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Experimental study of the deep-lying dielectronic recombination resonances of He-like germanium ions

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Abstract
Dielectronic recombination (DR) for He-like Ge^{30+} through both one-electron–one-photon and two-electron–one-photon (TEOP) stabilization of Li-like doubly excited states was studied with the Heidelberg electron beam ion trap. The DR resonance strength from He-like Ge^{30+} $1s^2$ $^1S_0$ to the Li-like Ge^{29+} specific configuration $1s2s^2$ $^2S_{1/2}$ was determined to be $(2.02 \pm 0.2) \times 10^{-20}$ cm^2 eV and the total KLL DR resonance strength was determined to be $(63.7 \pm 6.5) \times 10^{-20}$ cm^2 eV. The experimental results agree well with a theoretical prediction obtained with the configuration interaction Hartree–Fock method.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Dielectronic recombination (DR) is a resonant process, in which a free electron is captured into an ion while one bound electron is simultaneously excited. Thereby, an intermediate doubly excited state is formed; if this state is stabilized by emission of one or more photons, then the DR process is complete:

$$e^- + A^{q+} \rightarrow (A^{(q-1)+})^{**} \rightarrow A^{(q-1)+} + h\upsilon$$

The competing stabilization channel proceeds through an Auger process, in which case the DR is not 'successful', because no recombination eventually takes place. DR resonances are usually labelled in analogy with the nomenclature used for Auger processes, such as KLL, KLM, KLN, etc. The KLM DR process is shown schematically as an example in figure 1(a).

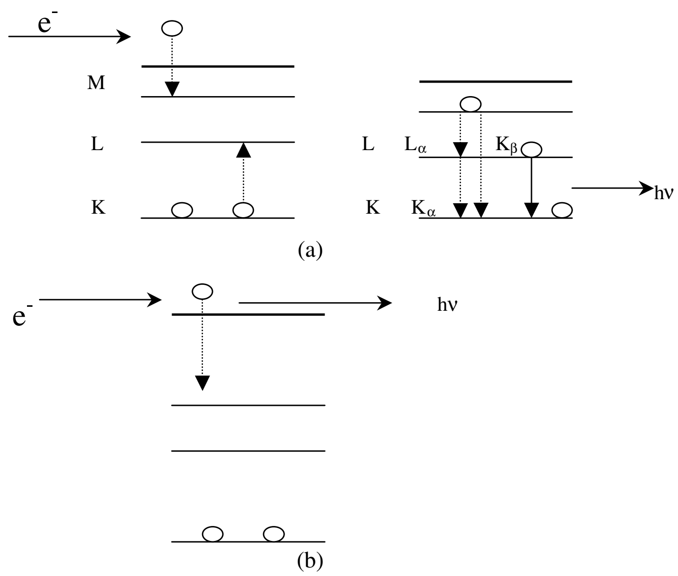

Figure 1. Schematic diagram of the KLM dielectronic recombination resonance (DR) and the radiative recombination process (RR).

A free electron recombines with a ground-state He-like ion forming a Li-like ion in a doubly excited intermediate state. During stabilization of the intermediate state, x-ray photons with different energies (through K_α, K_β or L_α transition) are emitted. Radiative recombination (RR) is always present when studying the DR process. In this process, a free electron is recombined with an ion releasing a photon to conserve energy (see figure 1(b)). This process is not resonant with respect to the electron energy, hence it produces a continuous spectral feature. The photon energy equals the sum of the electron kinetic energy and the ionization energy of the state upon which the electron settles.

At resonance energies, DR cross sections are several orders larger than other processes contributing to the charge state equilibrium in a plasma. Thus, knowledge of the DR resonance strength is imperative for our understanding of the physics of hot plasmas. Experimental studies for DR processes in He-like ions for several elements have also been carried out in heavy-ion storage rings (using the electron cooler technique) and electron beam ion sources (EBIS) (see [1–3]). The electron beam ion trap (EBIT) is an ideal environment in which to study this process [4]. Since the introduction of the first EBIT in 1986, experiments with He-like ions such as Ni^{26+}, Mo^{40+} and Ba^{54+} [4], Ar^{16+} [5, 6], Fe^{24+} [7, 8], Ti^{20+} [9], Kr^{34+} [10], among others, have been reported using this method. The state-resolved DR process of Ar^{16+} has been investigated and DR through two-electron–one-photon (TEOP) correlative stabilization observed [6] using the Freiburg EBIT [11]. This device was relocated to Heidelberg in 2001. After the commissioning of a laser ion source [12], the present experimental study of Ge^{30+} was carried out at the new location.

