CONF-900933--2

UCRL-JC-104992
PREPRINT

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Prepared for the Submittal to
Zeitschrift f. Physik D
Vth International Conference on
the Physics of Highly-Charged Ions,
Giessen, FRG

September 10-14, 1990

Received by OSTI

NOV 0 5 1990

September 7, 1990

Lawrence Livermore National Laboratory

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UCRL-JC--104992

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ELECTRON IMPACT IONIZATION CROSS SECTION MEASUREMENT OF LITHIUM-LIKE BARIUM IONS

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Abstract

The electron impact ionization cross section of Li-like Ba^{53+} has been measured at 22 keV using an electron beam ion trap. The measurement makes use of a novel technique, which is discussed in detail. We find a value somewhat higher than predicted by theory.

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I. Introduction

Accurate knowledge of ionization, excitation, and recombination cross sections of highly charged ions along an isoelectronic sequence are needed to check the scaling laws of theoretical calculations. In this regime relativistic effects become important. Until recently cross section measurements for ionization have been limited to medium charge states using crossed beams (U^{16+}) [1], theta pinches (Ti^{8+}) [2], and tokamaks (Fe^{21+}) [3]. However, with the advent of the Livermore electron beam ion trap (EBIT) very high charge states up to U^{82+} can now be studied.

In the following we describe a measurement of the ionization cross section of Li-like Ba^{53+}, i.e. of the process $1s^2 2s + e^- \rightarrow 1s^2 + 2e^-$. This is the first measurement based on a new technique that relies on x-ray observations and represents the highest charge state ionization measurement to date. Barium was chosen in the study because it is readily available as it evaporates from the electron gun. The technique will be applied in future measurements to study the ionization cross section of several ions along the Li-like isoelectronic sequence.

II. Description of Technique

EBIT was designed as an x-ray source [4,5]. Therefore, we have devised a technique for measuring the electron impact ionization cross section of Li-like ions based on studying the x-rays emitted from EBIT at 90° with respect to the electron beam. The measurement scheme uses the fact that if the electron beam energy is set to the KLL dielectronic resonance energy for He-like ions, dielectronic (DR) and radiative (RR) recombination of He-like ions is to a good approximation balanced by ionization of Li-like ions. The scheme is illustrated by the diagram in Figure 1. In this approximation, where we have neglected charge exchange recombination (CX), the density ratio of the He and Li-like charge states is approximately equal to the ratio of the cross sections for ionization and the sum of DR and RR. As a result, an x-ray emitted following DR is a good indicator that an ionization event has occured. Taking into account recombination due to RR, we can therefore determine an ionization cross section by counting the n = 2 to n = 1 x-rays.

The general equation for the density n_{He} of ions in the He-like charge state in steady-state is given by:

$$dn_{He}/dt = n_e v_e[\sigma_{ion}^{Li} n_{Li} - \sigma_{DR}^{He} n_{He} - \sigma_{RR}^{He} n_{He}] - n_0 v_0 \sigma_{CX}^{He} n_{He} = 0 \qquad (1)$$

where n_e, v_e is the electron density and velocity, σ_{ion}^{Li} the ionization cross section of Li-like ions, σ_{DR}^{He} the cross section of dielectronic recombination onto He-like ions, σ_{RR}^{He} the cross section of radiative recombination onto He-like ions, σ_{CX}^{He} the cross section of charge exchange with He-like ions, n_q the ion charge density of charge state q, and n_0, v_0 the density and velocity of neutral background gas. Solving for σ_{ion}^{Li}:

$$\sigma_{ion}^{Li} = (n_{He}/n_{Li})[\sigma_{DR}^{He} + \sigma_{RR}^{He} + (n_0v_0/n_ev_e)\sigma_{CX}^{He}]. \quad (2)$$

The x-ray intensities at 90° produced by DR onto He-like ions and RR onto Li-like ions can be expressed as:

$$I_{DR}^{He}(90°) = n_ev_e\sigma_{DR}^{He}(90°)n_{He} \quad (3)$$

$$I_{RR}^{Li}(90°) = n_ev_e\sigma_{RR}^{Li}(90°)n_{Li} \quad (4)$$

Substituting these into Eq. (2), we get:

$$\sigma_{ion}^{Li} = [I_{DR}^{He}(90°)/I_{RR}^{Li}(90°)]\sigma_{RR}^{Li}(90°)[\sigma_{DR}^{He}/\sigma_{DR}^{He}(90°) + \sigma_{RR}^{He}/\sigma_{DR}^{He}(90°) + (n_0v_0/n_ev_e)\sigma_{CX}^{He}/\sigma_{DR}^{He}(90°)]. \quad (5)$$

