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Current Research with Highly Charged Ions in EBIT-II and SuperEBIT

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Abstract

Using both the LLNL high-voltage electron beam ion trap, SuperEBIT, and its low-energy counterpart, EBIT-II, we are currently performing spectroscopic measurements with electron beam energies ranging from 150 eV to 150 keV on ions ranging from near neutral Ne to ions as highly charged as Tl^{80+}. Our measurements span photon energies from visible light to hard X-rays and focus on electron-ion interaction cross sections, line identifications and QED measurements, the determination of nuclear parameters, the investigation of charge transfer reactions, and radiative transition rates. An overview of some of the new instrumentation and a subset of the current experiments is given.

1. Introduction

The first electron beam ion trap (EBIT), developed by Marrs and Levine, was put in operation at Livermore nearly 15 years ago [1]. The machine design evolved from that of the electron beam ion source (EBIS) and was optimized the study of highly charged ions confined in the trap by observing their X-ray line emission. The addition of low-resolution Ge detectors, followed by high-resolution crystal spectrometers, allowed systematic studies of atomic structure, electron-impact excitation and dielectronic recombination cross sections [2]. Other regions of the electromagnetic spectrum have opened up with the subsequent addition of optical, UV, EUV, soft X-ray, and hard X-ray spectrometers specifically optimized for the electron beam ion trap geometry [3]. At present, this suite of instrumentation allows high-resolution detection of spectral emission from 2 eV to 35 keV. At the same time, new modes of electron beam ion trap operation have been developed at LLNL that open up new aspects of highly charged ion physics to experimental scrutiny. Complementing the "electron trapping mode", which is the normal mode of operation of an electron beam ion trap, we employ three other modes of operation: the "magnetic trapping mode" [4], which allows us to study ions in the absence of the electron beam; Maxwellian plasma generation [5], where we study spectral emission as a function of electron *temperature*; and the "inverted-trap mode" [6], which provides spectra of neutral and few-charge ions. An upgraded data acquisition system [7] provides multiparameter digitization of several dozen parameters simultaneously and allows us to perform detailed measurements of electron-ion interaction cross sections, charge transfer, radiative decay rates, and ionization balance evolution.

The scope of the current research program studying highly charged ions in EBIT-II and SuperEBIT is very broad and extends essentially over all wavelength bands, charge states, and electron-ion and ion-atom processes. Due to space constraints, we discuss only some of the spectroscopic instrumentation recently implemented on our electron beam ion traps and only a small sample of the results provided by it. This includes a dual-image monolithic crystal spectrometer for absolute wavelength measurements and tests of QED calculations, an optical monochromator for radiative lifetime determinations, grazing-incidence spectrometers for EUV and soft X-ray measurements, and a transmission grating optical spectrometer used in the search for the hyperfine transition in the 1s level of hydrogenlike Tl^{80+}.

2. Monolithic crystal for measuring absolute X-ray wavelengths

Monolithic crystals have two reflecting surfaces that produce a double image of a given spectral line of interest. Such devices can be used to make absolute wavelength determinations from a measurement of the spacing of the observed double image, the distance between the front and back reflecting surface, and the lattice spacing of the crystal. Two such monoliths have been manufactured at DESY in Hamburg from large pieces of crystalline silicon (cf. Fig. 1), one with reflecting surfaces cut to the (111) plane, the other to the (220) plane. In order to make an absolute wavelength measurement, the lattice spacing of the crystalline layers needs to be absolutely calibrated in a comparison with a wavelength standard. This was done in three steps. First, the lattice spacing of a reference crystal was calibrated at PTB Braunschweig using optical and X-ray interferometric measurements relative to wavelength standards. Second, the reference crystal was used to calibrate a Bond diffractometer at the University of Jena. Third, the lattice spacing of the monolith was determined using the

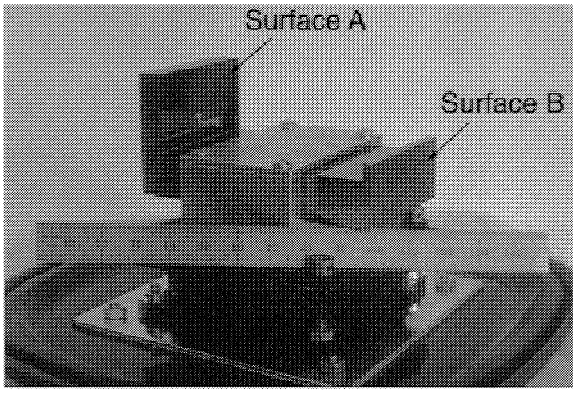

Fig. 1. Si(220) monolith deployed on EBIT-II for testing quantum electrodynamical theory in hydrogen-like ions. Two parallel reflecting surfaces, labeled A and B, were cut out of single silicon crystal and absolutely calibrated by comparison to optical frequency standards.

