

# High-resolution hard x-ray spectroscopy of high-temperature plasmas using an array of quantum microcalorimeters<sup>a)</sup>

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(Presented 12 May 2008; received 12 May 2008; accepted 15 May 2008; published online 31 October 2008)

Quantum microcalorimeters show promise in being able to fully resolve x-ray spectra from heavy highly charged ions, such as would be found in hot plasmas with temperatures in excess of 50 keV. Quantum microcalorimeter arrays are able to achieve this as they have a high-resolving power and good effective quantum efficiency for hard x-ray photons up to 60 keV. To demonstrate this, we present a measurement using an array of thin HgTe quantum microcalorimeters to measure the *K*-shell spectrum of hydrogenlike through carbonlike praseodymium ( $Z=57$ ). With this device we are able to attain a resolving power,  $E/\Delta E$ , of 1000 at a photon energy of 37 keV. © 2008 American Institute of Physics. [DOI: 10.1063/1.2953449]

## I. INTRODUCTION

The detection and diagnosis of high-temperature plasmas in the hard x-ray regime expose deficiencies in the current crop of detection schemes. The most prevalent types of detection systems for x rays are either crystal spectrometers or solid state detectors. Crystal spectrometers have been shown to be able to fully resolve the *K*-shell spectrum of elements up to xenon.<sup>1–3</sup> However, above a photon energy of 15 keV, the efficiency of crystal spectrometers makes it difficult to measure hard x rays (in all but the highest count rate sources) with enough statistical certainty to make a measurement viable. On the other hand, solid state detectors, such as high purity germanium (HPGe) detectors, are used to measure harder x rays and have shown much success for elements up to uranium.<sup>4,5</sup> Solid state detectors have high, if not unity, quantum efficiency (QE) at these photon energies, yet they have resolving powers of approximately 50–100 which makes accurately determining the spectral lines of heavy ion species in high-temperature plasmas difficult if not impossible.

In response to the deficiencies exhibited by using either detector system alone, hybrid detectors consisting of a high-quantum efficiency detector with a transmission crystal have been employed at a number of sources. However, to date, they either do not have the resolving power necessary to fully resolve the *K*-shell spectra of high-*Z* elements,<sup>6,7</sup> or require hundreds of hours to obtain statistically relevant spectra;<sup>3</sup> thus, an experiment must either choose high throughput or high resolution.

Thermal based detection systems such as quantum mi-

crocalorimeters promise to bridge the gap between high-resolution and high-quantum efficiency in the hard x-ray regime.<sup>8,9</sup> Microcalorimeters utilizing HgTe as an absorber material have been successfully operated in the laboratory,<sup>10,11</sup> on rocket borne experiments,<sup>12</sup> and also in orbit.<sup>13</sup> These microcalorimeters have, in general, been optimized to measure photons with energies between 0.1 and 10 keV, with high-quantum efficiency, and with energy resolutions between 5 and 10 eV. To extend to higher photon energies, and thus dynamic range, higher quantum efficiency absorbers are desired. This can be done by increasing the thickness of the absorber material that is used. However, increasing the thickness of the absorber material increases the heat capacity of the device and the resolution of calorimeters scales with heat capacity; thus, an interplay between resolution, dynamic range, and QE must be taken into account.

To test the concept of using a large array of thin absorber pixels to measure *K*-shell spectra from high-*Z* ions in a high-temperature EBIT plasma, we present a measurement of the *K*-shell spectrum of highly charged praseodymium ions using an array of 8  $\mu\text{m}$  HgTe absorber microcalorimeters.

## II. EXPERIMENT AND RESULTS

The XRS/EBIT quantum microcalorimeter is an array consisting of twenty eight  $624 \times 624 \times 8 \mu\text{m}^3$  mercury-telluride (HgTe) absorber pixels and four  $624 \times 624 \times 30 \mu\text{m}^3$  bismuth absorber pixels attached to doped silicon thermistors.<sup>14</sup> The array was originally designed as a hybrid array with both low-energy x-ray spectroscopy work (under 10 keV) and high-energy work performed on the same array. The bismuth pixels were used in an early attempt to obtain high-quantum efficiency for high-energy photons.<sup>8</sup>

The original operating parameters of the HgTe pixel array were optimized for 6 keV photons. This causes photons under 10 keV to have a detected full width at half maximum

<sup>a)</sup>Contributed paper, published as part of the Proceedings of the 17th Topical Conference on High-Temperature Plasma Diagnostics, Albuquerque, New Mexico, May 2008.