In this paper, the total KLL resonance strength is obtained, as well as the resonance strength of DR stabilized through the two-electron–one-photon process. The experimental results are compared with a theoretical prediction obtained with the configuration interaction Hartree–Fock method.

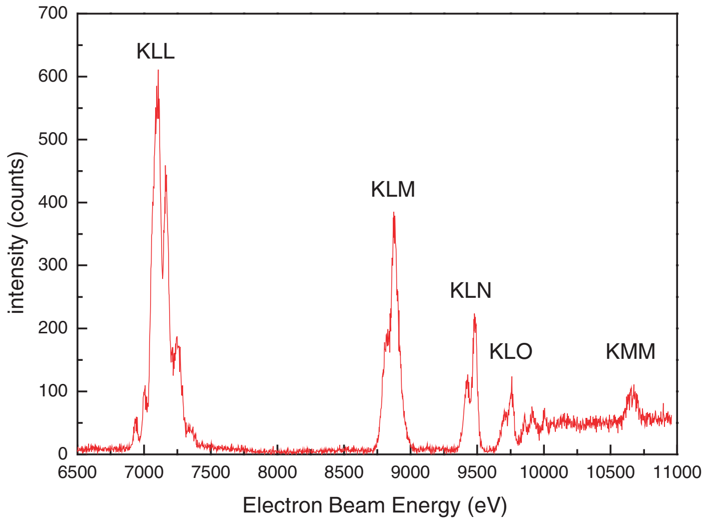

Figure 2. Overview spectrum of the DR experiment for He-like Ge ions. The first group of peaks from the left arises from the KLL resonance, the second group from KLM, and so forth.

2. Experiment

In this work, we measured the yield and energies of the x-rays emitted during the DR process as a function of the electron energy. X-ray photons emitted by the trapped ions were detected using a high-purity germanium detector with a resolution of about 150 eV. During the experiment, the electron beam energy was cyclically scanned through a range containing the different resonances of interest. When one photon was detected, the value of the electron energy and of the x-ray photon energy were recorded simultaneously by an event-mode data acquisition system (GOOSY), resulting in a two-dimensional map.

Singly charged Ge ions were injected into the EBIT from a pulsed laser ion source (for details, see [12]). In order to get an overview spectrum of DR processes for Ge^{30+}, the electron beam energy was rapidly scanned from 6.7 to 11.1 keV at a rate of 300 V s^{-1}. The beam current was 100 mA. Figure 2 shows the projection onto the electron beam energy axis of a cut taken from the two-dimensional data set along the K_α photon energy (10.2 keV). This spectrum includes all resonance peaks below the direct excitation threshold (labelled by KLL, KLM, KLN, KLO, etc) and the KMM resonance peak above it. In the present experiment, interest was focused on the KLL resonance. Therefore, in the following runs, the electron energy was scanned around only the KLL resonance (from 6.7 to 8.2 keV) in order to save time. The electron energy was changed so slowly (9 V s^{-1}) that EBIT could be considered to be running in a 'steady-state mode', in which the recombination and the electron impact ionization rates are considered approximately equal since charge exchange plays an important role. The acquisition time was roughly 10 h, in order to ensure that the statistical uncertainty of the intensity of the weakest peak was less than 2%. Figure 3 shows the corresponding KLL spectrum along with the theoretical calculation of DR resonance strengths for He-like Ge (dashed line; for calculation details see section 3). By using 60 mA electron beam current, the energy spread of electron beam (due mainly to the space charge of the beam, and hence linearly dependent on the beam current) was only about 35 eV. This allowed us

