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# DIELECTRONIC RECOMBINATION MEASUREMENTS OF HIGHLY-CHARGED HELIUMLIKE AND NEONLIKE IONS USING AN ELECTRON BEAM ION TRAP*

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## ABSTRACT

The electron beam ion trap (EBIT) at LLNL is a unique device designed to measure the interactions of electrons with highly-charged ions. We describe three methods used at EBIT to directly measure the dielectronic recombination (DR) process : (1) The intensity of the stabilizing X rays is measured as a function of electron beam energy; (2) The ions remaining in a particular ionization state are counted after the electron beam has been held at a fixed electron energy for a fixed time; and (3) High-resolution spectroscopy is used to resolve individual DR satellite lines. In our discussions, we concentrate on the KLL resonances of the heliumlike target ions ($V^{21+}$ to $Ba^{54+}$), and the LMM resonances of the neonlike target ions ($Xe^{44+}$ to $Th^{80+}$).

## INTRODUCTION

Dielectronic recombination (DR) is an important process in fusion plasmas, solar flares, and astrophysical systems because it strongly influences the ionization balance and emitted x-ray spectra. Measurements of DR in highly-charged ions are also of fundamental interest because they can test multi-electron atomic physics models in the high-Z, highly relativisitic limit. The EBIT machine[1-3] at LLNL is an ideal device in which to measure the DR resonances of highly-charged ions[4-9]. In this paper we report several complementary techniques used to measure DR of heliumlike and neonlike target ions.

DR is the resonant capture of electrons by ions. An intermediate state is formed when the energy gained by capturing an electron from the continuum resonantly excites one of the bound electrons. DR occurs when the ion, now with one less charge, decays by emitting a photon.

The DR resonances can be seen with x-ray or particle techniques by measuring either the intensity of the DR X rays or the ion abundance as a function of the interaction energy between the ion and the electron. We have previously used x-ray techniques to measure the KLL DR resonances of heliumlike $Ni^{26+}$ [4-5] and $Mo^{40+}$ [5] target ions and the LMM resonances of neonlike $Au^{69+}$ [6] target ions. We summarize these results and also report new results for heliumlike $Ba^{54+}$ and neonlike $Xe^{44+}$ and $Th^{80+}$ target ions. The cross sections determined with the x-ray technique are normalized to those of radiative recombination (RR), the nonresonant recombination of electrons with ions. A particle technique has previously been used to measure the abundance ratio, $Ar^{16+}/Ar^{15+}$, of ions extracted from

an electron beam ion source.[10] In this case, the DR cross sections were normalized to those of electron impact ionization. We also measure ion abundances by using the EBIT machine as an ion source.[3] Using ion-extraction techniques, we have measured DR of hydrogenlike $Ar^{17+}$ target ions[8] and, more recently, neonlike $Xe^{44+}$ target ions[9]. We summarize the latter experiment here. The extraction data is not normalized to obtain a cross section, but the relative strengths of the resonances are measured with the highest electron energy resolution yet from EBIT. We note that a process similar to DR has also been measured in resonant transfer and excitation (RTE) experiments where ions move through a gas target and interact with the target's electrons. The RTE equivalent of the KLL resonances of heliumlike $U^{90+}$ onto $H_2$ was observed[11].

We confine our attention in this paper to the KLL resonances of heliumlike target ions and the LMM resonances of neonlike target ions. These resonances are the strongest for the highly-charged ions which we consider. As an example, the LMM resonances in neonlike gold target ions are expected to have about 70% of the total DR resonance strength.

We note that the LMM resonances in neonlike ions differ from the KLL resonances in heliumlike ions in several ways: (a) the energy threshold for ionization to a neonlike state is 2-3 times the energy of the LMM resonances, whereas the threshold for ionization of a heliumlike state is below the energy of the KLL resonances. This means that extraction experiments on neonlike target ions cannot be normalized to an ionization cross section. (b) the LMM resonance strengths are at least an order of magnitude larger than the KLL resonance strengths. This means that the LMM experiments must be performed on a shorter timescale, because the number of neonlike ions is quickly depeleted. (c) the LMM resonances of neonlike target ions have 237 intermediate states whereas the KLL resonances of heliumlike target ions have only 16.