We note that the term $\sigma_{DR}^{He}/\sigma_{DR}^{He}(90°)$ in Eq. (5) accounts for the possibility that the DR x-ray intensity may be different at 90° from the 4π average. This factor arises because the x-rays are polarized and are emitted anisotropically [6] due to the fact that the atoms are excited by a unidirectional electron beam.

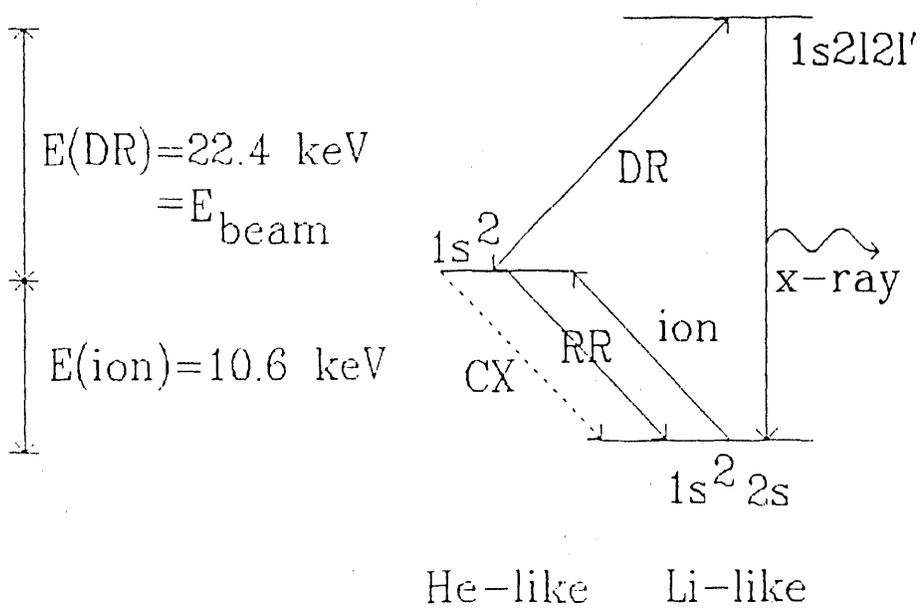

Figure 1: Measurement scheme for Li-like Ba. By counting the x-rays given off in the DR on He-like ions the ionization cross section can be measured, provided RR and CX are accounted for.

III. Experimental Procedure

The RR and DR x-rays are measured with a solid-state germanium detector. Typical results are shown in Fig. 2 for the RR x-rays and in Fig. 3 for DR x-ray data for Ba.

The sequence in which the spectra were taken is as follows: (1) We allow the Ba to ionize to the He-like charge state and come to steady-state at the electron beam energy equal to the DR resonanace energy, $E_{beam} = E_{DR}$. (2) We change the electron beam energy away from the DR resonance $E_{beam} \neq E_{DR}$ and measure RR x-rays onto He, Li, and Be-like Ba for 20 ms, Fig. 2. Note that this time is short compared to the theoretical ionization time of 200 ms for changing the charge balance. From this we determine the relative abundance of He and Li-like Ba ions. (3) Finally, we switch the beam energy back to the DR resonance $E_{beam} = E_{DR}$ and measure the DR x-rays, Fig 3. This period takes 40 ms which is long compared to theoretical DR time of 14 ms.

The RR x-ray signal, $I_{RR}(90°)$, shown in Fig. 2 contains contributions from He, Li, and Be-like ions. The relative He, Li and Be-like ion densities are determined from a fit of the RR data with known RR cross sections and photoionization energies. A 100-eV detector resolution (gaussian width) is assumed in the fitting procedure.