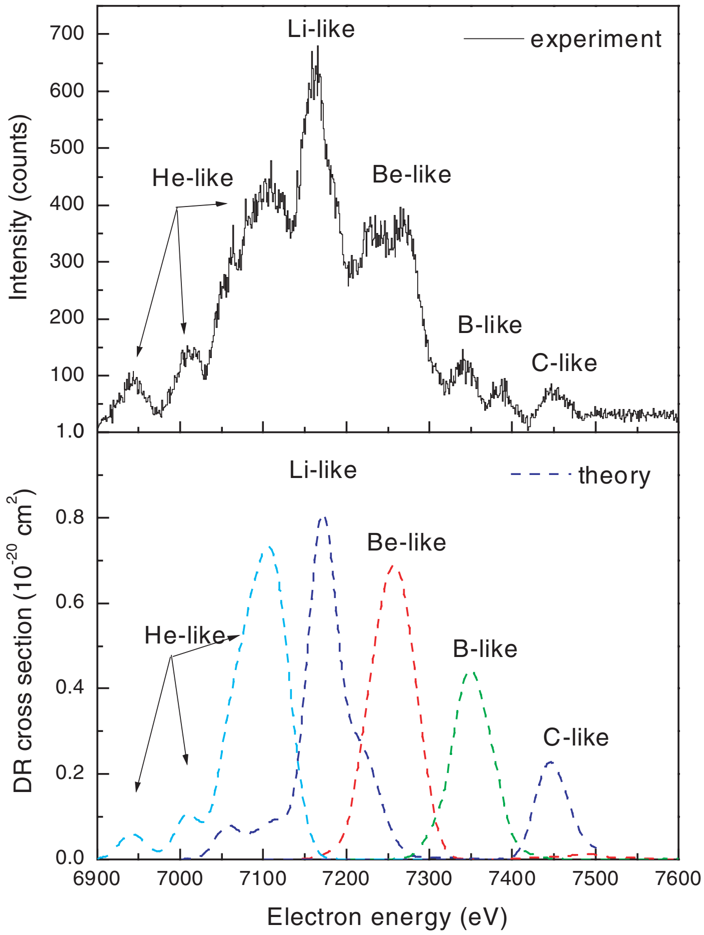

Figure 3. Spectrum of the KLL DR resonance for He-like Ge ions when the electron beam energy was scanned around only the resonance energy. Solid curve: experimental data; dashed curves: theoretical calculations.

to resolve the He-like Ge DR resonance to the $1s2s^2\,{}^2S_{1/2}$ state of Li-like Ge (the first peak from the left) from those arising from other configurations of Li-like Ge. The assignments of the peaks are also shown in the figure. The charge balance in this slow scan mode is shifted towards the Li-like average charge, in comparison with the fast overview scan, where the He-like state dominates. The explanation for this marked difference is simply that in the overview mode the electron beam energy dwells longer in regions outside the recombination resonance peaks, thus producing and accumulating a larger amount of He-like ions which recombine mainly while sweeping over the resonances. In contrast, scanning at slow speed over a narrow region around the KLL resonance causes a higher average rate of recombination, only compensated by the electron impact ionization at that instantaneous energy value and not by the previous accumulation of He-like ions at non-resonant energies. At this comparatively low current, charge exchange between the highly charged ions and residual gas atoms has also a stronger effect on the charge balance, and lower charge states such as Li-like and Be-like are rather pronounced.

3. Theory and calculation

The DR resonant strength can be written as

$$S_{ij} = \frac{\pi^2\hbar^3}{W_e E_{ij}} \frac{g_j}{2g_i} A^a(j \to i) B_j^r,$$

where j represents a doubly excited intermediate state, i represents the initial ground state. E_{ij} is the resonance energy, g_i and g_j are the statistical weights of states i and j. $A^a(j \to i)$ is the autoionization rate from level j to level i. The radiative branching ratio B_j^r can be written as

$$B_j^r = \frac{\sum_f A^r(j \to f)}{\sum_f A^r(j \to f) + \sum_k A^a(j \to k)}.$$

$\sum_k A^a(j \to k)$ and $\sum_f A^r(j \to f)$ are the total Auger and radiative decay rates of the state j, where f represents a non-autoionizing state. The resonant DR cross section is

$$\sigma_{ij}(E) = S_{ij}\delta(E - E_{ij}).$$

To compare this with the experimental measurement, we convolve the above cross section with a Gaussian profile assumed for the electron energy distribution in the beam:

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

where $\Delta = w/(2\sqrt{\ln 2})$ and w is the energy width of the electron beam (here $w = 35$ eV).

In the present work, we employ the flexible atomic code (FAC) developed by Gu [13] to calculate all basic atomic data, including energy levels and Auger and radiative transition rates. FAC uses a relativistic configuration interaction approximation to calculate bound–bound processes in atomic systems. Autoionization processes are treated in the first-order perturbation theory using a distorted-wave approximation for the continuum electrons.