## THE ELECTRON BEAM ION TRAP

The electron beam ion trap (EBIT) is a device specifically designed to study the X rays produced by very-highly-charged ions when they interact with free electrons[1-2]. The ions are available for study because they are electostatically trapped for seconds to hours in a narrow cylindrical region defined by biased electrodes in the axial direction and by a high-current-density electron beam in the radial direction. The energy of the electron beam can be varied reliably from 2 keV to about 40 keV with a typical energy spread of 50 eV FWHM. X rays from these interactions are observed at 90° to the electron beam direction. Recently, EBIT was upgraded to allow the ions to be extracted from the trap and magnetically analyzed by charge-to-mass ratio.[3]

## DR OF NEONLIKE TARGET IONS USING THE "EVENT-MODE" X-RAY TECHNIQUE

Typically, the DR resonances are measured using an "event-mode" data acquisition technique and a solid-state detector. A schematic diagram of the EBIT voltages for an experiment on neonlike target ions is illustrated in Fig. 1. First the ions are dumped out of the trap by turning off the electron beam and inverting the axial

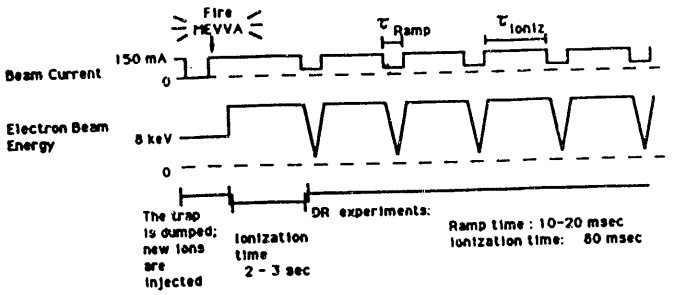


Fig. 1 Typical timing pattern for the electron beam current and the electron beam energy in an event-mode data acquisition experiment in EBIT. Parameters shown are those used for the neonlike Au experiment.

potential. Then, the beam is turned on, the axial trap is restored, and low-charged ions (q=+1 to +4) are injected into EBIT. These ions are successively ionized by the electron beam under conditions which maximize the ratio of neonlike ions to sodiumlike ions. This requires a high beam current and an electron beam energy that is just below the threshold for removing the 10th electron. Once the ionization balance is established, the DR experiment is performed. Dielectronic recombination is a strong recombining process, so setting the electron energy to the resonant energy would soon destroy the ionization balance. The resonances are probed by reducing the beam current and linearly ramping the energy of the electron beam down from the ionization energy to an energy below that of the dielectronic recombination resonances, and back up. The ionization conditions are then restored to maintain the ionization balance. The cycle is repeated about 200 times before the trap is again dumped. Note that the time spent on resonance (typically 17 uS for a 3keV/mS ramp) is too short to perturb the ionization balance at the reduced beam currents used.

X rays are observed during ramping with a solid-state Ge or Si(Li) detector. When an X ray is detected, its photon energy, the voltage used to accelerate the electron beam, and the time are recorded. If the voltage ramp is linear, the data is automatically normalized because the same amount of time is spent at each voltage.

The data from a typical run can be displayed as a scatter plot, as shown in Fig. 2 for neonlike gold. X-ray spectra are horizontal slices of this plot. Excitation functions (x-ray intensity versus electron energy) are generated by projecting selected events onto the electron beam energy axis. The DR excitation function of the data which is analyzed is the sum, for each electron energy, of all RR X rays to n=3 plus all n=3->2 DR X rays. Because the intermediate state of the ion has two electrons in the n=3 shell but only one hole in the n=2 core, there is only one n=3->2 X ray emitted for each recombination. The excitation functions are shown in Fig. 3a,b,c for the xenon, gold, and thorium, systems, respectively. As the target ion becomes more highly charged, individual DR resonances become easier to resolve because the spacing between the electron energy levels increase. However, the ionization balance in EBIT worsens, as evidenced by an increase in the number of peaks in the thorium data compared to the gold data. This is because the ionization cross section of sodiumlike ions scale like $1/Z^4$ while the recombination cross sections of neonlike ions are either approximately constant (radiative recombination) or scale like Z (charge exchange) so that the ratio of the number of neonlike ions to the number of sodiumlike ions in EBIT, scales, at best, like $1/Z^4$.

