1 and m_2 are fitting parameters. By taking the present results and incorporating the results from previous measurements, the parameters m_1 and m_2 can be recalculated to update the scaling formula. We have also performed similar measurements for highly charged silicon ions and the results are shown in Figure 3. In addition, we have also obtained fitting parameters for H-like isoelectronic sequence as given in Table 1.

The KLL DR resonance strengths of H- and He-like isoelectronic sequences for experimental and theoretical results published so far are shown in Figure 3 along with our experimental and theoretical data. The solid squares with error bars are the experimental values, while the filled circles are the theoretical values. Our measurements for sulfur and silicon are shown with dotted vertical lines. It is clear that this scaling law provides a very good fit to the experimental and theoretical results. As shown in the figure, the resonant strength decreases with increasing Z except for $Z = 14$, 16, and 18. This is due to the fact that the capture of electron into the doubly excited states becomes more difficult as Z increases; as a result, the resonant strengths become smaller with increasing Z. However, for the elements with atomic number $Z = 14$, 16, and 18, the Auger processes become significant and the doubly excited states could decay through the Auger processes to a significant extent. For large differences in the magnitude of the two transition rates (radiative and Auger), the DR resonance strength is proportional to the weaker of the two decay channels; hence, radiative decay is weaker in these low Z elements which increase the resonance strengths (see (4)).

4. Conclusions

We have measured the KLL DR resonance strengths for highly charged H- and He-like sulfur and silicon ions. The results agreed well within the experimental error bars with our calculations performed with the fully relativistic distorted wave approximation approach. In addition, we have obtained the new fitting parameters to estimate the DR resonance strengths by using scaling formula. More benchmark measurements are required over a wide range of atomic numbers to extend the applicability of this formula, especially for low Z elements (below $Z = 14$).

Conflict of Interests

The author declares that there is no conflict of interests regarding the publication of this paper.

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