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Recent results from the low temperature spare Astro-E microcalorimeter used at the LLNL

EBIT-I and EBIT-II

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Abstract. In the past year a spare NASA/GSFC Astro-E microcalorimeter has been installed, tested, and run successfully on the electron beam ions traps EBIT-I and EBIT-II at the Lawrence Livermore National Laboratory. The microcalorimeter complements crystal and grating spectrometers already part of the LLNL ebit program making it possible to measure a broad bandwidth (~0.3–10 keV) with moderate resolution while simultaneously measuring a narrow bandwidth (~0.7–1.3 keV) with high resolution. An overview of recent work, including measurements by the microcalorimeter of absolute excitation cross is presented. These results continue our effort to provide atomic data of high quality to be used as benchmarks of theoretical calculations and to be included in atomic data bases employed by spectral fitting packages used to interpret spectra obtained by *XMM-Newton* and the *Chandra X-Ray Observatory*.

INTRODUCTION

High-resolution X-ray spectra obtained by *XMM-Newton*, the *Chandra X-Ray Observatory*, and soon Astro-E2, put new demands on atomic data used by spectral fitting packages to deduce the physical properties of astrophysical sources. Over the last decade the spectroscopy group at the Lawrence Livermore National Laboratory electron beam ion traps EBIT-I and EBIT-II, in collaboration with the Columbia University Astrophysics Laboratory, and recently, NASA's Goddard Space Flight Center, has developed an extensive laboratory astrophysics program to address these demands. This program includes the development of an ensemble of crystal, grating, and solid state spectrometers, and the development and implementation of unique measuring techniques. The most recent addition is a spare NASA/GSFC Astro-E XRS microcalorimeter [1], which has been installed, tested, and run successfully on both EBIT-I and EBIT-II.

The XRS microcalorimeter complements crystal and the grating spectrometers at EBIT-I making it possible to measure a broad band-width (~0.3–10 keV) with moderate resolution while simultaneously measuring a narrow bandwidth (~0.7–1.3 keV) with high resolution. The XRS maintains a resolution of ~ 8–10 eV FWHM across its entire bandpass. The resolution, in conjunction with the ability to integrate for up to 12 hours with high gain stability [2] the large effective area, and the well calibrated response, have made it possible for our group to measure the absolute excitation cross sections of Fe L-shell transitions relative to radiative recombination. A brief synopsis of this measurement is given here.

Absolute excitation cross sections

Excitation cross sections are one of the basic atomic parameters used to model x-ray spectra. Previously, we have measured cross sections with crystal spectrometers by normalizing to theory at high energy [3]. Although this type of normalization can be fairly reliable, especially at high electron-ion collision energies, the accuracy is limited to 15–30%, and may be much worse (factors of two or more), if the levels are affected by configuration interactions. A more reliable method is to normalize to radiative electron capture, i.e. radiative recombination (RR). RR and occurs when a free electron is captured into a vacant level in an ion with the emission of a photon. The energy of the photon is equal to the sum of the electron's kinetic energy plus the ionization potential of the target level. Because this process involves only one electron, one ion, and one photon, RR cross sections have been both measured and calculated at high electron energies to accuracies of ~ 3–5 %. Once a cross section is normalized to RR, it is "absolute" in the sense that it is normalized to the most well known atomic process available.

Photon emission produced by RR is relatively weak because their cross sections are generally ~ 1000–10000 smaller than for direct excitation. This makes it impossible to measure RR with crystal spectrometers because of their relatively low efficiency. In the past, we have used high-purity germanium detectors to measure RR emission for normalization of K-shell iron excitation cross sections [4]. Unfortunately, these detectors are not able to resolve the Fe L-shell RR. The XRS microcalorimeter is the only instrument that offers the energy resolution, large effective area, and the ability to integrate for long times with a stable energy gain to reliably detect and resolve the weak RR photon emission. The XRS also simultaneously measures the line emission from direct electron impact excitation (EIE). To resolve blends occurring in the microcalorimeter, we simultaneously measure the EIE spectra with crystal spectrometers. The overlapping EIE line emission measured in both the microcalorimeter and in the crystal spectrometers is used to normalize these instruments to one another. Using this technique of normalization to RR and then normalizing the XRS to the crystal spectrometers, we are able to provide absolute cross sections for the discrete Fe L-shell x-ray lines.

