EBIT

Electron Beam Ion Trap

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Experimental Physics

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Cover Picture

Photo of the RETRAP Device (upper left)

"Time of Flight" spectrum of sputtered negative ions (lower left)

High resolution x-ray spectrum for 2p-2s transitions in Li- to Ne-like U (lower right)

CCD camera image of compressed electron beam (background center)

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INTRODUCTION

The experimental groups in the Electron Beam Ion Trap (EBIT) program continue to perform front-line research with trapped and extracted highly charged ions (HCI) in the areas of ion/surface interactions, atomic spectroscopy, electron-ion interaction and structure measurements, highly charged ion confinement, and EBIT development studies.

The ion surface/interaction studies which were initiated five years ago have reached a stage where they can carry out routine investigations, as well as produce breakthrough results towards the development of novel nanotechnology. New results, e.g. extraordinary high sputter yields following Th^{80+} incidence on SiO_2 show the potential for major advances in surface analysis technology. First measurements of HCI induced electron emission from insulators were performed and the existence of HCI in solids has been derived from measurements on non-equilibrium energy loss of HCI in insulators. HCI induced "Coulomb explosions" have been demonstrated from systematic studies of the effect of incident charge on both positive and negative secondary sputter ion yields. The existence of a non-resonant charge transfer in HCI-solid interaction has been shown for grazing angle charge exchange studies.

At EBIT and SuperEBIT studies of the x-ray emission from trapped ions continue to produce significant atomic structure data with high precision for few electron systems of high-Z ions. Furthermore, diagnostics development for magnetic and laser fusion, supporting research for the x-ray laser and weapons programs, and laboratory astrophysics experiments in support of NASA's astrophysics program are a continuing effort. The spectroscopic measurements include high-precision Lamb shift and nuclear size measurements (^{223}U , ^{238}U), analysis of spectroscopic data for laser fusion research, identification of line coincidences for optical transfer of level populations in laser research, and the development of new spectral line diagnostics for studying young supernova remnants. A new effort in optical spectroscopy has been started. Technical advances include the development of a high-pressure proportional counter for recording very high energy x-ray transitions, the development of an ultra-high resolution x-ray spectrometer for studying cold ions, as well as of a Fourier-transform ion-cyclotron-resonance mass spectrometer for SuperEBIT.

The two-electron contributions to the binding energy of heliumlike ions were measured for the first time. The results are significant because their precision is an order of magnitude better than those of competing measurements at accelerators, and the novel technique isolates the energy corrections that are the most interesting. Ionization cross section measurements of hydrogenlike uranium as well as other high-Z hydrogenic ions are continuing. The technique is extended to the uranium L shell and cross section data have been obtained for several ionization stages of uranium.

The RETRAP project which was initiated three years ago has reached a stage where trapping, confining and electronic cooling of HCI ions up to Th^{80+} can be performed routinely. Measurements of the rates and cross sections for electron transfer from H_2 performed to determine the lifetime of HCI up to Xe^{q+} and Th^{q+} ($35 \leq q \leq 80$) have been studied at mean energies estimated to be ~ 5 q eV. This combination of heavy ions with very high charges and very low energies is rare in nature, but may be encountered in planned fusion energy demonstration devices, in highly charged ion sources, or in certain astrophysical events. A significant step, the installation of a laser laboratory and transfer lines, are

completed and the laser capability has been tested. A modification of the trap configuration currently in progress will allow us to perform the major task of this project: the production of Coulomb crystals with highly charged ions and to study binary ionic mixtures of ions at rest.

The EBIT program continues to contribute significant results to research involving low energy very highly charged heavy ions. Much of the research effort is conducted through fruitful collaborations with researchers from universities and laboratories from both the U.S. and abroad. The excellent educational capabilities of the EBIT facilities are demonstrated through the research conducted and involving a number of graduate students from U.S. and foreign universities. A strong collaborative research effort also exists between the EBIT program and Historical Black Colleges and Universities.

Much credit is deserved by the scientists and project leaders [Peter Beiersdorfer, Mike Briere, and Ross Marrs] within the EBIT program for a wide variety of experimental physics.

This work was performed under the auspices of the US Department of Energy by the Lawrence Livermore National Laboratory under contract #W-7405-ENG-48. Acknowledgment of funding support from other organizations is noted at individual abstracts of the report.

Dieter H. G. Schneider

I. ATOMIC STRUCTURE MEASUREMENTS

EBIT X-ray Spectroscopy in Support of Photo-Pumped X-ray Lasers

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Several pumping mechanisms have been suggested for x-ray lasers including collisional excitation, recombination, photo-ionization and photo-pumping. The success of photo-pumping as an x-ray laser scheme hinges on sufficient overlap of the emission and absorption lines. For such a scheme to exhibit gain, the difference of the energies of the two lines must be within the line widths determined by the plasma dynamics, such as Doppler and opacity broadening. Typically, an overlap of a few parts in 10^4 is required. Due to correlation effects, high- n levels of multi-electron ions are difficult to calculate and are reliable to roughly a part in 10^3 . These differences are large enough to preclude accurate predictions of successful overlaps. As a result, precise measurements of the overlaps are needed. The continued interest in photo-pumping schemes lies in its potential to improve the laser output. It also allows the excitation of lasing transitions not accessible to other mechanisms and thus to test laser kinetics from a different perspective.

The EBIT facility provides an ideal source for determining the degree of overlap between pump and absorber. We can practically "dial up" the transition of interest, and with the high-resolution spectroscopic equipment available, very precise measurements can be made. During the past year we have studied a variety of photo-pumping coincidences on EBIT [1,2]. These include pumping of the 2p-4d transition in neonlike Fe by the 1s-2p transition in hydrogenic Ne, pumping of the 2p-4d transition in neonlike Cu by the 1s-2p transition in heliumlike Mg, and pumping of the 2p-3s transition in neonlike Fe by the 1s-2p transition in heliumlike F [3]. We also studied pumping the 2s-4p transition in neonlike Co with the Ly- α transitions in hydrogenic Na [4] as well as pumping the 2s-3p transition in neonlike Ge with the Ly- α transitions in hydrogenic Mg [5]. Moreover, we investigated several schemes that pump nickellike x-ray lasers. These include pumping the 3d-4f transition in nickellike Er [6] as well as pumping various 3d-5f and 3d-6f transitions in nickellike Ag, Sn, Gd, Yb, Ta, Ir, Th, and U [7]. We found several resonances better than 200 ppm that are possible candidates for resonant photopumping. These resonances add to a variety of good overlaps found in the previous years with EBIT. By contrast, in our experiments we also determined that several potential resonances that appeared very promising based on theoretical predictions were too far apart to be useful in photopumping experiments.

We have also investigated another type of photopumping scheme. This scheme is based on neonlike Rb pumping lithiumlike Al. Here, x-ray lasing might take place between two autoionizing levels in lithiumlike Al [8]. Such a scheme avoids radiation trapping that could reduce laser gain and promises high efficiencies, if it were made to work. A schematic of the levels involved is shown in Fig. 1. Our measurements determined an energy difference of 0.7 ± 0.1 eV or 380 ppm between the pump and absorber. Several other such coincidences are possible among a variety of ion pairs. We plan to study some of these potential overlaps in the coming year.

Fig. 1. The Rb²⁷⁺ pumped Al¹⁰⁺ laser scheme.

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Systematic Studies of 3d-4f, 5f, 6f Transitions in Nickellike Ions

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Like heliumlike and neonlike ions, which have a completely filled K-shell and L-shell, respectively, nickellike ions have a completely filled M-shell. The ions are therefore relatively stable over a wide range of plasma conditions and radiate strongly in the x-ray regime. The x-ray transitions of nickellike ions, however, have not been investigated in as much detail as those of heliumlike and neonlike ions. Using high-resolution x-ray spectroscopy on EBIT we have performed systematic studies of the 3d-4f, 3d-5f, and 3d-6f transition energies of various nickellike ions between Ag ($Z=47$) and U ($Z=92$) to investigate systematic trends in the level structure of nickellike ions [1,2,3]. These measurements have improved the accuracy of published transition energies by over an order of magnitude.

FIG. 1. Residuals of a linear fit of the reduced transition energy (E/Z) for the data available prior to our EBIT measurements.

Until our measurements, the only data on 3d-4f transitions in nickellike ions stemmed from laser-produced plasmas and spark discharges. An overview of these data is given in Fig. 1. These data were fitted to interpolate for transitions in elements that had not been measured. Using this fit, the transition energy of the 3d-4f transitions in nickellike Er, for example, is predicted to be 1727.3 eV. Measuring this transition on EBIT we found 1725.9 ± 0.3 eV, which is well below the interpolated value [3]. Measuring three additional elements (Pr, Yb, and Pt) we found that none agreed with the interpolated values, as illustrated in Fig. 1. Since our measurements were more than an order of magnitude more precise than previous measurements, we reexamined the fit including our data. The results are shown in Fig. 2. Most older measurements still overlap with our new fit. The new fit, however, provides interpolated data with much higher accuracy.

FIG. 2. Residuals of a quadratic fit of the reduced transition energy (E/Z) for all data including our EBIT measurements.

Systematic measurements of the 3d-5f and 3d-6f transition energies of nickellike ions between Ag and U have revealed similar differences between measured and calculated energies [1,2]. The calculated energies are typically offset from the measured values by 1.0 to 2.0 eV depending on the particular finestructure transition considered. The offsets are attributed to inadequate treatment of electron-electron correlations in the calculations.

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High-Precision Measurements of the Transition Energies and QED Contribution in Heliumlike Krypton (Kr^{34+})

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Spectra of He-like ions have been a subject of intense research interest, since these ion provide an ideal setting for testing approaches to solve the many-body problem. Theoretical predictions of the energy levels tend to vary significantly mainly due to the different ways to account for the many-body quantum-electrodynamical corrections. Therefore, experimental results are necessary in order to guide the development of accurate theoretical approximations. This is especially important for high- Z He-like ions, as differences among predictions tend to increase strongly with atomic number[1, 2, 3].

He-like $K\alpha$ radiation has been studied for ions as heavy as Xe^{52+} [6], and U^{90+} [7], but only up to Kr^{34+} with high-resolution crystal spectrometers [8, 9]. The highest accuracy for the Kr^{34+} $K\alpha$ transition energies was achieved by Indelicato et al. [9] at the GANIL accelerator facility (24 ppm) but the experimental results differ significantly from all recent calculations. Thus, there is a strong interest in remeasuring the energies of the $K\alpha$ transitions of He-like krypton. Moreover, the $K\alpha$ radiation of Kr^{34+} proves to be a useful tool for ion temperature diagnostic of tokamak plasmas [4]. In collaboration with the Princeton Plasma Physics Laboratory we try to improve the reliability of the Kr^{34+} x-ray emission as an indicator of the ion temperature by identifying possible interference of the He-like $K\alpha$ lines with satellite lines [5].

Our measurement was performed at the Electron Beam Ion Trap (EBIT)[10] facility at LLNL using a von Hámoss-type[11] high-resolution crystal spectrometer with a cylindrically bent 200-LiF crystal ($2d = 4.027\text{\AA}$, $R_c = 75\text{cm}$), achieving a precision of 20 – 33 ppm [12, 13]. The spectrometer was set to a Bragg angle $\theta = 28^\circ$. This setup measures the Kr $K\alpha$ radiation in second order and the H-like Mn and He-like Fe spectra used for calibration in first order Bragg reflection as shown in Figure 1. The labeling is according to the notation of Gabriel[14].

Figure 1: (a) Superimposition of the H-like Mn spectrum ($\text{Ly}_{\alpha_{1,2}}$), and the He-like Fe spectrum, showing the $1s2s^3S_1 \rightarrow 1s^2^1S_0$ transition, labeled z . (b) Krypton $K\alpha$ spectrum (w, x, y, z) measured in second order. Both the Kr and Fe spectra also show collisional satellite lines of lower charge states. Some Li-like (r, q, t) and one Be-like (β) of these satellites are labeled.

The uncertainty in the determination of the transition energies results from the uncertainty of the calibration lines, the uncertainty in the determination of the centroid of each line, and the uncertainty of the dispersion along the detector [15]. The accuracy of our measurements was limited mainly by the uncertainty of the iron calibration lines (up to 59 ppm). Unlike earlier measurement at the GANIL accelerator facility[9], the results of our measurement are in agreement with most recent calculations [13]. Best agreement is found with the theory of Cheng et al. [3], where the average difference between our measured values and their predictions is (0.05 ± 0.36) eV. Their calculations match the accuracy of the relativistic energies of Plante et al. [2], while including a new approach for estimating the QED contributions. For the $1s2p \rightarrow 1s^2$ transitions Cheng et al. predictions are around 10.8 eV. Our measurements test this value to within 3%. Moreover, our measurements are sensitive enough to test the 1.4-eV QED contribution to the energy of the $1s2s$ levels.

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Two-Electron Contributions to the Ground-State Energy of Heliumlike Ions

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Spectroscopic studies of the energy levels of few-electron high- Z ions can be used to understand the effects of quantum electrodynamics (QED) and multielectron contributions in strong Coulomb fields. These effects appear as a difference between the physical energy and the Dirac-Coulomb energy of an atomic state. The one-electron (hydrogenlike) ions are the easiest to treat theoretically, and calculations of their energy levels are thought to be highly accurate even for very high Z . The heliumlike ions are the simplest multielectron system. However, in contrast to the hydrogenlike ions, there is no exact solution for the structure of high- Z heliumlike ions. Thus the "two-electron" contributions to the energy of heliumlike ions are at the frontier of current theoretical and experimental interest.

We have used a novel experimental approach that exploits radiative recombination (RR) transitions into the K shell of bare and hydrogenlike ions for a direct measurement of the two-electron part of the ground-state energy in heliumlike ions [1]. We measure the difference in the energy of RR x rays emitted in electron capture by stationary bare and hydrogenlike target ions. This difference is equal to the difference in the ionization potential between the hydrogenlike and heliumlike ion, which is exactly the two-electron contribution to the ground state energy of the heliumlike ion. It should be noted that the one-electron contributions to the binding energy, such as the finite-nuclear-size correction and the one-electron self energy, cancel out in this type of experiment, which makes such measurements unique.

The experimental setup is shown in Fig. 1. Energy calibration lines from a radioactive source are mixed with the RR x-ray lines from trapped ions. We have obtained data for Ge($Z=32$), Xe($Z=54$), Dy($Z=66$), W($Z=74$), Os($Z=76$), and Bi($Z=83$). A typical spectrum from the xenon data is shown in Fig. 2. The splitting between the two members of the RR($n=1$) doublet is exactly equal to the difference in the ionization potential between the hydrogenlike and heliumlike ion. We determined this

Fig. 1. Experimental arrangement used for the binding energy measurements. The ^{169}Yb source consists of several removable pieces attached to an annular holder. The detector was located 46 cm from the trapped ions.

splitting from fits to the RR peaks using the lineshape function for our detector. The RR($n=1$) feature for three other elements is shown in Fig. 3. The population of bare target ions in the trap decreases rapidly as Z increases, which prevents us from going beyond bismuth in the periodic table

Fig. 2. A sample spectrum from the data used to determine the difference in ionization potentials for hydrogenlike and heliumlike xenon.

Fig. 3. The K-shell RR lines for germanium, dysprosium, and bismuth as observed in typical runs.

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Lamb Shift of the $2s_{1/2}$ - $2p_{3/2}$ Transition in Lithiumlike Th^{89+}

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Following up our initial measurement of the Lamb shift of the $2s_{1/2}$ - $2p_{3/2}$ transition in lithiumlike uranium U^{89+} [1], we performed additional measurements including those of the $2s_{1/2}$ - $2p_{3/2}$ transition in lithiumlike thorium Th^{87+} [2,3]. A typical spectrum is shown in Fig. 1. (Also confer the cover page.) The measurement provides a confirmation of our earlier results and improves the accuracy with which the Lamb shift is measured by 50%. In fact, the thorium measurement provides the highest accuracy with which the QED contributions to the $2s_{1/2}$ - $2p_{3/2}$ transition have been determined in any measurement. This is illustrated in Fig. 2 where we plot the difference between theory and measurement as a fraction of the size of the QED contribution. Our thorium point (as well as our earlier uranium measurement) is a much better test of QED theory than any previous measurements performed on tokamaks or heavy-ion accelerators.

FIG. 1. Crystal-spectrometer spectrum of the $2s_{1/2}$ - $2p_{3/2}$ transitions in lithiumlike Th^{87+} through fluorinlike Th^{81+} . The lines are labeled by the ionization stage. For example, Be denotes the $2s_{1/2}$ - $2p_{3/2}$ transition in berylliumlike Th^{86+} ; the $2s_{1/2}$ - $2p_{3/2}$ transition in lithiumlike Th^{87+} is denoted Li.

FIG. 2. Difference between measured and predicted energies of the lithiumlike $2s_{1/2}$ - $2p_{3/2}$ transitions expressed as a fraction of the QED contribution. Theoretical energies are from Ref. 4. Experimental values are from Ref. 5 except for the thorium and uranium points, which are from EBIT measurements. The present result for thorium is displayed as a solid circle.

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II. DIAGNOSTICS FOR FUSION AND ASTROPHYSICS

Radiative Lifetime of the $1s2s\ ^3S_1$ Levels in Heliumlike Ions

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Radiative transition rates provide information of the long-range behavior of atomic wavefunctions. Measurements of radiative transition rates thus complement energy level measurements, which primarily test atomic wavefunctions near the nucleus. Calculations of the radiative decay rates of dipole-forbidden transitions are highly sensitive to the theoretical approaches used and thus theoretically the most uncertain. As a result, measurements of the lifetimes of metastable levels is of particular interest. Moreover, the radiative lifetime of the metastable $1s2s\ ^3S_1$ level in heliumlike ions determines the range over which the K-shell emission lines from heliumlike ions can be used as electron density diagnostics, as illustrated in Fig. 1. Accurate knowledge of the lifetime of the $1s2s\ ^3S_1$ level is thus of great importance to plasma diagnostics, especially of solar and astrophysical plasmas.

FIG. 1. Lifetime of the metastable $1s2s\ ^3S_1$ level in heliumlike ions as a function of atomic number. The critical density at which the level is depopulated by electron collisions is given on the y-axis. The shaded areas indicate the regimes that can be tested with other techniques, such as the beam-foil, Penning-trap, and storage-ring method. The EBIT measurement of neon and magnesium are the first to test heliumlike lifetimes relevant for determinations of densities in stellar atmospheres.

Last year we have developed a novel EBIT-based technique for measuring radiative lifetimes in highly charged ions [1]. The technique relies on rapid switching of the energy of the electron beam, above and below the excitation threshold of the 3S_1 level, and determining the lifetime of the metastable 3S_1 level from its fluorescent decay while the beam energy was below threshold. Adding to our previous measurement of heliumlike neon we have determined this year the radiative lifetime of the 3S_1 level in heliumlike magnesium [2].

The new technique can be used over eight order of magnitude in time, from a few nsec to hundreds of msec. Most of this region is inaccessible to any other existing method such as accelerator beam-foil measurements, laser fluorescence techniques, ion traps on ECR sources, or ion storage rings. Our technique represents thus a powerful new tool for investigating the properties of highly charged ions in regime uncharted by earlier measurements. It enables measurements of radiative lifetimes in heliumlike ions that are useful density diagnostics in the range 10^8 cm^{-3} to 10^{15} cm^{-3} , as illustrated in Fig. 1. Adding to our previous measurement of heliumlike neon we have determined this year the 13.6- μs radiative lifetime of the 3S_1 level in heliumlike magnesium [2], which is used as a diagnostic in plasmas with electron densities near 10^{12} cm^{-3} .

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High Resolution Measurements of the $K\alpha$ Spectra of Low Ionization Species of Iron: New Spectral Signature of Non-Equilibrium Ionization Conditions in Young Supernova Remnants

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For plasmas in collisional ionization equilibrium, the dominant contributions to the iron K emission come from the hydrogenlike and heliumlike ions, Fe XXVI and XXV, respectively. This is because these charge states dominate at the high electron temperatures required for collisional excitation of the K-lines. At slightly lower temperatures, lithiumlike and berylliumlike satellites are also expected, primarily due to dielectronic recombination onto heliumlike iron. However, $K\alpha$ emission for lower ionization species should be suppressed. As a result, no high resolution observations of iron $K\alpha$ lines exist from charge states below fluorinelike (Fe XVIII).

$K\alpha$ satellites from lower charge states can be produced copiously, however, if the emitting gas is out of ionization equilibrium. An important astrophysical situation in which this might be observed occurs in young supernova remnants, where the timescale for ionization equilibrium to be established following shock heating can substantially exceed the timescale for dynamical evolution of the remnant. The recently shocked gas is thus expected to be underionized or ionizing with time. The resulting x-ray spectrum is then characterized by two parameters, the electron temperature, T_e , and an ionization timescale, $\eta = n_e t$, where n_e is the electron density and t is the time since shock passage. Masai [1] shows that at low values of η , $\ll \text{few} \times 10^{11} \text{ cm}^{-3} \text{ s}$, the iron $K\alpha$ complex is dominated by low ionization satellites. A similar situation also occurs on much shorter timescales during the early phases of solar flares [2].

We have performed the first experimental simulation of this process in a controlled laboratory environment, using the capabilities of EBIT [3]. Specifically, we used a data routing technique, recording a series of spectra shortly after the injection of ions into the trap [4]. The measurements were made with a high-resolution crystal spectrometer in the von Hámos configuration, and are confined to the wavelength range 1.925 - 1.950 Å, which includes the two resonance transitions of Fe XVIII: $1s^2 2s^2 2p^5 {}^2P_{1/2} - 1s 2s^2 2p^6 {}^2S_{1/2}$ (F1, at 1.92769 Å) and $1s^2 2s^2 2p^5 {}^2P_{3/2} - 1s 2s^2 2p^6 {}^2S_{1/2}$ (F2, at 1.93079 Å), and their satellites from the lower charge states Fe XVII down to Fe X. For charge states lower than Fe XVIII, the $K\alpha$ transitions are excited both by direct excitation and fluorescence following inner-shell ionization. The rates for the two processes are actually comparable, so it is advantageous to perform the experiments at a beam energy above the inner-shell ionization threshold at 8.68 keV. For these experiments, we used a beam energy of 12 keV. To facilitate the line identifications, particularly of the lower ionization satellites which have never previously been measured, we performed atomic structure calculations using a relativistic, multiconfiguration parametric potential model, the Hebrew University Lawrence Livermore Atomic Code (HULLAC) [5].

Figure 1 presents data accumulated during the first two time groups after injection of iron in the trap, from 0-7 and 7-14 ms, respectively. Also shown are the predicted positions for the lines of Fe XVII through Fe X, as determined from the

HULLAC code. The spectra clearly show the presence of the $K\alpha$ emission from charge states lower than Fe XVIII. The dominant line in the spectrum is the Fe XVIII transition F1. Most of the features, however, including the other Fe XVIII line (line F2) are blended together. It is evident from looking at the spectrum recorded from 7 to 14 ms after injection, that the overall intensity of the lower charge states is greatly reduced relative to the first time group, and that only the two Fe XVIII lines are still prominent.

FIG. 1. K-shell spectra of iron in the region 1.925-1.950 Å measured with EBIT's high-resolution von Hámos spectrometer at a beam energy of 12 keV, recorded from 0 - 7 ms and 7 - 14 ms after injection into the trap, respectively. Shown below the data are theoretical predictions for the line positions of lines from Fe XVIII through Fe X computed from the HULLAC code.