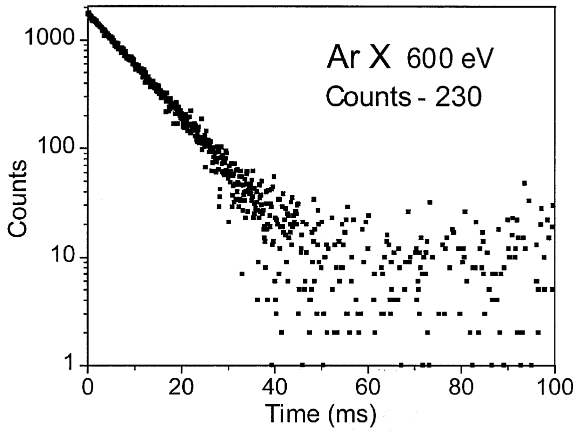

Fig. 2. Decay curve of the $2s^22p^5\ ^2P_{3/2}$–$^2P_{1/2}$ transition in Ar^{9+} emitting at 5533.4 Å after the electron beam was turned off. A constant background of 230 counts has been subtracted from the data.

Bond diffractometer. The accuracy of the measured lattice spacing in SI units is better than 1 ppm. We have successfully implemented these crystals in our vacuum spectrometer, enabling us to make very precise absolute measurements of the wavelengths of the Lyman-alpha transitions of hydrogenlike Si^{13+} and Ar^{17+}. These measurements follow an earlier determination of the absolute wavelengths of the Lyman-alpha transitions of hydrogenlike Mg^{11+} at the EBIT-II facility using a quasi-monolith of quartz (100) [8].

3. Measurements of the radiative rates of optical transitions

Upon the implementation of time-resolved X-ray spectroscopy on EBIT-II, we developed techniques to measure the radiative lifetimes of metastable levels in highly charged ions by recording the temporal evolution of the spectral lines after cessation of their excitation [9]. The technique allows measurements of lifetimes in the regime from about 100 ns to 100 ms. For microsecond lifetimes, this is the only method at present available for multi-charged ions. Initially we applied these techniques to X-ray transitions [10]. Recently, we have constructed a monochromatic optical imaging system that allows us to make similar measurements of transitions in the visible. Among others, we applied our technique to the visible lines in Ar^{9+}, Ar^{13+}, and Ar^{14+}. The radiative lifetimes associated with these lines are in the millisecond range and have been measured before by Church *et al.* using a Kingdon trap [11]. These authors found significant discrepancies with theory. This seemed out of line with the better agreement found using storage ring measurements of higher-Z ions.

A decay curve of the visible line in Ar^{9+} measured on EBIT-II taken after the device was switched from the electron to the magnetic mode is shown in Fig. 2. Excellent statistics were obtained; moreover, our systematic errors are small allowing us to determine the 9.3-ms radiative lifetime associated with the transition to within 1.3%. Unlike Moehs *et al.* [11], we find excellent agreement with calculations for the three visible lines we measured in Ar, and similarly we improved on our earlier measurements on siliconlike Kr^{22+} [12].

4. EUV spectroscopy

The EUV and soft X-ray region from 15–400 Å contains radiation from many charge states of elements such as W and Au that are important for magnetic and inertial confinement fusion. We have opened this wavelength band to scientific scrutiny by implementing two soft X-ray spectrometers [3]. To illustrate our new capabilities we reexamined the $4s_{1/2}$–$4p_{3/2}$ transitions in Cu-like ions that had previously been studied by Seely *et al.* on the NOVA laser [13]. Our electron beam ion trap data as well as the NOVA data are shown in Fig. 3. Compared to the earlier measurements our data have three times the accuracy and reveal much better agreement with theory [14]. This is an important test of the development of complex atomic structure calculations, as the Cu-like ion has 28 electrons in a closed shell, and only one valence electron. The older measurements suggested that the structure calculations for this system are not as accurate as claimed. We find that this suggestion is not true.

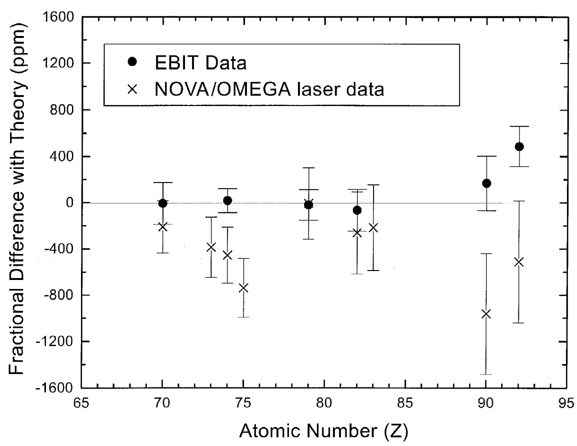

Fig. 3. Reexamination of NOVA laser measurements of the wavelengths of $4s_{1/2}$–$4p_{3/2}$ transitions in copperlike ions in the extreme ultraviolet. The data produced with our new spectrometers provide upto three times higher accuracy and better agreement with modern theory [14] validating current theoretical efforts.