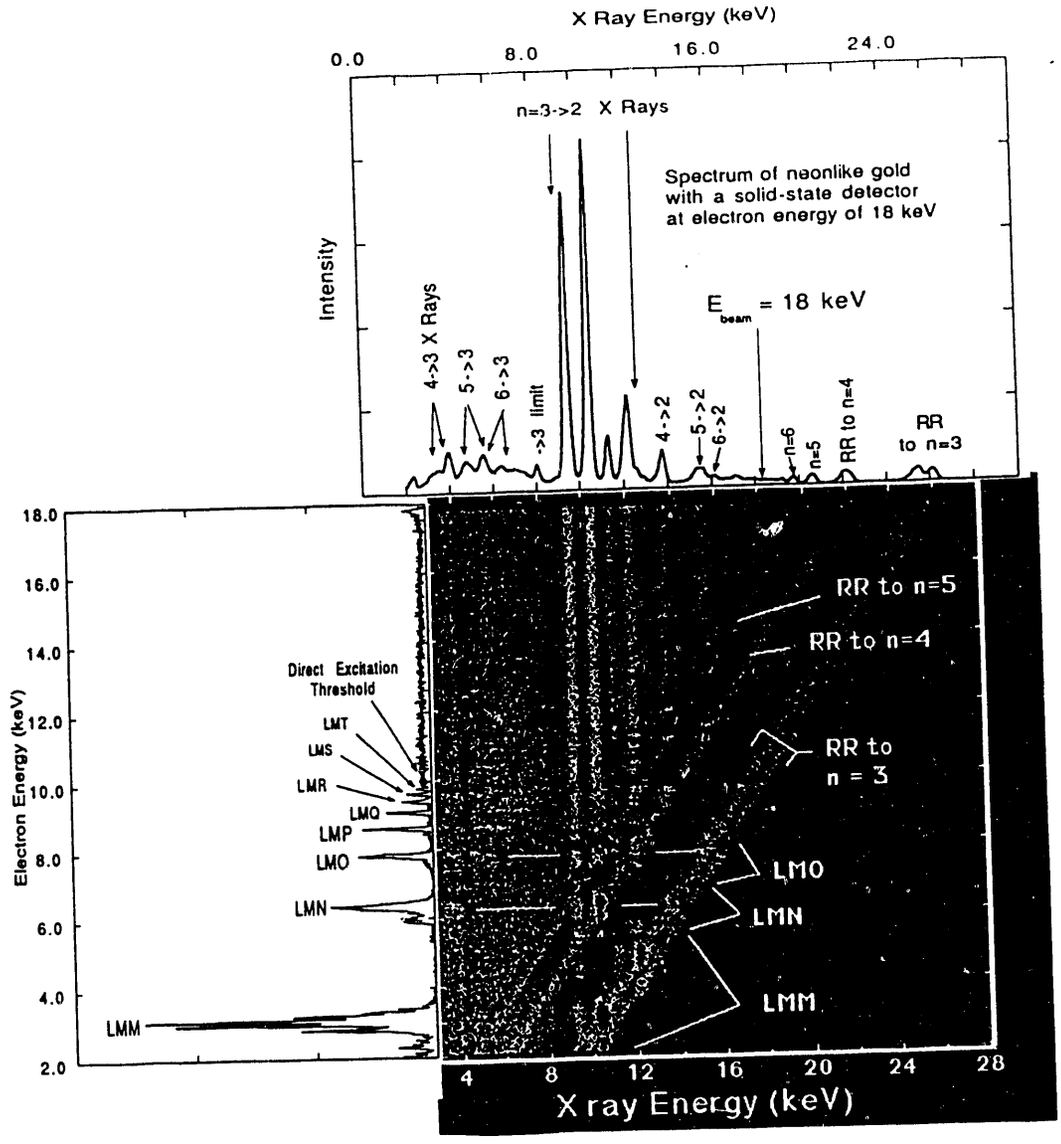


Fig. 2 The data from a DR experiment on neonlike gold target ions displayed in a scatter plot (middle figure) which maps x-ray intensity on a greyscale versus x-ray energy (x-axis) and electron beam energy (y-axis). X-ray excitation lines appear as vertical bands; radiative recombination (RR) X rays appear in diagonal bands. The high intensity peaks at the intersection of the excitation lines and RR bands are the DR resonances. A horizontal cut through the scatter plot gives an x-ray spectrum at a fixed electron energy. This is illustrated in the top figure for the ionization energy of 18 keV. The n=3->2 x-ray excitation lines are identified. A vertical cut along a fixed x-ray line gives a DR excitation function. The figure on the left is a vertical cut through the brightest n=3->2 X-ray line. The DR resonances are labeled. The strongest resonances are the LMM resonances.

Note that a diagonal cut along an RR band gives a complementary DR excitation function.

