ATOMIC PHYSICS OF HIGHLY CHARGED IONS
IN AN ELECTRON BEAM ION TRAP

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ABSTRACT

Two electron beam ion traps are in use at LLNL for the purpose of studying the properties of very highly charged ions and their interactions with electrons. This paper reviews the operation of the traps and discusses recent experiments in three areas: precision transition energy measurements in the limit of very high ion charge, dielectronic recombination measurements for the He-like isoelectronic sequence, and measurements of x-ray polarization.

INTRODUCTION

Since its first operation at Livermore almost four years ago, the Electron Beam Ion Trap (EBIT) has developed into a versatile tool for addressing many of the outstanding questions in the field of very highly charged ions.¹⁻⁴ Most of the ionization stages of almost any element in the periodic table can be produced and trapped for long times (The most highly charged ion studied to date is Ne-like U^{82+}). This allows us to study atomic structure and electron-ion reactions in the high field limit where relativistic and QED effects must be taken into account. In addition, the ion species available for study in EBIT include all of those whose x-ray emission is seen in spectra from astrophysical sources, tokamaks, and laser produced plasmas.

The most distinctive feature of EBIT, which sets it apart from any other method of studying highly charged ions, is the ability to obtain high resolution x-ray spectra from monoenergetic electron excitation. An additional feature is the ability to preselect an ionization stage with one electron energy and probe it with another. These features can be used to perform many types of measurements which have not been possible before. In this article we first explain the operation of the trap, and then show how it is being used for atomic physics measurements in three selected areas: precision transition energy measurements in the limit of very high ion charge, dielectronic recombination measurements for the He-like isoelectronic sequence, and measurements of x-ray polarization.

OPERATION OF THE TRAP

As its name suggests, the electron beam ion trap operates by trapping ions electrostatically within an electron beam. In the radial direction the ions are trapped by the negative space charge of the ~ 150 mA electron beam, and in the axial direction they are trapped by a ~ 100 volt barrier applied to two end electrodes (drift tubes). Four characteristics of the EBIT design account for its success: high electron beam intensity, retention of ions in the beam for long times, access for spectrometers in the radial direction, and rapid switching of the electron beam energy with good energy resolution.

At present there are two, nearly identical, EBIT's in operation at LLNL and two others under construction elsewhere. The general layout for both of the LLNL EBIT's is shown in Fig. 1. The electron beam is injected vertically from a Pierce gun mounted at the bottom of the vacuum chamber. It travels along the axis of the drift tubes and finally strikes the inside wall of a copper collector maintained at 77 K by a continuous flow of liquid nitrogen. In the trapping region the electron beam is compressed to

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current densities of up to 4000 A/cm^2 by the 3 Tesla field of two superconducting Helmholtz coils. The cylindrical copper drift tubes that contain the trapped ions are maintained at a temperature of 4 K in order to minimize the density of neutral background gas, which has a large cross section for charge exchange with highly charged ions.

Fig. 1. The electron beam ion trap. Cooling gas is injected from the side through an aperture that replaces one of the beryllium x-ray windows. Ions are injected into the trap from the MEVVA in a direction antiparallel to the electron beam.

The trap is loaded by injecting ions in low charge states downward through the collector. The ions are obtained from the cathode electrode in a MEVVA source,⁵ which is fired periodically to refill the trap. Highly charged ions are then obtained by successive ionization in the electron beam, and the final charge state is determined by the electron beam energy. For example, a large abundance (often $> 80\%$) of the closed-shell He-like and Ne-like ion species can be achieved by setting the electron beam energy just below the ionization potential for those ions. Li-like and Na-like ions are easily obtained from the He-like and Ne-like ionization stages by recombination.