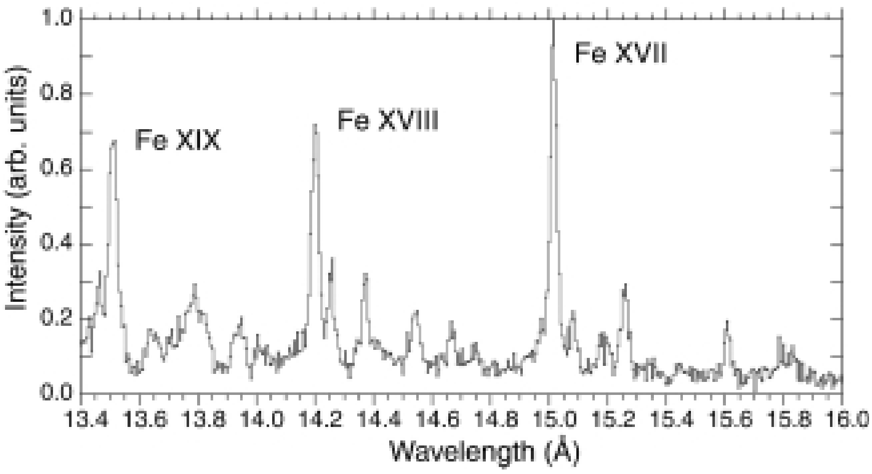

Fig. 4. Spectrum of the 2p-3d transitions in neonlike, fluorinelike, and oxygenlike iron recorded on EBIT-II at a simulated electron temperature of 1 keV.

4. Temperature-dependent soft X-ray spectra

Most laboratory and astrophysical plasmas are characterized by an electron temperature. In order to reproduce such conditions in EBIT-II, we have developed a technique to simulate a Maxwellian electron distribution by quickly varying the beam energy and current to sweep out the corresponding electron distribution function in time [5]. We are using this technique to record emission line spectra as a function of electron temperature. A spectrum of the iron L-shell emission recorded with EBIT-II at an electron temperature of 1 keV is shown in Fig. 4.

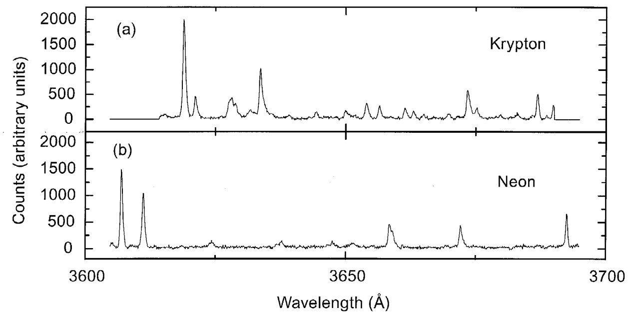

Fig. 5. Spectra recorded with the new optical spectrometer: (a) neutral and near-neutral lines of Ne and (b) neutral and near-neutral lines of Kr obtained in the inverted-trap mode.

5. High-resolution optical spectroscopy

During the past years we made successful measurements of the 1s hyperfine splitting in the hydrogenlike ions Ho^{66+} and Re^{74+} [15]. These were the first measurements to observe this type of decay in highly charged ions using emission spectroscopy. They were carried out with a broad-band optical spectrometer that afforded 20-Å line widths, allowing us to measure the wavelength of the hyperfine lines to within about 1–3 Å. This is not bad, as compared to differences of 50 Å and more between early theoretical values and measurements [16]. Recently, better calculations that include QED, nuclear charge distributions, nuclear magnetization etc. have become available [17]. Thus, to fully uncover the physics that can be learned from a comparison between electron beam ion trap measurements and these new calculations, we have improved our instrumentation so that we will be able to measure these lines with 0.5 Å line widths and an accuracy of about 0.02–0.05 Å. To this end, we have implemented a very high-resolution spectrometer optimized for light near 3800 Å, which is the wavelength of light corresponding to the hyperfine splitting of the orbital of a single electron bound to a thallium nucleus, Tl^{80+}. The spectrometer contains a large-diameter transmission grating which is 6 inch in diameter and has line densities of 2850 lines/mm.

The spectrometer was already used to measure the $3d^4\ {}^5D_2$–${}^5D_3$ transition in Ti-like W^{52+} near 3650 Å with an accuracy of 0.1 Å [6]. Calibration of the optical spectra uses the inverted-trap technique, which we developed at LLNL to dispense with external reference sources. In this method emission lines from neutral, singly, and doubly ionized ions are observed while trapping is turned off. Typical spectra from neon and krypton obtained with this method are shown in Fig. 5. The wavelengths of many of these emission lines are well known and provide a high density of calibration lines for excellent anchoring of the wavelength scale.

6. Summary

The results presented were enabled by an ongoing effort to apply carefully chosen instrumentation to the scientific problems at hand. In addition, we continue to develop and use novel electron beam ion trap operating modes to maximize the scientific return. Here we have been able to present only a small sub-set of our current measurements. However, many of our results are currently being prepared for publication and thus will be available in the near future.

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