A multiconfiguration Dirac-Fock (MCDF) calculation[12-13] of the resonance strengths and positions are used to fit each excitation function for an energy offset, an electron beam energy resolution, and an amplitude of each target ionization state for up to four target ionization states (neonlike to aluminumlike). Accurately calculated radiative recombination cross sections[14] are used for the background term. For the calculation of the DR resonance strengths, the target ions were assumed to be initially in their ground state because the electron density was so low ( $< 3 \times 10^{12} cm^{-3}$) that the time between an electron-ion collision was longer than the lifetime of any metastable state of the ion. The atomic energy levels and bound-state wave functions were calculated using the MCDF model in the extended average-level scheme.[12] The effects of quantum-electrodynamic corrections, the finite nuclear size, the transverse Breit interaction, and relaxation were included in the calculations of the transition energies. The relativistic Auger and radiative rates for each intermediate state were calculated using first-order perturbation theory. Because the DR resonances have much narrower widths than the beam resolution, they

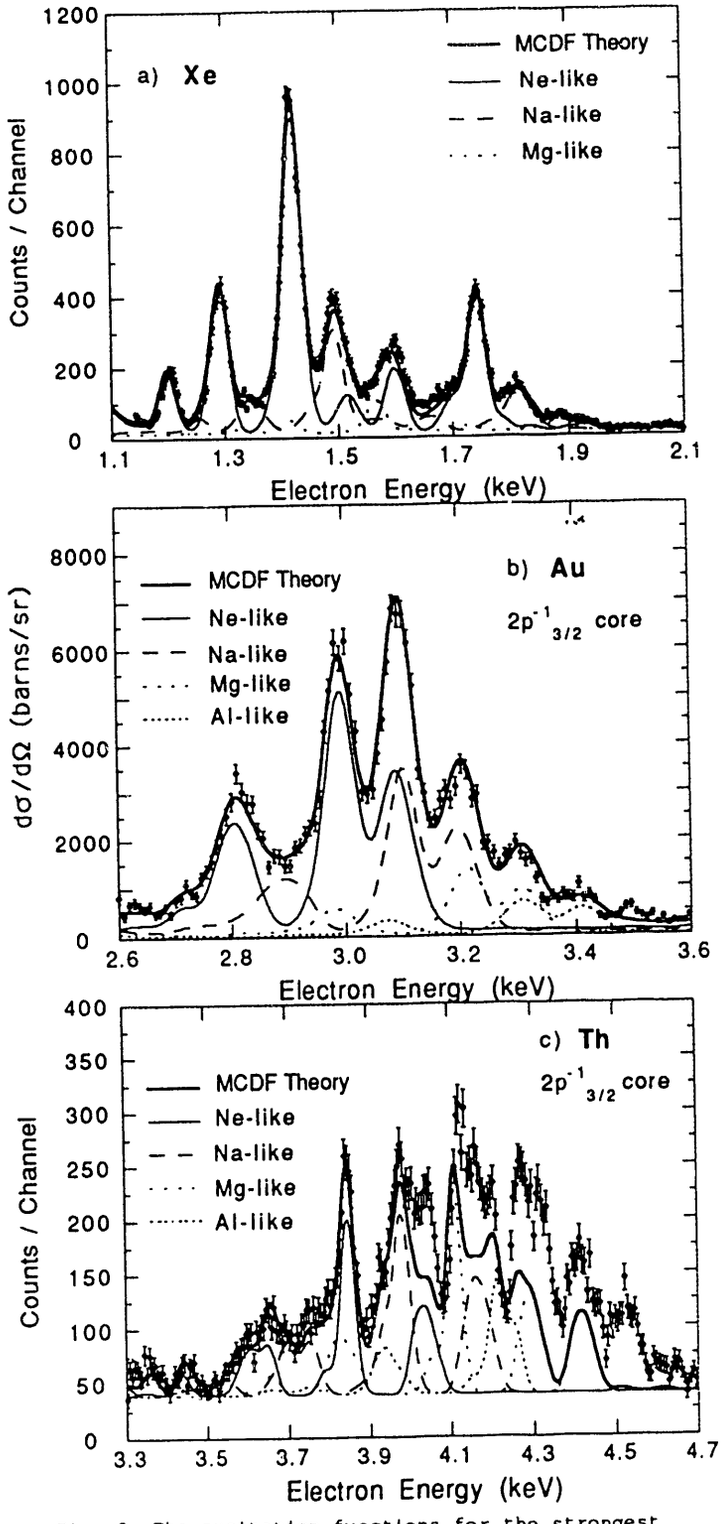


Fig. 3 The excitation functions for the strongest portion of the LMM resonances for neonlike (a) $Xe^{44+}$, (b) $Au^{69+}$, and (c) $Th^{80+}$ target ions, respectively.

were treated as $\delta$ functions normalized to the energy-averaged cross sections as defined by Lagattuta and Hahn[15]. The cross sections for emission of X rays at 90° to the electron beam were expressed as resonance strengths averaged in energy bins of 1 eV. A more complete presentation of the techniques used is given in Ref. 13.

