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High-resolution x-ray spectroscopy with the EBIT Calorimeter Spectrometer

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Abstract. The EBIT Calorimeter Spectrometer (ECS) is a production-class 36 pixel x-ray calorimeter spectrometer that has been continuously operating at the Electron Beam Ion Trap (EBIT) facility at Lawrence Livermore National Laboratory for almost 2 years. The ECS was designed to be a long-lifetime, turn-key spectrometer that couples high performance with ease of operation and minimal operator intervention. To this end, a variant of the *Suzaku*/XRS spaceflight detector system has been coupled to a low-maintenance cryogenic system consisting of a long-lifetime liquid He cryostat, and a closed cycle, ^{3}He pre-cooled adiabatic demagnetization refrigerator. The ECS operates for almost 3 weeks between cryogenic servicing and the ADR operates at 0.05 K for more than 60 hours between automatic recycles under software control. Half of the ECS semiconductor detector array is populated with mid-band pixels that have a resolution of 4.5 eV FWHM, a bandpass from 0.05-12 keV, and a quantum efficiency of 95% at 6 keV. The other half of the array has thick HgTe absorbers that have a bandpass from 0.3 to over 100 keV, an energy resolution of 33 eV FWHM, and a quantum efficiency of 32% at 60 keV. In addition, the ECS uses a real-time, autonomous, data collection and analysis system developed for the Suzaku/XRS instrument and implemented in off-the-shelf hardware for the ECS. Here we will discuss the performance of the ECS instrument and its implementation as a turnkey cryogenic detector system.

Keywords: X-ray detector, Calorimeter, X-ray Spectroscopy, Laboratory Astrophysics
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INTRODUCTION

Cryogenic x-ray calorimeter spectrometers have been in development for spaceflight since the early 1980s and are scheduled to fly on several future x-ray observatories including *Astro-H* and the International X-ray Observatory. The x-ray calorimeter will revolutionize x-ray astrophysics due to its superb energy resolution, large simultaneous bandpass, high efficiency, and its ability to observe extended sources without degrading its performance. These same attributes make a calorimeter spectrometer extremely useful in some ground applications as well, although with some notable limitations: fairly low count rates (10s-1000s counts/sec), small collecting areas (~10s of mm^2), complex cryogenic systems, and complex data analysis. One nearly ideal ground application is for measurements in atomic physics and laboratory astrophysics with an Electron Beam Ion Trap (EBIT).

An EBIT is a plasma source that can generate nearly pure ionization states of almost any element up to bare uranium with electron densities approaching 10^{12}/cm^3, similar to stellar coronae. Almost every astrophysically interesting species in every ionization state can be produced and the resulting emission measured and compared to atomic models and the atomic synthesis codes that are used to model astrophysical observations. An x-ray calorimeter system complements the plasma source extremely well since the plasma source can be tuned within the x-ray calorimeter's count-rate range. In addition, the energy resolution, broad dynamic range, and non-dispersive nature of the calorimeter spectrometer complement well the very-high-resolution dispersive instruments also used with the EBIT source.

In 2000 we deployed an Engineering Model of the 32-channel x-ray calorimeter system designed for the *Astro-E* spaceflight system at the EBIT facility at the Lawrence Livermore National Laboratory (LLNL).

The system was then upgraded in 2003 with improved electronics and a higher spectral resolution detector array [1]. This system, known as the XRS/EBIT, operated continuously for almost 7 years and was used for many measurements in laboratory astrophysics including line identification, absolute cross sections, lifetimes, line ratios, and observations of charge-exchange recombination[2]. In 2007 we deployed a new instrument, the EBIT Calorimeter Spectrometer (ECS)[3], at the LLNL EBIT facility that was designed from the ground up to be an easy-to-use, virtually autonomous, x-ray calorimeter spectrometer. The ECS has now been in operation for almost two years and has produced spectacular results[4]. Below we briefly describe the ECS detector system, the ECS cooling system, and the ECS control and analysis system.

ECS DETECTOR SYSTEM

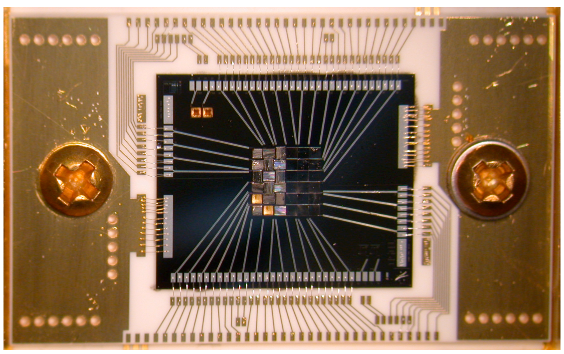

FIGURE 1. The ECS 6x6 detector array. The left half of the array are 624 x 500 x 100 μm hard-band pixels and the right half are 624 x 624 x 8 μm mid-band pixels.

