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Spectroscopic studies of xenon EUV emission in the 40-80 nm wavelength range using an absolutely calibrated monochromator

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Abstract. We have measured and identified numerous Extreme UltraViolet (EUV) radiative line structures arising from xenon (Xe) ions in charge state q = 1 to 10 in the wavelength range 40-80 nm. To obtain reasonable intensities of different charged Xe ions, we have used a compact microwave plasma source which was designed and developed at the Lawrence Berkeley National Laboratory (LBNL). The EUV emission of the ECR plasma has been measured by a 1.5 m grazing incidence monochromator that was absolutely calibrated in the 10-80 nm wavelength range using well known and calibrated EUV light at the Advanced Light Source (ALS), LBNL. This calibration has enabled us to determine absolute intensities of previously measured EUV radiative lines in the wavelengths regions investigated for different ionization stages of Xe. In addition, emission spectra of xenon ions for corresponding measured lines have been calculated. The calculations have been carried out within the relativistic Hartree-Fock (HF) approximation. Results of calculations are found to be in good agreement with current and available experimental and theoretical data.

1. Introduction
Recently, the extreme ultraviolet (EUV) region of the electromagnetic spectrum has become increasingly important in technological applications [1]. The EUV spectra of highly charged ions are mostly studied in high temperature laboratory sources such as laser-produced plasmas (LPP), discharge produced plasmas (DPP), and astrophysical plasmas [2]. Such spectra are widely used for plasma diagnostics, providing important information on plasma densities and temperatures. While there are different methods to generate EUV radiation, such as synchrotrons, free electrons lasers, LPP, and DPP, only the latter two have proven to be economically viable solutions for EUV lithography. In particular, table-top light sources are under rapid development. Such sources allow for both elemental and chemical identification. They can be accommodated in research and production laboratories at a modest price. Thus research continues towards the development of table-top EUV sources that can produce intense light in the short wavelength range. For this purpose a novel Electron Cyclotron Resonance Ion Source (ECRIS) was developed by the Ion and Plasma Source Technology Group at LBNL [3]. This ECRIS promises to be an efficient and cost-effective system for providing multiple charged ions. When used to produce Xe¹⁰⁺ and coupled with advanced EUV polycapillary lenses, it may become a source of sufficient EUV radiation useful for 13.4 nm lithography [4].
In an earlier paper [5] we suggested the identification of the specific ionization stages from which several radiative transition arrays in highly ionized xenon originated within the 10-16 nm wavelength range only. In this work we provide more line identification at an extended wavelength range (40-80 nm). Moreover, absolute intensities of measured lines arising from Xe\textsuperscript{q+} (q = 1 to 10) are also given. This normalization has been possible after we have absolutely calibrated our 1.5 m grazing incidence monochromator in the 10-80 nm wavelength range using well known and calibrated EUV light at the Advanced Light Source (ALS), Lawrence Berkeley National Laboratory (LBNL). In addition, we compared our measurements with calculations that have been carried out within the relativistic Hartree-Fock (HF) approximation.

2. Experimental apparatus and absolute normalization procedure
In this study the EUV emission of the ECR plasma has been measured by a 1.5 m Grazing Incidence Monochromator under the condition of medium and high wavelength resolution. To discriminate between the highly excited xenon spectral components associated with different charge states, the EUV spectrometer is connected to the plasma source chamber via a glass capillary system in order to maintain high vacuum on the monochromator, while the source reaches a gas pressure of about 1 mTorr. In addition, this configuration has allowed applying high voltage to the EUV source independently from the monochromator. The photons emitted in the source chamber enter a 500 mm long glass capillary with 4 mm inner diameter before passing through an entrance slit with a varying width (5 \( \mu \)m to 3 mm), depending of the desired resolution to be achieved. Then they strike a reflection grating at an angle of incidence of 88°. The 1.5 meter radius concave grating with 600 grooves/mm and a blaze angle of 5° is positioned on a Rowland circle mounting. In this configuration the spectrometer covers a wavelength range of 4-90 nm. After reflection the photons pass through an exit slit also of a varying in width (5 \( \mu \)m to 3 mm) where they are then detected by a channeltron detector. With both slits set at 100 \( \mu \)m, a resolution of 0.1 nm at wavelength of about 30.4 nm is obtained, corresponding to a spectral resolution of (\( \lambda/\Delta \lambda \)) \( \approx \) 304. A PC controlled data acquisition system has been used to operate the apparatus and to record the data. A complete description of this experimental setup is given by Bruch and co-workers [6,7].