The theoretical fit to the Xe data required three target ionization states, the Au data needed four states, but the Th data requires at least six states (which were not yet available). The results are shown in Fig. 3, along with the contribution of each target ionization state. The shapes of the resonances for the Xe and Au data are in very good agreement with theory. The part of the Th data involving the neonlike target state is also in good agreement with theory. The Gaussian FWHM of the electron energy was 30 eV for the xenon data, 60 eV for the gold data, and 40 eV for the Th data. The Au data has the poorest resolution because of noise on the high-voltage power supply used to accelerate the electron beam in that experiment. The Th data has slightly worse resolution than the Xe data because it was obtained at a beam current of 50 mA, and the Xe data was obtained with a 30 mA current.

To obtain an absolute cross section, the overlap of the ions with the electron beam must be known. Because this is not possible, the strength of the dielectronic recombination resonances were normalized to that of radiative recombination. The normalization factor, in counts per cross section, is obtained by dividing the number of RR X rays at each electron energy by the detector efficiency times the sum of the fraction of each ionization state (obtained from the theoretical fit to the DR excitation function) times its calculated radiative recombination cross section. The RR cross sections for X rays emitted at 90° to the electron beam for each ionization state were calculated using a relativistic distorted-wave code.[14] Care was taken to use only those regions of the RR bands to n=3,4,5 which were uncontaminated by other processes.

About 20 out of 50 LMM DR resonances onto the neonlike ion, 40 out of 115 onto the sodiumlike ion, 20 out of 60 onto the magnesiumlike ion, and 40 out of 160 onto the aluminumlike ion make significant contributions to the DR cross sections for the Au and Th data shown in Fig. 3. The dominant contribution is from high angular momentum intermediate states with a $2p^{-1}{}_{3/2}$ core and at least one DR electron in the $3d_{5/2}$ subshell.

The final measured total resonance strength for DR in neonlike gold between 2.6 and 3.6 keV is $1.0 \pm 0.15 \times 10^{-17}$ cm$^2$-eV; the theoretical value is $0.95 \times 10^{-17}$ cm$^2$-eV. The principal source of error comes from the uncertainty in the normalization factor.

We have also carefully examined the LMM resonances in neonlike gold with intermediate states with $2p^{-1}{}_{1/2}$ and $2s^{-1}{}_{1/2}$ core configurations. Figure 4 shows the data in this region compared to the MCDF theory with the ionization balance, beam width, and normalization factor from the data in Fig. 3b. A discrepancy was found for the peak at 4.55 keV. The MCDF theory predicts this peak to be composed of two neonlike DR resonances: 80% from an intermediate state composed mainly of the $(2p^{-1}{}_{1/2}3p_{3/2}3d_{3/2})_{J=5/2}$ state and 20% from an intermediate state composed mainly of the $(2s^{-1}{}_{1/2}3s_{1/2}3d_{5/2})_{J=5/2}$ state. It is likely that the theory

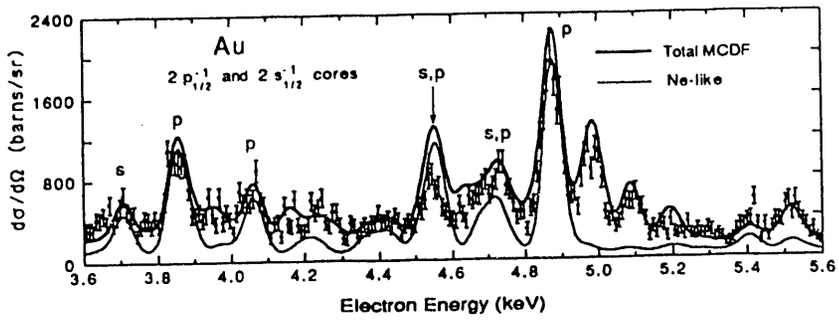


Fig. 4 DR excitation function data of neonlike $Au^{69+}$ target ions for the $2s^{-1}_{1/2}$ and $2p^{-1}_{1/2}$ core regions. The theory uses the parameters from Fig.3b. The major neonlike peaks are identified by s or p for the different cores. The arrow identifies the peak with biggest discrepancy with the MCDF theory.

overestimates the mixing between these two states, making the resonance of the mainly $2s^{-1}{}_{1/2}$ state too large.