Figure 1 shows the iron spectrum measured at EBIT-II during the XRS/EBIT microcalorimeter's first experimental run. This shows both the strong direct excitation and the weak RR emission measured by the XRS. Figures 1a and b show the XRS spectrum compared to the high-resolution crystal spectrum. The RR spectrum shows recombination onto helium-, lithium-, berylium-, and boron-like iron. There are two peaks associated with the helium-like RR owing to recombination into the $1s^22s$ and the $1s^22p$ levels. The 50 eV separation of these peaks is equal to the difference in ionization potentials of the 2s and the 2p electrons. Each of the other recombination peaks consists of several blended fine structure components. The blending is not a result of the resolution of the microcalorimeter, but a result of the fact that the electron beam in this experiment was ~ 45 eV wide, while the fine structure levels are separated by an energy that is as little as 10 eV. This does not prohibit the ability to normalize to the RR because recombination onto different charge states is resolvable.

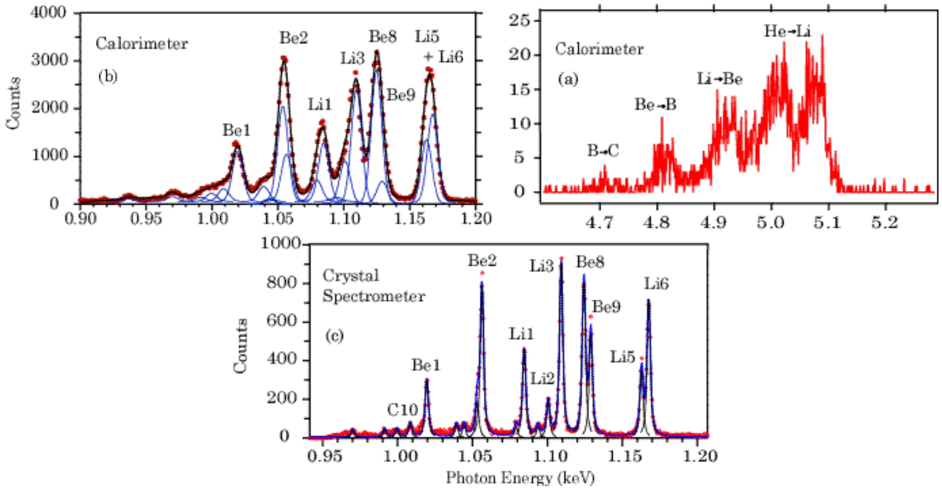

FIGURE 1. Spectrum measured with the XRS (a and b) and with the crystal spectrtometers (c) at an electron beam energy of 3.0 keV. using the radiative recombination photon emission in (b), we are able to provide absolute cross sections of electron impact excitation.

The analysis for the absolute cross sections of the three strong Fe XXIV 3 → 2 lines Li3, Li5, and Li6 has been completed and is reported in Chen et al. 2001 [5]. With the normalization to the RR, we are able to provide an absolute scale for the y-axis for the previous crystal spectrometer measurements of these lines. Figure 2 shows the absolutely calibrated Fe XXIV lines Li3, Li5, and Li6 each measured as a function of energy with the crystal spectrometers and then normalized to the RR. This normalization also provides the scaling for the cross section for dielectronic recombination and resonance excitation. This particularly important because DR has been identified as one of the main sources of uncertainty in charge balance calculations.

We also use the RR emission to measure charge balance. The relative intensity of the recombination peaks associated with each ion is a measure of the relative ion abundance. Our measurements of charge balance can immediately be used to test Fe ion balance calculations at constant energy.

SUMMARY

Here we have presented a brief overview of one of the measurements taking place at the LLNL electron beam ion trap EBIT-I using an Astro-E engineering spare microcalorimeter array. We have demonstrated long integration times and high gain stability, and a resolution of 8–10 eV. The microcalorimeter array has made it possible for our group to explore new regions of laboratory astrophysics. For example, the XRS/EBIT microcalorimeter has made it possible for the first time to use the radiative recombination photon emission to measure absolute cross sections of Fe L-shell transitions. These types of laboratory tests of atomic data will undoubtedly improve the reliability of astrophysical spectral models.

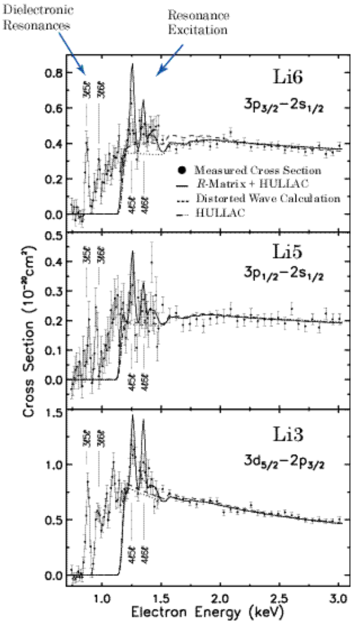

FIGURE 2 Absolutely calibrated excitation cross sections for three Fe XXIV line LI3, Li5 and LI6. as a function of energy.

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