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MEASUREMENTS OF ELECTRON EXCITATION AND RECOMBINATION FOR Ne-LIKE Ba^{46+}

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A new facility at Lawrence Livermore National Laboratory has been used to obtain measurements for electron-impact excitation, dielectronic recombination and radiative recombination for the neon-like Ba^{46+} ion. The experimental technique consists of trapping highly charged ions inside the space charge of an electron beam and measuring their x-ray emission spectra.

1. INTRODUCTION

Until now there has been no way to directly measure the electron interaction cross section for very-highly-charged ions. Measurements of dielectronic recombination (DR) and electron-impact excitation cross sections have been limited to charge states of $q \lesssim 6+$ by the available techniques of merged or crossed beams (1,2); while radiative recombination (RR) has not been measured at all. The only exception is one observation of DR onto Ar^{13+} using an electron beam ion source (EBIS) (3).

We have constructed a new device at Lawrence Livermore National Laboratory which, for the first time, makes it possible to measure all of these cross sections for highly charged ions. The technique consists of trapping ions inside an electron beam compressed to a density of order 2000 A/cm^2. Cross sections are determined from x-ray spectroscopic measurements of the trapped ions excited by the electron beam. Because the target ions are prepared in a single charge state and the electron beam is monoenergetic, it is possible to unravel all of the separate cross sections which contribute to x-ray emission.

The first highly charged ion to be studied in our electron beam ion trap (EBIT) was neon-like Ba^{46+}. Electron-impact excitation, cascade decays, dielectronic recombination, and radiative recombination have all been observed for Ba^{46+}, and early results are presented here as an illustration of the capabilities of EBIT.

2. ELECTRON BEAM ION TRAP

As shown schematically in Fig. 1, the ion trap for the Ba^{46+} measurements consisted of a copper cylinder with an inside diameter of 10 mm in the central trap region and 3 mm at the ends. The electron beam, which follows the central magnetic field line of the superconducting Helmholtz coils, was injected vertically from a commercial gun of the Pierce type having a perveance of 0.5×10^{-6}. After injection the beam was adiabatically compressed in the increasing Helmholtz coil field. The electron currents used ranged from 60 to 100 mA.

The drift tube and the surrounding Helmholtz-coil assembly were operated at a temperature of 4 K. X-rays were observed at 90° to the electron beam (in the midplane of the Helmholtz coils) through 2.5-mm wide slots in the drift tube. Holes in the 4-K (liquid helium) and 77-K (liquid nitrogen shield) structures were covered by 12.5-µm beryllium foils for x-ray transmission. It is important to keep the drift tubes as cold as possible in order to achieve a vacuum of ~ 10^{-12} Torr in the ion trap, which is necessary to prevent recombination with residual gasses. Hence the drift tubes were operated at liquid helium temperature.

Barium atoms (along with an unwanted tungsten contaminant) were introduced into the space between the drift tube and the intermediate electrodes (see Fig. 1) by evaporation and sputtering from the dispenser-type cathode of the electron gun. The amount of barium ionized and captured by the trap could be adjusted by changing the bias on the electrode closest to the gun end of the drift tube. Approximately 2 x 10^4 Ba^{46+} ions/cm were trapped inside the electron beam. The barium charge state was selected by keeping the electron energy between the 3.66-keV and 8.33-keV ionization potentials of Ba^{45+} and Ba^{46+}. The trap was operated in a continuous dc mode for data runs up to several hours in length.

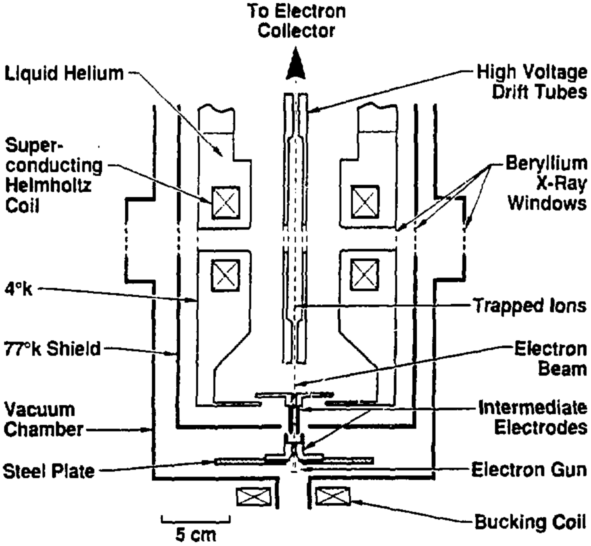

FIGURE 1
Arrangement of the electron beam ion trap.