Two regions are indicated for each charge state for the HULLAC predictions in Fig. 1. These correspond to the wavelength regions where we predict the locations of the strongest lines of each charge state based on our oscillator-strength calculations. The lower-wavelength structure for each charge state corresponds to a $1s_{1/2} - 2p_{3/2}$ $K\alpha_1$ transition with spectator electrons. The higher corresponds to a $1s_{1/2} - 2p_{1/2}$ $K\alpha_2$ transition. Each of the two regions marks the locations of the satellites of the two fluorinelike transitions, F1 and F2, respectively.

The measured spectra are consistent with theoretical predictions for line positions and ionization balance calculations. Although the intensity of the $K\alpha$ emission for charge states below Fe XVIII is comparatively weak, the observation of this emission, in which inner-shell ionization plays an important role, can provide a signature and be used to identify ionizing plasmas in young supernova remnants. We also point out that a large number of charge states have their $K\alpha$ emission confined to a relatively narrow wavelength range (≤ 25 mÅ). This makes it possible to observe simultaneously these features with very high resolution and therefore potentially allows a detailed study of time dependent charge state distribution.

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Experimental Calibration of Iron L-Shell Line Emission: Fe XXIV $n = 3 \rightarrow n = 2$ and $n = 4 \rightarrow n = 2$ Transitions in Collisionally Dominated Plasmas

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The launching in 1993 of the Advanced Satellite for Cosmology and Astrophysics (ASCA) has opened a new era in X-ray astrophysics. The large collecting area and moderate spectral resolving power of the spectrometers on ASCA are yielding high signal-to-noise X-ray spectra of many astronomical plasmas. Astrophysical interpretations of these spectra, however, are compromised by fundamental uncertainties that still remain in our understanding of the basic atomic physics processes that generate the observed X-ray spectra. For example, in the spectral range 0.7-2.0 keV, significant discrepancies exist between observations and the predictions of standard plasma emission codes [1]. These discrepancies cannot be eliminated by invoking multi-temperature distributions nor by varying relative elemental abundances. Transitions in iron L-shell ions (Fe^{16+} to Fe^{23+}) of the type $n=n'$ to $n=2$ are one of the dominant sources of line emission in the 0.7-2.0 keV spectral range; and the discrepancies are attributed to errors in the atomic data used in the plasma codes for the electron impact excitation rate coefficients of these ions [2]. To experimentally address the source of these discrepancies, we have initiated a series of experiments to measure the properties of the iron L-shell ions using an electron beam ion trap. Our initial results on $n=3$ to $n=2$ and $n=4$ to $n=2$ line emission in Li-like Fe^{23+} are in poor agreement with the calculations of Liedahl et al. [2].

Figure 1. A portion of the 3 to 2 spectrum of Li-like and Be-like Fe containing the $3p\ ^2P-2s\ ^2S$ doublet in Li-like Fe at 10.62 and 10.66 Å, a blend of Li-like and Be-like Fe lines between 10.98 and 11.03 Å, and the $3d\ ^2D-2p\ ^2P$ doublet at 10.18 Å.

Figure 2. A portion of the 4 to 2 spectrum of Li-like and Be-like Fe containing the $4p\ ^2P-2s\ ^2S$ doublet in Li-like Fe at 7.99 Å and a blend of Li-like and Be-like Fe lines at 8.30 Å.

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K-Shell Plasma Diagnostics

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The plasma diagnostic potentials of He-like ions and their K-shell spectra have long been recognized [1]. The K-shell spectra of He-like ions is comprised of direct excitation of He-like ions, cascades from recombination of H-like ions, and satellite lines of Li-like ions generated by inner-shell excitation and by dielectronic recombination of He-like ions. As a result the spectra of He-like ions can be used to determine electron temperature and density as well as the H-like to He-like and Li-like to He-like relative ionic abundances of the observed plasma.

We have undertaken an investigation of these various plasma diagnostics taking into account both the charge balance and temperature of the observed plasmas and the spectral resolving power of existing and also planned X-ray satellite observatories. Our results indicate that the electron temperature and density diagnostics are strongly affected by the fractional ionic abundance of H-like and Li-like ions in the observed plasma. The sensitivity of the electron density and temperature diagnostics to the charge balance in the observed plasma, thus reduces the usefulness of these diagnostics for plasmas where the charge balance is unknown.

The charge balance can, in principle, be determined from the spectrum of the H-like, He-like, and Li-like K-shell transitions. However, the K-shell transitions of these ions may be blended together by the resolving power of the spectrometer used for the observations or by thermal broadening of the observed lines. This can be seen in Fig. 1 which presents synthetic Fe K-shell spectra for a plasma in coronal equilibrium and at a temperature of 3.5×10^6 K. The spectra have been computed taking into account the spectral resolving power of existing and planned X-ray satellite observatories. As can be readily seen, significant blending of the various K-shell lines will occur for observations with the Advanced Satellite for Cosmology and Astrophysics (ASCA) and with the Advanced X-ray Astrophysics Facility (AXAF). Observations by ASCA and AXAF will thus have to rely on modeling the observed line emission in order to infer conditions in the emitting plasma. Observations by ASTRO-E of the Fe K-shell spectrum will begin to distinguish individual lines in the spectrum; but significant line blending still occurs and modeling will be required to infer conditions in the emitting plasma. Only observations by Spectrum Roentgen-Gamma will have a high enough resolving power that simple line diagnostics will be able to be used to infer conditions in the emitting plasma. He-like plasma diagnostics must therefore be recast into forms which account for both instrumental spectral resolving power and the temperature and charge balance of the observed plasmas.

Figure 1. Synthetic iron K spectra for the resolving power ($E/\Delta E$) of the different spectrometers of those X-ray satellite observatories already launched or expected to be launched later in this decade. Dot-dash line, the Solid-state Imaging Spectrometer of the Advanced Satellite for Cosmology and Astrophysics ($E/\Delta E = 50$); long-dashed line, the High Energy Grating Spectrometer planned for the Advanced X-ray Astrophysics Facility ($E/\Delta E = 200$); short-dashed curve, the X-Ray Spectrometer planned for ASTRO-E ($E/\Delta E = 900$); solid line, the Objective Crystal Spectrometer planned for Spectrum Roentgen-Gamma ($E/\Delta E = 3200$).

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Measurement and Identification of L-shell Transitions in FeXVII through FeXXIV

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The L-shell spectrum of iron is very complex extending over a very large wavelength range from about 17 Å for the longest-wavelength 3-to-2 transition in neonlike Fe XVII to about 9 Å for the shortest-wavelength transition in lithiumlike Fe XXIV. Using the EBIT low-energy flat-crystal spectrometer [1] we have begun to investigate the iron L-shell spectrum. The present measurements focus on line identification and wavelength determinations and aim to aid the analysis and interpretation of solar and astrophysical iron L-shell spectra.

A spectrum of the L-shell transitions in Fe XVII is shown in Fig. 1 (a). This spectrum was obtained by setting the electron beam energy to 1280 eV, i.e., to a value just above the threshold for ionizing Fe XVII at 1262 eV. Setting the beam energy to higher values we can excite and

FIG. 1. L-shell spectra of iron recorded on the EBIT facility at three electron energies: (a) 1250 V, (b) 1350 V, and (c) 1450 V. These energies are slightly above the values required to ionize Fe XVII (1266 eV), Fe XVIII (1366 eV), and Fe XIX (1466 eV), and the spectra are dominated by L-shell emission from Fe XVII, Fe XVIII, and Fe XIX, respectively. Each spectrum is a composite of data from four spectrometer settings.

measure the L-shell transitions in yet higher charge states of iron. For example, setting the beam energy to 1370 eV, i.e., to a value just above the threshold for ionizing Fe XVIII, we produce the spectrum of Fe XVIII shown in Fig. 1 (b), setting the beam energy to 1470 eV, i.e., to a value just above the threshold for ionizing Fe XIX, we produce the spectrum of Fe XIX shown in Fig. 1 (c). Because a particular ionization stage of iron dominates at each beam energy, as summarized in the ionization balance calculation given in Fig. 2, this procedure allows us to unambiguously identify the iron L transitions. Using well known calibration lines from hydrogenic and heliumlike ions of oxygen, fluorine, neon, sodium, magnesium, and aluminum we are able to accurately determine the wavelengths of the iron lines.

Fig. 2. Calculated ionization balance in EBIT as a function of the electron energy.

The EBIT measurements are compared to elaborate modeling calculations that incorporate not only a full array of excitation processes but also electron density effects. The comparison allows us to identify particular lines that are useful for plasma diagnostics. Several lines that are sensitive to the electron densities in EBIT have already been identified.

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High-resolution Measurement of the He- β Spectra of Heliumlike Chromium for Possible Diagnostic of Laser-produced Plasmas

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X-ray spectroscopy of highly-charged ions have proved to be a useful tool for the diagnostic of the electron temperature and density of ultrahigh density ($n_e \geq 10^{24} \text{ cm}^{-3}$) laser-produced plasmas [1,2]. Measurement of $n = 3 - 1$ transitions in heliumlike ions (He- β spectrum) is of particular interest because, unlike the $n = 2 - 1$ transitions, these lines are optically thin at these high densities. Moreover, high-Z dopants can be included in the pusher for indirectly driven implosions and be used for the diagnostic of its behavior [3]. Since the emission from the He- β line is expected to be blended with its associated Li-like satellites due to the significant Stark broadening of the lines [2], it is crucial to have accurate atomic data for these transitions in higher-Z elements for a reliable diagnostic of future ICF plasmas.

To test the atomic parameters associated with He- β spectra in the low density limit, we measured a high-resolution He- β spectrum of He-like chromium, including the associated $n = 2$ dielectronic satellites. The data was recorded with a high-resolution spectrometer in the von Hámos configuration on the Livermore Electron Beam Ion Trap (EBIT), with an electron density $n_e \leq 5 \times 10^{12} \text{ cm}^{-3}$ [4]. Our spectral resolution $\lambda/\Delta\lambda$ of $\sim 2,600$ makes it possible to resolve the resonance line from its satellites and therefore allows a detailed comparison with theory.

Figure 1 presents a He- β spectrum of chromium measured above threshold for direct excitation, at a beam energy of 8 keV. The chromium spectrum shown in Fig. 1 is dominated by the two $n = 3 - 1$ lines due to transitions $1s^2 1S_0 - 1s3p 1P_1$ (He- β_1) and $1s^2$

$1S_0 - 1s3p 3P_1$ (He- β_2). Also present in the spectrum are four electron impact excitation features, labeled A, B, C, and D, respectively.

FIG. 1. He- β spectrum of chromium measured above threshold for direct excitation at a beam energy of 8 keV.

Figure 2 presents spectra of the lithiumlike chromium dielectronic satellites in the wavelength range from 1.870 - 1.886 Å, recorded with a beam energy swept between 4.96 and 5.28 keV. The beam energy was swept in order to have a full contribution of all dielectronic satellites since they each have a slightly different resonance energy. Superimposed to the data in Fig. 2 is a least-squares fit which we used to identify nine dielectronic satellite features. Each feature consists of several unresolved lines, and their width was fixed to the value determined from a fit of the He- β_1 line shown in Fig. 1. Along with the envelope of all nine peaks which includes the fitted background, each individual peak fit is shown in Fig. 2 without the background contribution.

FIG. 2. Dielectronic recombination He- β spectrum of chromium recorded with a beam energy swept between 4.96 and 5.28 keV. Superimposed to the data is a least-squares fit for the most prominent features.

The results of the fit shows good overall agreement with theoretical predictions from the HULLAC code using a relativistic, multiconfiguration parametric potential model [5] as well as with calculations from Vainshtein and Safronova using the Z-expansion technique [6]. However, the $[1s^2 2p_{3/2}]_{3/2} - [1s 2p_{3/2} 3p_{1/2}]_{3/2}$ transition, with a predicted wavelength of 1.8785 Å according to the HULLAC code, could not be fitted to the data although its line strength is comparable to that of the neighboring lines under peaks 3 and 4. This suggests an overestimate of the predicted line strength for this line, which is indicated as "Blend" in Fig. 2. Moreover, there are many weaker transitions in the spectrum (with a predicted line strength $< 10^{12} \text{ s}^{-1}$) which enhance the

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Tokamak Spectroscopy of Line Coincidences for Photopumping of X-ray Lasing Transitions

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Several measurements of line coincidences of interest to photopumping of x-ray lasers were carried out using x-ray spectroscopy on tokamaks. The measurements were performed in collaboration with scientists at the Princeton Plasma Physics Laboratory and complemented data from EBIT observations by providing an independent set of wavelength data and by demonstrating that a given set of ions could coexist in a plasma environment. Two tokamak experiments were reported in 1994. The first represented a measurement of an excellent coincidence between the $3s_{1/2} \rightarrow 2p_{3/2}$ ($J=1$) transition in neonlike La^{47+} and the $1s^2\ ^1S_0 - 1s2p\ ^1P_1$ line in heliumlike Ti^{20+} [1]. The second considered the coincidence between the Ly- α line of hydrogenic magnesium and the $3p_{1/2} \rightarrow 2s_{1/2}$ ($J=1$) transition in neonlike germanium [2]. Both measurements were made on the PLT tokamak in Princeton.

Spectral measurements of the coincidence between the $3s_{1/2} \rightarrow 2p_{3/2}$ ($J=1$) transition in neonlike La^{47+} and the $1s^2\ ^1S_0 - 1s2p\ ^1P_1$ line in heliumlike Ti^{20+} are shown in Fig. 1. A spectrum from plasma seeded with Ti only is shown in Fig. 1(a). This spectrum shows lines w , x , y , and z , which denote transitions from upper levels $1s2p\ ^1P_1$, $1s2p\ ^3P_2$, $1s2p\ ^3P_1$, and $1s2s\ ^3S_1$, respectively, to the $1s^2\ ^1S_0$ heliumlike ground state. The transition denoted q represents the lithiumlike transition $1s^22s\ ^2S_{1/2} - 1s2s2p\ ^2P_{3/2}$. A spectrum from plasma seeded with both Ti and La is shown in Fig. 1(b). Subtracting the spectrum (a) from (b) results in the L-shell spectrum of La^{47+} shown in Fig. 1(c). The lanthanum spectrum shows the $(2p_{3/2}-3s_{1/2})_{J=1}$ electric dipole transition and the $(2p_{3/2}-3s_{1/2})_{J=2}$ magnetic quadrupole transition in neonlike La^{47+} , labeled $3G$ and $M2$, respectively. Features on the long-wavelength side are from $3s_{1/2} \rightarrow 2p_{3/2}$ transitions in neighboring charge states. In particular, the lines labeled A , B , and C are ascribed to transitions in La^{46+} , La^{45+} , La^{44+} , respectively. The electron temperature of the plasma was about 5 keV during all measurements.

The measurements indicated an excellent line coincidence between the La line $3G$ and the Ti line w . The separation is a mere $0.25 \pm 0.10\ \text{m}\text{\AA}$ or $96 \pm 38\ \text{ppm}$. For comparison, thermal motion of the titanium ions in a 1-keV plasma will broaden the heliumlike resonance line by $0.92\ \text{m}\text{\AA}$. The resonance condition for successful photo-pumping is thus satisfied to a very high degree. The possibility of success of the $\text{La}^{47+}-\text{Ti}^{20+}$ photo-pumping scheme is increased by the fact that the resonance transition in heliumlike titanium is the most intense line in the titanium K-shell spectrum, thus providing maximal pump strength. Moreover, Ti^{20+} and La^{47+} can be produced and coexist over a wide range of plasma conditions, as proven by our measurements. In fact, the abundance of each ion is maximized under similar plasma conditions, as each ion has similar ionization potentials — 6.4 keV for Ti^{20+} and 8.6 keV for La^{47+} . Neonlike lanthanum La^{47+} has not yet been produced in a laser-plasma interaction. It may, however, be attained in future facilities, such as the planned National Ignition Facility.

FIG. 1. Spectra of (a) Ti^{20+} , (b) Ti^{20+} and La^{47+} , and (c) La^{47+} .

Spectral measurements of the coincidence between the Ly- α line of hydrogenic magnesium and the $3p_{1/2} \rightarrow 2s_{1/2}$ ($J=1$) transition in neonlike germanium (labeled 3B) are shown in Fig. 2. At the electron temperature of the measurements (1.5 keV) the neonlike Ge line was found blended with a strong transition from oxygenlike Ge. The measurement helped explain a puzzling discrepancy between several measurements of the wavelength of line 3B in laser-produced plasmas. In many cases the blend with the transition from oxygenlike Ge was not recognized, leading to a faulty wavelength determination [2].

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III. ION/SURFACE INTERACTION STUDIES

Secondary Ion Mass Spectroscopy Using Very Highly Charged Primary Ions up to Th^{70+}

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The advent of new ion source technologies, such as the LLNL EBIT (Electron Beam Ion Trap), has made low emittance ($< 0.2 \pi \text{ mm mrad}$) beams of slow ($\leq 3 \text{ keV/amu}$) very highly charged ions (in principle up to $\text{U } 92+$) available for ion-solid interaction studies. The prominent features of such interactions, compared to that for singly to moderately charged ions, is the dominance of electronic over collisional effects. While such an incident ion approaches a solid surface, up to several hundred electrons are emitted from an area of only a few square nanometers. In insulators, this local disturbance of the charge equilibrium cannot be compensated before the lattice relaxes in a "Coulomb explosion", resulting in the emission of large numbers of secondary particles and the production of nanometer size defects. This work represents the first systematic study of the sputtering process due to such mechanisms.

The secondary ion yield, due to the impact of slow highly charged ions has been studied for various targets ranging from gold and graphite to silicon dioxide, calcium fluoride and lithium fluoride. The measurements were performed under UHV conditions ($< 10^{-10}$ Torr) and the sample surfaces were sputter cleaned using 500 eV Ar^+ ions to insure reproducible surface composition. Results for Th^{70+} ions, extracted from EBIT at an energy of $7 \text{ keV} \cdot q$, incident on thin SiO_2 films on Si and obtained using a novel single detector technique for the detection of both positive and negative secondary ions (as described elsewhere in this report), are presented here. Figure 1 shows the time-of-flight spectrum for positive secondary ions, before and after correction for blocking effects inherent to the one-stop-per-start electronics used here. Figure 2 shows the resultant integrated mass spectrum of secondary positive ions. It can be seen that the secondary ion yield is significantly enhanced over that for singly or moderately charged ions of 10^{-3} to 10^{-2} . In fact, the integrated secondary ion yield can greatly exceed the total ablation rate due to collisional cascades, in this case 3 atoms/ion. The time-of-flight spectrum for the negatively charged secondary ions is shown in Figure 3 with the associated integrated mass spectrum given in Figure 4. Significant production of large secondary ion clusters are evident. Such large cluster yields are also found for other targets as shown in Figures 5-7.

Figure 1: Positive secondary ion time-of-flight spectrum for $5.5 \text{ keV} \cdot q$ Th^{70+} incident on (500 eV Ar^+ sputter) cleaned 100 nm thick SiO_2 film on Si. The effective sample to detector distance was 6.7 cm with a sample bias of +1.5 kV. Dashed line is the as measured spectrum, solid line is the spectrum after correction from blocking effects of previous events for the one-stop-per-one-start (TAC) electronics used.

Figure 2: Mass spectrum of positive secondary ions for 5.5 keV * q Th⁷⁰⁺ incident on SiO₂ obtained through integration of peaks of the corrected time-of-flight spectrum shown in Fig. 1 and conversion of time-of-flight to mass.

Figure 3: Negative secondary ion time-of-flight spectrum for 9 keV * q Th⁷⁰⁺ incident on (500 eV Ar⁺ sputter) cleaned 100 nm thick SiO₂ film on Si. The effective sample to detector distance was 6.7 cm with a sample bias of -2 kV. Dashed line is the as measured spectrum, solid line is the spectrum after correction from blocking effects of previous events for the one-stop-per-one-start (TAC) electronics used.

Figure 4: Mass spectrum of negative secondary ions for 9 keV * q Th⁷⁰⁺ incident on SiO₂ obtained through integration of peaks of the corrected time-of-flight spectrum shown in Fig. 2 and conversion of time-of-flight to mass.

Figure 5. Time-of-flight spectrum for negative secondary ions produced by the impact of 2.3 keV/u Th^{68+} on (500 eV Ar^+ sputter) cleaned (100) CaF_2 .

Figure 6. Time-of-flight spectrum for negative secondary ions produced by the impact of 2.3 keV/u Th^{68+} on (500 eV Ar^+ sputter) cleaned (220) LiF .

Figure 7. Time-of-flight spectrum for negative secondary ions produced by the impact of 2.3 keV/u Th^{68+} on (500 eV Ar^+ sputter) cleaned Highly oriented pyrolytic graphite, (0001) C.

Coulomb Explosions due to the Impact of Slow Very Highly Charged Ions on Insulating Surfaces

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It has long been suggested that the incidence of highly charged ions should cause a violent response in insulating target surfaces, known as "Coulomb explosions" (e.g. E. Parilis 1970 [1]). Here, the slow electronic response of the insulator to the extreme violation of the charge neutrality of the surface associated with intense potential electron emission [2] leads to permanent displacement of the target atoms, including emission into the vacuum. This is very analogous to the well studied situation of extreme ionization density in solids due to kinetic energy transfer from high energy heavy ions to target electrons, known as nuclear tracks [3]. There has, however, yet to be any direct experimental evidence for such effects on surfaces due to highly charged ion impact. Such evidence is presented here for the first time. A schematic representation of this phenomenon at the solid surface is shown in Figure 1. Some of the ionized target atoms in the near surface and central region of the space charge are ejected from the solid through mutual repulsion, while remaining ionized target atoms are compressed and initiate a shock wave. The shock wave is capable of causing the desorption of large numbers of large molecular species from the surface. Such shock-wave effects are discussed elsewhere in this report. A threshold in the occurrence of such phenomena are expected, where the energy density stored in the ionized volume exceeds the binding energy density in that volume. Salient features of the Coulomb explosion effect, a definite threshold and an increase in the material volume involved with increasing target ionization, have been observed in each of two independent investigations.

Figure 1. Schematic representation of the "Coulomb explosion" effect at an insulator surface due to the local charging of the surface layers by potential electron emission during the interaction with slow very highly charged ions. The explosion is allowed if the surface space charge survives longer than the time constant for ionic motion in such a plasma, about 10^{-12} to 10^{-13} sec. For bulk insulators, the neutralization time, determined by the electron conductivity, exceeds 10^{-10} sec. In response to the explosion and momentum carried by the ablated target atoms, a shock wave is produced which is capable of promoting the desorption of large molecules (see next report).

Figure 2: Integrated secondary positive and negative ion yields vs. incident charge state of the primary ion for a 100 nm thick SiO_2 film on Si. A constant EBIT extraction potential of 7 kV and a sample bias of ± 1.5 kV were used. The ion counts are normalized to the number of TAC start counts. The yield is determined using an effective detection efficiency of 10%.

Figure 3: Measured ratio of oxygen to silicon positive secondary ions (single and doubly charged) vs. the charge state of the primary ion for a 100 nm thick SiO_2 film on Si. A constant EBIT extraction potential of 7 kV and a sample potential of + 1.5 kV were used. Above a threshold, the ratio is constant at the stoichiometric value of 2, indicating a hot plasma source of the secondary ions.