4. Results and discussion

In the 'steady-state mode,' the electron beam energy was varied so slowly that at each energy the ion charge distribution was essentially identical to that of the static case. Hence, we use the method developed by Zou [6] to obtain the DR strength. The experimental curves were fitted using the following equation which comes from [6] after some corrections:

$$R_e(E_e) = N(\varepsilon, j_e/e, n)W(\theta)\sigma_{DR}(E_e)/(\sigma_{DR}(E_e)/\sigma_{ILi\text{-like}} + (n_{Li\text{-like}}/n_{He\text{-like}})_0 + 1). \qquad (1)$$

$R_e(E_e)$ is the DR event rate at electron energy E_e, and $N(\varepsilon, j_e/e, n)$is a coefficient including the photon detection efficiency ε, the electron current density j_e/e and the total number density of He-like and Li-like Ge ions n. The coefficient $W(\theta)$ is the angular dependence of the photon emission caused by the polarization of the photon. $\sigma_{DR}(E_e)$ is the Gaussian form of the DR cross section σ_{DR} folded with the electron beam energy resolution (35 eV) for He-like Ge ions. The electron-impact ionization cross section for Li-like Ge ions is denoted by $\sigma_{ILi\text{-like}}$. The off-resonance density ratio is $(n_{Li\text{-like}}/n_{He\text{-like}})_0 = \sigma_{RR}/\sigma_{ILi\text{-like}} + en_0\, v\sigma_{CHe\text{-like}}/(j_e\sigma_{ILi\text{-like}})$, where σ_{RR} is the RR cross section of He-like Ge ions and $\sigma_{CHe\text{-like}}$ is the cross section for the electron capture by He-like Ge ions (with an average velocity of v) from the residual gas of density n_0.

In fitting of the experimental data with equation (1), one has to account for the fact that the radiation from the EBIT is in general anisotropic due to the magnetic field of the trap and the main velocity component of the electrons in the beam. The x-rays are observed through

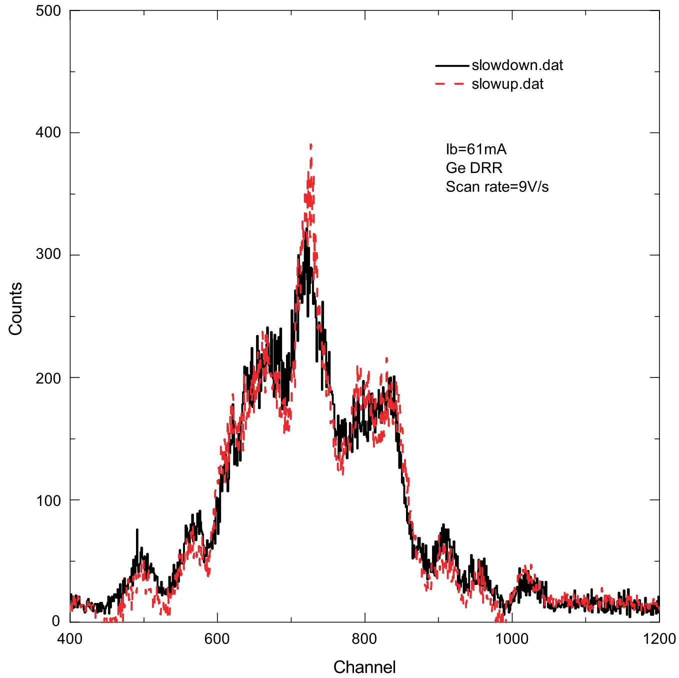

Figure 4. Comparison of the positive and negative slew data sets.

a port at 90° to the beam direction. For the electric-dipole radiation emitted during dielectric recombination, the angular correction factor that account for the anisotropy is

$$W(90^\circ) = \frac{3}{3 - P}, \tag{2}$$

where P is the degree of linear polarization [14]. Since the electric-dipole radiation dominates the DR process, we rely on this formula to determine the effect of angular distribution. According to [14], for isolated electric dipole lines $J \rightarrow J_r$ emitted during the DR process of ions initially in a state with zero total angular momentum, the photon emission from the $J = 1/2$ level is unpolarized, and the magnitude of the linear polarization associated with $\Delta J = 1$ transitions is at the 50–60% level. By calculating $W(\theta)$ for a large number of individual resonances, it was concluded that the average of the angular distribution correction for each resonance group is expected to be at the 90% level relative to the isotropic emission [10].

In the current analysis, the experimental data are fitted by equation (1) using six parameters: the four DR strength, $N(\varepsilon, j_e/e, n)$ and $(n_{\text{Li-like}}/n_{\text{He-like}})_0$. The largest uncertainty in the determination of the resonance strength arises from the assumption that the total ion number density, n, remains constant during the KLL DR process. In order to make sure the justice of this assumption, we compared the positive and negative slew data sets (which are shown in figure 4). It can be seen that there is no apparent difference between the two data sets. Thus, on the basis of a conservative estimate to account for possible deviations from that constant value of n depending on the resonance strength, we introduce an additional 10% uncertainty. Other error sources are the statistical uncertainty ($\sim$2%) and the overlap of resonance peaks, but their contribution is by far smaller than the main one.