3. X-RAY SPECTROSCOPY

EBIT was designed from the beginning for x-ray spectroscopic measurements of the trapped ions. Compared to the EBIS sources, EBIT uses a different and much smaller design which is optimized for x-ray spectroscopy. For the Ba^{46+} measurements x-rays were detected in two spectrometers: a 5-mm thick x 6-mm diameter Si(Li) detector and a flat crystal Bragg diffraction spectrometer consisting of a 5 cm x 2.5 cm PET crystal and a 5 x 0.8 x 0.8 cm position-sensitive proportional counter filled with a $Xe-CH_4$ gas mixture sealed behind a 500 µm beryllium entrance window. The PET crystal was located 20 cm from the trapped ions.

Examples of the x-ray spectra obtained in the Si(Li) detector are shown in Figs. 2 and 3. Both spectra show the Ba^{46+} L x-ray series extending up to the electron beam energy. X-ray lines above the beam energy are due to DR and RR. The energy of the end point of the RR for the contaminant tungsten ions implies that charge states up to W^{64+} were achieved.

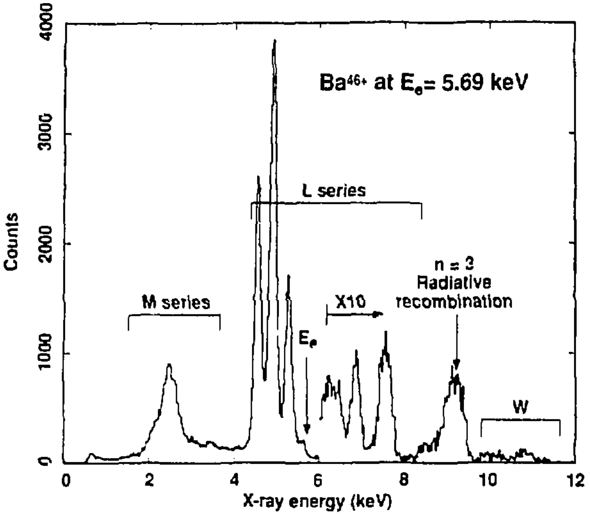

FIGURE 2
X-ray spectrum for Ba^{46+} observed in the Si(Li) detector at an electron beam energy of 5.69 keV. The spectrum is cut off below ~ 2.5 keV by absorption in the beryllium windows. The feature labeled W is attributed to RR onto tungsten ions, which were a contaminant in the trap. The spectrum has been multiplied by 10 above 6 keV for display purposes.

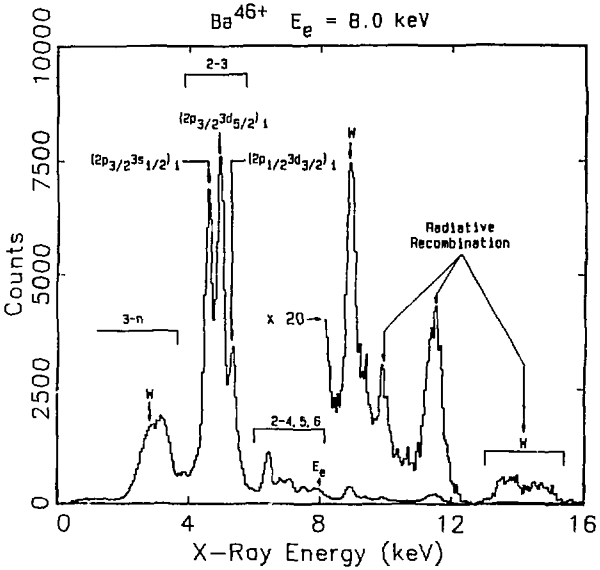

FIGURE 3
Similar to Fig. 2, but at an electron beam energy of 8.0 keV.

4. ELECTRON COLLISION STRENGTHS

Measuring absolute electron-ion cross sections in EBIT is difficult because of the uncertainty in the electron current density and the number of ions trapped in the beam. Relative cross sections, however, can be easily obtained from the x-ray spectra alone. By combining the information in the Si(Li) and crystal x-ray spectra it is possible to obtain experimental values for some of the n=2 to n=3 electron-impact-excitation collision strengths normalized to the RR cross section. We have done this for the two levels having the largest collision strengths: $(2p_{3/2}^{-1}\,3d_{5/2})_{J=1}$ and $(2p_{1/2}^{-1}\,3d_{3/2})_{J=1}$.