The ECS instrument is composed of a 6x6 detector array from the Suzaku/XRS program [5] but populated with a hybrid complement of absorbers and run at a lower operating temperature. The detector array, shown in Figure 1, is manufactured monolithically on a single silicon wafer [6]. The thermometers are ion implanted into the device layer of a silicon-on-insulator (SOI) wafer and the suspended calorimeter is then defined by deep-reactive-ion etching. The resulting calorimeter array then requires the attachment of x-ray absorbing tiles to each pixel to complete the detector.

The 36 channel ECS detector array (32 are read out) is a hybrid array, with half the channels optimized for the mid-band (0.05-12 keV) and the other half optimized for the hard x-ray band (0.3 to > 100 keV). The mid-band detectors use standard Suzaku/XRS 624 x 624 x 8 μm thick HgTe x-ray absorbers, and the hard band detectors use 624 x 500 x 100 μm thick HgTe absorbers that were cut from a single 500 μm thick HgTe wafer. This gives the mid-band pixels 95% quantum efficiency (QE) at 6 keV, and the hard-band pixels 32% QE at 60 keV.

The detector assembly is nearly identical to the *Astro-E* detector assembly [7] with the addition of larger load resistors (120 MOhm vs. 90 MOhm), IR absorbing coatings inside the 50mK detector cavity, and a collimator to reduce x-ray hits to the detector frame outside the main detector array. The detector assembly mounted on the ECS cryogenic package is shown in Figure 2.

ECS CRYOSTAT

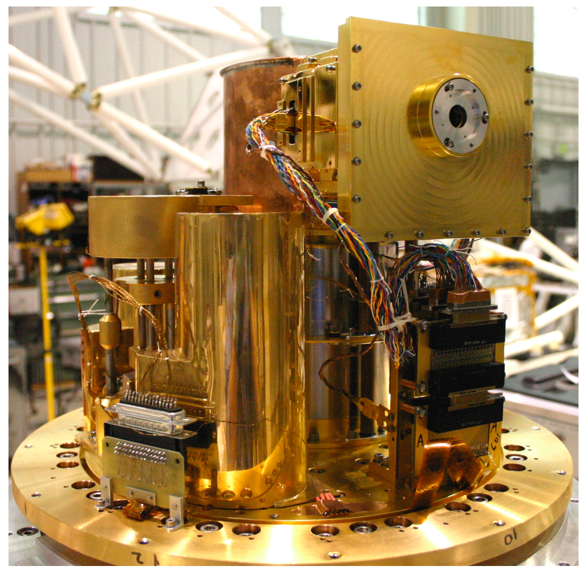

FIGURE 2. The ECS Cryogenics package is composed of the detector assembly (upper right), a $^3He/^4He$ sorption cooler (left), and a single-stage ADR (rear, obscured). The whole system requires only a sub-5 K interface and electrical connections to operate.

The ECS cryostat is composed of a standard, long-lifetime 32-liter liquid helium cryostat with a 25 liter liquid nitrogen shield. The liquid helium is operated at 4.2 K and atmospheric pressure and lasts for about 3 weeks between refills.

The ECS cryogenics package is composed of a Chase Cryogenics $^3He/^4He$ sorption refrigerator that pre-cools a single-stage adiabatic demagnetization refrigerator (ADR) designed and constructed at NASA/GSFC. The *Astro-E* detector assembly requires a heat sink below 2K to absorb about 100 μW of heat from the 130 K JFET amplifiers. This makes a two-stage ADR heat sunk at 4.2 K impractical but matches well with a custom designed sorption cooler. The ECS system uses the ^4He side of the sorption cooler, which has a base temperature of 0.81 K, to condense the ^3He and to absorb the heat of magnetization of the ADR. After the ADR is cycled to full field (4T), the ADR is demagnetized to 50 mK, and the He-3 sorption cooler is pumped to 0.34 K, providing a guard stage for the ADR and the detector assembly. The ADR is a 100 g FAA salt pill that is Kevlar suspended from 0.34 K and attached to the heat sink with a passive-gas-gap heat switch. The Chase Cryogenics sorption cooler is completely self-contained, with no external plumbing or actuators, as is the ECS ADR. Thus the entire cryogenic package needs only a sub-5K heat sink and electrical wiring to operate.

