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Overview of the Electron Beam Ion Trap Program at NIST

J. D. Gillaspy,[1] Y. Aglitskiy,[2] E. W. Bell,[3] C. M. Brown,[4] C. T. Chantler, R. D. Deslattes, U. Feldman,[4] L. T. Hudson, J. M. Laming,[4,8] E. S. Meyer, C. A. Morgan,[5] A. I. Pikin,[2] J. R. Roberts, L. P. Ratliff, F. G. Serpa,[6] J. Sugar and E. Takács[7]

National Institute of Standards and Technology, Gaithersburg, MD 20899, U.S.A.

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Abstract

This paper surveys the ongoing physics experiments at the Electron Beam Ion Trap (EBIT) facility at NIST, with particular attention paid to the underlying physical principles involved. In addition, some new data on the performance of our EBIT are presented, including results related to the determination of the trap width, ion temperature, and number of highly charged ions in the trap.

1. Introduction

With the Electron Beam Ion Trap (EBIT) at NIST now fully operational, a number of different experiments are progressing in parallel. This paper presents a survey of our current work and gives a preview of future plans. While an earlier paper [1] focused more on the general operation and performance of our EBIT, the present paper will focus on specific experiments. Detailed descriptions of the experiments surveyed here will appear in separate publications when the works are complete. Some additional material on machine performance is presented in the final section of this paper.

2. Survey of experiments

2.1. *Tests of bound-state quantum electrodynamics (QED)*

The importance of precise X-ray wavelength measurements for testing QED in the presence of the strong electric fields found in highly charged ions has been extensively reviewed in the Proceedings of Nobel Symposium 85 [2]. The use of an EBIT to measure QED effects in highly charged ions under conditions free of Doppler shift corrections (the main systematic effect in most previous experiments) was pioneered by Beiersdorfer and colleagues [3]. Ideas for further EBIT work have been proposed by Silver [4]. Our activity in this area is guided by the theoretical work of Mohr [5] and Kim [6] and the experimental work of Deslattes [7]. Additional theoretical guidance is provided by outside groups such as that of Indelicato [8], Safronova [9], Dubau [10], and Drake [11]. Our particular interest in two-electron systems grows out of our desire to extend to very high charge states our previous work in neutral helium [12] and along the lower third of the helium-like isoelectronic sequence [13–15].

The fractional contribution of QED to binding energies typically increases quadratically as the charge state is increased with fixed electron number, and as the first reciprocal power of the principal quantum number ($1/n$) as n is reduced with fixed nuclear charge. The Z-scaling can be understood simply by combining the elementary Coulomb and angular momentum behaviour of electronic wavefunctions with the fact that large QED effects occur when an electron comes within a Compton wavelength of the nucleus (thereby allowing the infinite bare charge of the electron to become unscreened by the virtual positron-electron pairs which form the structure of the vacuum of space) (Table I).

As a prelude to our primary work in this area, we have undertaken a study of systematic errors associated with measuring the resonance lines of neon-like barium ($Q = 46+$) with the aid of an external calibration source. The X-ray spectrum of barium takes on a particular importance in EBITs because of its presence in the cathode of the electron guns frequently employed in such devices. If no other ions are injected, the trap will automatically fill up with barium, providing a convenient source of X-ray spectra

[1] Internet address: Gillaspy@enh.NIST.gov
[2] University of Maryland, College Park, MD 20742.
[3] Joint Institute for Laboratory Astrophysics Boulder, CO 80309.
[4] Naval Research Laboratory, Washington, DC 20375.
[5] Texas A&M University, College Station, TX 77843.
[6] University of Notre Dame, Notre Dame, IN 46556.
[7] Institute of Nuclear Research (ATOMKI), Debrecen, Hungary.
[8] Sachs Freeman Associates Inc., Landover, MD 20785.