The complete absolute calibration procedure has been described by R. Bista and co-workers [8,9]. Hence only a brief description is given below. Several measurements in the 13-30 nm wavelength range with well resolved monochromatic light were examined at the ALS in order to find the dependence of the efficiency as function of wavelengths for our EUV monochromator. The flux \( \phi_0 \) of incident photons was measured with a photodiode before the entrance of the monochromator so that an absolute value was given before and after each set of measurements. For each measured wavelength, we have divided the final measured flux \( \phi_f \) by the incident flux \( \phi_0 \). This ratio corresponds to the efficiency of the system for a particular wavelength. The absolute flux is determined when we divide the measured data by the corresponding efficiency for a specific wavelength.

3. Results and Discussions
The emission spectra of xenon ions (from Xe\textsuperscript{+} to Xe\textsuperscript{10+}) have been calculated for the wavelength interval \( \lambda =10-80 \) nm. The calculations have been carried out within the relativistic Hartree-Fock (HF) approximation [10]. Between 25 and 38 configurations, including the ground state and single excited states, were taken into account in the configuration interaction calculations for each ion. The results of these calculations are in good agreement with available experimental and theoretical data [11-12]. Since there are thousands lines from Xe\textsuperscript{+} to Xe\textsuperscript{10+} ions in the interval \( \lambda =10-80 \) nm, in table 1 we present our relativistic HF theoretical results for initial and final configurations only.

The EUV emission from xenon generated by the CECR plasma source in this study are displayed in figures 1 and 2. The peak fitting analysis was performed using the software Origin (version 7.0). The measured spectra were fitted by means of a standard Gaussian peak shape. A linear function was used to fit the residual background. Because of the high signal-to-noise ratio, even weaker lines could now
be resolved with high accuracy. Firstly the second derivative spectrum was generated. The second derivative spectrum was used in identifying the hidden peaks. Secondly, the peaks obtained from the second derivative spectrum (by finding all local minima) were fitted allowing centroids, widths and peak amplitudes to vary simultaneously in the process generating the best spectral fit to the data. The spectral features observed in figure 1 and figure 2 are denoted from 1 to the maximum number of lines obtained through the peak fitting procedure for each spectrum (39 lines and 43 lines for figure 1 and figure 2 respectively) whereas only a few lines are shown on spectra for clarity. Table 1 shows peak details for some prominent lines of figure 1 while a more detailed description of all lines within the whole investigated wavelength region are given elsewhere [13].

In figure 1 we have plotted a high resolution Xe spectrum between 40 and 60 nm. It has been observed that the spectrum is dominated by xenon ions; however, residual contributions from oxygen and nitrogen ions are also present. The total peak number of 39 lines was found by peak fitting for the wavelength region. A comparison of some prominent observed line intensities and peak positions generated with our current computed HF calculations and previously predicted values [5] are given in Table 1. In particular we have found that the most dominant Xe line structures arise from a variety of ions such as Xe\textsuperscript{2+}, Xe\textsuperscript{5+}, Xe\textsuperscript{6+}, Xe\textsuperscript{8+} and Xe\textsuperscript{9+}. Additional observed line structures could be assigned to N\textsuperscript{4+}, O\textsuperscript{2+}, O\textsuperscript{3+} and O\textsuperscript{5+} fine structure transitions. Interesting features observed in this spectrum are radiative decays among (4d9nl) and (4d9nl') transitions for n = 5.