In one study, the secondary ion yield is measured using a time-of-flight spectrometer and in the other, the size of extended "blister-like" surface defects are determined using atomic force microscopy (AFM) [4]. Results for the secondary ion yields as a function of incident charge, for thin films of SiO₂ on Si, are presented. As can be seen in Figure 2, the data exhibit a linear dependence on increasing incident ion charge, with a threshold for onset near $q=25+$. A detection efficiency of 10 % has been estimated for the secondary ions, derived from electrostatic analysis of the secondary ion paths, yielding a collection efficiency of 35 % , as well as a 30 % efficiency of the micro-channel plate pair and the associated electronics for the generation of a measurable signal upon the incidence of keV secondary ions [5]. Together with the measured count rates, this suggests secondary ion yields of up to 15 per incident ion, significantly greater than the total ablation yield due to kinetic collision cascades of 3 atoms/ion in this case. Further evidence for the "Coulomb explosion" effect can be seen in the measured ratio oxygen to silicon ion yields. These data, shown in Figure 3, strongly suggest that the ionization probability for the secondary particles changes rapidly at, and is constant above, threshold. This ratio, usually determined by the so called "matrix effect" of relationships in chemical reactivity of the secondary particle and the target atoms [6], is usually found to be 100 to 1000 in the case of primary keV Cs⁺ ions. In the present case, the ratio is that of the target stoichiometry, 2:1, above threshold. It can be argued that the consistency of this ratio above threshold, together with its stoichiometric value, is a strong indication that the ions are produced in a very hot plasma and that the ionization probability in this case approaches unity, several orders of magnitude greater than that for the kinetic collisional sputtering contribution. This has very important implications for the application of highly charged ion induced sputtering for enhanced sensitivity [7] and quantitative analysis of sub-micron scale surface layers. Given the apparent consistency of the ionization rate above threshold, it is concluded that the linear increase in the ion yield of Figure 2 is due entirely to increasing total ablation yield, corresponding to larger volumes of the target surface region involved in the "Coulomb explosion". The values of the ablation rate (atoms/ion, including molecular ion constituents) are therefore seen to exceed more than 10 times that for collisional sputtering. Very similar results are found for the formation of defects on insulating surfaces. The results of AFM measurements of such defects on mica surfaces indicate an increase of defect size with incident ion charge, above a threshold of 30 to 35+ and are discussed elsewhere in this report. **This data represents strong evidence for the "Coulomb explosion" mechanism in the solid state response of insulators to the incidence of slow very highly charged ions.**

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High Yields of Large Molecular Cluster Ions due to Coulomb-Explosion Generated Shock-wave Induced Desorption

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Additional evidence for the "Coulomb explosion" behavior of solids, due to the impact of highly charged ions, is the emission of large molecular clusters. Such behavior has been observed in the case of very energetic heavy ions, such as 100's MeV Au on carbon [1] or insulators such as l-valine [2]. The mechanism responsible for this cluster emission is the propagation of a shock wave produced, in this case, by a "Coulomb explosion". Presented here, for the first time, is clear evidence for this phenomenon during the interaction of slow very highly charged ions with solid surfaces. The mass spectrum of secondary ions, measured using time-of-flight, exhibit a rich series of molecular cluster ions, especially in the case of negative secondary ions, as shown elsewhere in this report. In the case of SiO_2 , the clusters can be described the series $(\text{SiO}_2)_n^-$ and $(\text{SiO}_2)_n\text{O}^-$, where n is the order of the cluster. As shown in Figure 1, the yield of such clusters is found to decrease exponentially for relatively small clusters (to $n=4$), consistent with emission as clusters, and combinatorially for larger cluster orders ($n>4$), consistent with the formation of clusters through coalescence of smaller clusters directly after emission from the surface. This behavior is in very good agreement with that found for shock-wave induced desorption by high energy (MeV/u) heavy ions [2,3]. The emission of negative ions, predominantly O^- , are found to exhibit a similar threshold to the positive ion emission associated with the "Coulomb explosion", as shown in Figure 2. This strongly suggests a correlation between the mechanisms involved in the two emission processes. The cluster ion yield (e.g. $(\text{SiO}_2)_n\text{O}^-$) are found to increase strongly with the charge of the incident ion, as shown in Figure 3. In fact, the yield is found to increase as the cube of the incident charge, in excellent agreement with the results for swift heavy ions [4]. In the kinetically driven case, the ionization is due to energy transfer in binary collisions between the incident ion and the target electrons, the electronic stopping power. In the case of highly charged ions, the surface ionization is due to the extreme potential electron emission caused by the large electrostatic field associated with the incoming ion [5]. The potential electron emission yield has been found to increase linearly with incident charge for clean conductors and insulators (e.g. SiO_2 on Si) at least up to Th^{70+} , as described elsewhere in this report. Furthermore, as shown in Figure 4, the yield of the negative ions is proportional to the square of the thickness of the SiO_2 layer on Si. This is consistent with the "Coulomb explosion" induced shock-wave desorption mechanism, where (avalanche-style) field emission of electrons across the Si- SiO_2 interface, followed by transport across the oxide layer, would be expected to provide a square dependence on the oxide thickness for the fraction of the surface space charge which survives neutralization in such cases. This is clear evidence that the desorption of the negative ions is not due to de-excitation of inner shell vacancies, produced in binary collision events between the target atoms and incoming highly charged ions, as proposed by Schiwietz [6].

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Figure 1: Measured relative yield for negative ion clusters in the series $(\text{SiO}_2)_n\text{O}^-$ for 9 keV* q Th^{70+} incident on 100 nm thick SiO_2 on Si as a function of the cluster order n . The detection efficiency of approximately 10 % has not been included. The solid lines are best fits to the data, in the low and high n regimes.

Figure 2: Ratio of total positive to negative ion yields (integrated over time-of-flight spectrum) vs. incident ion charge state for a 100 nm thick SiO_2 film on Si. A constant EBIT extraction potential of 7 kV and a sample potential of ± 1.5 kV were used. Above a threshold, the ratio is constant, indicating correlation between the emission mechanisms involved.

Figure 3: Measured yield of SiO_3^- clusters vs. incident charge state of the primary ion for a 100 nm thick SiO_2 film on Si. A constant EBIT extraction potential of 7 kV and a sample bias of + 1.5 kV was used. The ion counts are normalized to the number of TAC start counts. The absolute yield is determined using an effective detection efficiency of 10%. The solid line is a best fit to the data.

Figure 4: Measured integrated negative ion yield vs. SiO_2 film thickness on Si. The solid line is a best fit to the data and indicates a square dependency. This is strong evidence for the "Coulomb explosion"-shock wave mechanism as opposed to that of local vacancy decay. The thinnest target is a native oxide on Si, taken to be 2 nm thick. The other oxide thickness have been measured by ellipsometry.

Comparison of SIMS with Highly-Charged Ions from an EBIT and Auger Spectroscopy

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Interactions between surfaces and highly-charged ions (e.g., Th^{70+} , Xe^{44+}) are being studied at the LLNL Electron-Beam Ion Trap (EBIT) facility. Topics of particular interest include electron extraction/emission as these ions approach the surface(s), photon emission, and ejection/sputtering of positive and negative ions and neutrals. In this last context a Time-of-Flight (TOF) system to detect — and subsequently identify — ejected ions has been developed. Details of this system are given in an accompanying poster.

As a validation of the performance of this system we have compared this TOF-SIMS method with Auger spectroscopy (performed here with a four-grid LEED optics system). In the Figures below we show spectra taken from a mica sample with different amounts of residual carbon on the surface.

Figure 1 shows an Auger spectrum taken after system bakeout, but before any sputtering. There is a significant amount of carbon in addition to the expected potassium and oxygen Auger lines. Figure 2 shows the corresponding TOF-SIMS spectrum, normalized to the oxygen peak.

There are strong peaks at masses corresponding to multi-atom carbon clusters C_n , where n varies from 1 to at least 8. These peaks have also been seen in TOF-SIMS spectra taken from clean, highly-oriented pyrolytic graphite (HOPG), as well as in spectra taken on other surfaces after system bakeout.

We then briefly sputtered the sample with an Ar^+ ion gun (500eV). Figure 3 shows the reduction of the carbon in the Auger spectra. This reduction is mirrored in the corresponding TOF-SIMS spectrum (Figure 4), again normalized to the oxygen peak. The carbon clusters are gone; peaks corresponding to the oxygen and SiO_2^- and SiO_3^- ions are clearly visible.

Similar changes (loss of carbon peaks) have been observed with a variety of other substrates, indicating that this TOF-SIMS system's behavior is well understood.

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Figure 1: Auger spectrum of mica sample after system bakeout.

Figure 3: Auger spectrum of mica sample after sputtering.

Figure 2: TOF-SIMS spectrum of mica sample after system bakeout.

Figure 4: TOF-SIMS spectrum of mica sample after sputtering.

AFM Investigations of Defect Formation on Mica by Very Highly Charged Ion Impact

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Defects formed on Mica due to the irradiation with slow very highly charged ions have been investigated with the Atomic Force Microscope (AFM). Kr^{30+} , Kr^{35+} , Xe^{35+} , Xe^{44+} , Xe^{50+} , U^{70+} and Th^{74+} were extracted from EBIT with kinetic energies between 300 and 500 keV. The potential energies range from 50 to 200 keV. As has been formerly reported [1], AFM imaging of the irradiated areas reveals the formation of blisterlike defects due to single ion impact with diameters between 10 and 80 nm and heights ranging from 1 to 2 nm. The blister volume has been found to increase linearly with incident ion charge in first order with a minimal threshold charge state around $q = 30$ (Fig. 1) but a dependence of the defect size on the ion species is also observed: While irradiation with Kr^{35+} leads to formation of defects detectable with the AFM, Xe^{35+} impact does not [2-4].

Fig. 1: Mean Volumes of Defects as a function of incident charge state. The error bars always represent the statistical width of each distribution.

To test the reproducibility of the irradiation experiment defects on targets irradiated during different independent experiments have been compared (Fig. 2). In Fig. 3 the volume distributions of defects on the same target imaged over a period of time is shown. Considering uncertainties in the AFM setup, the most important of which are tip sample convolutions, the defects appear to be stable over one year, during the target was stored in air.

Fig. 2: Mean volume distribution of defects due to irradiation with Xe^{44+} during different experiments. No parameter is denoted on the x-axis.

Fig. 3: Mean volume of defects on one sample imaged over time.

Defect formation in mica due to highly charged ion impact has been linked to electron emission, which shows a similar dependence on incident ion charge as the defect volume. Blisterlike defects have also been found on mica samples that were heated to 300°C for a few hours [5], which may infer a blister formation mechanism based upon the expansion of trapped gas volumes between different mica layers.

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Non-equilibrium Nuclear Energy Loss for Incident Very Highly Charged Ions in Insulators

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At present, it is unknown how long very slow (keV/u) highly charged ions (i.e. Ar^{16+} , Kr^{34+} , Th^{80+}) can retain a non-equilibrium charge state in solids. In fact, there is no evidence that even the inner shell vacancies of such ions exists beyond the first few monolayers below the solid surface. Recently, it has been predicted that an increased nuclear-nuclear energy transfer, due to long range Coulomb interactions in insulators, is expected for these ions [1]. The object of this experiment is to demonstrate that such an effect actually occurs. This is accomplished through differential transmission energy loss spectroscopy using ion time of flight, as shown in Figure 1. Previous attempts to measure such energy loss effects in SiO_2 , through highly sensitive RBS measurements of the projected range of Xe^{q+} , where $1 \leq q \leq 44$, have produced negative results [2]. It is believed that this is due to the covalent nature of the insulator and therefore its screening of the ionic charge through strong polarization of the target atoms. A better candidate for the effect is a strong ionic solid such as MgO or CaF_2 . Furthermore, enhanced sensitivity to the effect would be achieved for transmission energy loss measurements through thin films, where the non-equilibrium state may exist over a large fraction of the ion's path length in the solid.

The differential technique is based upon the idea that increased energy loss is expected only in ionic insulators (i.e. CaF_2) and not in metallic solids (i.e. C), since the conduction electrons should effectively screen the ion's potential at distances greater than the order of the lattice spacing. As depicted in Figure 2, a sandwich target structure is created under UHV conditions using thermal evaporation of several nanometers of CaF_2 on a thin (10 nm) carbon foil backing, supported by a Cu TEM grid. Both AFM and TEM microscopic investigations indicate that the film is continuous for a thickness of at least 2 to 4 nm. The transmitted energy loss spectrum of highly charged ions (i.e. Ar^{16+}) incident on the ionic solid (i.e. CaF_2) side of a two layer target structure is compared to that for ions incident on the metallic (carbon) side. Measurements of the charge state distribution of the ions transmitted through the 10 nm C foils indicate that charge state equilibrium is achieved within the foil (predominantly neutral and singly charged ions). Therefore, ions first passing through the C foil will interact with the CaF_2 film in equilibrium, whereas ions first entering the insulator will experience non-equilibrium effects. An asymmetry in the results for the two cases, therefore, indicates the existence of a non-equilibrium charge state in the solid. It should be noted that, energy loss measurements of Ar^{16+} through various thickness of C foils are in excellent agreement with equilibrium data, confirming one of the basic assumptions of the technique. **However, a significant increase in the transmitted energy loss for highly charged ions incident on ionic insulating targets has been observed.** In the case of 112 keV Ar^{16+} on a 5 nm CaF_2 film, shown in Fig. 3, the average energy loss for the non-equilibrium charge states, δE_2 , is a factor of four greater than that for the equilibrium charge state, δE_1 , as achieved through initial transmission through a 10 nm C foil. Additionally, a significant increase in the energy loss straggling is observed for the case of highly charged ions in ionic solids. This last effect is thought due to the influence of reduced screening for small impact parameter collisions on energy transfer cross sections, due to hollow atom formation in the solid. These results represent the first evidence for the existence of very slow highly charged ions inside solids and suggest several techniques to study the formation and decay of hollow atoms in solids. Measurements of this asymmetry in the energy loss can be used to determine the average decay process of the non-equilibrium charge state in solids.

Figure 1: Experimental arrangement for time-of-flight measurements of transmitted energy loss for incident highly charged ions. The annular micro-channel plate (MCP) detector, located in front of the sample, is used to detect electrons emitted at ion impact and provide a start signal to the time-to-amplitude converter (TAC). The large area MCP detector located beyond the target provides the stop signal for the time-of-flight of the ion and has a position sensitive anode, allowing for measurements of the scattered angle-energy correlation. The flight path is 0.75 m with a solid angle for the PS-MCP detector of ± 1.5 degrees.

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These results have been presented at the following conferences :

- 1) European Research Conf. on Particle-Solid Interactions, San Sabastian Spain, Oct. 1 -6, 1994.
- 2) 12th Int. Conf. on Ion Beam Analysis, Tempe Arizona, May 22-26, 1995
- 3) 19th ICPEAC, Whistler Canada, , July 26 - Aug. 1, 1995

Figure 2: A schematic representation of the experimental technique for the differential energy loss determination. First, the transmitted energy (time-of-flight) is measured for the bare 10 nm C foil. Then a thin film of CaF_2 is deposited under UHV conditions. The transmitted energy is then measured for the ions incident of each of the two sides of the resulting bi-layer structure. The energy loss is determined directly for each side by subtraction of the bare C foil results.

Asymmetric Energy Loss, $\Delta E_2 - \Delta E_1$, due to long range Coulomb Interactions with highly charged ion in solid.

Figure 3: Transmission time-of-flight results for Ar^{16+} incident on the bare a) 10 nm C foil (equilibrium) and the bilayer structure : b) C side first, : c) CaF_2 side first. A clear asymmetry exists between the results for the different incident sides of the same bilayer structure, indicating non-equilibrium effects in the insulator. The inset shows the results for the two sides of the same bare 10 nm C foils, indicating that the asymmetry is not a result of the experimental method.

Negative Ion Production from Shallow Angle Scattering of Slow Highly Charged Ions by Atomically Flat Surfaces of Highly Oriented Pyrolytic Graphite, C(0001)

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Highly charged ions of N, O, F and S; chosen for their electron affinities, were extracted from the LLNL EBIT II. After collimation, these ions struck a target of highly oriented pyrolytic graphite (HOPG) at an incident angle of 1.0 degrees. Ions scattered into an exit angle of 1.3 degrees, were electrostatically charge state analyzed and the predominant asymptotic charge state fractions were determined. Results indicate very high negative ion yields, proportional to the electronegativity of the incident ion. For example, incident S^{15+} yielded 13 % of the scattered ions as S^{1-} , while for incident F^{9+} at the same velocity, 35 % were negatively charged. At nearly the same incident velocity, S^{9+} produces a negative ion yield of 18%. These results are in agreement with those of previous HCI small angle scattering measurements at LLNL and indicate that the incident ions are predominantly in their ground state configuration when they leave the surface interaction region, after an interaction time of less than 50 fs.

One of the most fundamental issues in the rapidly developing field of slow highly charged ion-surface interactions, involves the time scales of the neutralization and vacancy decay processes, which provide the de-excitation mechanisms allowing the incident highly charged ion to reach its relaxed ground state. The presently accepted mechanisms of resonant electron transfer, from energetic state near the Fermi level of the solid to corresponding high lying Rydberg-like state in the ion, has been suggested for some time [1] and has been sufficiently refined [2] so as to allow experimentally verifiable measures of the time and distance scales involved in the neutralization of the incident ions and the corresponding formation of hollow atoms [3], at least in the case of metallic targets. However, an alternative model, based on field induced tunnel emission and subsequent electron-electron-ion collision dynamics, has been equally successful in explaining the experimentally measured properties of these interactions [4]. Even so, it remains far less clear, as to what the mechanisms and time scales for the inner decay (de-excitation) of these highly inverted atomic systems are, in the presence of solid surfaces.

It has recently been shown, that the earlier promoted concept of autoionizing cascades, is too slow to account for the rate of inner shell vacancy decay, as measured by X-ray emission energy shifts from their ground state values [5,6,7]. These same studies have clearly shown that energy level matching between the target and ion dynamic wavefunctions leads to direct electron transfer or "side-feeding" into the residual ion inner shell vacancies, at the time of surface impact. This transfer need not be resonant, however. As depicted in Figure 1, Auger neutralization processes may provide an effective charge transfer mechanism. The efficiency of this process is still strongly selective to the level level mismatch between the target and the ion, being a maximum for minimal ejected electron energy, E_e (i.e. the binding energy of the target electron, B_e). Light ions scattering off heavier or comparable Z target atoms are expected to reach the ground state very rapidly (fs) within one or possibly a few monolayers of the surface (or above the surface) through resonant over-the-barrier transfers. An interesting point, is the time scale for nearly bare heavy ions to reach the ground state when interacting with light Z targets, where

resonant transfer into inner shells is suppressed. It has been recently found, that hydrogen- and helium-like krypton ions are essentially in the ground state after reflective scattering off atomically flat pyrolytic graphite targets, as indicated by their predominantly neutral or singly charged asymptotic charge states after scattering [8,9,10]. At the same time, it has been found that highly charged light ions produced an enhanced asymptotic negative ion yield, as compared to cases for incident singly charged species [9,10]. Due to less well defined morphology and complications in interpretation of the results, respectively, the graphite targets are better suited to initial systematic investigations than the other two target systems. This negative ion formation effect after the small angle scattering of slow highly charged ions has since been verified, studied and reported on by other investigators, at least in the case of O^{q+} ions on higher Z targets such as Au [11,12,13]. It is interesting to note, that these results were found to be qualitatively the same for epitaxial Au(111) films on mica, as well as mica targets, and the HOPG samples [9]. Since the asymptotic charge states in all cases were measured after some 0.5 to 1 μs flight time, following scattering, it is assumed that the ions are in the ground state, since decay of an excited state would be expected to produce autoionizing transition, increasing the resulting charge correspondingly. If the ion has left the interaction region with the surface (0.2 to 1 nm), the resulting charge state must then be frozen in this relaxed condition. It is important to note, however, that little can be said to differentiate between transitions occurring on the incoming or outgoing path (or at the surface), from these measurements. Attempts to achieve such information, have been performed using Doppler broadening investigations of the Auger electron emission spectra [11]. In order to insure the interpretation of ground state behavior and to rule out possible new metastable configurations in the scattered ions, it was decided to measure the formation of negative ions as a function of ground state properties of the incoming ion, i.e. the Pauling electronegativity [12]. Here we report on the first results of such investigations.

The experimental arrangement used for the measurements of the total effective charge exchange, including the production of negative final charge state occurring during grazing incidence scattering ($\Theta_i \leq 1^\circ$) of very highly charged ions off atomically flat surfaces, at the LLNL EBIT, have been described elsewhere [8,9]. Measurements were performed in UHV of better than 10^{-8} Torr. The sample was highly oriented pyrolytic graphite (HOPG), with a mosaicity of 3.5° , as determined through small angle (rocking curve) x-ray diffraction measurements. The long range surface morphology was measured using a Dektak profilometer and was found to be $\pm 0.5^\circ$. The sample was freshly cleaved, using adhesive tape, within one hour of evacuation of the target chamber. Atomic force and scanning tunneling microscopic topological measurements of the cleaved surface, show extremely large atomically flat terraces of micrometer dimensions, as shown elsewhere in this report. It should be noted, that many studies have shown that the surface of HOPG samples remains atomically clean for time scales long compared to our experiments (e.g. weeks) under good vacuum conditions (e.g. 10^{-7} Torr or better) [ref.ref]. These properties make such targets nearly ideal for small angle scattering experiments. An incident angle of 1.0° was used for all charge exchange measurements presented here. It should be noted, that no significant effect of the charge state distribution was found for incident angles varying from 0.2 to 1.5° . A set of slits, positioned 0.45 m after the sample and directly before the analysis plates, provided an angular resolution of up to $\pm 0.15^\circ$. Charge state analysis was performed for ions within the acceptance angle, which was generally 30% of the half width of the total final angular distribution. The ions were always selected from the population on the small scattered angle side of the peak of the distribution, corresponding to an exit angle of 1.3° , in an effort to reduce any possible effects of multiple scattering contributions to the charge state distribution. The same relative portion of the angular distribution was used in all cases presented here. Earlier small angle scattering experiments used a resistive anode in the stop detector, while later investigations of the negative ion yield used a

backgammon type "wedge-strip-zig" (WSZ) anode, lithographically defined on a glass substrate with an aluminum ground plane.