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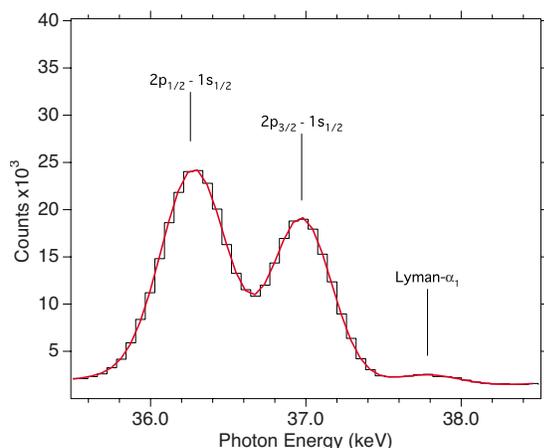


FIG. 1. (Color online) HPGe detector (IGLET) spectrum of H-like through C-like praseodymium taken at an electron beam energy of 127 keV. This spectrum was taken concurrently with the microcalorimeter measurement.

(FWHM) resolution of 6 eV and to not be saturated by the amplification system. By changing the detector parameters, namely, raising the temperature at which the detector is operated, the peak in voltage due to a photon being absorbed in the absorber material is reduced. This allows a hard x-ray event not to be saturated by the amplification system and the dynamic range of the microcalorimeter is extended to a photon energy of 60 keV. Praseodymium, which has *K*-shell spectral lines at approximately 37 keV, fits nicely into the usable bandwidth of the detector when operated at these new parameters. For this measurement we obtained a FWHM resolution of 37 eV, and the QE of a single 8  $\mu\text{m}$  HgTe pixel at a photon energy of 37 keV is 7%. A similar setup was employed to measure the gamma rays of  $^{229}\text{Th}$ .<sup>15</sup>

Praseodymium was injected into SuperEBIT via a laser ablation system.<sup>16</sup> The electron beam energy was set to energies of 127 and 46 keV. Two detection systems were used. The first was the XRS/EBIT quantum microcalorimeter which was set up to look perpendicular to the electron beam direction. The detector which is 3.7 mm on a side was situated approximately 65 cm from the electron beam center. The photons emitted from the EBIT plasma had to traverse two 5 mil beryllium windows that were used to hold off a 5 cm air gap. This air gap made it possible to insert a calibration source in front of the quantum microcalorimeter. The second detector used was a HPGe detector, which was set up perpendicular to the electron beam direction. The HPGe detector used was an IGLET-X detector system from EG&G and is 11 mm in diameter. It was situated approximately 50 cm from the EBIT plasma and the photons had to traverse only one 5 mil Be window with no air gap. The spectrum from the HPGe detector is given in Fig. 1, and spectra from the XRS/EBIT microcalorimeter are given in Figs. 2 and 3.

The two beam energies were chosen to investigate higher and lower average charge states for the plasma. At a beam energy of 127 keV, the electrons are energetic enough to make hydrogenlike praseodymium in sufficient quantities to allow for a measurement of the Lyman- $\alpha$  lines. The spectrum from the electron beam energy of 127 keV is shown in Fig. 2. At an electron beam energy of 46 keV the *K*-shell

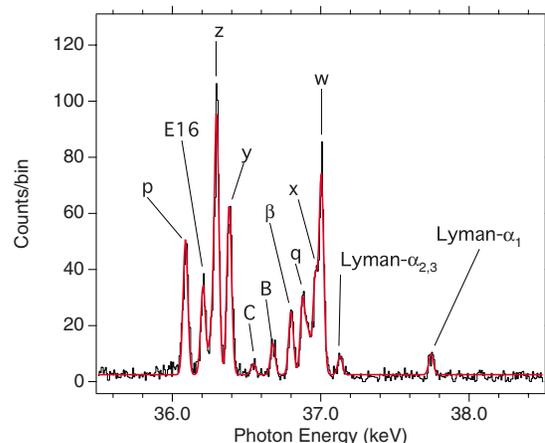


FIG. 2. (Color online) Quantum microcalorimeter spectrum of H-like through C-like praseodymium taken at an electron beam energy of 127 keV. Only the strongest lines are identified. The hydrogen like lines are labeled as Lyman- $\alpha_{1-3}$ ; the heliumlike and lithiumlike lines w, s, t, q, r, y, z, u, and v are labeled as according to Ref. 17; the berylliumlike lines  $\beta$  and E16 are labeled according to Refs. 18 and 19, respectively; and the boronlike and carbonlike resonance lines are labeled as B and C, respectively.

of praseodymium is not ionized and, thus, only charge states up to heliumlike praseodymium can be made. The spectrum from the electron beam energy of 46 keV is shown in Fig. 3. Since the electron beam energy is lower, the charge balance is shifted to lower charge states and the weaker lines from Be-like through C-like praseodymium are seen at the lower photon energies. This is evident when comparing Figs. 2 and 3.

