Laboratory Measurements of the Line Emission from Mid-Z L-Shell Ions in the EUV

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ABSTRACT

We are continuing EBIT measurements of line lists in the EUV region for use as astrophysical diagnostics and have recently measured the same transitions in much denser plasma of the NSTX tokamak. This allows us to calibrate density-sensitive line ratios at their upper limits. We compare our observations at low and high density with calculations from the Flexible Atomic Code.

1. Introduction

Satellite observations in the soft x-ray and EUV provide valuable diagnostic opportunities for astronomers and astrophysicists. This region contains a wealth of emission lines that can be used to determine plasma properties and elemental abundances over a temperature range from 10^5 to 10^7 K. Because this region had been poorly studied, even in the laboratory, the relevent data sets were nearly empty, hampering efforts to develop EUV diagnostics.

In order to address this deficiency, we are continuing measurements of line lists in the EUV region for use in astrophysical diagnostics. We have published line lists for M-shell iron (Fe VII - Fe X; Lepson et al 2002), L-shell argon (Ar IX - Ar XVI; Lepson et al. 2003), and L-shell sulfur (S VII - S XIV; Lepson et al 2005a). We are close to completing the analysis of L-shell silicon (Si V - Si XII; Lepson & Beiersdorfer 2005, Lepson et al. 2005b), and have measured magnesium and aluminum. These measurements, which included wavelengths and intensities, were carried out at the Lawrence Livermore National Laboratory's electron beam ion traps, which use a monoenergetic electron beam.

We have recently taken additional measurements for the same transitions in collisional plasmas produced in the Princeton Plasma Physics Laboratory's NSTX tokamak. Because the NSTX plasmas are two orders of magnitude denser than the EBIT plasmas, they provide an opportunity to calibrate these diagnostic ratios at their upper limits.

2. Spectroscopic measurements

Spectra were measured with two grazing-incidence spectrometers with variable line spacing flat-field gratings (Harada & Kita 1980, Nakano et al. 1984). The first has an average line spacing of 1,200 ℓ/mm with a 3° angle of incidence and an instrumental resolution of $\sim$ 300 at 100 Å. The second has an average line spacing of 2,400 ℓ/mm with a 1.3° angle of incidence and an instrumental resolution of $\sim$ 150 at 15 Å to $\sim$ 500 at 50–60 Å. Readouts were taken with a 1,024 x 1,024 pixel, liquid nitrogen cooled CCD.

Wavelength calibrations were performed periodically throughout the experimental runs using the well known hydrogenic and helium-like K-shell emission lines (commonly refered to as Lyman-α and w, respectively) of carbon, oxygen, and nitrogen and their higher orders, providing a calibration for 19–173 Å.