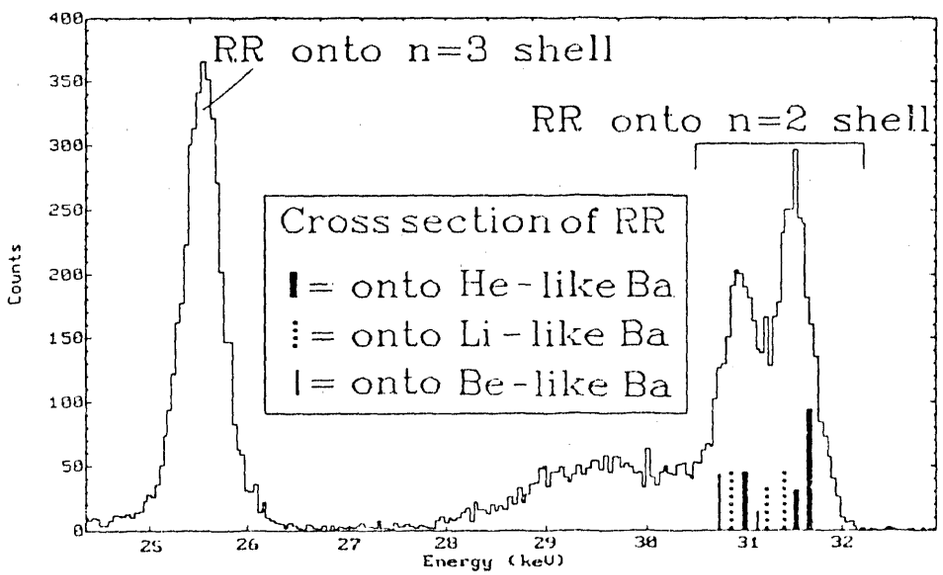

Figure 2: Radiative recombination (RR) x-ray spectrum, E_{beam} = 21.2 keV. The RR x-rays onto the n = 2 shell are fitted to determine a charge balance. The solid and dashed lines represent the relative theoretical cross sections of RR onto the different charge states.

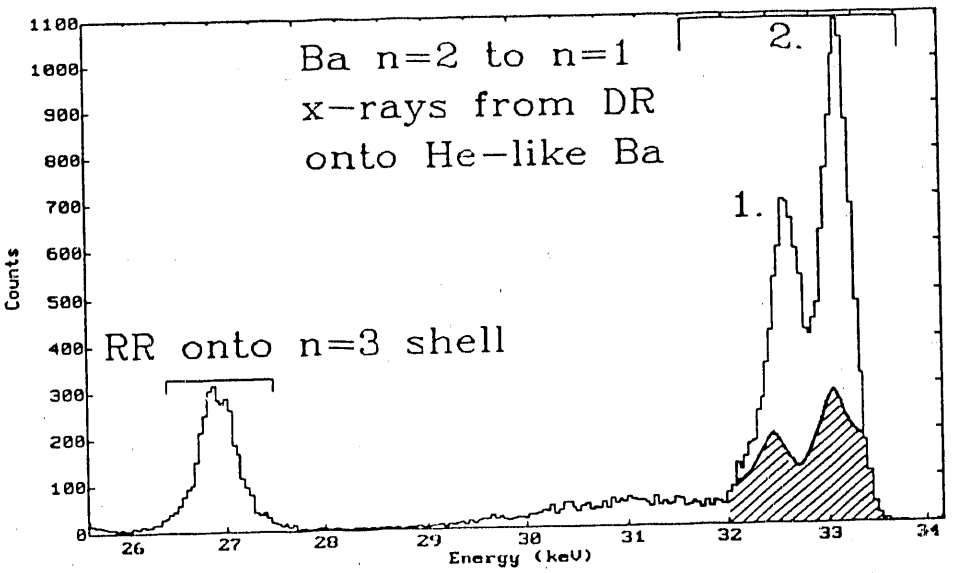

Figure 3: Dielectronic recombination (DR) x-ray spectrum, E_{beam} = 22.4 keV. The n = 2 to n = 1 feature contains a contribution from x rays due to RR onto the n = 2 shell of Ba (hatched area). Peak 1 is due to transition $[(1s2p)_1 2p_{3/2}]_{5/2} \rightarrow 1s^2 2p_{3/2}$; Peak 2 is due to transition $[(1s2s)_0 2p_{3/2}]_{3/2} \rightarrow 1s^2 2s$.