Figure 2 indicates the xenon spectral segment between 60 and 80 nm (43 lines). This portion of the spectrum can be predominantly assigned to radiative transitions arising from Xe\textsuperscript{2+}, Xe\textsuperscript{3+}, Xe\textsuperscript{5+} and Xe\textsuperscript{6+} excited states. Moreover several peaks due to O\textsuperscript{2+}, O\textsuperscript{4+}, O\textsuperscript{7+}, N\textsuperscript{4+}, N\textsuperscript{6+} and N\textsuperscript{8+} have been identified. From the presented EUV data it is evident that the observed EUV Xenon spectra are very rich. More detailed classification is given elsewhere [13].

In summary, using EUV spectroscopy, we have identified numerous lines arising form Xe\textsuperscript{q+} (q=1-10) in the 40-80 nm wavelength range. We have also carried out calculations of emission spectra of Xe ions (Xe\textsuperscript{+} to Xe\textsuperscript{10+}) within a relativistic Hartree-Fock approximation. Results of calculations have a good agreement with our experiment as well as previous studies. We have shown in this study that the cost-effective and extremely compact ECR source can produce highly charged xenon EUV radiation in the 40-80 nm region. Our absolute calibration provided in this study may be useful for future recalibration for different kinds of monochromators, EUV light sources, and/or EUV measured data. For example, we are now about to measure absolute total cross sections of electron impact on helium and test if our suggested benchmark theoretical results [18] would solve the discrepancy between all measured data and previously proposed theoretical calculations.
### Table 1. Some prominent line identification for the Xenon background subtracted spectrum in the wavelength range 40-60 nm and comparison with theoretical predictions

<table>
<thead>
<tr>
<th>Peak Number</th>
<th>Flux (photons/sec) (x 10^6)</th>
<th>Wavelength (nm)</th>
<th>Wavelength (nm) Literature</th>
<th>Wavelength (nm) HF this work</th>
<th>Ion</th>
<th>Line Identification</th>
<th>J - J</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>9.909</td>
<td>42.72</td>
<td>42.718</td>
<td>42.6816</td>
<td>Xe VII (^\alpha)</td>
<td>(5p(^5))P(^1)- (5p6(^6)p)P(^1)</td>
<td>1-0</td>
</tr>
<tr>
<td>6</td>
<td>13.537</td>
<td>44.29</td>
<td>44.303</td>
<td>44.301</td>
<td>Xe IX (^\delta)</td>
<td>(4d(^5)5d)G(^1)-(4d(^5)5f)H</td>
<td>4-4</td>
</tr>
<tr>
<td>9</td>
<td>14.488</td>
<td>45.11</td>
<td>47.767</td>
<td>49.058</td>
<td>Xe IX (^\alpha)</td>
<td>(4d(^5)5d)D(^1)- (4d(^5)5f)F</td>
<td>3-4</td>
</tr>
<tr>
<td>17</td>
<td>22.533</td>
<td>47.76</td>
<td>47.767</td>
<td>49.0986</td>
<td>Xe II (^\alpha)</td>
<td>(5s(^5)p(^3))F(^1)- (5s(^5)p(^3))P</td>
<td>2-3</td>
</tr>
<tr>
<td>23</td>
<td>35.224</td>
<td>53.14</td>
<td>53.117</td>
<td>53.117</td>
<td>Xe VII (^\delta)</td>
<td>(5s(^5)p(^3))F(^1)-(5s(^5)p(^3))P</td>
<td>1-2</td>
</tr>
<tr>
<td>33</td>
<td>19.933</td>
<td>53.80</td>
<td>53.761</td>
<td>53.9066</td>
<td>Xe VII (^\delta)</td>
<td>(5s(^5)p(^3))F(^1)-(5s(^5)p(^3))P</td>
<td>5/2-7/2</td>
</tr>
<tr>
<td>35</td>
<td>44.646</td>
<td>55.70</td>
<td>55.8266</td>
<td>55.8687</td>
<td>Xe VII (^\delta)</td>
<td>4p(^3)4f(^3)5p - 4p(^3) 5p 6d</td>
<td></td>
</tr>
</tbody>
</table>

*Callegari *et al [17] 
*Churilov and Joshi* [11] 
*Kooijman* [12] 
*Churilov and Joshi* [14] 
*Churilov and Joshi* [16] 
*Kelly* [15] 
*HF calculations (this work)*

### References