With the high resolving power that the XRS/EBIT microcalorimeter affords, the charge balance can be extracted readily from the spectra. The charge balance for the measurement at electron beam energies of 127 and 46 keV is shown in Table I. It was determined by fitting the resonance lines to electron-impact excitation calculations from the flexible atomic code.<sup>20</sup>

The spectra in Figs. 2 and 3 are an addition of 8 and 10 days, respectively, of data from 22 of the highest-resolution individual HgTe pixels. Calibration was done with an  $^{241}\text{Am}$  radioactive source.  $^{241}\text{Am}$  has a plethora of nuclear

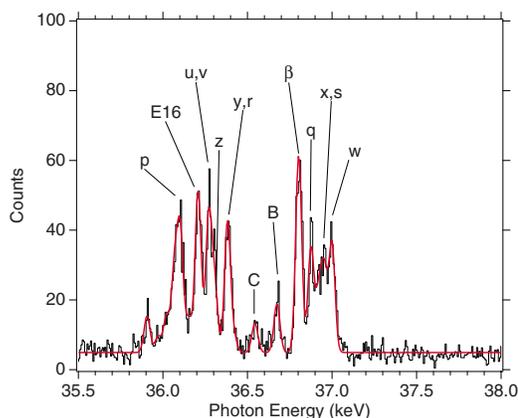


FIG. 3. (Color online) Quantum microcalorimeter spectrum of He-like through C-like praseodymium taken at an electron beam energy of 46 keV. Only the strongest lines in the spectrum are labeled and the lines are labeled in the same manner as in Fig. 2.

TABLE I. Charge balance for SuperEBIT plasmas at electron beam energies of 127 and 46 keV as measured with the XRS microcalorimeter.

Charge state	Charge balance (%)	
	127 keV beam energy	46 keV beam energy
H-like	9	...
He-like	37	18
Li-like	28	29
Be-like	13	27
B-like	9	15
C-like	4	11

decay  $\gamma$ -ray lines and neutral neptunium  $L$ -shell lines from 10 to 60 keV. Furthermore,  $^{241}\text{Am}$  has no strong lines in the region of interest, and is bright enough to have sufficient statistical certainty for each pixel and day. The data were also corrected for pulse height drift across any one day. The drift correction was done by placing the  $^{241}\text{Am}$  source in at the beginning of the day, for a 1 h period in the middle of the day and then left on overnight after the measurement was complete for the day, to accumulate statistics. A linear function for the centroid positions of the lines from the  $^{241}\text{Am}$  calibration source for the different times was then computed and the data shifted accordingly. No significant drifts were found.

The spectra from the two different energies reveal some of the atomic physics of higher- $Z$  ions. In  $j$ - $j$  coupling the lines split according to the  $j$ -level they are excited to. The XRS calorimeter is a great tool for displaying this split and shift of the lines relative to each other from lower- $Z$  ions. The spectra reveal a FWHM energy resolution of 37 eV and thus a resolving power,  $E/\Delta E$ , of approximately 1000. When compared to the Ge detector spectrum the advantages of using the quantum microcalorimeter array are magnified. The Ge detector has a resolving power of 80 at 37 keV and only three spectral features are seen. Whereas, in the calorimeter spectrum, many more features are seen and the charge balance of the plasma can be gleaned by simply fitting the known lines instead of fitting five to ten lines per spectral feature as would be needed in the Ge detector spectrum.

### III. CONCLUSION

The spectra from the XRS for the two  $K$ -shell measurements of highly charged praseodymium are striking. Never before has such a high-resolution spectrum been taken from such a high- $Z$  atomic ion. Even with the relatively low QE of any one detector element, the array is able to make a statistically relevant measurement by increasing the active area of the detector. This suggests using this type of detector system for high-temperature plasma spectroscopy and for determin-

ing the charge balance and other relevant plasma properties. Thus we have shown that arrays of thin HgTe pixels are desirable for the detection of high-energy photons when resolution is of importance.

### ACKNOWLEDGMENTS

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory in part under Contract No. W-7405-Eng-48 and in part under Contract No. DE-AC52-07NA27344 and supported by NASA APRA grants to LLNL and NASA/GSFC.

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