The experimental data and the results of the fits are shown in figure 5. The total KLL resonance strength is obtained, as listed in table 1. Due to insufficient energy resolution, the DR

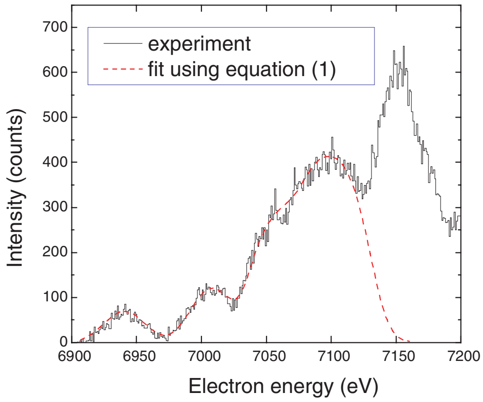

Figure 5. Spectrum of the KLL DR for He-like Ge ions and the corresponding fitting result using equation (1).

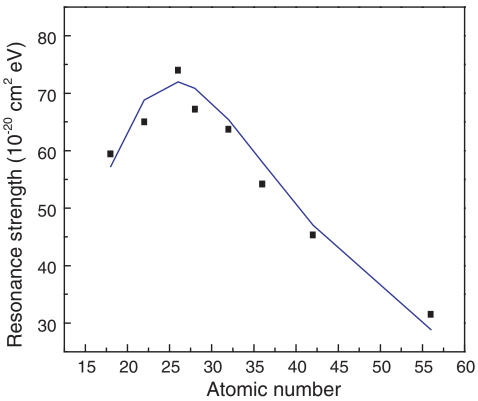

Figure 6. The KLL DR resonance strength of He-like ions measured with EBITs (Ni^{26+}, $Mo^{40+}$and Ba^{54+} [4], Ar^{16+} [5, 6], Fe^{24+} [7, 8], Ti^{20+} [9], Kr^{34+} [10], Ge^{30+} this work). The curve along the data points is drawn using the equation $S = (m_1 Z^2 + m_2 Z^{-2})^{-1}$ and the parameters ($m_1 = 1.06 \times 10^{15}$ cm^{-2} eV^{-1}, $m_2 = 4.55 \times 10^{20}$ cm^{-2} eV^{-2}) are taken from [8].

Table 1. The total KLL resonance strength for He-like ions obtained using EBIT.

	Experiment (this work)	Theory
$\sigma(1s2s^2\ ^2S_{1/2})$ (10^{-20} cm^2 eV)	2.02 ± 0.2	2.08
$\Sigma\sigma$(KLL) (10^{-20} cm^2 eV)	63.7 ± 7.5	63.12
		65.37[a]

[a] Obtained using equation (2) in [8].

processes for 1s2s2p and $1s2p^2$ could not been clearly separated in the spectrum. The second peak from the 1s2s2p configuration in particular disappeared under the larger peak from the $1s2p^2$ configuration. Therefore, no DR resonance strengths for the 1s2s2p and $1s2p^2$ are given. Since the $1s2p^2\ ^4P$ blends with a large Li-like DR resonance, an uncertainty of roughly 6% in KLL resonance strength determination for He-like ions is additionally included. Considering all these possible error contributions, a total KLL resonance strength of $(63.7 \pm 6.5) \times 10^{-20}$ cm^2 eV was obtained. Figure 6 shows this result along with the KLL resonance

Table 2. Cross sections for DR process stabilized through TEOP transition $1s^22p\ ^2P_{1/2,3/2}1s2s^2\ ^2S_{1/2}$.

	Experiment (this work)	Theory
Ar^{16+}	1.01 ± 0.1[a]	1.04
Ge^{30+}	2.02 ± 0.2	2.08

[a] From [6].

strengths of several other He-like ions obtained using EBITs. The curve through the data points is calculated using formula (10) and parameters found in [8]. A state-resolved DR resonance strength could also be extracted from the experimental data. The DR strength $(2.02 \pm 0.2) \times 10^{-20}$ cm^2 eV for the He-like Ge^{30+} $1s2s^2\ ^2S_{1/2}$ state was obtained. In table 2, we list the two results for the DR process stabilized through TEOP transition $1s^22p\ ^2P_{1/2,3/2}1s2s^2\ ^2S_{1/2}$ which have been measured with this EBIT: Ar^{16+} and Ge^{30+}. Also the theoretical results calculated using the FAC program are shown. It can be seen that the experimental results agree with the calculations quite well. However, at the present level of experimental precision, no distinctions between different theoretical models could be made. Future experimental improvements should allow us to distinguish between those in appropriate benchmark measurements.

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