EXTRACTION EXPERIMENTS

We have also measured the DR resonances of neonlike $Xe^{44+}$ using EBIT as an ion source.[9] In these experiments, an ionization balance is first established, and then the DR resonances are probed by lowering the beam current (typically to 5 mA) and the beam energy (to a probe energy ) for a given probe time. The beam current is then turned off and the beam energy increased to the fixed extraction energy. The ions are extracted by pulsing the axial trap to invert it. Those ions with a preselected charge are magnetically steered into a photomultiplier tube and counted. Two to five dumps per probe condition are usually performed, and then the probe energy or the probe time is changed. A plot of the number of neonlike $Xe^{44+}$ ions versus probe energy shows a large decrease in the number of $Xe^{44+}$ at its DR resonances. At each probe energy, the number of ions decreases exponentially with time because the only process occuring is recombination, so the experiment is repeated for several different probe times. For each probe energy, the data at different probe times is used to find the exponential decay rate. Fig. 5 showns the decay rate versus electron energy. This decay rate is proportional to the sum of the different recombination processes, dielectronic recombination, radiative recombination, and charge exchange with background gases. The latter two processes vary smoothly with energy, so the theoretical DR cross sections are used to fit the data in Fig. 5 for a smooth background, an electron energy resolution, and a scaling factor. The electron energy resolution for the data in Fig. 5 is 16 eV FWHM, as compared to the 30-eV FWHM for xenon data in Fig. 3a. The improved resolution is due to the low beam current and low axial trapping voltage (~10 V) used. While these two factors reduce the number of ions in the beam

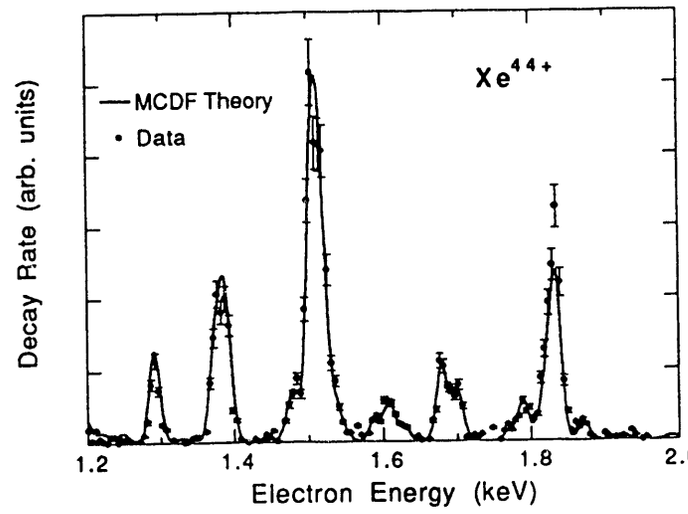


Fig. 5. Decay rate of the number of $Xe^{44+}$ ions extracted versus probe electron energy. The smooth curve is the MCDF theory for the DR resonance strengths convoluted with an electron energy resolution of 16 eV FWHM.

compared to an x-ray technique, there is still plenty of signal in the extracted ions. Under these conditions, the variance of the electron energy in the overlap of the ion cloud and electron beam is smaller, improving the resolution.

## NEW RESULTS ON HELIUMLIKE SYSTEMS

We have also used the "event-mode" data acquisition technique to measure the KLL resonances of heliumlike $Ni^{28+}$, $Mo^{44+}$ and $Ba^{54+}$ target ions. Fig. 6 shows the result. Again, the agreement with theory is excellent. The Ni and Mo data have been normalized. The electron energy resolution is 50-60 eV FWHM for this data. Some structure is resolved in the Mo and Ba data.

Recently, we obtained high resolution x-ray spectra of the DR resonances in heliumlike $V^{21+}$.[7] We used a Bragg crystal spectrometer in the von Hamos geometry[16] to record spectra at fixed electron energies, for values of the electron energy at and near the DR resonances. Since the KLL resonances are ABOVE the ionization threshold of Li-like to He-like ions in heliumlike systems, a steady-state ionization balance is reached at each electron energy. (Especially at electron energies near the DR resonances, the