One of the key features of the EBIT is the use of active ion cooling with a second ion species of much lower charge. Cooling is absolutely essential. Without it, the production of the highest ionization stages is not possible. Our "evaporative" cooling technique is described in more detail elsewhere.^{2,6,7} Briefly, a light gas (e.g. nitrogen) is injected radially through a series of apertures, ionized, and trapped along with the highly charged species to be cooled (e.g. Pt^{67+}). The two species approach the same temperature through ion-ion collisions and the lighter species, being less tightly bound, evaporates over the axial potential barrier, taking its kinetic energy with it. We have shown that large numbers of very highly charged ions can be retained in the trap for hours with this technique. Typically, about 10^5 highly charged ions are trapped for x-ray spectroscopy measurements.

TRANSITION ENERGY MEASUREMENTS

The accurate calculation of energy levels for the highly charged ions of heavy elements is at present an unsolved problem in atomic structure, even for the case of a single electron outside a closed shell. This is due to the difficulty of simultaneously treating electron correlation, relativistic corrections, and QED corrections in the context of a many electron ion.⁸ Since the leading term for both the relativistic and QED corrections scales as Z^4 , measurements at the end of the periodic table provide the most revealing information about these two corrections. Of particular interest is the screening of the one-electron Lamb shift. Transition energy measurements for atomic number up to about 60 are available for a few isoelectronic sequences from tokamak and laser produced plasmas, and already there are some systematic deviations from the most sophisticated theories.^{4,9,10} The EBIT program at LLNL is now able to extend these measurements to almost any element in the periodic table. We illustrate this here with recent results for two different isoelectronic sequences, one Na-like and one Ne-like.

A vacuum coupled Johann spectrometer is used to study $n=3$ to $n=3$ transitions in Na-like ions, as shown in Fig. 2. The most precise result obtained to date is for the ~ 650 eV $3s_{1/2} - 3p_{3/2}$ transition energy in Na-like Pt^{67+} ions.¹¹ In this case a cylindrically curved RAP crystal was used with a CsI-coated, position-sensitive, micro-annel-plate detector oriented perpendicular to the incident x rays. The resolution was dominated by the crystal rocking curve, resulting in a Voigt-profile lineshape of 1 eV FWHM. The wavelength scale of the spectrometer was calibrated in two steps. First, the dispersion was measured using the characteristic x rays from a manganese fluorescence source. Second, the absolute energy scale was accurately determined from the energy of the $\text{Ly}\alpha$ transition in H-like oxygen produced in EBIT. Because this transition is within 0.18 eV of the Na-like Pt transition, it provides an excellent calibration essentially free of systematic errors. Spectra from platinum ions and the calibration sources are shown in Fig. 3.

Fig. 2. Arrangement of the soft x-ray Johann spectrometer. The crystal, MCP detector and fluorescence source move as a unit during scanning operation.

Fig. 3. Observed spectra from (a) platinum 3s - 3p transitions excited at 18.5-keV electron energy, (b) oxygen Ly α excited at 3.6-keV electron energy, and (c) manganese K α (9th order) and K β (10th order) x rays excited by x-ray fluorescence of a manganese foil. The solid curves are fitted Voigt-profile lineshapes.

Our measured energy of 653.44 ± 0.05 eV for the $3s_{1/2} - 3p_{3/2}$ transition energy in Na-like Pt^{67+} is compared in Fig. 4 with other (lower Z) measurements and with theory. The data points are plotted with respect to a multiconfiguration Dirac-Fock calculation (MCDF) with the Lamb shift included.¹² As can be seen, the measured energies are systematically lower than the MCDF energy, and the present result is significantly lower than what would be expected based on extrapolation from the lower Z measurements (i. e. the curve labeled "low Z fit" in Fig. 4).¹⁰ Also shown in Fig. 4 is a multibody perturbation theory (MBPT) calculation with a hydrogenic (unscreened) Lamb shift.¹³ The difference between this calculation and the measured energies provides a value for the screening of the hydrogenic Lamb shift for this transition, which is the one correction missing from the MBPT calculations. The size of the Lamb shift for this transition is 5 eV or about 1% of the total transition energy.