Results for the asymptotic exit angular distribution of incident highly charged are reasonably narrow and Gaussian shaped, as discussed elsewhere in this report, exhibiting a FWHM of ca. 2-3°. Together with the linear shift of the final angular distribution with the incident angle, as well as a sharp energy distribution of the outgoing ions, also discussed elsewhere in this report, it is strongly suggested that these ions have undergone reflective scattering from a plane potential, rather than off individual atoms of the surface or the bulk (i.e. no surface penetration.). A typical measured asymptotic charge state distribution, in this case for incident S^{13+} , is shown in Fig. 2. It can be seen, that the individual charge states are well resolved and the background is essentially eliminated due to the coincidence restrictions provided by the time of flight. It is also interesting to note, that even for the case of S, no evidence for doubly charged negative ion formation has been found. To first order, no significant influence of the final charge states have been found for the final energy of the projectile, as determined from the time-of-flight (TOF) data, which has a resolution of about 1%, determined by the spatial extent of the scattering target, in the direction of the flight path. The results of investigations of the cross section for negative ions production for small angle scattering of very highly charged light ion systems such as N,O,F and S are given in Table 1. Whereas, no evidence for negative ion formation for incident N ions has been found (neither has it been found for any incident inert gas ion), the cross section for negative ion production is found to increase, for approximately the same incident velocity for hydrogenlike species of S to O and F. In fact, as shown in Figure 2, this cross section is directly proportional to the ground state property of Pauling's electronegativity. This is strong evidence for the fact that the ions are, in fact, in the ground state, when leaving the interaction region of ca. 0.2 to 1 nm above the surface. Furthermore, it can be seen, that higher velocities for a given incident charge state produce less negative and more singly charged positive ions. This is in agreement with previous observations for the velocity dependence of singly charged Kr^{qt} ions after similar scattering processes [9]. This, together with the fact that the presence of deeper lying vacancies in the incident ion is accompanied by increased positive and decreased negative ion yields, indicates that the rate of inner shell vacancy decay is on the same order of magnitude as the interaction time of the ions with the surface, or 50 to 100 fs, assuming single pass planar reflection. It is important to note, that these results are inconsistent with a model for inner shell vacancy decay through autoionization decay, as the total measured decay rate of less than 10^{-13} s is too fast for the requisite number of cascades. Rather, inner shell vacancy decay due to direct transfer from target atoms is suggested. Since the distance of closest approach for these projectiles is about 0.1 nm, molecular orbital effects can be neglected, especially in the case of the hydrogen-like ions. This indicates that resonant over-the-barrier transitions from the $1s^2$ C levels to the $n=2$ or 3 levels of the projectiles may be the most likely decay mechanism. It should be noted, however, that such transitions are not sufficient to explain the observation that even such few electron high Z ions such as Kr^{35+} and Xe^{44+} have been found to be at least 90% in either the neutral or singly charged state after similar small angle scattering events on carbon [8-10], where the $1s^2$ level of the target is not resonant with projectile levels below $n=6$ to 9 [see Fig. 1]. Extensions of the negative ion production investigations to few electron high Z projectiles, such as hydrogen-like Br and neon-like I, are underway, and should help to shed new light on this interesting phenomenon.

Figure 1: Schematic representation of relative energy level positions for inner shells of incident Ar, Fe and Kr compared to that of carbon. Note the absence of resonant or quasi-resonant transfer possibilities for electrons from the innermost levels ($1s^2$) of a carbon target to levels below $n=6$ to 9 in the case of incident Kr.

Figure 2: Asymptotic charge state distribution from 7 kV*q S^{15+} incident on HOPG (C) at an angle of 1° , projected from one axis of a position sensitive channel plate detector after electrostatic separation.

Incident Ion	Yield X1-	Yield X0	Yield X+	Yield X2+
N6+	0.000	0.911	0.089	0.000
O7+	0.270	0.060	0.060	0.007
F7+	0.399	0.514	0.075	0.012
F9+	0.351	0.548	0.101	0.000
S7+	0.231	0.604	0.149	0.016
S9+	0.181	0.582	0.198	0.039
S13+	0.146	0.546	0.257	0.052
S15+	0.130	0.560	0.271	0.039

Table 1: Summary of asymptotic final charge state measurements for various ion incident at 1° on HOPG(C) measured at an exit angle of 1.3° .

Figure 3: Measured fraction of negative ion formation for hydrogenlike incident ions of the same velocity, as a function of the electronegativity of the ground state of the incident ions. The data point for F^{8+} is actually the mean value of the results for F^{7+} and F^{9+} , shown in Table 1.

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Small Angle Scattering Behavior of Highly Charged Ions on HOPG

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The small scattering behavior of slow highly charged ions (e.g. keV/u Kr^{34+}) off atomically flat surfaces of highly oriented pyrolytic graphite have been performed at the LLNL EBIT facility. Investigations of the final asymptotic charge state distributions for such scattering events are discussed elsewhere in this report. The final angular distribution of the scattering ions were measured on a position sensitive microchannel plate detector, located between 0.5 and 0.1 m from the target, in coincident with the time of flight of the ions from the scattering event. The start signal for the timing measurement was provided by the potential emission of electron and photons during the formation and decay of the incident highly inverted atomic projectile. The front plate of the start detector was located 4 cm from the target surface, behind a grounded grid, parallel to the sample at 0 degrees and perpendicular to the direction of the incident beam. The angular distribution of the incident beam was less than 0.1° with a beam size of 1 mm in the scattering plane and 5 mm in the plane parallel to the sample at 0 degree incident angle. The value of this zero degree position was determined in several complimentary ways. First the minimum in the number of start signals and the maximum in the number of incident ions passing above the surface was determined. In the neighborhood of these maxima, the point at which the scattered ion coincident signal disappeared was measured. This procedure yielded a reproducible measure of the 0 degrees scattering angle to within 0.05° and was found in excellent agreement with the values found both through laser light specular scattering measurements and visual inspection of the sample angle with a telescope. Additionally, the results were confirmed through measurements of the scattering behavior of protons and neutralized highly charged ion beams (neutral-neutral scattering). The incident angle was varied using a precision manipulator controlled by a stepping motor (200:1), under the tension of a constant force spring, to remove any back-lash. The angular position of the sample was found to be reproducible to within 1 step of the motor drive, or 0.05° . The final angular distribution was determined by the position of the scattered ions on the position sensitive MCP detector, with a precision of 0.05 mm, normalized to the target-detector distance. This distance was determined precisely using the ion time of flight data. The absolute accuracy of the average final angle was therefore better than $\pm 0.1^\circ$. The sample surface was prepared by cleaving with adhesive tape immediately (< 1 hr.) before pumping the vacuum chamber down. The surface of these targets provide very large atomically flat monolayer high terraces of several square microns, as shown in Figure 1. A typical result for the relationship between incident and average final scattering angle is shown in Figure 2, for the case of 7 keV* q Kr^{34+} . The final angle in the limit of 0 incident degrees is interpreted as the effective microscopic impact angle due to the acceleration of the incident ion toward its own image charge at the target surface. The result of the measure of the intercept of such relationships for different incident charge states on HOPG is shown in Figure 3, along with the prediction of theoretical models. It can be seen that there is excellent agreement between these results and those of theory.

Figure 1 Atomically flat monolayer high terraces on a HOPG surface as imaged by AFM. Gray scale from 0 (dark) to 5 nm (light).

Figure 2 Incident vs. final angle for Kr^{34+} scattering off HOPG. The kinetic energy of the Krypton ions is $7 \text{ kV} \cdot q$.

Figure 3 Image charge acceleration of highly charged ions incident on a HOPG surface vs. charge state q as determined by small angle scattering, $\blacktriangle$; results from e^- yield measurements, $\bar{\Gamma}$. The solid line shows predictions from theory. Insert: Results from measurements of highly charged ion induced electron emission as a function of ion velocity. Image charge acceleration of incident ions (here Th^{79+} on Au) sets a limit to the minimum impact velocity. The solid line shows extrapolated electron yields with no image charge acceleration.

On the Dynamics of the Filling of the L Shell of Hollow Atoms

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We have studied the interactions of Ar^{16+} and Ar^{17+} ions on clean SiH surfaces. These ions were delivered by the AECR ion source of the joint LBL-LLNL ion facility at the LBL 88" cyclotron. For the first time, we observed the K and L X-ray spectra of Ar^{17+} (Fig. 1) and Ar^{16+} impinging on a SiH surface with a specially designed Si(Li) detector. As shown in Fig. 2, the L intensity is made of an array of satellites corresponding to the presence of 0 to 7 L shell spectator electrons during the radiative transition $M \rightarrow L$. The relative intensity of the K and L lines ($L/K \sim 12\%$) clearly demonstrates that about 8 L X-ray transitions are emitted for one K transition (there are 8 L holes for 1 K hole). The results based on the fluorescence yield of the L (1.3×10^{-3})^{1,2} and K shells (20%), is supported by the relative intensity of the L and $K\beta$ lines (Fig. 1) which originate from the M shell. This result means that the L shell is mainly fed by M or N electrons through Auger or X-ray transitions and not through the side feeding process which plays an important role for second row elements (N, O...). In the case of the third row elements, such as argon, the direct capture process populates the M and N shells of the ion.

We have compared in Fig. 3 the L X-ray spectra observed with Ar^{16+} (no K hole) and Ar^{17+} ions on the same target. The L X-ray spectrum of Ar^{17+} is, in theory similar to that of Ar^{16+} except that the K hole increases by one unit the effective charge of the inner core which shifts the energy of the lines by about 50 eV. Moreover, as seen in Fig. 3, the Ar^{17+} X-ray spectrum clearly shows that some of contribution to the intensity is from transitions to the L-shell while a K vacancy is present (high energy part of the L spectrum) and partly, similar to the Ar^{16+} , after the K-hole is filled. These results are in good agreement with the model describing the dynamics of the decay of the hollow atoms.

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Fig. 1: L and K X-ray spectrum of Ar^{17+} on SiH

Fig. 2: L X-ray spectrum of Ar^{16+} on SiH

Fig. 3: L X-ray spectra of Ar^{17+} and Ar^{16+} on SiH

First Observation of the Influence of the Chemical Nature of a Surface in the Interaction of Ar^{17+} Ions on Various Targets

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Most experiments to date on the interaction of highly charged ions of the second row of the Mendeleev's table, e.g., C^{5+} , N^{6+} , O^{7+} and Ne^{9+} with metal surfaces have been carried out by looking at the KLL (or LMM) Auger transitions emitted in flight by the ions. In the past few years some distinctions between the emission above and below the surfaces have been found. More recently some differences in the Auger spectra of this kind of ions on various surfaces have been found but not yet explained^{1,2}. With ions of the third row, such differences have never been found by looking at the $\text{K}\alpha$ X rays emitted by the ions although a great number of attempts have been made. We present in this contribution some very first results showing clear differences in the L and $\text{K}\beta$ X-ray spectra emitted by the same ion on various targets.

The experiment was carried out at the AECR ion source of the joint LBL-LLNL ion facility at the LBL 88" cyclotron that provides beams with intensities greater than 10^9 sec^{-1} for Ar^{17+} ions. These ions have been sent onto three different targets: pure carbon foil, SiO_2 and SiH; the last two being prepared by well-known semi-conductor industrial techniques.

The in-flight emitted X rays have been detected with a high resolution Si(Li) detector. Whereas no visible effects are found on the unresolved array of $\text{K}\alpha$ L^x satellites, some clear differences can be observed in Figs. 1, 2 and 3 on the L and $\text{K}\beta$ lines. These differences, which most likely come from the chemical nature of the surfaces, demonstrate undoubtedly that the capture processes below a surface result from some resonant charge exchange or electron promotion mechanisms.

Since the L shell is mainly filled through a cascade of Auger processes from the M or N shell, as discussed in an other contribution (this meeting), it is not surprising, a posteriori, that in a collision mainly populating the M and N shells of the ion, differences only appear from the lines issued from the M (N) shell (L or $\text{K}\beta$ lines). This clear, yet weak effect, will certainly lead in high resolution spectrometry to dramatic changes.

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Fig. 1: K X ray of Ar^{17+} on SiH and C targets

Fig. 2: K and L X ray of Ar^{17+} on SiH and C targets

Fig. 3: K X ray of Ar^{17+} on SiO_2 and C targets

Comparison of the Formation of Hollow Atom Configurations in Ion/Surface Collisions and Laser Produced Plasmas

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Recent studies of multiphoton excitation of Xe have demonstrated the production of highly excited states in "hollow" atom configurations. These highly inverted atomic configurations consist of multiple inner shell vacancies with electrons populating the outer shells with high n -quantum numbers. Some of the excited state configurations appear to be suitable candidates for the amplification of tunable x-rays. The experimental evidence for the direct multiphoton production of "hollow" atoms as the dominant channel for L-shell excitation has been obtained in studies of emission in the 2-3 Å range from gas phase clusters.¹ The observations demonstrate the production of excited species having multiple L-shell vacancies [e.g. Xe^{45+} ($2p^{43}s$)] involving an energy transfer to the neutral atom exceeding 70 keV. The spectroscopic results agree with studies of x-ray emission from Xe^{45-48+} ions following slow impact on solid surfaces and an experimentally supported model of strong-field/cluster interactions. The term "hollow" atom was first defined from observations of the radiative de-excitation of highly charged ions following the interaction with surfaces. Here the spectral structure of the observed x-ray emission depends sensitively on the charge state of the incident ion which defines the number of inner-shell vacancies. In the interaction electrons populate predominantly outer shells with high n -quantum numbers via capture of surface electrons. The excited states then decay via radiative and autoionizing cascading transitions. The formation and decay has been studied for a variety of highly charged (e.g. Ar^{18+} , Xe^{48+} , U^{73+}) ions and the availability of those spectra allows a comparison with multiphoton excited spectra.²

Figure 1 demonstrates a comparison between laser produced Xe M and L x-ray spectra and spectra produced with Xe^{45+} incident on a Cu surface. Figure 2 demonstrates a similar comparison. Here the laser excitation was performed with the LLNL Nova laser beam incident on a U target which the surface spectra were produced using U^{73+} ions incident on a Be target.

Fig.1 Comparison of Xe M , L x-rays.

Fig. 2 Comparison of U M x-rays.

It is noted that the transferred power density induced in a surface by a highly charged ion, is in the order of 10^{15} W/cm² or more which is at least comparable to the power density of present short pulse lasers.

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Calculation of the Radiative Transition Energies and Probabilities of Highly Charged Bi^{q+} Ions (q=50-71)

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In a follow-up experiment, the recently [1] proposed "internal dielectronic excitation" mechanism is investigated. This mechanism is assumed to be responsible to explain the vacancy production in the M-shell of U⁶²⁺ incident on surfaces (M x-ray emission observed).

Many body perturbation theory using a hydrogen basis set is applied to calculate the radiative transition energies and probabilities of various highly charged Bi ions [2]. The application of perturbation theory taking the electron repulsion term, $1/r_{ij}$ as the perturbation yields a series of $1/Z$ where Z is the atomic number. In the energy formulation, approximate screening parameters are introduced for the relativistic and nonrelativistic energy parts that allow us to limit our calculation to the first order interelectron interaction. These screening constants are found to improve the accuracy of the calculations. The energy values are averaged over the spin and angular momentum numbers (L and S) as a function of the electron occupation numbers (k_i) for the states:

$$Q = 1s^{k_1} 2s^{k_2} 2p^{k_3} 3s^{k_4} 3p^{k_5} 3d^{k_6} 4s^{k_7} 4p^{k_8} 4d^{k_9} 4f^{k_{10}} 5s^{k_{11}} 5p^{k_{12}} 5d^{k_{13}} 5f^{k_{14}} 5g^{k_{15}} 6s^{k_{16}} 6p^{k_{17}}$$

This method is applied to the analysis of the N and M x-ray emission spectra following the impact of highly charged Bi^{q+} (q=50-71) ions on a gold surface [3]. In particular, calculations of the $3\ell-n\ell'$ and $4\ell-n\ell'$ ($n \leq 7$), M and N x-ray transition energies for different initial charge states of Bi ions have been performed. We have also calculated the radiative transition probabilities and found that the most dominant transitions for the initial ionization states Bi⁷¹⁺ - Bi³⁸⁺ are 4f-3d for the M x-rays. However, the various $4\ell-5\ell'$ and $4\ell-6\ell'$ transitions are found to contribute to the N x-ray emission. In the initial charge states of Bi⁷¹⁺, Bi⁶⁴⁺, Bi⁶²⁺, Bi⁶⁰⁺, Bi⁵⁸⁺, Bi⁵³⁺ and Bi⁵⁰⁺, the peak region of the N spectra is most dominantly represented by the 5d-4p, 5f-4d and 5g-4f transitions and the peak region of the M spectra by the 4d-3p and 4f-3d transitions (see Figs. 1 and 2) [4].

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Fig. 1 Theoretical relative intensities of the dominant transitions for Bi^{71+} , Bi^{64+} , Bi^{62+} and Bi^{60+} properties. The difference in sizes of the bar diagrams indicates the difference in the relative intensities.

Fig. 2 Theoretical relative intensities of the dominant transitions for Bi^{58+} , Bi^{53+} and Bi^{50+} properties. The difference in sizes of the bar diagrams indicates the difference in the relative intensities.

IV. ELECTRON-ION INTERACTION STUDIES

Production of Cold Highly Charged Ions in EBIT

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The characteristic x-ray lines of highly charged ions from virtually all plasma sources are broadened by the thermal motion of the emitting ions. In fact, the line broadening induced by the thermal motion represents a standard technique for measuring the ion temperature of high-temperature plasmas. The line emission from laser-produced plasmas may be broadened further by opacity or density effects. The line emission observed in accelerator-based measurements is broadened by the Doppler effect, because the necessity for a finite acceptance angle entails viewing relativistic ions with different velocity components. The line emission from any of these sources may be broadened yet more by satellite lines populated by single or multiple electron capture into high-lying spectator levels. As a result of this broadening, the resolution and the precision with which measurements can be made is limited.

EBIT uses a monoenergetic electron beam to produce and excite highly charged ions in a trap. Because excitation processes can be selected by choosing the appropriate beam energies, the population of satellite transitions that may broaden a given line in plasma and accelerator sources are avoided. Moreover, the electron density is less than $5 \times 10^{12} \text{ cm}^{-3}$ so that opacity or density effects are unimportant and broadening effects that may affect high-density plasma sources are absent. On the other hand, interaction with the electron beam causes strong heating of the ions; thus ion thermal broadening is expected to play a role in determining the widths of x-ray lines produced with an EBIT device. The temperature of the ions, however, is limited by the fact that ions with enough kinetic energy to overcome the trapping potential will leave the trap and are lost.

The production of cold highly charged ions is of high importance to high-resolution spectroscopy because the precision with which transition energies can be measured is directly related to the line width. It is also of great importance to the success of experiments conducted with extracted ions. For example, the spread of the ion velocities is a crucial parameter in capturing and thus in re-trapping of extracted ions, as well as for bunching of ions interacting in short bursts with surfaces.

We have performed systematic studies to identify the parameters that affect the temperature of the ions produced and trapped in the EBIT device. By controlling these parameters we were able to change the temperature from as high as 1600 eV to well below 100 eV [1,2]. The reduction of the spectral line width of the $1s2p^2 (J=5/2) \rightarrow 1s^22p (J=3/2)$ (labeled *j*) and the $1s2p^2 (J=3/2) \rightarrow 1s^22p (J=1/2)$ (labeled *k*) in lithiumlike Ti^{19+} as the ion temperature changes from 685 eV to 70 eV is seen in Fig. 1. The line widths shown are among the smallest observed for x-ray transitions from highly charged ions and thus allow very precise energy determinations.

Fig. 1. Crystal-spectrometer spectrum of the lines *j* and *k* from lithiumlike Ti^{19+} ions: (a) 685-eV ion temperature and (b) 70-eV ion temperature. The line widths reflect the thermal Doppler motion of the emitting ion.

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Electron Impact Excitation Cross Section Measurements of Highly Charged Heliumlike and Lithiumlike Ions

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Extending an earlier measurement of the electron-impact excitation cross sections of heliumlike Ti [1] along the isoelectronic sequence, we measured the cross sections for electron-impact excitation of the heliumlike forbidden line z ($1s2s\ ^3S_1$), intercombination lines y ($1s2p\ ^3P_1$) and x ($1s2p\ ^3P_2$), and resonance line w ($1s2p\ ^1P_1$), together with the associated lithiumlike satellite lines q ($1s2s(^3S)2p\ ^2P_{3/2}$), r ($1s2s(^3S)2p\ ^2P_{1/2}$), t ($1s2s(^1S)2p\ ^2P_{1/2}$), u ($1s2s(^3S)2p\ ^4P_{3/2}$), and v ($1s2s(^3S)2p\ ^4P_{1/2}$) for Ti, V, Cr, Mn, and Fe ($Z=22-26$) on the Livermore electron beam ion trap [2]. The measurements were made at approximately 100 eV above the excitation threshold for line w where no other processes can contribute to the excitation of the lines. The measurement technique is based on relating the intensity of the individual $n=2-1$ direct excitation photons measured with a crystal spectrometer to the $K\alpha$ intensity observed with a solid-state Ge detector and normalizing to the $n=2$ cross sections for radiative electron capture. The uncertainties in the measurements are less than 8% for the heliumlike Fe transitions and between 11 and 15% for the lithiumlike Fe transitions together with a 3% systematic uncertainty from the normalization to theoretical radiative recombination cross sections. Results for the heliumlike transitions are shown in Fig. 1. We compared our measurements to results from a distorted-wave calculation and find good agreement for both the heliumlike and lithiumlike transitions.

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Fig. 1. Measurements of the effective electron-impact excitation cross sections of heliumlike ions (solid circles) for different elements for lines (a) w , (b) x , (c) y , and (d) z . The solid curve represents results from a relativistic distorted-wave calculation. Open triangles represent earlier measurements of the cross sections for heliumlike Ti.

Measurement of Dielectronic Recombination Resonances in Heliumlike and Lithiumlike Cobalt

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Dielectronic recombination (DR) is the dominant recombination process in low density plasmas such as those found in the sun's corona and in tokamak fusion devices. It is a resonance process in which a highly charged ion captures an electron and simultaneously excites a bound electron to an excited state. Such a doubly-excited autoionizing state may be stabilized by the emission of a photon (dielectronic recombination); or it may undergo autoionization. In the KLL process studied here, a heliumlike ion captures an electron into the L shell and excites an electron from the K to the L shell:

The stabilizing transitions generate lithiumlike satellites to the heliumlike $K\alpha$ lines. The emitted photon energies $h\nu'$ of the satellite transitions are close to the energies $h\nu$ of the heliumlike transitions,

$$1s2l \rightarrow 1s^2 + h\nu, \quad (2)$$

since the effect of the spectator electron $2l$ is rather small. Similarly, recombinations into the lithiumlike ground state with K-shell excitation lead to berylliumlike satellites of the heliumlike $K\alpha$ lines.

By measuring the x rays emitted in the stabilizing transition with a high resolution x-ray spectrometer we studied in a collaboration between Morehouse College in Atlanta and the Lawrence Livermore National Laboratory the dielectronic resonances in heliumlike and lithiumlike cobalt [1]. The ions were produced and trapped in the Livermore electron beam ion trap. By sweeping the electron beam energy across the individual dielectronic recombination resonances, we have determined the relative resonance strengths of the strongest resonances populating doubly excited levels in lithiumlike and berylliumlike cobalt. A spectrum showing the x-ray lines produced by sweeping over all KLL resonances is shown in Fig. 1. Here, stabilizing x rays from resonances in heliumlike cobalt are labeled with lower case letter; x rays from resonances in lithiumlike cobalt are labeled with numerals. Also shown are two theoretical spectra for comparison.

Most measured dielectronic satellite strengths compare well with theory. This is true especially for the strongest resonances that dominate the total recombination rate. A discrepancy with theoretical values is noted only for the weak resonances. These include the

resonance strengths associated with levels $(1s_{1/2}2p_{3/2}^2)_{3/2}$ and $(1s_{1/2}2s_{1/2}2p_{1/2})_{1/2}$. Their values of $49.8 \pm 3.2 \times 10^{-20} \text{ cm}^2\text{eV}$ and $22.9 \pm 6.4 \times 10^{-20} \text{ cm}^2\text{eV}$ respectively, are almost twice the size predicted by theory. Similar observations were made earlier in the case of iron [2], which is the neighboring element.