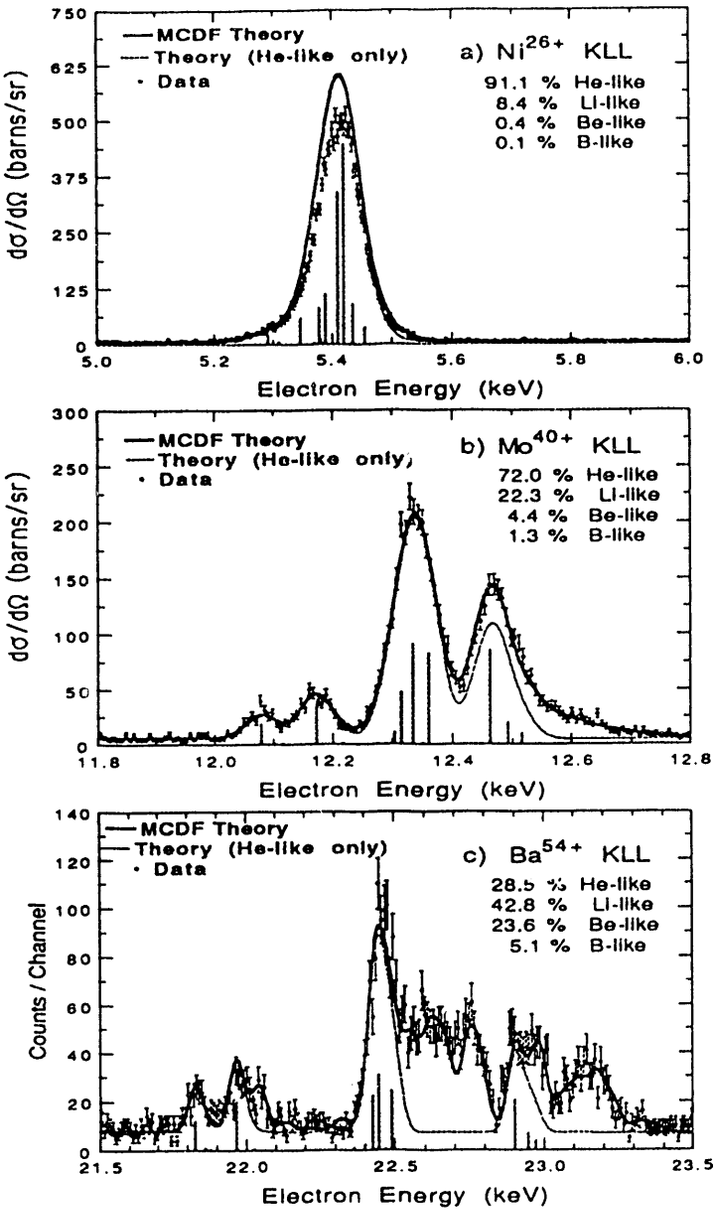


Fig. 6. Comparison of theory and experiment for the KLL DR resonances of heliumlike target ions using the event-mode x-ray technique. The vertical lines represent the theoretical resonance strengths of the heliumlike target ion. The curves are the theoretical resonance strengths folded with the experimental electron energy resolution. Theory curves are shown both for heliumlike target ions only, and for the actual ionization balance present in the trap. The measured amplitude is a) $Ni^{26+}$ 85 ± 7 %; b) $Mo^{40+}$ : 102 ± 6 % of the theoretical value.

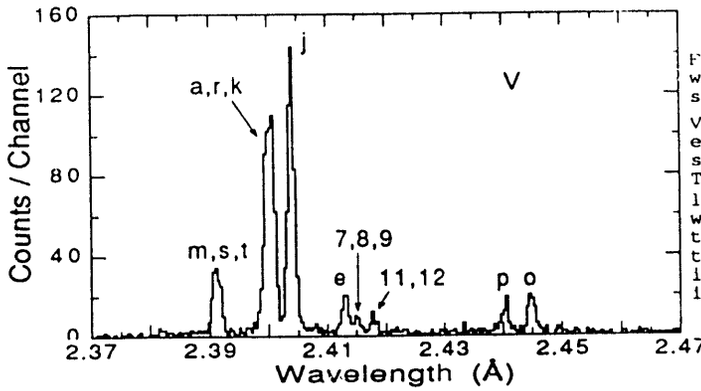


Fig. 7. X-ray spectrum taken with a Bragg crystal spectrometer of heliumlike $V^{21+}$ target ions. The electron energy is 60 eV below the strongest KLL resonances. Transitions in the recombined lithiumlike ions are labeled with lower case letters in the notation of Ref. 17, and the numerals label transitions in the recombined berylliumlike ions.

ionization balance is poor). Figure 7 shows a typical x-ray spectrum of V at an electron energy near the KLL resonances. The lithiumlike satellite line positions were measured with an average accuracy of 0.2 mÅ, which is a resolution ($\Delta E/E$ or $\Delta\lambda/\lambda$ ) of 8 x $10^{-4}$. The lithiumlike satellite lines e, o, and p were seen for the first time in such highly-charged ions.

We have added the von Hamos spectrometer to the event-mode data acquisiton system. We have used this to study the DR resonances of heliumlike $Cr^{22+}$ target ions. Figure 8 shows the scatter plot and an x-ray spectrum at the KLL resonances. This technique preserves the original ionization balance.

## SUMMARY

In summary, we have discussed several techniques used to measure DR resonances using an electron beam ion trap. The event-mode x-ray technique with a solid state detector gives an electron energy resolution of 50 eV FWHM, but poor x-ray energy resolution. However, the DR resonance strength relative to that of radiative recombination can be determined because the data acquisition process is self-normalizing. The event-mode coupled to a von Hamos spectrometer gives the same electron energy resolution but the resonances are resolved to 8 x $10^{-4}$ in x-ray energy. These x-ray experiments benefit from high beam currents to improve the data rate. The extraction technique, which uses EBIT as an ion source, allows very high resolution in electron energy (16 eV FWHM) because it can use a low beam current and low trapping voltage. Its disadvantage is the inability to normalize the resonance strengths.