In Ba^{46+} there are 36 n=3 singly excited levels spanning the energy range from 4.56 to 5.64 keV. The crystal spectrometer was set to cover this x-ray energy range. X-ray spectra were obtained at electron energies of 5.69 and 8.20 keV, as shown in Fig. 4. These energies avoid the strongest DR resonances. Since both of the energies are above threshold for direct excitation of the highest n=3 level, DR does not involve an n=3 electron. However, the n=2 to n=3 x-ray intensities could still be affected by cascade from n≥3 DR configurations. The purity of the charge state distribution can be judged from the near absence of satellite lines adjacent to the strongest lines in the crystal spectra.

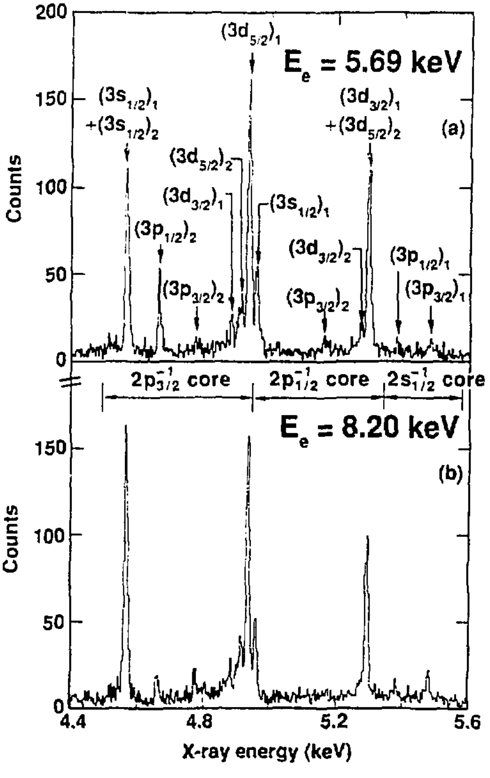

FIGURE 4

X-ray spectra for Ba^{46+} obtained with the crystal spectrometer at electron energies of 5.69 keV (top) and 8.20 keV (bottom). Lines are identified by (nl_j) of the excited electron and total angular momentum J. The spectral regions indicated by bars correspond to the three different core configurations for the identified lines.

The yields of three L x-ray lines and the (unresolved) n=3 RR lines were extracted from the Si(Li) spectrum by least squares fitting. Since the RR final state consists of a single n=3 electron outside a closed L shell, the calculated RR cross sections are expected to be reliable. We use a value of $\frac{d\sigma}{d\Omega}$ (90°) = 19.9×10^{-24} cm^2/sr at E_e = 5.69 keV. This is the sum of the separate RR cross sections to the five sodium-like n=3 levels calculated using a relativistic distorted wave code (4).

The contributions of the weaker and unresolved Ba^{46+} L x-ray lines were then estimated from the higher resolution crystal spectra and subtracted from the Si(Li) x-ray yields. Small corrections were made for differential absorption in the beryllium windows. The largest uncertainty, which we estimate to be about 20%, is due to the subtraction of a background (tungsten) feature from the RR peak.

Direct excitation from the ground state dominates the feeding of the $(2p^{-1}_{3/2}\ 3d_{5/2})_{J=1}$ and $(2p^{-1}_{1/2}\ 3d_{3/2})_{J=1}$ levels, so the strong E1 decay x-rays from these levels are a reliable measure of their collision strength. However, these transitions may have a nonisotropic angular distribution. Since x-ray measurements were possible only at 90°, the angular distribution corrections for the E1 transitions will have to await future theoretical calculations or measurements with a different trap geometry.

Neglecting the E1 angular distributions, and normalizing to the RR cross section value above, the electron-impact excitation cross sections at E_e = 5.69 keV for the $(2p^{-1}_{3/2}\ 3d_{5/2})_{J=1}$ and $(2p^{-1}_{1/2}\ 3d_{3/2})_{J=1}$ levels are 3.7×10^{-21} cm^2 and 1.9×10^{-21} cm^2, respectively. For comparison, the theoretical cross sections calculated using a relativistic multiconfiguration distorted wave code are 3.6×10^{-21} cm^2 and 2.0×10^{-21} cm^2 (5). The surprisingly close agreement with our measurements is probably fortuitous in view of the uncertainties mentioned above.