Fig. 1. Dielectronic recombination satellite spectrum for heliumlike cobalt. (a) experimental spectrum; (b) and (c) theoretical spectra from two different theories.

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L-Shell Ionization Cross Sections for Uranium Ions

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Previously, we measured the electron impact ionization cross sections for the tightly bound 1s electrons of several high-Z hydrogenlike ions [1]. For hydrogenlike uranium, our measured cross section was 50% larger than theoretical values available at the time [2], a discrepancy that has since been resolved by improvements to the theory. We obtained the ionization cross sections from the equilibrium abundance of bare and hydrogenlike ions in Super EBIT using the competing (and well known) process of radiative recombination for normalization [3].

Now that the K-shell ionization cross sections have been determined by our previous measurements, we are attempting to apply the same technique to the measurement of ionization cross sections for the L shell of uranium. We determine the equilibrium ionization balance for a population of uranium ions in charge states from U^{89+} (lithiumlike) to U^{82+} (neonlike) from the intensity of radiative recombination x rays associated with each charge state. Unlike radiative recombination into the K shell, for which the x-ray lines corresponding to bare and hydrogenlike target ions are completely resolved in a germanium detector, radiative recombination into the L shell of uranium produces incompletely resolved x-ray lines. This is illustrated in Fig. 1, which shows an x-ray spectrum obtained at 60-keV electron energy. The intensity of the radiative recombination x-ray lines associated with the different charge states, and hence the ionization balance, can be determined from least squares fits using the known relative positions of the x-ray lines. We have obtained data at several different electron energies. When the data analysis is completed, we expect to have ionization cross sections for all of the L-shell ions of uranium at each energy.

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Fig. 1. Top: Spectrum of radiative recombination x rays for uranium target ions. The L-shell lines separate into $j=3/2$ and $j=1/2$ components, each of which contains contributions from several charge states. Bottom: Enlargement of the $j=3/2$ feature. The smooth curve is a fit composed of separate lines whose position is indicated by the crosses.

V. RETRAP AND ION COLLISIONS

X-Rays from Ar^{17,18+} Collisions with C₆₀: Relation to Above Surface Behavior

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A multiply charged ion approaching a metallic surface, captures, at large distances (≈ 20 Å), many electrons into highly excited states. The excited ion then begins a decay through a cascade of Auger transitions, which is not completed before it strikes the surface where remaining excited electrons are "peeled off". In the interaction of a highly charged ion with C₆₀, electron transfer also occurs at radii which greatly exceed the 3.5 Å cage radius, and in the majority of the encounters, the ion passes above a small part of the fullerene surface. To a degree then, this encounter resembles that with an extended surface, however, here there is the possibility of observing the completion of the "above surface" behavior in most of the encounters. To this end, we have observed the K x-ray spectra resulting from the impact of Ar¹⁷⁺ and Ar¹⁸⁺ ions on C₆₀ polymers. We have used ion beams from the Advanced Electron Cyclotron Resonance ion source at the Lawrence Berkeley Laboratory 88" cyclotron, and a Si(Li) detector (160 eV resolution at 5.9 keV) which viewed the intersection of the ion beam and a fullerene vapor beam. C₆₀^{q+} product ions and fragments were also extracted into a time-of-flight analyzer and observed in delayed coincidence with x-rays for the case of Ar¹⁷⁺ projectiles. Figure 1 is a scatter plot of the coincidence data with x-ray energy on the horizontal axis and the ion time-of-flight on the vertical axis. The figure also includes projections on each axis.

We observe that, both for Ar¹⁷⁺ and Ar¹⁸⁺, the singles x-ray spectra are close (apart from intensity) to those from single capture collisions on residual gas in the experimental chamber (C₆₀ beam blocked), i.e. unperturbed He-like and H-like K α , β , γ lines. The coincidence data show, however, that several electrons are captured (C₆₀^{q+} with q up to 5), and there is an evolution of the x-ray spectrum as one moves from events coincidence with C₆₀⁺ to those with the higher charged fullerenes and the low mass fragments. There is some indication of the presence of outer electrons particularly in the emission from initial states with $n > 2$, (K β , K γ . . .).

Thus, although many electrons are captured into states with large principle quantum numbers, for the most part, all but one are ejected in the following Auger cascade. Thus by using C₆₀, perhaps the smallest carbon surface target, essentially above surface behavior is observed. Alternatively one may say that the C₆₀ target (apart from its fragmentation) behaves like a very large polarizable atom. This was the view of Walch et. al¹, and our observations are, at least in part, consistent with their studies with Ar⁸⁺ projectiles, where C₆₀^{q+} ions were observed associated with projectiles retaining only one or two electrons.

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Complex Substate Amplitudes Formed in Double Electron Capture

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The complex amplitudes, a_M , and their dependence upon the projectile scattering angle have been measured for populating the $|L, M\rangle$ substates of the doubly excited $1s[2s2p\ ^1P]\ ^2P$ and the $1s2p^2\ ^2D$ terms of C^{3+} formed in double electron capture by 25 keV C^{5+} ions from He atoms. This was accomplished using a coincident Auger electron/scattered projectile technique to determine the electron anisotropy with respect to the incident beam and scattering plane. The results are the most complete experimental description of a low energy double capture collision and should stimulate comparison with theoretical calculations at the finest quantum detail.

The experiments were done via analysis of the anisotropy in the subsequent Auger electron emission from the decay of the excited states. To determine the relative phases of the a_M the anisotropy must be measured with respect to the collision plane; this requires that a coincidence technique be used. We thus measure the $1s2\ell 2\ell'$; Auger spectrum emitted into a small solid angle at polar angle θ_e , with respect to the C^{5+} beam direction, in coincidence with two dimensional position sensitive detection of the scattered C^{4+} final state ions. A transformation of the coincident scattered projectile positions associated with each Auger line gives the azimuthal coordinate, ϕ_e of the electron emission with respect to the scattering plane and, θ_I , the projectile ion scattering angle. A previous noncoincidence study¹ provided values of the $|a_M|$ averaged over all scattering angles by measuring only the θ_e dependence of the Auger emission rate integrated over all ϕ_e .

The C^{5+} ions were produced by the LBL Electron Cyclotron Resonance ion source, operating at 5 kV potential, and transported via the joint LBL/LLNL beam line facilities. The spectrometer viewed the intersection of the C^{5+} beam with the He jet at angles, θ_e ranging from $\approx 35^\circ$ to $\approx 105^\circ$ with respect to the beam direction. At 0.75 m downstream from the jet the beam entered parallel plates charged to deflect the product C^{4+} ions 17° onto a 40 mm diameter position sensitive microchannel plate (MCP) ion detector located 1.05 m from the deflection plates. The parallel plate electron spectrometer includes a 25 mm diameter MCP detector mounted near the exit plane; the entrance slit is 1×10 mm. The Auger electrons from the $1s2\ell 2\ell'$ levels have energies near 240 eV in the emitter frame. We decelerate these to ≈ 70 eV at the entrance to the spectrometer; this provides resolution (≈ 0.7 eV) adequate to resolve and spread the lines across the detector face. A microcomputer/camac data collection system records 5 parameters for each event: the position of the electron hit from the spectrometer detector (x_e, y_e), the scattered ion position (x_I, y_I) and the output, t_{of} , from a time-to-amplitude converter (TAC) started by the electron and stopped by the ion signals. Position sensitive detection of the electron spectrum and the scattered ion was essential to achieve a usable coincidence rate.

We analyze our observations using a right hand coordinate system with z-axis along the beam direction and y-axis in the collision plane along the direction of the scattered ion's transverse momentum.

Figure 1 displays a sample of data from decay of the 2D term observed at $\theta_e = 54.7^\circ$, and describes the analysis process. The scattered C^{4+} ion positions on the projectile detector, associated with Auger electron emission from $C^{3+}\ 1s2p^2\ ^2D$ are displayed. The panels view the detector face from the beam (z) direction; the electron polar angle was 54.7° . (a) The relationship between the

detector fixed coordinates (x_I, y_I) and the event determined coordinates (x, y). (b) Events not coincident with electron emission (randoms), mostly products of single electron capture. (c) Events coincident with the electron emission from the D term together with randoms. The analysis subtracts (b) from (c), and fits $S_D(\theta_I, 54.7^\circ, \phi_e)$ to the resulting pattern. (d) is a contour plot representing (b)-(a) constructed from the results of the fit. The ions were deflected in the x_I direction for charge analysis. The center of the random pattern is offset from the origin because of the difference in the exothermicity (Q values) for single and double capture (x_I offset) and recoil from the (≈ 240 eV) electron emission (y_I offset). Figures 2 and 3 summarize the results of all measurements for the $C^{3+} 1s(2s2p \ ^1P) \ ^3P$ and for the $C^{3+} 1s2p^2 \ ^2D$ terms.

Figure 1 (see text)

In summary, we have developed experimental methodology which determines the scattering angle dependence of the complex anisotropy in doubly excited states formed in multiple electron capture collisions. This provides a significantly more complete experimental description of the angular character of the excited two-electron wavefunction and its dependence upon the projectile scattering angle (i.e. upon the impact parameter) than previously available. The variation of the charge cloud orientation with scattering angle for the $C^{3+} 1s(2s2p \ ^1P) \ ^2P$ term demonstrates clearly the effect of the loss of electron coupling to the rapidly rotating internuclear axis. Values for the angular momentum normal to the scattering plane suggest that a propensity rule favoring population of $M=L$ substates in single capture collisions may also hold for double capture. The relevant crossings between diabatic states of $[C^{5+}, He]$ (initial channel), $[C^{4+}(1sn\ell), He^+]$ and $[C^{3+}(1sn\ell n'\ell'), He^{++}]$ occur at internuclear separations less than 5 au. The duration of collisions reaching these crossings (at $v=0.3$ au) imply energy uncertainties (10 eV or more) which exceed the separation of the $C^{3+} (1s2\ell 2\ell')$ terms (3.1 eV between P and D). Most of this results from differential screening of the nuclear charge by 1s electron, with a smaller part from the Coulomb interaction between the $2\ell 2\ell'$ electrons. Thus it may be fruitful to regard double capture as the outcome of nearly independent single electron transfers with subsequent evolution into states more fully defined by the electron-electron interaction. A model based upon this approach has been described for population of He-like $3\ell 3\ell'$ and Be-like $1s^2 3\ell 3\ell'$ terms from H_2 and He targets.

Figure 2 (see text)

Figure 3 (see text)

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Auger Decay of Na-like Si^{3+} ($2p^5 3\ell n \ell'$) States Formed in Slow $\text{Si}^{5+} \rightarrow \text{He}$ and Ar Ion-atom Collisions

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High resolution autoionization spectra of multiply-charged Na-like states in silicon are presented. These states have been populated in collisions of Si^{5+} ions with 50 keV impact energy on two gas targets: He and Ar. The electron emission following the decay of core excited $2p^5 3\ell n \ell'$ ($n=3-6$) levels in Si IV has been measured. The comparison of electron spectra obtained after collisions with He and Ar is given. Theoretical Auger energies due to core-excited ($2p^5 3s^2$), ($2p^5 3s 3p$), ($2p^5 3p 3d$), ($2p^5 3s 4s$) and ($2p^5 3s 4f$) states have been calculated relative to the ($2p^6$) 1S limit by using the Multiconfiguration Hartree-Fock (MCHF) method. Additional theoretical estimates of Auger transition energies originating from ($2p^5 3^2$), ($2p^5 3d^2$), ($2p^5 3^2$), ($2p^5 3s 4d$), ($2p^5 3s 6s$), ($2p^5 3s 6p$), ($2p^5 3s 6g$) are also presented.

Studies of the collision dynamics and atomic spectroscopy of highly-excited ions produced by multi-electron capture processes from atomic-, molecular-, or surface targets are of fundamental importance to both basic atomic physics and applied research including technology applications (e.g. high-temperature laboratory and astrophysical plasmas, relevant for fusion and X-ray laser research and plasma diagnostic in general). Na-like systems have been studied intensively using Auger-electron¹⁻³ and optical emission spectroscopies.

In this work we present for the first time a detailed experimental and theoretical study of Na-like Auger spectra in Si IV produced in slow ion-atom collisions:

Auger spectra of Na-like PV were observed earlier in collisions of fast phosphorous ion beams using beam-foil excitation.¹ Moreover Auger energies and decay rates for various states of the P^{4+} ion (PV) with configurations ($2p^5$) $3s^2$, $3s 3p$, $3s 3d$, $3p^2$, $3p 3d$, $3d^2$ were calculated by Karim, Chen and Craseman. Projectile states of the Na-like isoelectronic sequence in SVI, ClVII, ArVIII, TiXII and FeXVI and CuXIX were observed recently in slow and fast ion-atom collisions using He, Ne and Ar as target gas.

In addition X-ray and EUV optical spectra in Na-like ions formed by dielectronic recombination processes were studied in a wide range of nuclear charge $Z=11+22$. These data are of importance for creation of electron recombination EUV and X-ray lasers on the basis of Na-like systems. Detailed theoretical analysis of L-shell Auger and radiative decays arising from the doubly excited $2p^5 3\ell 3\ell'$ states of sodium-like states was performed by Chen for a wide range of ions $Z=20-90$. In this work we focus on the identification of Si IV ($2p^5 3\ell n\ell'$) autoionizing states, in particular $2p^5 3\ell 3\ell'$ configurations.

The high resolution Auger electron spectra of silicon Si^{3+} (Si IV) ions presented in this paper were measured at the Lawrence Berkeley Laboratory (LBL) Electron Cyclotron Resonance (ECR) Ion Source at the 88" cyclotron. The experimental method was described in detail by Hutton et al.³ In brief Si^{5+} ion beams were accelerated and mass and charge analyzed by a 90° bending magnet. These autoionization electrons were separated from the ion beam by a coarse-resolution first stage parallel plate analyzer which was used an electron deflector and a second stage spherical high-resolution spectrometer. To minimize kinematic broadening effects the projectile electrons were observed under zero degree observation angle. The gas in the target was resulted to a pressure as low as 1×10^{-5} Torr. The optimum pressure in the gas cell was chosen after extensive pressure dependence studies to ensure single collision conditions.

Figures 1a and b show characteristic examples of our Si L-Auger spectra arising from interactions of 50 keV Si^{5+} ions on He and Ar. The energy scale and intensities were transformed from the laboratory to the projectile emitter frame. The comparison of Fig. 1a and b clearly indicates that the population of specific $2p^5 3\ell n\ell'$ states differs dramatically for He and Ar as a target.

We have compared a "prompt" spectrum and a time delayed spectrum for 50 keV $\text{Si}^{5+} + \text{He}$ collisions. The corresponding lines associated with the delayed spectrum arise from projectile states, decaying after the gas cell. As can be seen the spectra for $\text{Si}^{5+} + \text{He}$ are dominated by the $(2p^5 3s^2) 2P_{3/2,1/2} \rightarrow (2p^6 \epsilon p) 2P_{3/2,1/2}$ Coulomb allowed transitions. An interesting feature observed in this study is the different intensity ratios for the $(2p^5 3s^2) 2P_{3/2,1/2}$ line structure for the prompt and time delayed transitions, which deviate in both bases from the statistical ratio of 2:1.

In order to classify the observed Auger spectra we have performed detailed theoretical calculations.

The Multiconfiguration Hartree-Fock method has been used very successfully for core excited states belonging to various isoelectronic sequences. The sodium like systems were studied through optical transitions between different core-excited states. The relative position of the $2p^5 3s 3p$ and the $2p^5 3p^2$, $2p^5 3s 3d$ and $2p^5 3s 4s$ configurations was established for some long-lived states. The MCHF calculations predicted the position and lifetime of these states in good agreement with observations. In the calculations three different decay branches were included: optical transition between core excited states, short wavelength, optical transitions to "normal states" (with closed $2p^6$ core) and autoionization to the $2p^6 \epsilon \ell$ 2L continua. We have predicted the Auger transition energies of the core-excited states, relative to the $2p^6$ 1S limit.

In conclusion we have identified 55 new Auger structures in Si L-Auger spectra subsequent to $\text{Si}^{5+} + \text{He}$ collisions. In particular the observed $2p^5 3\ell 3\ell'$ and $2p^5 3\ell 4\ell'$ configurations in Si IV exhibit strong electron correlation effects. Our theoretical MCHF calculations are in excellent agreement with the assigned experimental peak positions. Our spectroscopic results are of importance to unravel the

details of the collision dynamics for two electron capture in multicharged Si ions interacting with gaseous targets. For example, we have found evidence here for strong non statistical population of the $(2p^5 3s^2)^3P_{3/2,1/2}$ fine structure levels in 50 keV $\text{Si}^{5+} + \text{He}$ and $\text{Si}^{5+} + \text{Ar}$ single collisions. This interesting new process should be analyzed theoretically in the new future. We also plan to extend our calculations of $2p^5 n\ell n\ell'$ states of other ions of the Na-like isoelectronic sequence.

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Fig. 1 a),b). Projectile Auger spectra of Si IV formed in a) 50 keV $\text{Si}^{5+} + \text{He}$ and b) 50 keV $\text{Si}^{5+} + \text{Ar}$ collisions. Electron energies are given in the projectile frame.

Measured Charge Exchange Between Highly Charged Ions and a Neutral Gas

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Charge exchange rates between highly charged ions (e.g., Th^{72+}) and a neutral background gas have been measured in a cryogenic Penning trap (RETRAP).¹ The highly charged ions are produced in the LLNL electron beam ion trap (EBIT). The ions are then extracted from EBIT with about $q \times 5000$ V of kinetic energy, transported through a selecting magnetic (EBIT produces a plethora of charge states) from which a single charge state emerges. The selected ions are further transported into a cryogenic vessel where some are decelerated and captured in the Penning trap. We determine the charge exchange rate by monitoring the number of ions of various charge states in the trap as a function of time.

The cryogenic Penning trap consists of two endcap electrodes, two compensation electrodes and one central electrode for axial confinement and a 6T magnet for radial confinement. The lengths of the electrodes are chosen so that low energy, trapped ions are in a nearly harmonic potential with an axial oscillation frequency f_z given by,

$$f_z = \sqrt{qV_0C_2 / (md^2)} / (2\pi) \quad \text{Eq. (1)}$$

Here, q and m are an ion's charge and mass respectively, V_0 is the endcap voltage, $C_2 = 0.5449$ and $2d^2 = (z_0^2 + r_0^2 / 2)$ where r_0 is the radius of the trap and $2z_0$ is the sum of the lengths of the central and two compensation electrodes. An inductor is connected between the compensation electrodes, which in conjunction with stray capacitance creates a tuned circuit with a central frequency of 1.215 MHz. The tuned circuit, with a cryogenic, low noise amplifier connect to one end of the inductor, has a Q of about 200.

The tuned circuit amplifies the induced signal on the compensation electrodes due to ions whose axial frequency is near the tuned circuit frequency. Figure 1-b shows an example of the tuned circuit signal when the voltage on the end electrodes is varied (see Fig. 1(a)). The spike in the signal is due to Xe^{44+} ions whose axial frequency matches the tuned circuit frequency when the end voltage is about 90 V (see Eq. (1)). The data in Fig. 1(b) was obtained two seconds after the ions were captured. Figure 1(c) shows a similar plot taken 102 seconds after the ions were captured. Charge capture by the trapped ions from a background gas has produced several lower charge state Xe ions (note the vertical scale change). Scans similar to those in Fig. 1(b) and (c) are taken every 10 seconds and the Xe^{n+} peaks are fitted to obtain the relative number of Xe^{n+} ions as a function of time.

In figure 2 the relative number of ions for various charge states of Xe, where Xe^{45+} is initially captured, are plotted versus time. The solid lines are a fit to the data. The fit yields the charge exchange rate (76s) and the ratio of double electron capture rate to the total electron capture rate. Charge exchange rate data for various charge states of Be, Ar, Xe and Th ions have been measured.

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Fig. 1 Ramped endcap electrode voltage (a). Tuned circuit signal 2 sec. (b) and 102sec. (c) after Xe^{4+} ions are captured.

Fig. 2 Relative number of Xe^{n+} ions as a function of time.

Demonstration of Stacking of Highly Charged Ions In RETRAP

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Ions stored in RETRAP are cooled by adjusting the voltage of the endcap electrodes to make the axial ion oscillation frequency equal to the resonance frequency of an external tuned circuit. Image currents induced by ions on resonance are amplified by a preamp in the RETRAP chamber [1].

In order to trap highly charged ions in RETRAP it is necessary to pulse the top electrode. The top electrode is held at a low voltage for at least one axial oscillation period. The voltage on the electrode must change on a time scale which is fast relative to the oscillation time of an ion in RETRAP. In previous RETRAP experiments the top electrode was pulsed down to zero volts for ion insertion. In principle this allows for ions to be inserted with arbitrarily low energy.

In order to increase the density of ions in RETRAP, we attempted to "stack" the ions from several EBIT pulses. The voltage of the top endcap during insertion remained high enough so that cold ions remain trapped (see figure 1). Ions inserted must have sufficient energy to make it over the potential barrier of the top electrode to get into the trap. Consequently, they enter with enough energy that they could escape during the next insertion phase. However, if the ions cool sufficiently during the holding phase, they will not be able to escape during the next insertion. It is important to note that, because the position of the potential minimum is different during the holding and injection phases, all ions stored for multiple injection cycles will be heated somewhat during each injection.

Figure 2 shows data from a recent experiment. The trap is empty during the first cycle, and the increase in signal strength indicates that at least some ions remain confined over multiple injection cycles and new ions are successfully added. However, signal strength is a convolution of ion number and ion energy. Results must be considered preliminary in that it is as yet unknown how much of the signal increase is due to an actual increase in ion number and how much is due to a change in ion energy.

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Figure 1

Xenon Stacking

Figure 2

Ion Cooling at RETRAP

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Highly-charged high- z ions (HCHZI) from EBIT have been successfully ejected from and re-trapped in a Penning ion trap to permit the ions to be cooled, since they no longer interact with an electron beam. Cooling is the first step toward forming condensed (crystallized) ion states, and for experiments like ultra-precision laser-ion spectroscopy.

Initially, the ions have a mean kinetic energy near $2 q$ eV after capture in the Penning trap (q denotes the ion charge state). Although this kinetic energy is extremely low for most highly-charged ion research, it is still large compared to the value needed for crystallization, and comparable to typical inter-ion potential energies. To eliminate the possibility of ion-ion electron transfer when binary mixtures of ions are required for cooling or astrophysical studies, it is desirable to cool the ions electronically. This can be accomplished by coupling the harmonic axial motion of the stored ions to a high-impedance parallel L-C circuit composed of the Penning trap electrode capacitance and an external inductor (see Figure 1). When the ion motional frequency is tuned to the circuit resonance, the randomly moving ions induce fluctuating currents through the tuned circuit, which dissipate energy in the tuned circuit resistance. This energy must come from the ion motion. An alternative way of understanding the same effect is that the induced currents produce voltages, and hence fields, across the trap which oppose the ion motion. These voltages on the tuned circuit constitute a signal proportional to the ion number and mean energy in the trap.

The damping time constant T for one-dimensional axial damping is given by the expression $T = 4\pi m d^2 / q^2 R$, where the ion mass-to-charge ratio is m/q , d is a characteristic trap dimension, and R is the resistance of the tuned circuit at resonance. With typical parameters for highly-charged ions, T has values of a few hundred milliseconds, close to the observed value[1] (see Figure 2). One sees that the extra "noise" signal produced by the confined ions is damped exponentially for short times.