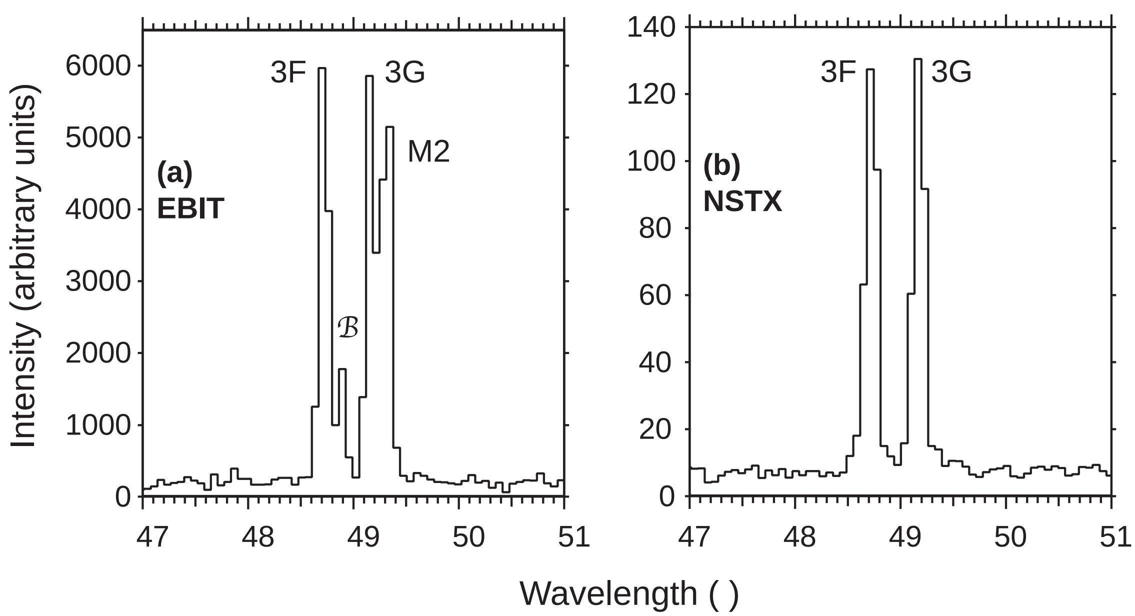

Fig. 1.— Comparison of $3s \rightarrow 2p$ transitions of Ar IX in (a) low density plasma from EBIT and (b) high density plasma from NSTX. The B V line at 48 Å was removed for clarity.

Spectra on NSTX were taken with a grazing-incidence spectrometer utilizing the 2,400 line/mm flat-field grating as described above. Wavelength calibrations were performed using the well known hydrogenic and helium-like K-shell emission lines of oxygen, carbon, and boron (from boronization of the tokamak), which provided a calibration for 19-60 Å. Nitrogen was typically not visible in NSTX spectra.

We used the program IPLab to remove cosmic rays using the "bad pixel" filter and manually subtracted the background by fitting a smoothed curve to the shots we examined. We fitted Gaussian curves to the lines using the program Igor. After identification, we measured the relative fluxes of the emission lines for each charge state, and corrected for differing sensitivity of the spectrometer (grating detector) at different wavelengths (Lepson et al. 2003, May et al. 2003).

We used the density differences between the EBIT and NSTX plasmas to investigate the density-sensitive lines of Ar IX and Ar XIV. Electron density in the electron beam ion traps, as determined using the ratios of the helium-like nitrogen lines commonly known as z and y (Chen et al. 2004), was approximately $10^{11}\mathrm{cm}^{-3}$. Electron density in the tokamak, as determined by Thompson scattering using in situ probes, was approximately $10^{13}\mathrm{cm}^{-3}$.

In Fig. 1 we focus on the $3s \rightarrow 2p$ transitions of neon-like Ar IX. Fig. 1a shows a low-density spectrum from EBIT-II. The 3F, 3G, and density- sensitive M2 lines are easily seen and nearly equal in strength. In adddition, we note the presence of a line, labelled $\mathcal{B}$, which is a newly described magnetic field diagnostic (Beiersdorfer et al. 2003). Fig. 1b shows a high-density spectrum from NSTX. Note that at this density the M2 line has essentially disappeared. The magnetically sensitive line $\mathcal{B}$ is also gone.

Figure 2 shows curves of the M2/3F and M2/3G line ratios as calculated by the Flexible Atomic Code (Gu 2003) for a range of electron densities from 10^5 to $10^{16} cm^{-3}$. We used these ratios to infer the density of the EBIT plasma (dashed lines). As both line ratios are present at the same time, they should yield the same result. In fact, the inferred densities differ by factor of 5, indicating that theory still needs some work.