Table I. *Dependence of various atomic quantities on nuclear charge (Z). Some of the notes in the right-hand column refer to semiclassical arguments for circular electron orbits, but the results hold true generally. For a more precise analysis, refer to Ref. [20], for example*

Physical parameter	Z-Scaling	Notes
Angular momentum ($r \times p$)	None	(Fundamentally quantized)
Linear momentum (p)	Z	(From $T = p^2/2m$ below, and rp = const)
Kinetic energy (T)	Z/r	(Coulomb-like, from the virial theorem)
Coulomb energy (U)	Z/r	(Definition)
Bohr radius (r)	$r \sim 1/Z$	(Consequence of first two items)
Coulomb wavelength (l)	$1/Z^2$	($h\nu = U$; scaling holds for $\Delta n > 0$ transitions)
Electron fraction at nucleus (S)	Z^3	($1/r^3$ density of electronic wavefunction)
QED wavelength shift	Z^4	($Z{*}S$ from perturbation theory)
Fractional QED shift	Z^2	(Relative to Coulomb energy)

for diagnosing the performance of the EBIT. Although periodic trap-dumping can be used to remove the barium when it is unwanted, without this action barium provides a natural background spectrum whenever other elements are being studied in EBIT. With sufficient prior study, this natural background spectrum can be used as a built-in calibration reference.

Although many spectroscopic lines from highly charged barium ions have been studied by the Livermore group [16], precise wavelengths for the strongest lines observed in that work (the $2p$–$3d$ transitions in neon-like charge states) have not been published. We are presently measuring these lines using Bragg crystal spectrometers calibrated with external X-ray sources. QED effects for certain transitions in neon-like barium are predicted to become significant if wavelengths are measured to an accuracy of 0.1% or better [9].

2.2. *X-ray polarization*

Typically one associates polarized emission of photons with the presence of a strong external field which provides a quantization axis. Although the magnetic field in EBIT is "strong" by conventional standards (3 tesla), it is weak with regard to the very intense internal fields present in highly charged ions. It is interesting to compare the external field to the relativistically induced magnetic field that an electron sees as it orbits through the strong electric field provided by the nucleus. Because the Bohr radii which characterize highly charged ions are very small, the electrons are moving at velocities approaching the speed of light and the relativistically induced magnetic fields are strong. For an electron in the outermost shell of a neon-like barium ion, the induced fields are of order 7,000 tesla, and scale with the 4th power of Z. This 7,000 tesla field is the order of magnitude one would need to apply externally in order to affect the energy levels to an extent comparable to the spin-orbit splitting. With this in mind, it is easy to understand why highly charged ions are relatively unaffected by fields of order 3 tesla. An alternative way of looking at the problem is to note the ratio of a 3 tesla Zeeman shift to the transition energy. For the 5 kev resonance lines of neon-like barium, this ratio is of order 10^{-7} to 10^{-8}, a sufficiently small number that there is little hope of resolving it with present day X-ray spectroscopic techniques, and even if one could do so it would be fundamentally blurred by the natural widths of the lines themselves. This blurring of the lines typically has a strong dependence on nuclear charge ($\Delta v/v = Z^2$, for E1 transitions).

Although the presence of the magnetic field is often negligible for analyzing the emission of X-rays in EBIT, the uniaxial nature of the electron beam is highly significant, and actually provides a strong quantization axis for the polarized emission of radiation. Because atomic electrons are excited by impact with free electrons in the beam, momentum transfer considerations leave the ion in a preferentially aligned state. Upon spontaneous emission, the alignment of the ion is reflected in the polarization of the emitted radiation.

The situation is more complex if the electron beam is tuned to a sufficiently high energy to populate levels above the upper level of the transition of interest. In this case, cascade feeding becomes important, and one must take into account all the various paths through the magnetic sublevels which feed the transition. Because increasing the electron beam energy can bring higher levels into consideration and change the cascade pattern, the polarization of the emitted radiation can depend significantly on the beam energy.

We are presently engaged in theoretical and experimental studies of this dependence of X-ray polarization on electron beam energy. Results of this study are important for testing the most sophisticated calculations of electron-impact excitation cross sections which contain information about the magnetic quantum sublevels. The analysis of polarized X-ray emission is being increasingly recognized for its importance in diagnosing technological devices such as Tokamak reactors as well.