Because $\sigma_{DR} > \sigma_{RR}$, the DR x-ray signal in Fig. 3 is more intense than the RR signal in Fig. 2. $I_{DR}(90°)$, however, has contributions from x rays due to RR onto He, Li, and Be-like ions due to the fact that at $E_{beam} = E_{DR}$ the DR x rays and RR x rays appear in the same energy region. Because E_{beam} (Fig. 2) is approximately equal to E_{beam} (Fig. 3), RR is approximately the same in both spectra. Thus, we can determine $I_{DR}^{He}(90°)$ by subtracting the $I_{RR}(90°)$ signal in Fig. 2 from the $I_{DR}(90°)$ signal in Fig. 3, $I_{DR}^{He}(90°) = I_{DR}(90°) - I_{RR}(90°)$. We checked the validity of this approach by comparing the x-ray signal of RR onto the n=3 shell, which is seen in both the RR and DR x-ray spectra, and verified that they are equal.

Substituting the experimental quantities into the theory expression in Eq. (5) we obtain:

$$\sigma_{ion}^{Li} = [I_{DR}(90°)-I_{RR}(90°)/I_{RR}^{Li}(90°)]\sigma_{RR}^{Li}(90°)[\sigma_{DR}^{He}/\sigma_{DR}^{He}(90°) + \sigma_{RR}^{He}/\sigma_{DR}^{He}(90°) + (v_0 n_0/v_e n_e)\sigma_{CX}^{He}/\sigma_{DR}^{He}(90°)]. \quad (6)$$

Thus, we can determine σ_{ion}^{Li} from a measurement of $I_{DR}(90°)$ by normalizing to $\sigma_{RR}^{Li}(90°)$ and σ_{RR}^{He}. The result is affected by CX, which we treat as a pertubation.

IV. Results

The results for Li-like Ba are given in Table I for three energies corresponding to the energies of the dielectronic resonances in He-like Ba. We use theoretical calculations for $\sigma_{RR}^{Li}(90°) = 6.6 \times 10^{-23}$ cm^2, $\sigma_{RR}^{He} = 9.2 \times 10^{-23}$ cm^2 [7], $\sigma_{CX}^{He} = 2.3 \times 10^{-13}$ cm^2 [8], $\sigma_{DR}^{He}/\sigma_{DR}^{He}(90°) = 1.0, 1.0, 1.23$ for the three DR resonance energies in order of increasing energy [9], and v_e, n_e, and v_0 are determined by the operating parameters of EBIT. The only unknown in the equation is the neutral particle density n_0, which is related to the pressure of the background gas. This unknown determines the CX contribution and is discussed in the following paragraph. The results with and without CX are compared to theoretical values calculated by Reed using the distorted wave code of Zhang [10] and Moores [11] and to the semiempirical Lotz formula [12]. We measure an ionization cross section 1.8x theory without CX and 2.5x theory with CX.

In order to determine the effect of CX, we have measured the x-ray signal at energies away from the DR resonance. In this regime ionization is approximately balanced by CX and RR. Knowing RR we can infer CX. Since the CX contribution does not change as a function of E_{beam}, we can use this to correct the DR data.

Table I. Electron impact ionization cross section of Li-like Ba in units of 10^{-21} cm^2. * denotes sum of adjacent resonances. Energy in units of keV.

	Experiment		Theory		
Energy	no CX	with CX	Zhang	Moores	Lotz
21.83	0.24 ± 0.16	0.36 ± 0.28	0.143	0.141	0.142
21.97	0.25 ± 0.17	0.38 ± 0.29	0.143	0.141	0.142
22.44*	0.25 ± 0.13	0.36 ± 0.24	0.143	0.141	0.142

Because of the low resolution of the Ge detector there is a large uncertainty in the determination of the charge balance from the the RR data. The error bars are, therefore, calculated assuming maximum possible variations in the charge states n_{He}, n_{Li}, and n_{Be}. For example, the lower limit is calculated by assuming that n_{Li} = 100%, even though this assumption is unphysical. Measurements are in progress to determine the charge balance with improved accuracy.

Acknowledgments

We thank D. Nelson, E. Magee, and A. Hinz for their technical support. This work was performed under the auspices of the U. S. Department of Energy by Lawrence Livermore National Laboratory under contract No. W-7405-ENG-48.

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