Fig. 4. Comparison of theoretical and measured energies for the Na-like $3s_{1/2} - 3p_{3/2}$ transition. The baseline (zero energy difference) of the figure is an MCDF calculation by M. H. Chen²¹ (with the Lamb shift included) using Grant's code;¹² the data points and curves are the differences from that calculation. The solid data point is the present result, and the other points are tokamak and laser-produced-plasma measurements.¹⁰ The lower curve is the MBPT result from ref. 13 with the hydrogenic Lamb shift included. The upper curve is a fit to the low-Z points from ref. 10.

By studying the Z scaling of the transition energies for several different configurations it is possible to unravel the separate correction terms to the energies of atomic levels. For example, a recently published EBIT measurement of the $(2s_{1/2}2p^63p_{3/2})_{J=1} \rightarrow (2s^22p^6)_{J=0}$ transition energy in Ne-like Yb^{68+} is primarily sensitive to the self energy of the 2s electron.⁴ On the other hand, the $(2s^22p_{3/2}^{-1}3s_{1/2})_{J=2} \rightarrow (2s^22p^6)_{J=0}$ magnetic quadrupole transition energy is sensitive to a different combination of corrections in the Ne-like system, and we use this as a second example.

For atomic numbers above $Z=75$, the energy of this transition, denoted M2, is in the range of 10 - 15 keV, and a spectrometer with very high resolving power is required to obtain interesting results. For studying these energetic transitions, we have constructed a von Hamos type spectrometer optimized for use with EBIT.¹⁴ This spectrometer takes advantage of another important property of the EBIT device, the narrow ($\sim 70 \mu\text{m}$) width of the x-ray emission region. Since this is less than the spatial resolution of most position sensitive detectors, a Bragg diffraction crystal which is flat in the dispersion plane can be used with no entrance slit. The layout of the von Hamos spectrometer used in recent EBIT measurements is shown in Fig. 5. A typical spectrum for the case of Ne-like Au^{69+} is shown in Fig. 6. In this case the resolving power ($\lambda/\Delta\lambda$) was 1400, and the splitting of the $(2s^2 2p_{3/2} - 13s_{1/2})$ $J=1$ and $J=2$ levels is clearly resolved.

Fig. 5. Layout of the von Hamos spectrometer in the horizontal (diffraction) plane and its relationship to EBIT. The EBIT electron beam propagates in the vertical direction (out of the page) through the center of the drift tube.

We have obtained energy measurements for transition M2 in five elements from $Z=56$ to $Z=90$. The results are shown in Fig. 7 together with five additional data points from the PLT tokamak.⁹ As above, the plotted points are the difference between experiment and MCDF calculations. As can be seen from the figure, the MCDF energies are systematically low by 1 to 3 eV.

Wavelength calibrations for the EBIT von Hamos measurements were obtained from the Rydberg series of H-like and He-like ions of the appropriate elements, also produced and excited in EBIT. Typically, H-like calibration spectra and Ne-like data spectra are recorded in several alternating running periods without touching the spectrometer setup in between.

Fig. 6. X-ray emission from Ne-like Au^{69+} observed in two different instruments. Top: Spectrum from a planar Ge detector showing all x rays above ~ 2 keV energy. Bottom: Narrow-band spectrum from the von Hamos spectrometer. The separation between lines M2 and 3G is 9.5 eV. The feature labeled Au^{68+} consists of satellite lines from adjacent ionizations stages.

Fig. 7. Difference between measured and calculated energies for the magnetic quadrupole transition in neonlike ions. The solid circles are the present EBIT measurements, and the open circles are from the PLT tokamak.⁹ The theory is an MCDF calculation by M. H. Chen using Grant's code.^{9,12}

DIELECTRONIC RECOMBINATION FOR HELIUMLIKE IONS

Dielectronic recombination (DR) is the capture of an incident electron by a target ion with the formation of a doubly excited intermediate state and its subsequent decay by photon emission:

It is a resonant process which is allowed only when the incident electron energy matches the excitation condition for an available intermediate state. However, the cross section for DR is large and it is a very important process in hot plasmas, whose x-ray emission spectra usually contain characteristic DR lines. Frequently, the relative intensity of DR lines is used to diagnose the plasma. In addition, DR of highly charged ions has been the subject of many theoretical calculations, and some attempts to measure it indirectly using the related process of resonant transfer and excitation of MeV ion beams in thin targets.^{15,16} However, in spite of the high interest, the only DR cross section measurements for very highly charged ions are those from the EBIT at LLNL.³

Since the publication of our first EBIT DR measurements (for He-like nickel target ions),³ the experimental technique has been improved and the cross section measurements have been extended to He-like Mo⁴⁰⁺ and Ba⁵⁴⁺ target ions, as well as to several Ne-like ions. We use EBIT to obtain DR cross sections in two different ways: counting the deexcitation x rays, and measuring the charge-state abundance ratio for ions extracted from the trap. In both cases the measurements are made as a function

of electron beam energy. Here we will discuss only the x-ray measurements for He-like target ions.

On resonance, the DR cross section for He-like ions is much larger than the opposing ionization cross section for Li-like ions, so the process of observing DR destroys the He-like charge state. Previously we overcame this problem with an electron beam energy switching pattern that spent roughly 90% of the time at an off-resonance ionization energy and 10% of the time at a preselected DR energy. We now use a sawtooth timing pattern that continuously ramps the electron beam energy through the entire region of interest quickly enough to avoid any significant change in the ionization balance. Both of these methods require the ability to slew the electron energy quickly (within a few milliseconds) and to follow a programming voltage very precisely.

Data are recorded as two parameter events consisting of the x-ray energy and the instantaneous value of the electron beam energy obtained by sampling the drift tube voltage at the time of x-ray detection. Examples of DR excitation functions obtained in this way for He-like nickel and molybdenum targets are shown in Fig. 8. A germanium detector positioned at 90 degrees to the electron beam was used for x ray detection, and the excitation functions shown in Fig. 8 were generated with a gate on $n=2$ to $n=1$ x rays. The inset in Fig. 8 shows the consistency between the downward going and upward going portions of the energy sweep. In order to determine the cross section scale, theoretical radiative recombination (RR) cross sections were used for normalization.¹⁷ The RR x rays form clearly defined bands in the two parameter data (on top of which sit the DR peaks) and can be used to account for any energy dependence of the beam-ion overlap integral. The different features in Fig. 8 are labeled according to the configuration of the intermediate state. For example, KLL refers to all $1s2l2l'$ resonances.

There are 16 DR resonances of the form $1s2l2l'$ for He-like target ions, 8 of which make a significant contribution to the KLL feature in our data. The 50 eV FWHM energy spread of the EBIT electron beam is sufficient to obtain some information about the distribution of strength among the different KLL resonances, particularly in the case of molybdenum where four different KLL peaks are resolved, but it is insufficient to resolve all of the individual resonances. For example, the $1s2p^2$, $2D_{5/2}$ and $2D_{3/2}$ resonances, which are the largest contributors to the DR cross section, are separated by only 10 eV electron energy for nickel. Even this limitation can be overcome, however, because very high resolution can be obtained in the exit channel by using a Bragg diffraction spectrometer for x-ray detection.

We have used the high resolution von Hamos spectrometer described above to study DR for a few selected cases. A spectrum of DR x rays from the KLL resonances for He-like V^{21+} target ions is shown in Fig. 9. In this case the ~ 2.5 eV FWHM x-ray energy resolution allows a clear measure of the relative strength of the $2D_{5/2}$ and $2D_{3/2}$ resonances, which are responsible for the lines labeled j and k, respectively.

For the most highly charged ions, the Auger and radiative rates that determine the DR cross section are expected to be influenced by relativity and QED.¹⁸ Comparisons of our DR measurements with theoretical calculations¹⁹ are in progress.