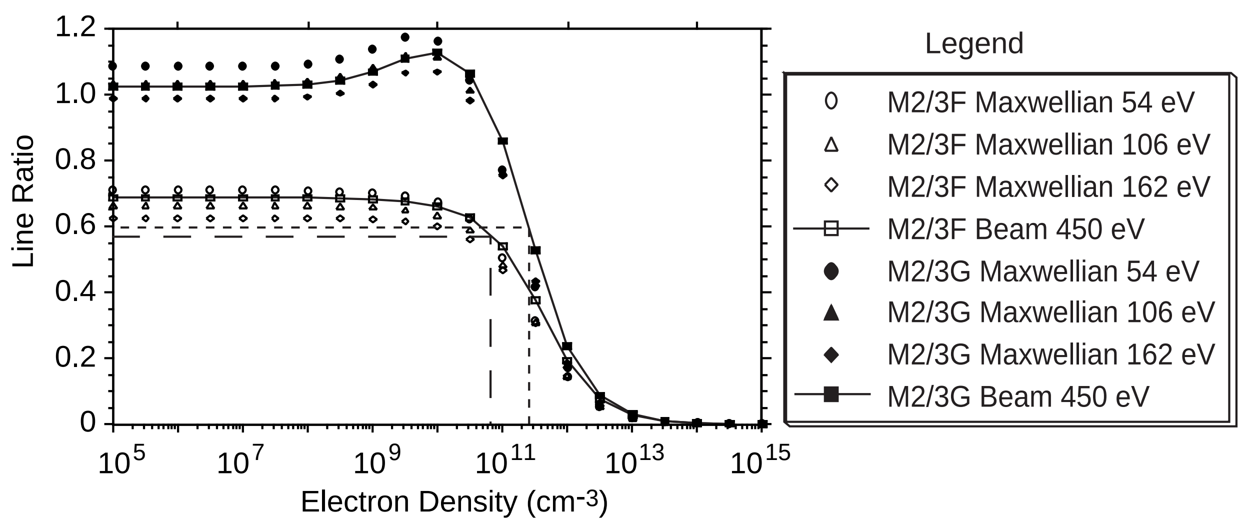

Fig. 2.— Comparison of density-sensitive line ratios using the Flexible Atomic Code. Points are shown for Maxwellian plasmas of three densities and for a monoenergetic plasma.

3. Conclusions

We have made considerable progress using the LLNL EBITs to compile a comprehensive catalogue of extreme ultraviolet and soft x-ray emission lines from highly charged ions of astrophysically relevent mid-Z elements. We have published line lists of iron, argon, and sulfur, with silicon nearly ready and other elements in progress. By comparing these data to modeling calculations and measurements in higher density tokamak plasmas we have identified a variety of density-sensitive lines, allowing us to better calibrate theoretical models.

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REFERENCES

Beiersdorfer, P., Scofield, J. H., & Osterheld, A. L. 2003, Phys. Rev. Lett. 90, 235003.

Chen, H., Beiersdorfer, P., Heeter, L. A., Liedahl, D. A., Naranjo-Rivera, K. L., Trbert, E., Gu, M. F., & Lepson, J. K. 2004, ApJ, 611, 598.

Gu, M.F. 2003, ApJ, 582, 1241.

Harada, T., & Kita, T. 1980, Appl. Opt., 19, 3987.

Lepson, J. K., & Beiersdorfer, P. 2005, Phys. Scripta T120, 62.

Lepson, J. K., Beiersdorfer, P., Brown, G. V., Liedahl, D. A., Utter, S. B., Brickhouse, N. S., Dupree, A.K., Kaastra, J.S., Mewe, R., & Kahn, S.M. 2002, ApJ, 578, 648.

Lepson, J. K., Beiersdorfer, P., Behar, E., & Kahn, S.M. 2003, ApJ,590, 604.

Lepson, J. K., Beiersdorfer, P., Behar, E., & Kahn, S.M. 2005, ApJ,625, 1045.

Lepson, J. K., Beiersdorfer, P., Behar, E., & Kahn, S.M. 2005, NIMB, 235, 131.

May, M., Lepson, J., Beiersdorfer, P., Thorn, D., Chen, H., Hey, D., & Smith, A. 2003, Rev. Sci. Instrum., 74, 2011.

Nakano, N., Kuroda, H., Kita, T., & Harada, T. 1984, Appl. Opt., 23, 2386.