The ECS cryogenic system operates for about 65 hours at 50 mK, limited by the volume of ^{3}He before recycling. We have recently (2008) produced a cryogen-free version of the ECS using a CryoMech PT405 pulse-tube cooler that operates for over 100 hours, again limited by the lifetime of the ^{3}He. Both systems have a heatload below 50 nW at the ADR and can operate below 30 mK for their entire cycle. The sorption cooler and the ADR are recycled together, in a completely automated process requiring about 2 h.

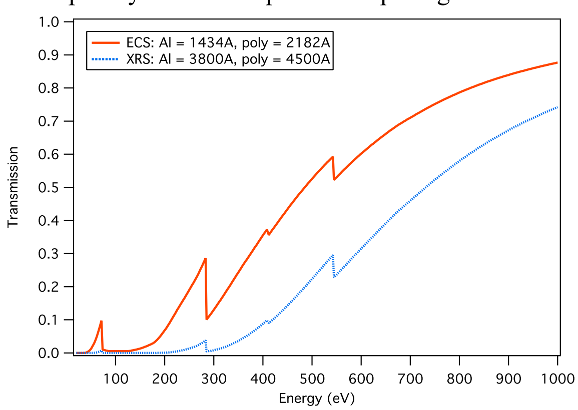

FIGURE 3. Total transmission of the four thin infrared blocking filters used in the ECS. The transmission is significantly improved over the filter stack used for the Suzaku/XRS instrument, shown in blue.

X-ray calorimeters require infrared blocking filters in the aperture to prevent photon shot noise from impacting the detector resolution, and to prevent heating of the detectors, the ADR, and the liquid helium bath. The ECS uses four thin aluminum-on-polyimide filters staged at 50 mK, 320 mK, 4.2 K, and 77 K with a total thickness for the four filters of 2182 Å of polyimide and 1434 Å of aluminum. The filters used in the ECS are much thinner than those used on the Suzaku/XRS instrument. The total transmission curve is shown in Figure 3. The filters are baffled from room temperature and from the multi-layer insulation surrounding the liquid nitrogen tank to prevent water ice from forming on the outer filter. Similar baffling was used on the older XRS/EBIT instrument, preventing water contamination of the filter transmission during years of operation.

ECS CONTROL AND ANALYSIS

The ECS cryogenic system is fully automated using a custom C++ control and visualization system. The sorption cooler heat switches, and the ADR are controlled using software PID controllers, and the cryogenic cycle controlled by a state-machine. The ADR is controlled at 50 mK to better than 200 nK RMS and thus thermal fluctuations in the ADR control contribute negligibly to the detector resolution.

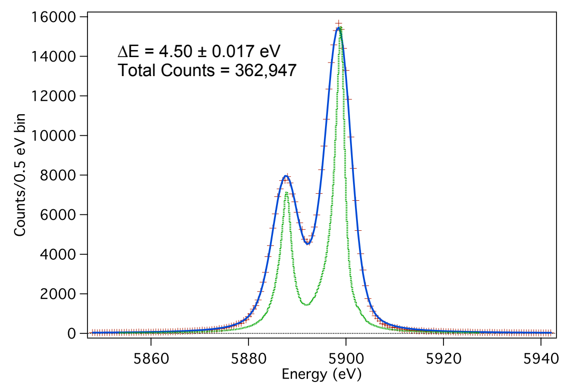

FIGURE 4. ECS measurement of Mn Kα emission from a ^{55}Fe source. The natural line shape is shown in green. The ECS response (blue) is purely Gaussian with a resolution of 4.5 eV FWHM at 6 keV (sum of all mid-band channels). The integration time was 29 hours.

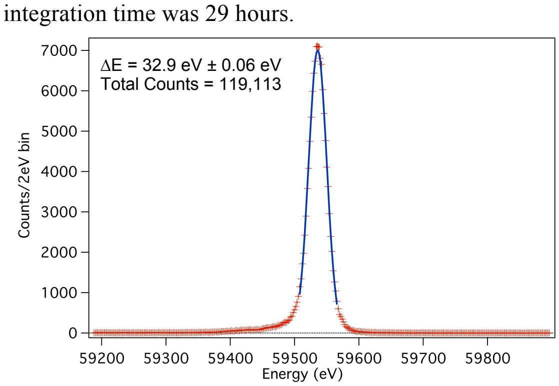

FIGURE 5. ECS measurement of 60 keV γ-emission from a ^{241}Am source. The ECS response is almost purely Gaussian, with a small low energy tail with a resolution of 33 eV FWHM at 60 keV (sum of all hard-band channels). The integration time was 19 hours.