X-RAY POLARIZATION MEASUREMENTS

The measurement of x-ray polarization (and the x-ray angular distribution to which it is related) serves two purposes in the EBIT program. First, since electron-ion collision cross sections are usually derived from the x-ray intensity at 90 degrees to the electron beam direction, the x-ray angular distribution must be accounted for in a determination of total cross section. (For example, this applies to the DR cross sections

Fig. 8. Excitation function for DR resulting in $n=2$ to $n=1$ x-ray emission at 90° for He-like Ni^{26+} and Mo^{40+} target ions. The inset shows an enlargement of the KLL feature for Mo^{40+} . The electron beam energy spread is approximately 50 eV FWHM, sufficient to resolve some of the fine structure in molybdenum. The energy above which K x rays can be produced by impact excitation is labeled "threshold."

discussed above.) Second, the polarization information itself is of interest as a more detailed test of theory. Here we discuss one example of the second type: polarization of x-ray emission lines from He-like scandium as a probe of the hyperfine interaction. A more complete report of these results is in preparation.²⁰

Fig. 9. X-ray spectrum from DR on He-like V^{21+} target ions obtained with the von Hamos spectrometer. Transitions in the recombined Li-like ions are labeled with lower case letters in the notation of Gabriel.²² Lines labeled Be-like are due to Li-like target ions that are also present in the trap.

We measured the linear polarization of the $n=2$ to $n=1$ emission lines in He-like Sc^{19+} at 90 degrees to the electron beam direction. As shown in Fig. 10, there are four (resolved) transitions involving several multiplicities and denoted w, x, y, and z. Sc^{19+} was chosen because it is the He-like ion most suitable for study with our apparatus. In particular, the transitions of interest occur at wavelengths that correspond to Bragg angles of about 45 degrees for the Ge(220) curved crystal installed in the Johann spectrometer. At these angles the crystal is a near perfect polarization analyzer. Scandium is monoisotopic with a $I=7/2$ nuclear spin, and the polarization of the emitted x rays can be influenced by the hyperfine interaction with the nuclear magnetic moment.

Measurements were made at two crystal orientations, called horizontal and vertical. In the horizontal orientation the crystal dispersion plane is normal to the electron beam, and in the vertical orientation the spectrometer is rotated by 90 degrees. The x-ray polarization was obtained from the intensity ratio for the two orientations. Radiation from the unpolarized $Ly\alpha_2$ ($1s2p^2P_{1/2}$) line of H-like scandium was used to determine the relative efficiency of the spectrometer in the two orientations. We chose an electron beam energy of 4.36 keV since this is just above threshold for excitation of the $n=2$ levels, so that the only population mechanism is direct impact excitation. Spectra for both crystal orientations are shown in Fig. 11, and the measured polarizations are given in Table I. The polarizations for x, y, and z are all near zero, while the polarization for w is quite large.

Fig. 10. Energy level diagram for He-like Sc^{19+} showing the observed transitions. The broken line indicates the electron beam energy used for excitation.

Theoretical polarizations excluding the hyperfine interaction agree with observation for lines w and z but disagree for x and y. We have found that this disagreement can be completely removed by including the hyperfine interaction. In this case the theoretical polarizations for x and y are greatly reduced to a level consistent with observation. The results are summarized in Table I.

Table I. Polarization of the $n=2$ to $n=1$ x rays in He-like scandium at 4.4 keV incident electron energy. The theory for line y assumes an unresolved blend of the (unpolarized) 3P_0 decay at one third the intensity of line y.

	Theory No Hyperfine	Theory With Hyperfine	Experiment
w	0.60	0.60	0.70 ± 0.06
x	-0.52	-0.07	-0.05 ± 0.09
y	-0.37	-0.05	0.00 ± 0.09
z	0.00	0.00	-0.02 ± 0.10

Fig. 11. Spectra from He-like Sc^{19+} excited at 4.36 keV electron energy for the two different orientations of the polarimeter. In the horizontal orientation all four lines could not be observed simultaneously with the same spectrometer setting, so the spectrum is split between two different runs with appropriate normalization.

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