2.3. *Visible light spectroscopy*

In a recent review paper [17], Marrs has remarked that one of the most exciting future developments in EBIT will be the extension of spectroscopy into the visible range of the spectrum. We have successfully done this by observing forbidden (M1) transitions within the ground term of titanium-like barium and xenon using a grating monochromator [18]. These transitions are of particular interest for their use in the remote monitoring of ion temperatures by Doppler broadening in large future tokamak fusion machines.

Because the light detected in these experiments arises from transitions between very close-lying levels, the wavelength is sensitive to small Zeeman shifts which are usually negligible in X-ray spectra. For the M1 transitions studied in our work, the Zeeman shifts appear at the 10^{-4} level of resolution, rather than the 10^{-7}–10^{-8} level which is typical for the X-ray transitions discussed above.

When used to detect Doppler shifts, there are other advantages, though less fundamental, which visible light spectroscopy has over X-ray spectroscopy. Although the fractional resolution required to detect Doppler shifts from a moving ion is independent of wavelength, the availability of advanced refractive and reflective optics for visible light allows one to achieve both high efficiency and high resolution simultaneously. This opens up new opportunities, and makes the detection of Doppler shifts feasible with relative ease. For example, we have recently applied Fabry-Perot interferometry to achieve a resolution sufficient to see Doppler-blurred Zeeman broadening from ions in the trap (see Fig. 1 and Section 3.3 below).

The present accuracy of our measurement of the wavelengths of the visible light is sufficient to reveal large disagreements ($\sim$4%) with *ab initio* Dirac-Fock theoretical predictions [19]. Our present identification of these lines is confirmed by the isoelectronic behaviour of fitted calculations using the Cowan code [20]. This experiment should challenge theorists to improve their understanding of how electron-electron interaction affects level separations in a regime not widely addressed previously.

2.4. *Ion-surface interactions for technology*

The interaction of highly charged ions with surfaces has been studied for many years at accelerator facilities, and at least one company has come to produce a successful commercial product from this work [21]. Experiments with highly charged ions at accelerators, however, typically

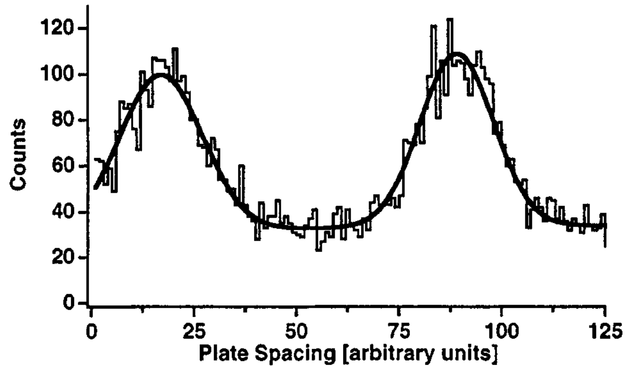

Fig. 1. Fabry–Perot interferometry (scanning mode) of the M1 transition near 400 nm in the ground term of titanium-like barium. The free spectral range (distance between peaks) is approximately 0.3 nm. The end cap potential on EBIT was 300 V.

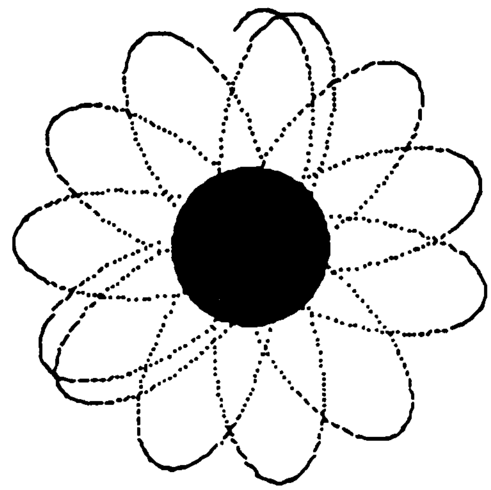

Fig. 2. Numerical simulation of an ion orbit through an electron beam with Gaussian density profile. Conditions: charge = 30 proton charges, Mass = 100 proton masses, magnetic field = 3 T, electron beam diameter containing 86% of charge = 60 μm (shown as shaded area in figure), drift tube diameter = 1 cm, space charge potential = 200 V, initial coordinates and velocity: $X_0 = Y_0 = 10\,\mu m$, $v_0 = v_x = 4.0 \times 10^4$ m/sec (corresponding to an ion temperature of 1 keV).