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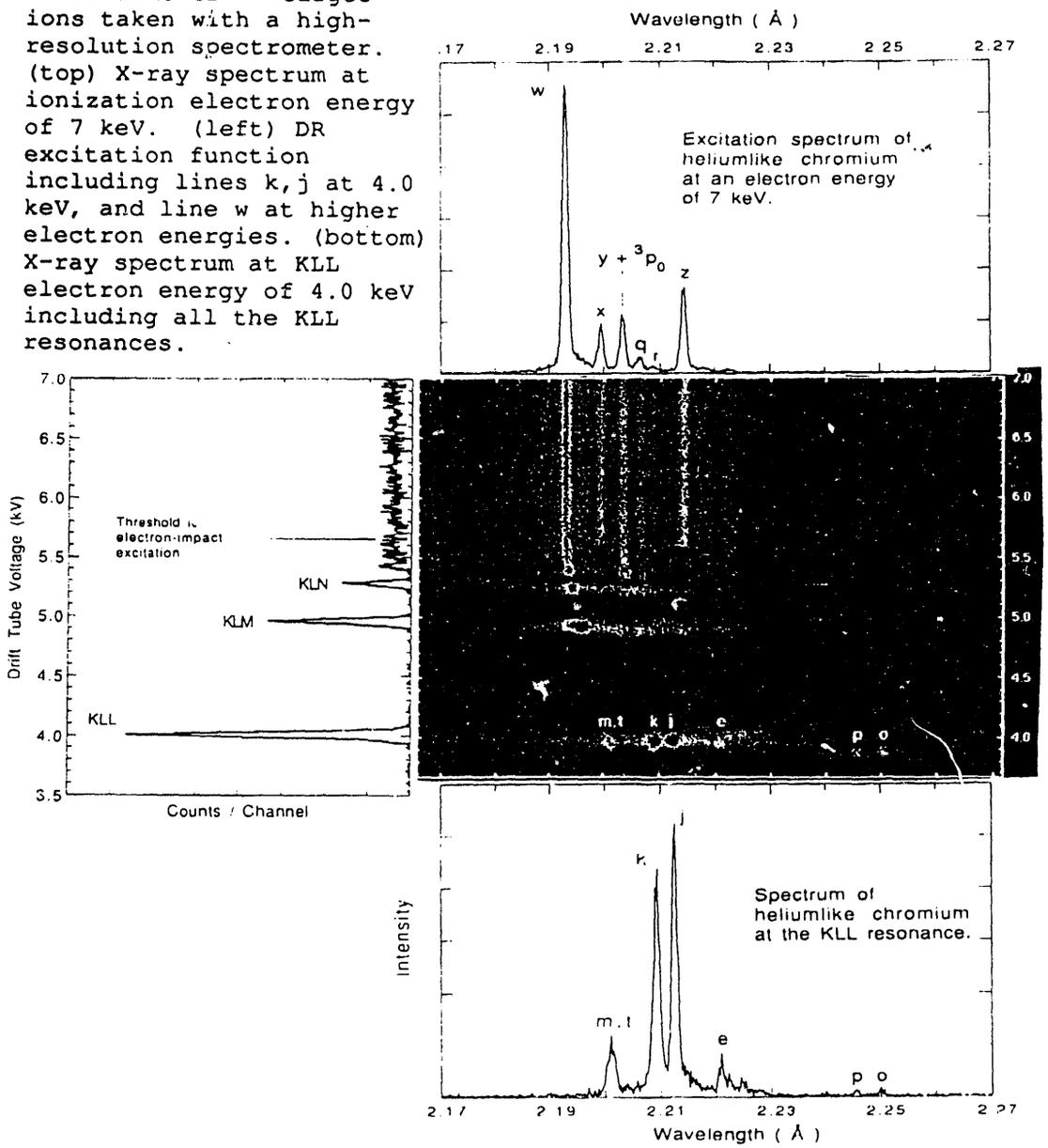
Fig. 8: (middle) Scatter plot of events from heliumlike $Cr^{22+}$ target ions taken with a high-resolution spectrometer. (top) X-ray spectrum at ionization electron energy of 7 keV. (left) DR excitation function including lines k,j at 4.0 keV, and line w at higher electron energies. (bottom) X-ray spectrum at KLL electron energy of 4.0 keV including all the KLL resonances.



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