Fig. 1. Schematic of open-ended cylinder trap and detection circuit.

Fig. 2. Signal of one Xe^{44+} ion (solid line). The thermal noise of the tuned circuit has been subtracted. The dotted line is a fit of a single exponential decay function to the measured data. The fit-curve with a decay time constant of 0.83 s describes the measurement quite well.

This cooling method will cool all degrees of freedom (even internal) of the ion motion if they are coupled to the tuned circuit, e.g. by ion-ion collisions. This coupling multiplies the cooling time constant by 3 for fast coupling of the motional degrees of freedom, but ten time constants, sufficient to cool the ions from 2 q eV to near 50 K temperature, are still ten times shorter than current HCHZI storage times in the trap. So far, the lowest temperatures for electronic cooling have been limited by the axial-radial motional coupling times, associated with the small numbers of ions trapped at one time.

Since electronic cooling couples energy out of the stored ion center-of-mass motion, it is not obvious that the ions can be directly cooled to the 10 K temperatures required for crystallization wholly by this means. An alternative, which is expected to work well for ion temperatures under 1 eV, is a form of laser cooling. Stored Be^+ or Mg^+ ions, which have resonance transitions in the cw (frequency-doubled) laser range, can be directly laser-cooled by scattering photons tuned just below the ion transition frequency. If a small number of electronically pre-cooled HCHZI are introduced (merged with) a larger number of laser-cooled ions, the ion-ion Coulomb collisions between the two species at different temperatures should further cool the HCHZI. The energy transferred to the Be^+ ion "heat sink" will be removed by continued laser cooling. Since the collision cross section increases as the relative collision energy decreases, this cooling method is expected to be particularly effective at sub-eV energies. A special Penning trap system has been designed to facilitate separate laser-cooling of Be^+ ions, electronic cooling of HCHZI, and ion merging (stacking).

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Design of a Hyperbolic Trap System for Sympathetic Ion Cooling in RETRAP

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The proposed study of highly correlated plasmas and precision hyperfine structure measurements of highly charged, high Z ions (HCHZI) in a Penning trap requires ions at low temperatures ($kT \ll 1$ eV). The lowest temperatures of trapped, low charge state ions has been achieved by means of laser cooling¹. Unfortunately the HCHZI cannot be laser cooled directly due to the high energy difference of the electronic states. Therefore an indirect cooling of the HCHZI has to be implemented. The $2s^2S_{1/2}(M_I, M_J) = (-3/2, -1/2) \rightarrow 2p^2P_{3/2}(-3/2, -3/2)$ transition of $^9\text{Be}^+$ with a wavelength of $\lambda = 313$ nm can be used for laser cooling¹. By simultaneous trapping $^9\text{Be}^+$ and HCHZI the latter lose their kinetic energy due to collisions with the $^9\text{Be}^+$ ions until thermal equilibrium is established.

Since such a cooling scheme is impossible in our present open ended cylindrical trap a new trap with hyperbolic electrodes has been designed. As can be seen from Figure 1 the trap actually consists of two Penning traps. The lower trap is for catching, electronic precooling (by means of a tuned circuit attached to the endcaps) and laser cooling of the $^9\text{Be}^+$ ions. The upper trap will be used to catch and electronically cool HCHZI. After transferring the HCHZI into the lower trap a further reduction of their energy due to collisions with the Be ions will take place.

Fig. 1. Sketch of the new trap. It consists of two Penning traps with hyperbolic electrodes. $^9\text{Be}^+$ ions will be caught in the lower trap while the upper trap is for catching HCHZI. The electrode geometry is chosen to minimize the ion frequency dependence on the setting of the compensation electrode potential².

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VI. INSTRUMENTAL DEVELOPMENT

Implementation of a Very High Resolution Crystal Spectrometer on EBIT

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The ion temperature represents a determining parameter for the trapping and production of highly charged ions in an electron beam ion trap. In EBIT, ions are contained electrostatically. Radially they are confined by the space-charged potential of the electron beam and axially by a potential applied to the top and bottom electrodes of a cylindrical trap. While the latter potential can be set to an arbitrarily high value (typically $V_{ax} \leq 500$ V), the radial potential is limited by the achievable beam current and beam density to about 10 V at the edge of the beam. As a result, ions with a transverse temperature $T_i \geq 10q$ eV will not be confined in the volume of the beam and may leave the trap. Measurement and control of the ion temperature is thus crucial for long trapping times. It is also crucial for attaining very high charge states. For example, the time to fully strip uranium by electron-impact ionization is about 25 s. Thus, the uranium ions of various intermediate charge states must remain "cold", i.e., below a temperature of a few hundred eV, if they are to stay long enough in the trap to become fully ionized.

For measuring the ion temperature we implemented a very high-resolution Bragg crystal spectrometer with nominal resolving power $\lambda/\Delta\lambda \leq 22,000$ [1]. The resolving power of the instrument exceeds that of previous instruments by almost an order of magnitude. With this instrument we infer the ion temperature from the width of a characteristic x-ray line that is broadened by the Doppler effect.

The design of our high-resolution crystal spectrometer is based on the geometry proposed by von Hámos [2]. A spectrometer based on this geometry functions like a flat-crystal spectrometer in the plane of dispersion but provides focusing for rays perpendicular to the plane of dispersion. To achieve this the analyzing crystal is bent cylindrically and placed such that the axis of the cylinder lies in the plane of dispersion. The von Hámos geometry requires a point or line x-ray source. The implementation of the von Hámos geometry on extended sources, such as tokamaks, necessitates, therefore, the use of an entrance slit. The use of an entrance slit is unnecessary on EBIT, because EBIT represents a slit-like line source whose dimensions are determined by the 60- μ m diameter electron beam and the 2-cm long trap length.

The resolving power of our instrument is determined by various factors. Aberrations are introduced by the finite height h of the source, which in the case of a crystal with an opening angle $\phi < \theta/\sqrt{2}$ limit the resolving power of the spectrometer to $\lambda/\Delta\lambda > 4R^2/h^2$. This must be compared to the limitation caused by the finite diameter of the line source Δx , which yields $\lambda/\Delta\lambda = 2D \tan\theta/\Delta x$, and by the finite spatial resolution Δs of the detector, which yields $\lambda/\Delta\lambda = 2D \tan\theta/\Delta s$. Here, $D = R/\sin\theta$ is the distance between crystal and detector as well as between crystal and source. An increase in the resolving power of the spectrometer is accomplished by increasing the radius of curvature of the crystal and thus by increasing the overall dimensions of the spectrometer. In our instrument we employed $120 \times 50 \times 0.25$ mm³ crystals with four different values of curvature $R = 30, 75, 120$, and 240 cm. The nominal resolving powers attainable with these crystals at a Bragg angle $\theta = 45^\circ$ are $\lambda/\Delta\lambda = 1860, 6300, 10,700$, and 22,000, respectively, as illustrated in Fig. 1.

Here, we take $h = 1.2$ cm, $\Delta x = 60$ μm , and $\Delta s = 300$ μm . In all cases but $R = 30$ cm, the resolving power is limited by the spatial resolution Δs of the detector. The actual resolving power achieved also depends on the intrinsic resolving power of the particular type of crystal employed. To attain the best resolving power we employed quartz crystals with intrinsic resolving powers better than 100,000 in our instrument.

The new instrument was successfully used to measure the temperature of ions in EBIT. Under standard operating conditions for x-ray spectroscopy a typical temperature in excess of 1000 eV was found [1]. However, after systematic attempts to lower the ion temperature line widths better than $\lambda/\Delta\lambda = 12,000$ were observed corresponding to temperatures less than 100 eV [3].

FIG. 1. Nominal resolving power of our crystal spectrometer as a function of the radius of curvature of the analyzing crystal.

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Fourier Transform Ion Cyclotron Resonance Mass Spectrometry: A New Tool for Measuring Highly Charged Ions in EBIT

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The EBIT was originally designed for studying trapped ions by analyzing the emitted x rays. The analysis of the emitted x rays was the only diagnostic technique available until the advent of an extraction system that allowed the study ions outside the EBIT. In a collaboration with the University of Mainz, we have recently begun to develop Fourier-transform ion cyclotron resonance (FT-ICR) mass spectrometry as another *in situ* method to study highly charged ions in EBIT. Initial application of FT-ICR mass spectrometry to EBIT ions was highly successful [1]. It demonstrated (1) good coupling between the exciter signal and the ions, (2) a long confinement of the ions in the trap, (3) a long coherence time for the collective cyclotron motion, and (4) reasonable low noise characteristics of the trap [1]. Our efforts in the past year have established the reliability of the method by comparing FT-ICR results to those obtained from standard x-ray spectroscopy [2].

For many years the FT-ICR method has been applied with great success to the study of singly or few-times ionized atoms and molecules. It makes use of the characteristic ion cyclotron frequency ω associated with the circular ion motion in a homogeneous magnetic field B to determine the ratio of mass m and charge q ,

$$\omega = qB/m$$

The cyclotron frequency is measured in three steps: excitation, detection, and Fourier transformation. In the first step, the cyclotron motion of the ions is excited by sweeping over a range of frequencies that includes their resonant cyclotron frequency. Excitation at the resonant frequency forces the ions to perform a coherent cyclotron motion. The coherent cyclotron motion in turn induces image charges on detection electrodes, resulting in a transient signal that when Fourier analyzed provides the value of ω . Typical cyclotron frequencies for the highly charged atomic ions in EBIT's 3-T magnetic field are near 20 MHz.

A typical FT-ICR spectrum is shown in Fig. 1, which illustrates the frequency spectrum obtained following an excitation by sweeping over a frequency range from 17.5 to 19.5 MHz in a 300- μ s interval. The spectrum shows the location of the resonance peaks from heliumlike $^{84}\text{Kr}^{34+}$, hydrogenic $^{84}\text{Kr}^{35+}$, and bare $^{84}\text{Kr}^{36+}$. No signal averaging has been applied in the FT-ICR spectrum. The signal-to-noise ratio can be significantly increased by averaging several transients.

FIG. 1. FT-ICR spectrum heliumlike, hydrogenic, and bare ^{84}Kr ions excited by a 300- μ s broadband sweep from 17.5 to 19.5 MHz.

Broadband excitation provides a good way of locating the respective resonances of particular ions [3]. Moreover, the intensity of the resonance peaks is related to the number of ions executing coherent cyclotron motion, and, in principle, provides a means for determining the relative ion abundances. However, the radial nonuniformity of the magnetic field has so far prevented us from obtaining a reliable value of the relative ion abundances when using a broadband sweep over several resonances. This is because the ions change their resonance frequencies as they assume larger cyclotron orbits sampling weaker magnetic fields. Instead we used a slow excitation sweep (500–1000 μ s) for a single resonance that followed the drop in the resonance frequency of a particular ionization stage as the ions moved to larger orbits [2].

With the slow excitation sweep we measured the abundance ratio of bare and hydrogenic krypton ions shown in Fig. 2. The ratio was measured as a function of time after injecting krypton into EBIT. The time evolution of the production of bare krypton is clearly seen. To check the reliability of the FT-ICR results, we determined the abundance ratio concurrently using x-ray techniques to count the photons produced by the radiative capture of beam electrons into the 1s level of bare and hydrogenic krypton ions. This method has been shown earlier to provide accurate charge states abundances [4]. The values obtained with the x-ray technique are also plotted in the figure, and excellent agreement between the two methods can be seen.

FIG. 2. Relative abundance of hydrogenic Kr35+ and bare Kr36+ as a function of time after injection into the EBIT trap. Measurements were made with the FT-ICR method and an x-ray technique. The solid and dashed lines are drawn to guide the eye.

The excellent agreement between the FT-ICR results and the x-ray data proves the reliability of the FT-ICR method. There is, however, a significant difference between the two methods: the FT-ICR method provided a time-dependent abundance ratio within about 20 minutes of observation time and achieved a 5-% uncertainty; the x-ray measurements required about 8 hours and achieved only a 10-% statistical uncertainty. This time advantage opens the possibility for studying time-dependent ionization and recombination processes, such as charge-exchange recombination of highly charge ions with neutrals.

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Improvements to SIMS TOF Detection and UHV Vacuum Systems

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Improvements in the single detector time-of-flight (TOF) spectrometer system, developed at LLNL [1,2] for the measurement of secondary ion yields following the incidence of slow very highly charged ions (SVHCIs) on clean surfaces, have been made. Additionally, improvements in the vacuum system have been performed [3] and UHV ($< 10^{-10}$ Torr) conditions are now readily and regularly obtained. A typical quadrupole mass spectrum of the residual gas in the scattering chamber under operating conditions, all beam-line valves open and samples in scattering chamber, is shown in Figure 1.

The experimental arrangement for SIMS measurements, shown schematically in Figure 2, is demonstrated to allow for absolute measurements of the secondary ion yields produced by the impact of SVHCIs on solid surfaces. This system incorporates a 40 mm diameter channel plate detector and provides an improved and quantifiable detection solid angle and efficiency over the previous 25 mm dia. single micro-channel plate annular detector design, described earlier [1,2]. In addition, the position sensitive anode allows for angular distribution measurements of secondary ions and for average distributions of potential electron emission, necessary for accurate relative electron yield measurements, as described elsewhere in this report. The sample is biased at a high potential (e.g. 1 to 2 kV), and the detector grid is grounded, providing an accelerating field for the emitted particles. Due to the nature of the highly charged ion - solid interaction, many electrons and photons (UV) are emitted at the time of projectile incidence on the target [4,5]. These multi-particle events can be used to trigger the start input of a time-to-amplitude converter (TAC) or time-to-digital converter (TDC). The polarity of the sample bias is determined by the nature of the secondary ions under investigation (i.e. positive or negative secondary ions).

Since the secondary ions arrive at the detector individually, they produce smaller amplitude signals than the multiple particle events do. These smaller signals are used to trigger the stop input of the TAC or TDC. Typical bimodal pulse height distributions from both fast and slow amplifier outputs for such an arrangement, with the sample (SiO_2 film on Si) biased at -2000 V and an incident Th^{65+} beam, are shown in Figure 3. Therefore, the events due to secondary ions can be discriminated against those due to the electron emission. Similar pulse height distributions are found for positive bias, though the average signal amplitude due to photon emission is several times less than that for electrons, under comparable conditions. The discrimination is accomplished via standard electronics, with a delay between the amplifier output and the start constant fraction discriminator (CFD), allowing for investigations of the effect of the single TAC setup on the measurement of multiple ion production (detector opacity). In this way, a measure of the correlation of the various emitted ions can be determined. Because of this correlation, the data must be corrected for the associated blocking effect of early events on the measurement of latter events. A detection efficiency of 10 % has been estimated for the secondary ions: derived from electrostatic analysis of the secondary ion paths, yielding a collection efficiency of 35 %, as well as a 30 % efficiency of the micro-channel plate pair and the associated electronics for the generation of a measurable signal upon the incidence of keV secondary ions [6]. Together with the fact that each incident SVHCI produces one start pulse, absolute secondary ion yields can be determined. The timing signals are produced through capacitive decoupling of the front or rear channel plate bias, allowing for position (e.g. angular distribution) information to be extracted from the anode. This arrangement has provided 100% detection efficiency for HCI flux measurements. It should be noted that due to the nature of the single particle detection scheme, an incident flux of only 100 to 1000 ions / s is required.

Figure 1: Residual gas spectrum in ion scattering chamber under operating conditions. The y axis measure, detector current from an electron multiplier, has been calibrated to be equal to the partial pressure in Torr, normalized to the response of N_2 .

Figure 2: Schematic representation of single detector TOF SIMS set-up. PA and MA: pre and fast filter amplifier, CFD: constant fraction discriminator, TAC: time-to-amplitude converter and PS-MCD: position sensitive micro-channel plate detector.

Figure 3: Pulse height distribution for very highly charged ions incident on SiO_2 surfaces from a) rear channel plate and fast filter amplifier (fast-10ns) and b) resistive anode and spectroscopic amplifier (slow-0.25 us).

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4-Grid LEED-Auger System

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We have installed a 4-grid LEED-Auger system [1-3] in the sample preparation chamber in order to characterize our samples during experiments at EBIT. The system comprises reverse-view LEED /Auger optics from Princeton Research Instruments, a Perkin-Elmer 11-020 LEED power supply, a Stanford Research Systems SR830 lock-in amplifier, a TREK programmable high-voltage supply, a Keithley 617 multimeter, and a home-built preamplifier/battery-box. The system is controlled over a GPIB interface. The system is shown schematically in Figure 1.

Figure 1: Block diagram of 4-Grid LEED / Auger system.

The logic is as follows:

- overall control of the system is done via a GPIB interface.
- the SR830 is used to generate the programming voltage for the TREK programmable supply as well as the sine-wave modulation voltage used in this type of system:
 - depending on what retarding voltage is needed, computer causes the SR830 to generate a 0 to -10 volt DC signal. This signal goes to the TREK programmable supply, which generates the desired 0 to -1000 volt retarding voltage. The sine wave output of the SR830 is superimposed onto this DC retarding voltage in the 'mixing box' and sent to grids 2 and 3 of the LEED system.
- the collected signal from the phosphor screen of the LEED system is pre-amplified and passed to the input of the SR830. The strength of the second-harmonic of this signal is read from the SR830 by the computer, via the GPIB bus.
- the computer also (optionally) reads the sample current from a Keithley 617 multimeter.

- this process is repeated for each point in the spectrum.

The spectrum can then be stored, rescaled, and printed.

Although the electron gun is rated for 25 to 50 μA beam current at up to 3kV beam energy, we operate the system at much lower power levels — typically several μA beam current at 1.6kV beam energy — to reduce damage to our samples. Electron beam spot sizes on the sample are below 1mm.

A sample spectrum, of sputter-cleaned mica, is shown in Figure 2.

Figure 2: Auger spectrum of a sputter-cleaned mica sample.

This particular spectrum (1 sweep, 1 second per point) was acquired with a primary beam energy of 1.6kV, a primary beam current of 3.5 μA , a modulation voltage of 3.4VAC (rms), and a modulation frequency of 1kHz. The noise level in the carbon region is less than 2% of the oxygen peak-to-peak height.

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A Universal Scattering Chamber for Photon-Atom Interaction Studies at LBL's Advanced Light Source

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We have built a universal scattering chamber for measurement of EUV photon interaction cross sections with atomic and molecular targets. This chamber is shown in Figure 1 and has been tested recently at the Advanced Light Source on the new atomic physics beamline 9.0.2. First high resolution photon measurements of ionization-excitation of He have been made using a novel four-channel multilayer mirror spectrometer and other new unique EUV instrumentation. The base vacuum of the main chamber is high 10^{-8} Torr and is pumped on by a 1500 l/sec turbo pump. The entire chamber can be back-filled with a uniform density of target gas and is isolated from the ultra-high vacuum of the ALS by a highly effective differential pumping cross. With a chamber pressure of 5×10^{-5} Torr of Helium, the pressure at the output of the differential pumping cross is 2×10^{-7} Torr. The remaining pumps in the ALS beamline further reduce this pressure to the mid 10^{-9} Torr range at the switching mirror. Higher target pressures can be achieved for other measurements by using a gas cell.

Figure 1. Schematic SIDE view of experimental setup for photoionisation of gaseous targets. The Setup includes a 4-channel polychromator for fluorescence measurements and an electron spectrometer for autoionisation studies.

The chamber is equipped with a remotely adjustable precision rotatable bearing mounted on a general purpose optical table, located at chamber center. The table and bearing can be used to mount photon, ion, and electron spectroscopic instruments for fixed and/or angular dependent measurement in the horizontal scattering plane. A double layer of magnetic shielding significantly reduces the background magnetic field making the chamber suitable for low energy/high resolution electron spectroscopy measurements. A general purpose chamber such as this can allow many independent users to field their instruments with a minimum set-up time which is a key factor at the heavily subscribed atomic physics beamline.

Figure 2. Schematic TOP view of experimental setup for photoionisation of gaseous targets. This figure illustrates the multi-faceted capabilities of the experimental apparatus which includes angular distribution studies in two independent planes and multi-parameter coincidence experiments.

First on-line Experiment with Microcalorimeter to Study X-Ray Emission Following a Highly Charged Ion Interaction with a Surface

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A high resolution, broad band x-ray microcalorimeter has been used for the first time to investigate the radiative deexcitation of highly charged 7 keV/q Ar¹⁷⁺ ions as they interact with a beryllium surface at normal incidence. The 20 eV energy resolution of this instrument made it possible to clearly distinguish the argon K α and K β , γ complex simultaneously. The intensity ratio of the K β , γ to K α emission is 31%, compared to the 8% found in the neutral argon atom. There is strong evidence that the relative intensities of the KLⁿ (n=1-8) satellite transitions do not agree with those obtained previously with crystal spectrometers.

X-ray spectra have been obtained in ion-surface experiments with low resolution ($E/\Delta E \sim 50$) semiconductor ionization detectors for Ne^{9+,10+}, Ar^{17+,18+}, Kr³⁶⁺, Xe⁴⁴⁺⁻⁴⁸⁺ and U⁶²⁺⁻⁷³⁺ [1]. High resolution measurements have been made on Ne⁹⁺ and Ar^{17+,18+} using crystal spectrometers ($E/\Delta E \sim 500$) [2]. Early experiments were performed by Donets, who bombarded a beryllium target with Ar¹⁷⁺ ions with a velocity of 3×10^7 cm/s and measured the x-ray emission with a germanium ionization detector. Similar measurements by Briand et al. [2] were made with a lithium-drifted silicon ionization detector. The energy resolution of the detector was not sufficient to separate the contributions of the individual α , β , γ transitions without the use of a spectral model. The entire spectrum covering the Ar K α , β , γ emission from 2.6 keV to 4.2 keV was obtained simultaneously.

Briand et al. [2] also conducted more detailed studies of the narrow band K α emission with a crystal spectrometer. Although the crystal spectrometer is rather inefficient, it was capable of resolving the emission from L-K transitions with the number of L electrons ranging from 1 to 8.

Here we report on the first use of a high resolution, broad band microcalorimeter as an x-ray spectrometer for the study of Ar¹⁷⁺ ions interacting with a beryllium target at normal incidence. This experiment took advantage of the ion source capability of the Electron Beam Ion Trap (EBIT) at the Lawrence Livermore National Laboratory (LLNL) to produce these highly charge-state ions. The microcalorimeter not only can measure efficiently the broad energy band covered by the semiconductor ionization detector, but it can simultaneously provide an energy resolution comparable to that of a crystal spectrometer.

Microcalorimeter development has been motivated to date by space-based, high energy x-ray astronomy applications. Operating at temperatures between 50 mK and 300 mK, microcalorimeters provide high resolution spectra without the bandwidth and sensitivity limitations of a crystal spectrometer. In a calorimeter x-ray photons are absorbed and thermalized in a detector which is weakly coupled thermally to a cold bath. Their resulting rise in the detector's temperature is measured with a thermal sensor, resulting in a signal proportional to the x-ray energy. For the temperature rise to be measurably large the material must possess a very small heat capacity. In an ideal microcalorimeter the photon-

induced temperature rise must be measured above background temperature noise caused by the random exchange of energy through the thermal link between the cold stage and the detector. This phonon noise manifests itself in the calorimeter as thermal fluctuations. The mean square value of this thermal noise is $\langle dT^2 \rangle = kT^2/C_v$, integrated over all frequencies. If other noise terms are absent, phonon noise would be the only factor limiting the signal to noise ratio, and hence the resolving power is $\Delta E = (kT^2C_v)^{1/2}$. With the proper choice of materials, the resolution of an x-ray calorimeter operating at a temperature of 100 mK, can in principle, be < 1 eV. This resolution is independent of the x-ray energy.