involves high kinetic energy impact with surfaces. The use of EBITs (or EBISs [22]) to generate highly charged ions at rest in a small-scale laboratory environment offers new opportunities. Efforts in this area are underway at Livermore [23], Kansas State [24], and Hitachi Ltd. [25], as this technique may have application in the novel fabrication of technological devices. We have begun a concentrated program to assess the feasibility of using slow highly charged ions to fabricate an active electronic device such as a quantum dot diode. In collaboration with the recently formed Advanced Lithography Group consortium of industrial labs [26], we are also looking closely at the potential which highly charged ions may hold for future generations of projection lithography techniques.

3. New detail on EBIT device operation

Several earlier papers describe the operation of EBIT devices [1, 17, 27–28]. In this section we discuss several important parameters for which detailed data have not been published.

3.1. *Trap size*

Although it has often been said that the trap length for EBITs of the Berkeley-Livermore design is 2 cm, the actual length of the center drift tube if often longer (in our case, 3 cm). The external view of our trap is restricted by a 1.5 cm diameter hole in the surrounding liquid helium shield, so a typical detector will collect light from a section of the trap which is approximately 2 cm in length due to parallax at the edges. Using pinhole images of X-ray emissions, the Livermore group has measured the width of the electron beam to be 70 μm [28] but the width of the trapped ion cloud should be larger since the ion orbits are predicted to extend outside of the electron beam (Fig. 2). The X-ray imaging experiment is not affected by this because excited state lifetimes for typical X-ray transitions are of the order of femtoseconds, and therefore the ions travel less than 0.1 nm (a small fraction of an ion orbital cycle) before emitting a photon. By studying visible-wavelength photons from long-lived states, we are able to obtain data which determine the full spatial extent of the ion cloud. In this case, the ions can move through many orbital cycles before emitting a photon. To obtain data on the width of the ion cloud, we focused the center of EBIT onto the entrance slit of a grating monochromator which was mounted on a large precision translation stage. After adjusting the monochromator to be spectrally centered on one of the M1 transitions, we moved the spectrometer along a direction perpendicular to the line of sight into EBIT and monitored the strength of the observed signal. The result, shown in Fig. 3, is consistent with a 180 μm wide cloud of trapped ions, after correction for optical demagnification of the lens system. It should be possible to use this technique to monitor changes in the ion cloud width as the ion kinetic temperature is lowered by evaporative cooling.

3.2. *Number of ions in the trap*

The longstanding and vexing question of how many ions are in the trap has still not been definitively answered. Previous estimates based on calculation from spectroscopic data taking into account the solid angle of observation and other parameters, or on ion-extraction measurements, have yielded widely scattered values with large uncertainties. Recent work at Livermore using ion-cyclotron resonance [29] of the trapped ions may eventually yield highly reliable values, but present uncertainties seem to be as high as a factor of 10 [30]. In the meantime, the best estimate may be achieved from well-characterized measurements of an isolated spectral line. Since the location of a radiative recombination line can be adjusted by varying the electron beam

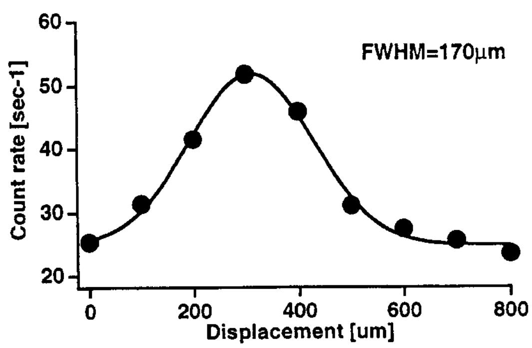

Fig. 3. Signal strength of visible light from Ti-like barium as a function of transverse position of a grating spectrometer.

