

In-Situ Studies of Highly Charged Ions at the LLNL EBIT

P. Beiersdorfer

This article was submitted to the U. S. Department of Energy, Office of Science, Office of Basic Energy Sciences, Research Meeting of the Atomic, Molecular, and Optical Physics Program, Tahoe City, CA, September 30-October 3, 2001

U.S. Department of Energy

August 16, 2001

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This work was performed under the auspices of the United States Department of Energy by the University of California, Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.

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Peter Beiersdorfer

Lawrence Livermore National Laboratory
7000 East Avenue, L-260
Livermore, CA 94550

E-mail: beiersdorfer@llnl.gov

- **Program Scope**

The properties of highly charged ions and their interaction with electrons and atoms is being studied *in-situ* at the LLNL electron beam ion traps, EBIT-II and SuperEBIT. Spectroscopic measurements provide data on electron-ion and ion-atom interactions as well as accurate transition energies of lines relevant for understanding QED, nuclear magnetization, and the effects of relativity on complex, state-of-the-art atomic calculations.

- **Recent Progress**

The main effort during the past year of *in-situ* measurements of highly charged ions in the Livermore electron beam ion traps has been focusing on the identification and measurement the 1s hyperfine transition in hydrogenic thallium [1]. This measurement yields information that is crucial for understanding the atomic-nuclear interactions needed for atom-based parity violation experiments.

Two measurements of hydrogenic bismuth and lead were carried out in the past at the heavy-ion storage ring at the GSI facility in Darmstadt, Germany; three measurements of rhenium (two isotopes) and holmium were carried out at the Livermore SuperEBIT facility. These measurements have shown that the predicted wavelengths are off by as much as 40 Å, or 1% — a huge discrepancy given that these are “simple” one-electron ions.

We have set out to measure the 1s hyperfine transition in the two thallium isotopes because thallium has the best understood nuclear properties: both the nuclear charge distribution and its magnetic moment are well known from other measurements. Moreover, thallium is used in atom traps for parity violation experiments, and our measurements can therefore be directly used to improve the atomic calculations for the parity violation experiments. Moreover, we have constructed a very high-resolution optical spectrometer that in principle will allow us to measure the thallium lines with much higher accuracy than any previous measurement of the 1s hyperfine transition.

Before using the new optical spectrometer for the thallium measurements we performed careful measurements on a variety of optical transitions in order to understand the properties of the new instrument, understand the calibration procedures, and what problems may arise limiting the accuracy of our measurements. For example, we performed a measurement of the 3800-Å line in Ti-like tungsten that was published as a Rapid communication in Physical Review A [2]. This measurement achieved an accuracy of 0.1 Å, useful to test sophisticated predictions such as those carried out by Donald Beck in Michigan. Although the accuracy of our measurement was ten

times worse than we hoped for, it was five to twenty times better than comparable measurements at NIST and the Tokyo electron beam ion trap facility. The limitations in the accuracy were caused by thermal shifts in the instrumentation, and we learned how to avoid them in future measurements.

We also carried out a range of other measurements in the optical, ranging from nitrogen, neon, and argon spectra to krypton and xenon [3-5]. These measurements were designed to help us develop the best methods for calibration of our measurements. We developed a new technique dubbed “inverted-trap measurements”. This technique allows us to calibrate optical spectra *in situ* with well known lines (tabulated in reference books on spectroscopy) from neutral and singly charged ions. We also carried out a series of radiative lifetime measurements that ascertained the role of metastable ion populations in our trap [6-8].

After these preparations, the measurement of the two thallium isotopes proceeded as planned. The only problem was that SuperEBIT had not run for 18 months. Upon startup the achievable charge balance was depressed, and the device could not produce as many hydrogenlike thallium ions as it otherwise would have. Our measurements were, therefore, limited by the count rate, as the signal was weak, requiring about 3 months of continuous operation to identify and measure the lines.

The results were $3858.22 \pm 0.30 \text{ \AA}$ for the 1s hyperfine transition in 203-Tl^{80+} and $3821.84 \pm 0.34 \text{ \AA}$ in 205-Tl^{80+} . Despite the poor statistics, the accuracy of our measurement is twice as good as the best previous measurement (that of 209-Bi^{82+} by the GSI group). As SuperEBIT improves with time, we will achieve better statistics, increasing our measurement at least by a factor of five.

The improved accuracy is highly important for basic physics. Our present measurement of the two thallium isotopes for the first time showed that scaling the anomalous magnetic moment from measurements of neutral atoms does not provide the accuracy needed for parity violation studies. Our measurement of the anomalous magnetic moment of hydrogenic thallium differed by three sigmas from the scaled neutral value. This required a reassessment of theory that found that the difference is due to the assumption of a point magnetic dipole interacting with an extended charge distribution. The correct approach that provided agreement with our measurement is to assume an extended magnetization interacting with the extended charge distribution of the nucleus. Without doubling the accuracy of the measurements this crucial find would not have been possible.

In addition to the hyperfine measurements, we have pursued the physics of ion-electron interactions, including the measurement of dielectronic recombination with Prof. Smith from Morehouse College [9,10], electron-impact excitation measurements [11], and magnetic sublevel excitation cross section measurements [12,13], as well as the physics of ion-atom collisions [14-17]. A review of our BES-supported measurements was given in [18].

- **Future plans**

The SuperEBIT device has been moved to its new location in B194 (LLNL), and is again operating in the low energy mode (0.1 – 20 keV), as EBIT-I, and in the high-energy mode (< 250 keV), as SuperEBIT. It is now dedicated to *in-situ* ion research. As a result of its new focus, we expect to have an increased availability of run time during the upcoming year for investigating

important atomic physics issues with high accuracy. This also means we will have increased run time available for our current collaborators and future collaborators, who would like to utilize our facility.

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