To convert the calorimeter temperature changes into useful voltage signals, experimenters have traditionally taken advantage of the strong temperature dependence of resistance, R , in doped semiconductor crystals. Maximizing the thermistor responsivity, $\alpha = 1/R(dR/dT)$, and minimizing the electronic noise will make the best microcalorimeters. Several electronic readout schemes are used and the reader is referred to the literature.

In practice, the microcalorimeter must be divided into two major components. To maximize the collecting area, the x-rays are absorbed in a high-Z superconductor thermistor is the dominant contribution to the device, the thermistor must be made as small as possible and attached to the superconducting absorber. Our recent experiments at 80 mK with NTD (neutron transmutation doped) germanium thermistors coupled to a superconducting absorber of tin demonstrated high spectral resolution (18-20 eV) and high quantum efficiency (95%-100%) over the energy band from 0.5 keV to 7 keV.

In the surface physics experiment presented here, the microcalorimeter was used for the first time³ to investigate the radiative deexcitation of highly charged 7 keV/q Ar^{17+} ions as they were steered out of the EBIT and into a thin beryllium surface at normal incidence. The microcalorimeter cryostat was connected to the vacuum beam line in such away as to allow the highly charged ions to travel into the cryostat where it struck a 25 μm beryllium target. This target was mounted on the end of a collimating tube connected to the 1.8 K (pumped He^4) stage that served as part of a two component thermal radiation shield. A radioactive source of Fe^{55} was incorporated into the beam line on a linear feed through for in-situ calibration of the microcalorimeter at 5.89 keV and 6.49 keV ($\text{Mn K}\alpha$, $\text{M}\beta$). Approximately 10^3 Ar^{17+} ions were extracted from the EBIT during a 100 ms extraction cycle. Since the detector subtended a solid angle at the point of ion impact on the beryllium target of $\approx 2.5 \times 10^{-3}$ sr, the net count rate on the detector was ~ 2 photons per ion dump.

Ar^{17+} ions with a velocity of 8×10^7 cm/s struck the 25 μm beryllium target. The microcalorimeter spectrum, including the calibration lines from $\text{Mn K}\alpha$ and $\text{Mn K}\beta$, is shown in Figure 1. Using the Mn K x-rays, we measured the energy resolution of the microcalorimeter to be 20 eV. This resolution is an improvement of at least seven times over the previous measurements obtained with silicon and germanium ionization detectors at 6 keV. At 3 keV the improvement is at least a factor of six. This made it possible to clearly and unambiguously distinguish the argon $\text{K}\alpha$ and $\text{K}\beta, \gamma$ complex simultaneously, which are shown in an expanded view in Figure 2. The intensity ratio of the $\text{K}\beta, \gamma$ to $\text{K}\alpha$ emission is 31%, compared to the 8% found in the neutral argon atom. The vertical lines in the spectrum represent the energies of the L-K transitions measured previously with a crystal spectrometer with 5-6 eV resolution. The 20 eV resolution of the microcalorimeter just begins to resolve the strong KL^5 and KL^6 components. More importantly, the spectrum indicates that the contributions from transitions KL^5 and KL^6 are the most intense. This is in marked contrast to the measurements made with crystal spectrometers by Briand et al. and the results inferred from the measurements with a germanium ionization detector made by Donets.

Fig. 1 The microcalorimeter spectrum obtained from Ar^{17+} ions as they strike a $25\text{ }\mu\text{m}$ beryllium target with a velocity of $8 \times 10^7\text{ cm/s}$. The calibration lines from Mn K α and K β , measured in-situ, are also shown.

Fig. 2 An expanded view of the Ar K α and K β,γ complex. The intensity ratio of the K β,γ to K α emission is 31%. The vertical lines represent the energies of the L-K transitions measured previously with a crystal spectrometer with 5-6 eV resolution [4].

The high resolution of the microcalorimeter made it possible to measure the Ar^{17+} $K\alpha$, $K\beta$, and $K\gamma$ x-ray spectra simultaneously for the first time. It also enabled us to observe KL^n transitions with relative intensities differing from work performed previously. To compare the overall spectral shapes of the measurements made to date, we have scaled the crystal spectrometer data from Figure 2, overlayed it on the microcalorimeter data and display them together in Figure 3. We have also convolved the crystal data with the microcalorimeter instrument response function and depict the result by the smooth solid curve. It is clear that the relative intensities of the KL^n ($n=1-8$) transitions observed with a crystal spectrometer are very different than those observed with the microcalorimeter. Discussions in the literature of the crystal spectroscopy data state that the intensities of the eight K-L transitions in Ar^{17+} were comparable to within a factor of two, regardless of incident velocity. The crystal spectrometer data reproduced in Figure 7 are a subset of the experiments done for varying incident velocities and are consistent with this finding. The data also show that the low and high n states are stronger relative to the $n=5$ transition than that observed by the microcalorimeter.

Fig. 3 A comparison of the crystal spectrometer data for $\text{Ar } K\alpha$ from Figure 2 (dotted) with the microcalorimeter data (solid histogram). The thin, smooth, solid curve represents the convolution of the crystal spectrometer data with the microcalorimeter instrument response function using an energy resolution of 20 eV. The convolved spectrum is normalized so that its peak intensity equals the intensity of the KL^5 transition measured by the microcalorimeter. If the relative intensities of the KL^n transitions were the same for both measurements, the smooth curve would coincide with the microcalorimeter data.

The reasons for these discrepancies are not clear at this time. It has been suggested that the KL^n distribution strongly depends on the nature of the target and surface. We note, however, that a crystal spectrometer would have required an ion source 300 times more intense or an observation time 300 times longer to achieve equivalent results on the EBIT. The broad band sensitivity of the microcalorimeter also eliminated the uncertainties associated with cross-calibrating a series of narrow band measurements with one or more Bragg crystal spectrometers. These may be hints to why the measurements are different.

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A Wire Probe Injector for Rare Isotopes

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Several important EBIT experiments require isotopes or elements available only in trace quantities. Examples include ^{233}U , ^{235}U , and ^{249}Cf , which can not be obtained from any of the ion injectors presently used with EBIT or EBIS devices. These injectors require large quantities of feed material. For example, the MEVVA sources used for injection into an EBIT require a quantity of feed material on the order of 100 mg or more. We have developed a novel injection technique that enables EBIT and Super EBIT operation with only nanogram quantities of feed material, 100-million-times smaller than previously possible [1].

As shown in Fig. 1, a small wire probe is positioned near the compressed electron beam of our Super EBIT in the region where the beam passes through the ion-trap structure. A small amount of feed material is plated on the pointed tip of the wire. The electron beam is surrounded by a cloud of trapped ions, some of which impact the sample and remove material from it by sputtering. On the order of 0.1% of the sputtered material comes off as positive ions and is captured in the EBIT trap. The rate of sputtering is controlled by the position of the probe and the bias voltage applied to it. The impact of ions on the probe is a very strong function of position due to the change in potential between the electron beam and the tip of the probe (illustrated in Fig. 2).

After ions from the sample material have been loaded into the trap they may be used for x-ray measurements or any other EBIT experiment. Figure 3 shows a typical x-ray spectrum obtained with the wire probe injector.

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Fig. 1. A schematic view of the wire probe injector showing the placement of the probe with respect to the electron beam and ion trap electrodes. The probe location is controlled by a standard vacuum positioning device.

Fig. 2. Top: A plot of the potentials that control the rate of sputtering of the sample. Potentials are shown for neon ions. Bottom: The profile of the electron beam and the probe tip.

Fig. 3. A ^{235}U x-ray spectrum obtained from Super EBIT at 143-keV electron energy. The peaks above 143 keV are due to radiative recombination. The tungsten and osmium, which produced a peak at roughly 165 keV, are contaminants from the cathode of the electron gun.

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High-Pressure Position-Sensitive Proportional Counter

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As fusion plasmas reach increasingly higher plasma temperatures, they generate higher-energy x rays, and diagnostic instruments will be needed to operate in those high-energy regimes. For example, central ion temperature diagnostics in future-generation tokamaks may be based on the K-shell emission from krypton which emits radiation at 13 keV[1], and not on iron or nickel, which emit at 6 to 8 keV. To address these needs, we have constructed, tested, and operated a position-sensitive proportional counter (PSPC) that delivers improved counting efficiency in the 8-20 keV range[2]. The detector extends upon a design originated by Källne *et al.*[3], by increasing the gas operating pressure from 16 psig to 78 psig, while maintaining the excellent performance characteristics of the original design.

The new high-pressure detector is 27 cm high, 19 cm wide, and 3.5 cm thick, and employs a parallel-plane geometry. The high-voltage anode comprises horizontal wires mounted on a frame to form an equipotential plane. The cathode, composed of two printed circuit boards attached back-to-back with vertical conducting strips etched at 1-mm intervals on their faces, forms another plane, 2 mm behind the anode. Adjacent strips on the opposing board are linked diagonally so that the entire array forms a flat, rectangular helix, which acts as a 160-ns delay line. The anode sits equidistant from the cathode board and the entrance window, which acts as a second cathode plane. The beryllium entrance window restricts the active area to 9.5 cm wide by 3 cm.

To boost the detector's efficiency over that of earlier designs we raised the pressure of the fill gas. This required several modifications to accommodate the increased stresses. First we substituted a 1-mm thick sheet of beryllium for the original 0.13-mm thick foil window. Also, for additional strength and rigidity, a 0.5" steel cover plate (which holds the window) replaces the 0.38" aluminum one. The window support ribs are different as well. Instead of crossed horizontal and vertical ribs, the new detector has three horizontal ribs, 0.06" thick. The ribs block out 15% of the incident x rays, but eliminate the 0.1" dead spot in the center caused by the vertical rib. Standard BNC and SHV electrical feeds leak under high pressure and were replaced by custom-built connectors. The enclosure and connectors were successfully tested at 140 psig; the seal between the beryllium window and cover plate operates successfully up to 80 psig.

For optimal absorption of high-energy x rays, a proportional counter needs a high-Z fill gas, typically krypton or xenon. We use xenon (70% by volume) with methane for the buffer gas. The higher pressure requires a higher bias voltage – 4.5 kV, compared to 2.3 kV with the 16-psig detector. We calculated the expected counting efficiency as a function of x-ray energy, of both the low-pressure (16 psig) and high-pressure PSPCs, adjusted for absorption by the beryllium windows. The predicted efficiencies, shown in Fig. 1, were then compared to measurements made with x rays from various radioactive sources. The figure plots the results for both low and high-pressure detectors. The increased efficiency is readily apparent. A factor of

two improvement is attained for K-shell x ray of krypton at 13 keV. Also shown is the theoretical efficiency curve computed for a 90% krypton mixture. This gas mixture offers somewhat better absorption for x-ray energies above the krypton K edge at 14.3 keV, increasing the efficiency of the new detector by more than a factor of four above the krypton K edge.

FIG. 1. Detector efficiency. The dashed curve is the computed efficiency of the 16-psig detector, the solid curve the computed efficiency for the 78-psig detector. A mixture of 70% Xe and 30% CH₄ is used in both cases. The data points represent measured values. The dotted curve was computed for a mixture of 90% Kr and 10% CH₄ at 78 psig.

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Measurement of Photon Induced Fluorescence in the Extreme Ultraviolet

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Photon induced fluorescence spectrometry is a powerful tool used to extract information on electronic structure and correlation effects in atoms and molecules. Intermediate-energy x-ray beams of unprecedented intensity and energy resolution are now available from the Advanced Light Source (ALS) at Lawrence Berkeley Laboratory. Using this unique photon source, angle resolved photon and ejected electron spectroscopy can reveal details of photon-atom interactions previously inaccessible to other techniques. A joint collaborative experiment between Lawrence Livermore National Laboratory and the University of Nevada, Reno (UNR) has been undertaken at the ALS and at the ECR ion source at UNR, in order to explore some aspects of these interactions. Novel instrumentation used to study angle resolved photon and electron emission as well as polarization effects, has been developed in collaboration with Russian scientists from the Ioffe Physical Technical Institute and the Institute for Physics of Microstructures.

For this long-term project we designed and constructed a universal scattering chamber for the study of EUV photon interactions with gaseous and solid targets. The chamber is equipped with a remotely adjustable precision rotatable bearing mounted on a general purpose optical table located at the chamber center. The table and bearing can be used to mount photon, ion, and electron spectroscopic instruments for fixed and/or angular dependent measurements in the horizontal scattering plane. Through specific design, photon polarization effects can be studied as well by means of new multi-channel photon spectrometers via rotation about the beam axis in the vertical plane. A double layer of magnetic shielding significantly reduces the background magnetic field making the chamber also suitable for low energy high resolution electron spectroscopy measurements. Effective differential pumping allows the chamber to be back-filled with target gas up to 5×10^{-5} Torr while the beamline remains in the mid 10^{-9} Torr range. In addition a gas jet can be utilized for angular distribution measurements. This chamber and new instrumentation has recently been tested at the ALS.

First high resolution photon measurements of ionization-excitation of He have been made using a novel four-channel spectrometer and other new unique EUV instrumentation based on applications of state-of-the-art multilayer mirror (MLM) technology. This new technique was used, for the first time, to study doubly-excited

states of helium below the $n=3$ to $n=6$ thresholds[1] by means of fluorescence spectrometry[2]. Four spherical normal incidence Mo-Si MLM's were manufactured, characterized, and assembled together with filters and channeltron detectors in a polychromator, allowing the simultaneous detection of the HeII lines. Intensities from $np \rightarrow 1s$ transitions in He^+ ($\lambda_1=30.4$ nm, $1s-2p$; $\lambda_2=25.6$ nm, $1s-3p$; $\lambda_3=24.3$ nm, $1s-4p$; $\lambda_{4(5,6,\dots)} \approx 23.7$ nm, $1s-5p$, [5]) have been measured using the four-channel multilayer mirror spectrometer. The spectral resolution, $\lambda/\Delta\lambda$, of these multilayer mirrors ranges from about 10-30, increasing with decreasing wavelength. By measuring the fluorescence line intensity ($1s-np$) we can extract the cross-section for the excitation process. The experiment was performed at the ALS undulator beamline 9.0.1 for atomic physics. This beamline is capable of producing extremely bright photon beams in the energy range 20 to 300 eV[3].

Figure 1. Schematic view of a single detection channel of the four channel multilayer mirror spectrometer.

A schematic view of one fluorescence channel is shown in Figure 1. The throughput of the polychromator exceeds by about two orders of magnitude that of conventional grazing incidence spectrometers. This, in conjunction with the high intensity of

the ALS undulator radiation, enabled us to observe new resonance features in the sequence of doubly excited He^{**} resonances as measured previously[2].

A characteristic $\text{Ly}\alpha$ fluorescence spectrum in the incident photon energy range 71.0 eV to 73.3 eV is shown in Figure 2. Compared to earlier results our data shows several new resonance structures below the $n=3$ threshold. Due to the increased sensitivity of our apparatus and the extreme brightness of the ALS undulator beamline, we are able to achieve an energy resolution of 10 meV. The theoretical predictions shown in the figure are from reference [4]. Even higher resolutions have been achieved for some measurements. With this new experimental capability we are able to measure the energy position, width, and line profile of the observed resonances to very high accuracy which puts stringent tests on the theoretical models.

Figure 2. $\text{Ly}\alpha$ (304Å) fluorescence of $\text{He}^+ (2p)$ resulting from autoionization of $(3lnl')^1\text{P}^\circ$ states below the $n=3$ threshold.

In the near future we plan to extend these measurements to absolute EUV emission cross sections, angular distributions, and polarization measurements of various targets.

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APPENDIX

I. Publications, Invited Talks, and Conference Contributions

- A. Publications
- B. Contributed Conference Papers
- C. Invited Talks and Seminars

II. Scientific Activities Centered Around EBIT

- A. Visitors and Participating Guests
- B. V-Tea Seminar Series in N-Division of LLNL

III. Graduate Education

IV. Personnel

V. Scientific Cooperations

I. Publications

I-A. Refereed Journals (*published or submitted in 1994*)

- Beiersdorfer, P., B.J. Wargelin, "Low Energy X-ray Spectrometer for an Electron Beam Ion Trap, *Rev. Sci. Instrum.* **65** (1), (1994).
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I-B. Contributed Conference Papers

- Beck, B.R., D. Schneider, D. Church, G. Weinberg, J. Steiger, D. Knapp, "Trapping of Highly Ionized Ions in a Cryogenic Penning Trap." Submitted to 36th Annual Meeting, APS Division of Plasma Physics, Nov. 7-11, 1994, Minneapolis, MN, UCRL-JC-118237
- Beck, B., S. Becker, P. Beiersdorfer, S. Elliott, L. Schweikhard, "Application of Ion-Cyclotron Resonance Modes To Highly Charged Ions In An Electron Beam Ion Trap." Submitted the 7th International Conference on The Physics of Highly Charged Ions, Vienna, Austria, Sept. 19-23, 1994, UCRL-JC-117177.
- Beck, B.R., P. Beiersdorfer, S. R. Elliott, R. Marrs, L. Schweikhard, "Results of FT-ICR Mass Spectroscopy on Very Highly Charged Ions in an Electron Beam Ion Trap", Annual Meeting of the American Society of Mass Spectroscopy, May 1994.
- Beck, B.R., P. Beiersdorfer, S. R. Elliott, R. Marrs, L. Schweikhard, "Results of FT-ICR Mass Spectroscopy on Very Highly Charged Ions in an Electron Beam Ion Trap", 1994 Joint April Meeting of the American Physical Society and the American Association of Physics Teachers, Crystal City, VA, April 18-22, 1994.
- Beiersdorfer, P., V. Decaux, K. Widmann, "Measurement of The Temperature of Cold Highly Charged Ions Produced In An Electron Beam Ion Trap." Submitted to the 7th International Conference on The Physics of Highly Charged Ions, Vienna, Austria, Sept. 19-23, 1994, UCRL-JC-117178.
- Beiersdorfer, P., M. Chen, S. Elliott, D. Knapp, "Measurement of the 2s Lamb Shift in Lithiumlike Th^{87+} ." Submitted to the 7th International Conference on The Physics of Highly Charged Ions, Vienna, Austria, Sept. 19-23, 1994, UCRL-JC-117181.
- Beiersdorfer, P., "Measurement of Few-Electron Uranium Ions on a High-Energy Beam Ion Trap". Submitted to 13th International Conference on Application of Accelerators in Research & Industry, Denton, TX, Nov. 7-10, 1994, UCRL-JC-117697.
- Beiersdorfer, P., S. Elliott, D. Knapp, D. Schneider, "Lamb Shift Measurements on EBIT and SuperEBIT." Submitted to the 1994 Joint April Meeting of APS and AAPT, Crystal City, VA, April 18-22, 1994, UCRL-JC-116066.
- Beiersdorfer, P., V. Decaux, S. Elliott, K. Widmann, K. Wong, "Ti Measurements of Ions in an Electron Beam Ion Trap." Submitted to the 10th Topical Conference on High-Temperature Plasma Diagnostics, Rochester, NY, May 8-12, 1994, UCRL-JC-116086.
- Beiersdorfer, P., "Experiments With Highly Charged Ions up to Bare U^{92+} on the Electron Beam Ion Trap." Submitted to the Proceedings of the 14th International Conference on Atomic Physics, Boulder, CO, July 31-Aug. 5, 1994, UCRL-JC-118297.
- Briere, M., M. Reaves, Q. Kessell, E. Pollack, W. Smith, "Negative Ion Production From Shallow Angle Scattering of Slow, Highly Charged Ions By Highly Oriented Pyrolytic Graphite, C(0001)." 7th International Conference on The Physics of Highly Charged Ions, Vienna, Austria, Sept. 19-23, 1994, UCRL-JC-117189.
- Briere, M., D. Schneider, T. Schenkel, C. Ruehlicke, M. Reaves, "The Scattering Behavior of Highly Charged Ions Under Grazing Incidence Conditions on Automatically Flat Graphite." 7th International Conference on The Physics of Highly Charged Ions, Vienna, Austria, Sept. 19-23, 1994, UCRL-JC-117186.
- Briere, M. A., D. Schneider, T. Schenkel, C. Ruehlicke, "Studies On The Effect of The Incident Charge State on The Energy Loss and Range of Highly Charged Ions In Thin Solid Films." 7th International Conference on The Physics of Highly Charged Ions, Vienna, Austria, Sept. 19-23, 1994, UCRL-JC-117185

- Briere, M. A., D. Schneider, C. Ruehlicke, T. Schenkel, G. Schiwietz, J. Biersack, T. Cahill, "The Effects of Incident Charge State on Secondary Ion and Total Sputter Yields for Few Electron High Z Ions Incident on Insulators." 7th International Conference on The Physics of Highly Charged Ions, Vienna, Austria, Sept. 19-23, 1994, UCRL-JC-117184.
- Briere, M.A., T. Schenkel, C. Ruehlicke, D. Schneider, "Inelastic Processes During the Interaction of Very Highly Charged Ions with Solid Surfaces." 10th International Workshop in Inelastic Ion Surface Collisions, Grand Targee Ski & Summer Resort, Wyoming, Aug. 8-12, 1994, UCRL-JC-117426.
- Briere, M., D. Schneider, C. Ruehlicke, T. Schenkel, G. Schiwietz, "Enhanced Secondary Ion Yield Due to High Incident Charge States of keV/u Ions." 17th Surface/Interface Research Meeting of NCCAVS, Livermore, CA, June 23, 1994, UCRL-JC-117477
- Briere, M. "Recent Results on the Interaction of Slow Few-Electron High Z Ions with Solids." 13th International Conference on the Application of Accelerators in Research & Industry, Denton, TX, Nov. 7-10, 1994, UCRL-JC-118238.
- Church, C.A., D. Schneider, G. Weinberg, J. Steiger, B. Beck, J. McDonald, D. Knapp, E. Magee, L. Brewer, D. DeWitt, "Penning Trap Confinement of Highly Charged Ions Extracted from EBIT." International Conference on Atom Physics ICAP-XIV, Boulder, CO., July 31-Aug. 4, 1994, UCRL-JC-117427.
- Decaux, V., P. Beiersdorfer, S. Elliott, A. Osterheld, E. Clothiaux, "High-Resolution Measurement of the He β Spectra of Heliumlike Chromium for Possible Diagnostic of Laser-produced Plasmas." Submitted to the 10th Topical Conference on High-Temperature Plasma Diagnostics, Rochester, NY, May 8-12, 1994, UCRL-JC-116307.
- Decaux, V., P. Beiersdorfer, A. Osterheld, "High-resolution Tokamak Measurement of the K β Spectra of Heliumlike Argon." Submitted to the 36th Annual Meeting, APS Division of Plasma Physics, Minneapolis, MN, Nov. 7-11, 1994, UCRL-JC-118239.
- Decaux, V. P. Beiersdorfer, A. Osterheld, "Excitation Mechanisms of $2s_{1/2}$ - $2p_{3/2}$ and $2p_{1/2}$ - $2p_{3/2}$ transitions in U $^{82+}$ through U $^{89+}$." Submitted to the 7th International Conference on the Physics of Highly Charged Ions, Vienna, Austria, Sept. 19-23, 1994, UCRL-JC-118363.
- Elliott, S., P. Beiersdorfer, J. Nilsen, "EBIT X-ray Spectroscopy Studies for Applications to Photo-Pumped X-ray Lasers." Submitted to the 4th International. Coll. on X-ray Lasers, Williamsburg, VA, May 16-20, 1994, UCRL-JC-116836.
- Elliott, S., "Studies With Highly Charged Ions With EBIT and Super-EBIT." Submitted to the 7th International Conference on The Physics of Highly Charged Ions, Vienna, Austria, Sept. 19-23, 1994, UCRL-JC-117182.
- Knapp, D., J. Tanis, "Measurements Of KLM, KLN, and KMM Dielectronic Recombination Resonances In Near-Heliumlike Uranium Ions." Submitted to the 7th International Conference on The Physics of Highly Charged Ions, Vienna, Austria, Sept. 19-23, 1994, UCRL-JC-117183.
- Knapp, D., J. Tanis "Observation of KLM Dielectronic Recombination Resonances in Highly Charged Uranium Ions, Submitted to the 7th International Conference on The Physics of Highly Charged Ions, Vienna, Austria, Sept. 19-23, 1994, UCRL-JC-118724.
- Knapp, D., "The Uses of Electron Beam Ion Traps in the Study of Highly Charged Ions." Submitted to Physics with Multiply Charged Ions, July 18-30, 1994, Cargese, Corsica. UCRL-JC-119193.
- Marrs, R.E., S.R. Elliott, T. Stoehlker, "Studies of One and Two Electron High-Z Ions with the LLNL SuperEBIT". Submitted to the International Conference on Atom Physics ICAP-XIV, Boulder, CO, July 31-Aug. 4, 1994, UCRL-JC-117448.