energy in the EBIT, one can move such lines to a well-isolated region of the spectrum and obtain clear and clean results. Even more importantly, the radiative recombination cross sections can be calculated very accurately. With the number of EBIT laboratories growing, we suggest that a standardized procedure be adopted to compare the performance of different machines, as well as individual machines under varying circumstances. To this end, we present here detailed results for measurements taken on a particular radiative-recombination line in neon-like barium (Fig. 4), and infer a best estimate of 310 000 ions in the trap from the following formula which relates the rate of photons detected (N_p) to the number of neon-like barium ions (N) in the trap:

$$N = \pi r^2 q N_p [f \Omega \varepsilon T I \lambda \, \mathrm{d}\sigma(E, \theta)/\mathrm{d}\omega]^{-1}$$

where ε is the efficiency of the detector, T is the transmission of the X-ray window at the photon energy, f is the fraction of ions in the trap which are unobscured, I is the electron beam current, r is the spatial FWHM of the electron beam, q is the charge of the electron, λ is an overlap factor which corrects for the spatial and temporal overlap of the ion cloud with the electron beam, $\mathrm{d}\sigma(\varepsilon, \theta)/\mathrm{d}\Omega$ is the differential cross section for emission of radiative-recombination photons (summed over the five sodium-like $n = 3$ levels contained within the finite resolution of the detector), E is the electron beam energy, θ is the angle of observation with respect to the electron beam, and Ω is the solid angle subtended by the detector. For our case, $\varepsilon = 100\%$ (SiLi detector @ 9 keV), $T = 100\%$ (0.007″ thick Be foil at 9 keV), $f = 0.67$, $I = 100\,\mathrm{mA}$, $r = 35\,\mu\mathrm{m}$ $\Omega = 5.8 \times 10^{-4}$ str (13 mm^2 detector at 18 cm distance), $\lambda = 18\%$ (estimated for 1 kev, Ba^{46+} ions with 250 V applied end cap potential), $N_p = 10.86\,\mathrm{s}^{-1}$ (obtained by binning data into 10 eV wide channels for 20 minutes and fitting the peak with two Gaussians and a subtracted linear background), $\mathrm{d}\sigma/\mathrm{d}\Omega = 19.9 \times 10^{-28}\,\mathrm{m}^2/\mathrm{sr}$ at $E = 5.69\,\mathrm{keV}$ and $\theta = 90°$ [31].

3.3. *Ion temperature*

The question of ion temperature – whether there is one, to begin with – is controversial due to the complex nature of the trap dynamics. If we assume an ion temperature, then the spectral linewidth observed can put an upper bound on its value. With adequate understanding of instrument profiles and proper account for Zeeman broadening, the ion temperature can be accurately determined. Our preliminary Fabry-Perot data (Fig. 1 above) corresponds to an ion temperature below 1 keV. This ion temperature is a factor of 10 lower than the axial trap depth for an ion with charge 34+ contained by 300 V end cap potentials, suggesting the presence of strong evaporative cooling by interaction with lower charge state ions which see a shallower trap.

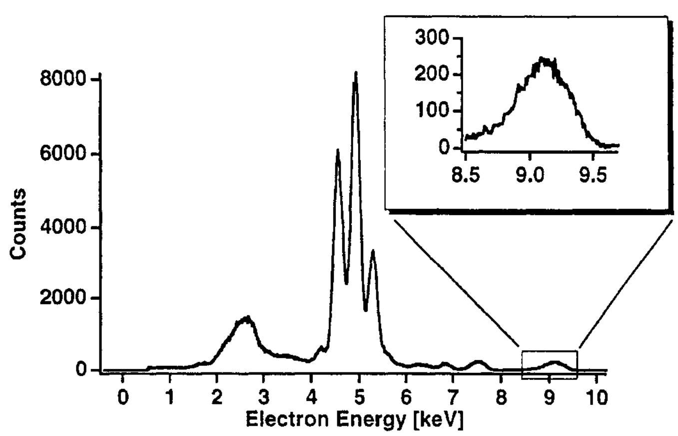

Fig. 4. X-ray spectrum show the radiative recombination line used to estimate the number of ions in the trap. The electron beam energy was set at 5.69 keV.

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