5. DIELECTRONIC RECOMBINATION

Because of the good (~ 15 eV) electron energy resolution of EBIT, it is particularly well suited for measuring DR cross sections. An example of this capability is shown for Ba^{46+} in Figs. 5 and 6. The DR process is: $e + (\mathrm{Ba}^{46+}) \rightarrow (\mathrm{Ba}^{45+})^{**} \rightarrow (\mathrm{Ba}^{45+})^{*} + h\nu$. Its signature is a resonance in the yield of the stabilizing photon, hν, in an electron excitation function.

In the sodium-like Ba^{45+} system DR resonances of the form $(2p^{-1}_{3/2}\ 4d_{5/2}\ 5\ell)$ are expected at electron energies of $E_e \approx 5.2$ keV. Figure 5 shows x-ray spectra obtained on and off this DR resonance at electron energies only 100 eV apart. The change in the yield of the $(2p_{3/2}\text{-}4d_{5/2})$ transition is dramatic. A plot of the measured yield of this x-ray as a function of electron energy is shown in Fig. 6. Because of the low electron energy used and the effect of the DR process itself on the ionization balance, charge states lower than 46+ are also present in the trap as target ions and contribute unresolved satellite lines to the observed x-ray yield. Hence it is not possible to give an unambiguous value of the DR cross section for Ba^{46+}. However, the peak DR cross section is roughly 1/2 of the $(2p_{3/2}\ 3d_{5/2})_{J=1}$ direct excitation cross section, and its measured width of 70 eV agrees with the expected fine-structure spreading of the DR resonance in the $(\mathrm{Ba}^{45+})^{**}$ system.

6. SUMMARY AND CONCLUSION

The processes of electron-impact excitation, DR, and RR have been observed and studied for the highly charged Ba^{46+} ion by x-ray spectroscopy of ions trapped in an electron beam. Measured electron-impact excitation cross sections have been compared with theoretical values. These measurements demonstrate the power of the electron beam ion trap for studying highly charged ions, and the technique can now be applied to many other ions.

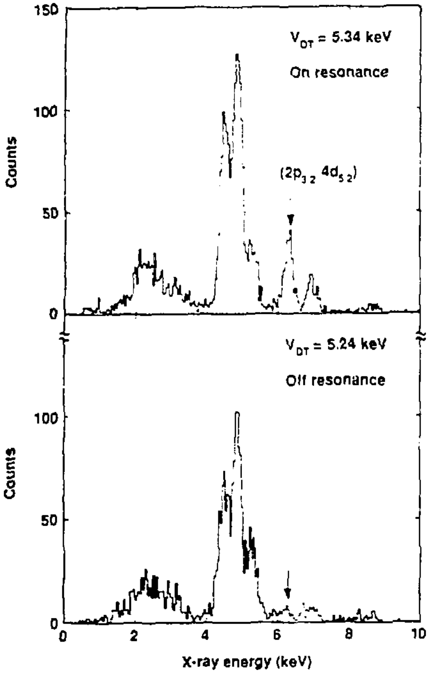

FIGURE 5
Examples of Si(Li) x-ray spectra obtained on and just off a DR resonance. The arrows indicate the $(2p_{3/2}-4d_{5/2})$ transition, whose yield is almost entirely due to the resonance.

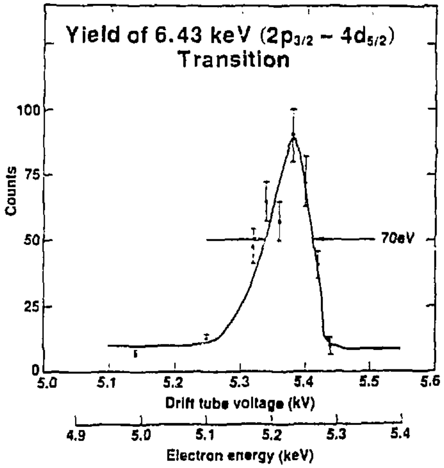

FIGURE 6
Measured excitation function for the $(2p_{3/2}-4d_{5/2})$ transition. The electron energy scale is offset from the drift tube voltage by the calculated 150 V space-charge potential of the electron beam.

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