- Osterheld, A., P. Beiersdorfer, "Excitation Mechanisms of $2S_{1/2}$ - $2P_{3/2}$ and $2P_{1/2}$ - $2P_{3/2}$ Transitions In U^{82+} Through U^{89+} Produced and Trapped In An Electron Beam Ion Trap". Submitted to the 7th International Conference on The Physics of Highly Charged Ions, Vienna, Austria, Sept. 19-23, 1994, UCRL-JC-117180.
- Ruehlicke, C., M.A. Briere, D. Schneider, "AFM-Studies of A New Type of Radiation Induced Defect on Insulating Surfaces Caused By Few Electron High Ion Impact." Submitted to the 7th International Conference on The Physics of Highly Charged Ions, Vienna, Austria, Sept. 19-23, 1994, UCRL-JC-117187.
- Ruehlicke, C., M. Briere, D. Schneider, "AFM Studies of a New Type of Radiation Defect on Mica Surfaces Caused by Highly Charged Ion Impact." Submitted to 13th International Conference of Applications of Accelerators in Research and Industry, Nov. 7-10, 1994, Denton, TX, UCRL-JC-117817-Rev 1.
- Schneider, D., D. DeWitt, D. Knapp, K. Reed, M. Chen, "Measurements of Cross Sections and Resonance Structures Following Electron-Impact Excitation/Ionization of Na-Like Kr and Xe." 13th Internal Conference of Applications of Accelerators in Research and Industry, Nov. 7-10, 1994, Denton, TX, UCRL-JC-112929.
- Schneider, D., D. Church, G. Weinberg, J. Steiger, B. Beck, J. McDonald, E. Magee, D. Knapp, "Trapping of Highest Charge State Ions In A Cryogenic Penning Trap." 7th International Conference on The Physics of Highly Charged Ions, Vienna, Austria, Sept. 19-23, 1994, UCRL-JC-117188.
- Schneider, D., D. Church, G. Weinberg, J. McDonald, J. Steiger, B. Beck, D. Knapp, "RETRAP-A Facility for Experiments with Trapped Highest Charge State Ions." 1994 Joint April Meeting of APS and AAPT, Crystal City, VA, April 18-22, 1994, UCRL-JC-116084.
- Schneider, D. "Confinement In a Cryogenic Penning Trap of Highest Charge State Ions from EBIT." 13th International Conference on the Application of Accelerators in Research & Industry, Denton, TX, Nov. 7-10, 1994, UCRL-JC-117767.
- Schweikhard, L., J. Ziegler, B. Beck, P. Beiersdorfer, S. Elliott, "Excitation and Detection of ICR Modes for Control and Analysis of A Multi-Component Plasma." Submitted to the 10th Topical Conference on High-Temperature Plasma Diagnostics, May 8-12, 1994, UCRL-JC-116808.
- Schweikhard, L., B. Beck, P. Beiersdorfer, S. Elliott, R. Marrs "FT-ICR-Nachweis hochgeladener atomarer Ionen", Spring Meeting of the German Physical Society in Hamburg, Germany, March 1994.
- Stefanelli, G., P. Beiersdorfer, V. Decaux, K. Widmann, "Lifetime Measurements of the $1s2s^3S_1$ Level in He-like Mg^{10+} ." Submitted to the Joint April Meeting. of APS & AAPS, Crystal City, VA. April 18-22, 1994, UCRL-JC-117129.
- Stefanelli, G., P. Beiersdorfer, V. Decaux, K. Widmann, "Lifetime Measurements of the $1s2s^3S_1$ Level in He-like Mg^{10+} ." 7th International Conference on the Physics of Highly Charged Ions, Vienna, Austria, Sept. 19-23, 1994.
- Vogel, D., P. Beiersdorfer, V. Decaux, K. Widmann, "Positive-Sensitive Gas Proportional Counter For 10-20 keV X Rays." Submitted to the 10th Topical Conference on High-Temperature Plasma Diagnostics, Rochester, NY, May 8-12, 1994, UCRL-JC-116085.
- Widmann, K., P. Beiersdorfer, V. Decaux, S. R. Elliott, D. Knapp, A. Osterheld, "Studies of He-like Krypton for Use in Determining Electron and Ion Temperatures in Very High-Temperature Plasmas." Submitted to the 10th Topical Conference on High-Temperature Plasma Diagnostic, Rochester, NY, May 8-12, 1994, UCRL-JC-116330.
- Widmann, K., P. Beiersdorfer, V. Decaux, S. Elliott, D. Knapp, A. Osterheld, M. Bitter, A. Smith, "High-Resolution Measurements of He-Like Krypton Spectra Using an Electron Beam Ion Trap (EBIT)." Submitted to 35th Annual Meeting of Plasma Physics, St. Louis, MO, Nov. 1-5, 1994, UCRL-JC-114345.

I-C. Invited Talks and Seminars

- P. Beiersdorfer, "Highly Charged Ion Research with EBIT and SuperEBIT", Johannes-Gutenberg-Universität Mainz, Institut für Physik, January 1994.
- P. Beiersdorfer, "Highly Charged Ion Research with EBIT and SuperEBIT", Friedrich Schiller Universität Jena, Max-Planck-Institut für Röntgenoptik, January 1994.
- P. Beiersdorfer, "Polarized Line Emission from Highly Charged Ions", US-Japan Workshop on Plasma Polarization Spectroscopy, Los Alamos National Laboratory, February 1994.
- P. Beiersdorfer, "Highly Charged Ion Research with EBIT and SuperEBIT", Auburn University, Department of Physics, April 1994.
- P. Beiersdorfer, "Perspectives of the SuperEBIT", Workshop of Measurements of the Lambshift in Few-Electron Heavy Ions, GSI Darmstadt, Germany, September 1994.
- P. Beiersdorfer, "Experiments with Highly Charged Ions up to Bare Uranium on the Electron Beam Ion Trap", 14th International Conference on Atomic Physics, Boulder, CO, July 31 - August 5, 1994.
- M. A. Briere, "Negative Ion Production from Shallow Angle Scattering of Slow, Highly Charged Ions by Highly Oriented Pyrolytic Graphite, C(0001)", 7th International Conference on the Physics of Highly Charged Ions (HCI-94), Vienna, Austria, September 1994.
- M. A. Briere, "The Interaction for Few Electron High Z Ions with Solid Surfaces", University of Osnabrueck, Osnabrueck, Germany, September 1994.
- M. A. Briere, "High Energy Density Deposition Effects at Solid Surfaces Due to the Impact of Very Highly Charged Ions", GSI, Darmstadt, Germany, September 1994.
- M. A. Briere, "Interaction of Few Electron High Z Ions with Solid Surfaces", European Research Conference on Particle-Solid Interactions, San Sabastian, Spain, October 1994.
- M. A. Briere, presented by A. E. Schach v. Wittenau, "Recent Results on the Interaction of Slow, High-Z Ions with Solids", 13th International Conference on the Application of Accelerators in Research & Industry, Denton, Texas, 1994.
- S. R. Elliott, "Studies of Highly Charged Ions with EBIT and Super-EBIT", 7th International Conference on the Physics of HCI, Vienna, Austria, September 1994.
- R. Marrs, "The LLNL SuperEBIT", Franco-American Workshop on Ion Sources, University of Versailles, Versailles, France, February 1994.

- R. Marrs, "The Super Electron Beam Ion Trap", Nobel Symposium on Trapped Charged Particles and Related Fundamental Physics, Lysekil, Sweden, August 1994.
- D. Schneider, "EBIT, A Unique Source for Highly Charged Ion Physics", University of Versailles, Versailles, France, (Franco-American Workshop on Ion Sources), February 1994.
- D. Schneider, "Highly Charged Ion Induced Surface Defects", GSI, Darmstadt, Germany, February 1994.
- D. Schneider, "Progress of Physics Experiments at the LLNL EBIT", University of Frankfurt, Frankfurt, Germany, March 1994.
- D. Schneider, "Selected Experiments at the LLNL EBIT Facilities", MPI, Berlin, Germany, March 1994.
- D. Schneider, "New Results from Ion Surface Studies at EBIT", Hahn-Meitner Institut, Berlin, March 1994.
- D. Schneider, "Surface Physics Experiments at the LLNL EBIT Facility", Nobelsymposium, Stockholm, Sweden, September 1994.

II. Scientific Activities Centered Around EBIT

II-A. Visitors and Participating Guests

DATE	VISITOR OR GUEST	INSTITUTION		HOSTED BY
<i>JANUARY</i>				
18	Gerd Fussmann	Max-Planck-Institut für Plasmaphysik	Berlin, Germany	Schneider
18-21	Rainer Radtke Andreas Schmid	Fritz-Haber-Institut der Max-Planck-Gesellschaft	Berlin, Germany	Schneider/ Briere
20	Alexis Schach von Wittenau	Lawrence Berkeley Laboratory	Berkeley, CA	Briere/ Schneider
<i>FEBRUARY</i>				
1	Thomas Schenkel	Institut für Nuclear Physics Goeth Univ.	Frankfurt, Germany	Schneider/ Beiersdorfer
1-5/10	Stefan Becker	University of Mainz	Germany	Beiersdorfer
28-3/4	Christian Roethig	Arizona State University	Tempe, AZ	Briere
<i>MARCH</i>				
1	Chun-Fai Chan Ka-Ngo Leung Malcome Williams	Lawrence Berkeley Laboratory	Berkeley, CA	Marrs/ Schneider
2	Horst Schmidt-Böcking	Institut für Kernphysik	Frankfurt, Germany	Schneider
3-6	Quentin Kessel	University of Connecticut	Storrs, CT	Reaves/ Schneider
10	Makoto Sakuri	University of Electro-Communications	Toyko, Japan	Schneider
12-20	Hirofumi Watanabe	Morehouse College	Atlanta, GA	Beiersdorfer
17	Augustine Smith	Department of Energy	Washington, DC	Schneider
21-25	Joseph Martinez	University of Connecticut	Storrs, CT	Schneider/ Reaves
21-25	Quentin Kessel	Western Michigan University	Kalamazoo, MI	Schneider
24-26	Winthrop Smith	GSI-Darmstadt	Germany	Schneider
30	Edward Pollack	University of California	Berkeley, CA	Beiersdorfer
<i>APRIL</i>				
5-28	Reinhold Schuch	Manne Siegbahn Institute of Physics	Stockholm, Sweden	Schneider/Briere
5	Ralf Herrmann	University of Frankfurt	Germany	Schneider
13-12/31	Daniel Savin	UC Berkeley	Berkeley, CA	Beiersdorfer
13	Michel Druetta	Université Jean Monnet/St. Etienne	France	Church/ McDonald
18-19	Maria Ulbel	Institut für Experimentalphysik	Graz, Austria	Widmann/ Beiersdorfer
18-5/13	Manfred Poeckl	Max-Planck-Institut für Plasmaphysik	Berlin, Germany	Schneider
27	Rainer Radtke	Harvey Mudd College	Claremont, CA	Knapp
28	Ron Zasadzinski	University of Nevada	Las Vegas, NV	Schneider
<i>MAY</i>				
1-5/1/96	R. Rohatgi	Stanford Research Systems	Sunnyvale, CA	Cowan
6	Chun-Fai Chan	Lawrence Berkeley Laboratory	Berkeley, CA	Marrs/ Schneider
12	Ka-Ngo Leung	Argonne National Laboratory	Argonne, IL	Schneider
19-20	Malcome Williams	GSI	Darmstadt, Germany	Beiersdorfer
20	Donald Gemmell	Oak Ridge National Laboratory	Oak Ridge, TN	Schneider
24	Martin Jung	Lawrence Berkeley Laboratory	Berkeley, CA	Schneider
	Charles Havener			
	Hocine Khemliche			

DATE	VISITOR OR GUEST	INSTITUTION		HOSTED BY
JUNE				
1-8/19	Michelle Slater	Spelman College	Atlanta	Beiersdorfer
2-3	Charles Rhodes	University of Illinois at Chicago	Chicago, IL	Schneider
7	Hans Dehmelt	University of Washington	Seattle, WA	Marrs
8	Augustine Smith	Morehouse College	Atlanta, GA	Beiersdorfer
16	Reinhard Bruch	University of Nevada/Reno	Reno, NV	Schneider
	Elizabeth Rauscher, Wolfgang Zinck Edward Maynard			
22-7/1	Eugene Clothiaux	Auburn University	Auburn, AL	Beiersdorfer
27	C. Fred Moore	University of Texas at Austin	TX	Schneider
JULY				
5-31	Thomas Stoehlker	GSI	Darmstadt, Germany	Marrs
8	Markus Miki	Institut für Technikfolgen	Wien, Austria	Beiersdorfer/ Widmann
13	Kai-Anja Luers	University of Munich	Germany	Schneider
14-15	Thomas Ruge	N.I.S.T.	Gaithersburg, MD	Knapp
15-22	Erick Meyer	Univ. of CA	San Diego, CA	Beck
27-29	Francois Anderegg Alfred Muller	Institut für Strahlenphysik	Stuttgart, Germany	Schneider
AUGUST				
1-2	Jochen Biersack	Hahn-Meitner-Institut	Berlin, Germany	Briere
8-10	Andreas Wolf	Universität Heidelberg	Germany	Beiersdorfer
8-17	Peter Bauer	Johannes-Kepler University	Linz, Austria	Briere
18-19	Uwe Glatzel	Technical University	Berlin, Germany	Briere/Schmid
19-22	Roland Schmidt	Humboldt-Universität zu Berlin	Germany	Schneider/Briere
30	Helmut Winter Heinrich Neitzert	Centro Studie Laboratori Telecomunicaxioni	Torino, Italy	Briere
SEPTEMBER				
7	Richard Marrus	University of California	Berkeley, CA	Schneider
8-12	David Church	Texas A&M University	College Station, TX	Schneider
8-9	Christian Kurz	Massachusetts Institute of Technology	Cambridge, MA	Beiersdorfer
OCTOBER				
19-20	Karl Schartner	Universitat Giessen	Germany	Schneider
21-28	David Church	Texas A&M	College Station, TX	Schneider
25-28	Horst Schmidt-Böcking	Institut für Kernphysik	Frankfurt, Germany	Schneider
NOVEMBER				
3	Stuart Freedman David Weiss Eric Wasserman Lincoln Carr	University of California	Berkeley, CA	Schneider
4	Rainer Hippler	Universität Bielefeld	Germany	Schneider/ Ruehlicke
16	Hans Schempp	Johann Wolfgang Goeth-Universität	Frankfurt, Germany	Schneider
21	Thomas Kessler	Incatronik-Phenix	Frankfurt, Germany	Briere/ Schenkel
21-12/5	Thomas Stoehlker	GSI	Darmstadt, Germany	Beiersdorfer/ Marrs
DECEMBER				
1-7	David DeWitt	Manne-Siegbahn-Institut	Stockholm, Sweden	Schneider
4-11	David Church	Texas A&M	College Station, TX	Schneider
12-24	Greg Brown	Auburn University	Auburn, AL	Beiersdorfer
20	Ravi Marawar	University of Nevada	Las Vegas, NV	Schneider
27-1/7	Augustine Smith	Morehouse College	Atlanta, GA	Beiersdorfer

II-B. "V-Tea" Seminar Series in N-Division of LLNL

<i>JANUARY</i>		
20	Andreas Schmid	<i>"Growth of Epitaxial Co Thin Films on Cu(100) Studied by Scanning Tunneling Microscopy"</i>
20	Alexis Schach von Wittenau	<i>"Angle Resolved Photoelectron Defraction Study of S/Cu (001) System"</i>
<i>FEBRUARY</i>		
24	Stefan Becker	<i>"FT-ICR and Time-of-Flight Measurements in Penning Traps"</i>
<i>MARCH</i>		
3	Christian Roething	<i>"STM Studies of Metal Surfaces"</i>
24	Paul Mokler	<i>"Atomic Physics Experiments at the GSI Heavy Ion Storage Ring"</i>
<i>APRIL</i>		
28	John Farley	<i>"Laser Spectroscopy of Ions"</i>
<i>MAY</i>		
12	Donald Gemmell	<i>"Interaction of 600 MeV Xe Ions with Buckey Balls"</i>
19	Martin Jung	<i>"Bound Beta Decay and Other Experiments at the ESR at GSI"</i>
26	Daniel Savin	<i>"Absolute Measurements of Field-Enhanced Dielectronic Recombination and Electron Impact Excitation of CIV"</i>
<i>JUNE</i>		
2	Charles Rhodes	<i>"Multi-Kilovolt X-Ray Amplification with Molecular Design"</i>
<i>JULY</i>		
28	Alfred Müller	<i>"Recombination and Ionization in Highly-Charged Ion-Electron Collisions"</i>
<i>AUGUST</i>		
10	Andreas Wolf	<i>"Experiments in Merged Electron and Ion Beams at the Cooler Storage Ring TSR"</i>
16	Peter Bauer	<i>"Chemical Effects in Electronic Energy Loss"</i>
<i>SEPTEMBER</i>		
8	Christian Kurz	<i>"Spectroscopy of UV and Visible Light from the Plasma Edge of Alcator C-Mod"</i>

III. Graduate Education

The education of graduate students represents a major part of the EBIT program. During 1994 a total of six graduate students had been active in the program. The students came from many different institutions, both national and international. One student finished her thesis for the degree of "Diplom-Physicist":

"AFM Investigations of Ion Impact Induced Defects on Mica" (Christiane Rühlicke supervised by M. Briere and D. Schneider).

The EBIT program also routinely involves undergraduate students. Twice a year students from the Undergraduate Summer Institute Research Program have a chance to actively participate in ongoing research for a two-week period. During 1994, six undergraduates took advantage of this opportunity. Moreover, the EBIT program has a continuing commitment to minority participation in its activities, and one student researcher supported by the Office of Equal Opportunity actively participate in ongoing research during the summer months.

Collaboration with Historically Black Colleges and Universities:

A collaborative research effort between Historically Black Colleges and Universities (HBCU) and the EBIT Program was started in October 1993. The scientific effort centered on the investigation of the x-ray spectra and their diagnostic applications in magnetic and laser fusion. This involved faculty (Prof. Augustine Smith) and students from Morehouse College in Atlanta as well as from Spelman College in Atlanta, GA. Several experimental run periods in 1994, in coincidence with school holidays or semester breaks, were devoted on the EBIT facility to collaborative experiments. These included measurements of the dielectronic satellite spectrum of heliumlike Co^{25+} , of the polarization of K-shell transition from heliumlike Mg^{10+} , and of high-n satellites in Ar^{16+} to address the issue of line broadening in ICF diagnostics. Much of the data reduction was carried out at the HBCU facilities. For this purpose, LLNL provided Morehouse College with a computer workstation and software as well as salary support for employment of undergraduate students. The collaborative efforts have been very successful and several papers have been submitted for publication or are in preparation. The program has been extended into FY95, and increased participation of minority researchers in the EBIT program is expected in 1995 or 1996.

List of Students at EBIT:

Sophie Bardin (University of Paris, France). Research in ion/surface interactions towards Ph.D. thesis.

Joe McDonald (Western Michigan University, Kalamazoo). Research in ion/surface interactions towards Ph.D. thesis.

Christiane Rühlicke (University of Bielefeld, Germany). Research on trapped highly charged ions towards a Ph.D. thesis.

Thomas Schenkel (University of Frankfurt, Germany). Research in ion/surface interactions toward Ph.D. theses.

George Weinberg (Texas A&M University). Research on trapped highly charged ions towards Ph.D. thesis.

Klaus Widmann (University of Graz, Austria). Research in atomic structure towards Ph.D. thesis.

IV. Personnel

Associate Director Physics & Space Technology: *Richard J. Fortner*

N Division Leader: *Mike Kreisler*

EBIT Program: *Dieter Schneider [DIETERS@IMAGER.LLNL.GOV]*

Scientific Staff Members:

Peter Beiersdorfer
Michael Briere (term)
David Knapp
Roscoe Marrs
Dieter Schneider

Post-doctorals:

Bret Beck
José R. Crespo Lopez-Urrutia
Vincent Decaux
Steven Elliott
Daniel Savin
Joachim Steiger
Alexis Schach von Wittenau
Andreas Schmid

Students:

Sophie Bardin
Joseph McDonald
Christiane Rühlicke
Thomas Schenkel
George Weinberg
Klaus Widmann

Technical Support Staff:

Phil D'Antonio
Ed Magee
Dan Nelson
Ken Visbek

Guest Scientists and Consultants:

Peter Bauer
Stefan Becker
Jochen Biersack
Manfred Bitter
Jean-Pierre Briand
Greg Brown
David Church
Eugène Clothiaux
Brigitte d'Etat
Eckhart Förster
Ken Hill
Steve Kahn
Gregor Schiwietz (NATO)
Horst Schmidt-Boecking
Lutz Schweikhard (NATO)
Augustine Smith
Greg Stefanelli
Thomas Stoehlker
Keith Wong

Secretary:

Diane Rae
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V. Scientific Cooperations

U.S. Cooperations:

Auburn University, Auburn, AL
California Institute of Technology, Pasadena, CA
Kansas State University, Manhattan, KS
Lawrence Berkeley Laboratory, Berkeley, CA
Morehouse College, Atlanta, GA
Princeton Plasma Physics Laboratory, NJ
Texas A&M University, College Station, TX
University of California-Berkeley, Berkeley, CA
University of Nevada-Las Vegas, Las Vegas, NV
University of Nevada-Reno, Reno, NV
Vanderbilt University, Brentwood, TN
Western Michigan University, Kalamazoo, MI

International Cooperations:

GSI, Darmstadt, Germany
Hahn-Meitner-Institut, Berlin, Germany
Institut für Allgemeine Physik, Wien, Austria
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