The ECS uses a software version of the Suzaku/XRS real-time pulse analysis system known as the software calorimeter digital processor (SCDP) which is described more fully by Adams[8]. The SCDP is connected via a network connection to a real-time-visualization system also developed for the Suzaku/XRS instrument. The result is that the ECS is a real-time spectrometer, with little or no post processing of the data necessary before spectral analysis and interpretation. The ECS SCDP has an additional feature that allows it to be phase synched to the EBIT injection cycle. This unique feature allows the ECS to separate the parts of the EBIT cycle that produce only the data of interest from times when the plasma is either out of equilibrium or in a pre-heat or preparatory mode. This is important since the EBIT cycles usually only last a few seconds and several thousand are usually needed to produce a spectrum with sufficient statistics.

PERFORMANCE AND CONCLUSIONS

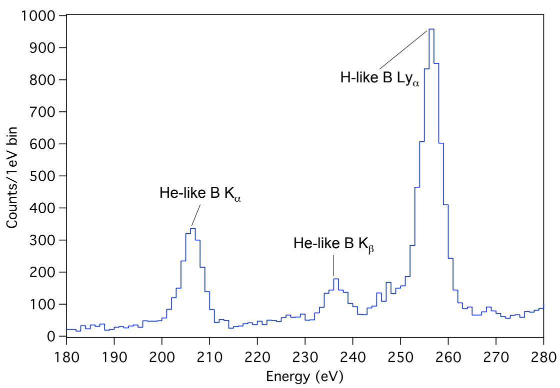

FIGURE 6 ECS measurement of highly ionized He-like and H-like B produced in the LLNL EBIT, showing the ECS performance at low energies.

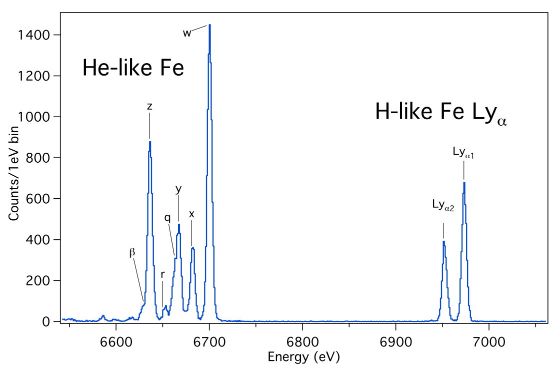

FIGURE 7 ECS measurement of highly ionized He-like and H-like Fe produced in the LLNL EBIT showing the ECS performance at mid-band energies.

The ECS detector system has performed very well. After an ADR/sorption cooler cycle, the platform is stable enough that the x-ray data generally do not require gain drift correction over the entire 65-hour cycle. The energy resolution of the summed mid-band pixels is 4.5 eV FWHM at 6 keV as shown in Figure 4. The energy resolution of the hard-band pixels is 33 eV FWHM at 60 keV as shown in Figure 5. Figures 6-8 show measurements of highly ionized boron, iron, and xenon [9] produced in the EBIT and observed with the ECS. These measurements span more than two orders of magnitude in energy and demonstrate the performance of the ECS in operation.

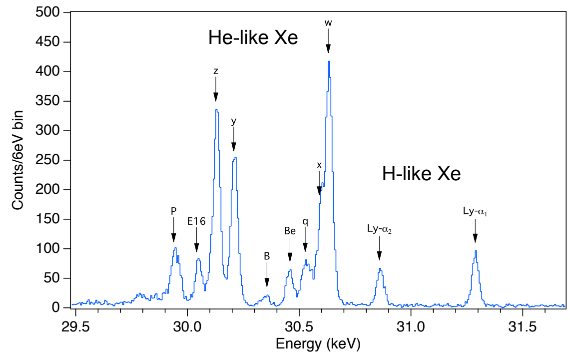

FIGURE 8 ECS measurement of highly ionized He-like and H-like Xe produced in the LLNL EBIT showing the ECS performance at high energies.

In summary, the ECS was designed as a high performance, nearly turnkey, cryogenic x-ray spectrometer and has performed flawlessly for almost 2 years at the LLNL EBIT facility. In addition, we have recently produced a cryogen-free version of the ECS using the same cryogenic package mounted to a 3 K mechanical pulse-tube cooler, providing even simpler operation, and an ADR hold time below 30 mK of nearly 100 hours. Finally, we are currently designing a replacement for the ECS with our colleagues at NIST that will feature a 320 pixel TES detector array attached to the cryogen-free ECS cryogenics package. The TES system, known as the Transition-Edge Microcalorimeter Spectrometer (TEMS), will feature a hybrid high-mid-low band detector array with ~2 eV spectral resolution at 6 keV, and a bandpass from 0.05 to >100 keV and will be deployed at the LLNL EBIT in 2011.

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