Laboratory Calibration of Density-Dependent Lines in the Extreme Ultraviolet Spectral Region

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Abstract. We have been making spectral measurements in the extreme ultraviolet (EUV) from different laboratory sources in order to investigate the electron density dependence of various astrophysically important emission lines and to test the atomic models underlying the diagnostic line ratios. The measurement are being performed at the Livermore EBIT-I electron beam ion trap, the National Spherical Torus Experiment (NSTX) at Princeton, and the Alcator C-Mod tokamak at the Massachusetts Institute of Technology, which together span an electron density of four orders of magnitude and which allow us to test the various models at high and low density limits. Here we present measurements of Fe XXII and Ar XIV, which include new data from an ultra high resolution ($\lambda/\Delta\lambda$ >4000) spectrometer at the EBIT-I facility. We found good agreement between the measurements and modeling calculations for Fe XXII, but poorer agreement for Ar XIV.

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INTRODUCTION

A number of astrophysically important emission lines are sensitive to electron density in the EUV and soft X-ray regions. Lines from Fe XXII, for example, have been used in recent years as diagnostics of stellar coronae, such as Capella, EX Hya, and the active variable AB Dor [1, 2, 3]. Studies of the W UMA-type active binary, 44i Boo, utilized diagnostics from several charge states of iron, but the densities derived from these diagnostics varied by two orders of magnitude, illustrating the need for accurate benchmarking of these diagnostics [4].

Here we report on spectral data of Fe XXII and Ar XIV from laboratory sources in which the electron density is known from either K-shell density diagnostics (for lower-density plasma in electron beam ion traps) or from non-spectroscopic means (for higher-density plasmas in tokamaks), ranging from 5×10^{10} cm^{-3} to 5×10^{14} cm^{-3}. This provided the opportunity to measure density-sensitive line ratios at their low and high density limits. These measurements were used to test the atomic data underlying the density-diagnostic line ratios, complementing earlier work [5].

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MEASUREMENTS AND CALCULATIONS

Spectra from the Livermore EBIT-I [6] electron beam ion trap were taken with two spectrometers. Argon spectra were taken with a varied-line-spacing flat-field grating spectrometer with a mean spacing of 2400 lines/mm, a Rowland radius of 15.9 m, and a spectral resolution of 0.1 Å. Data were collected on a liquid nitrogen cooled CCD camera with an image size of 1024 $\times$ 1024 pixels. Wavelength calibrations were periodically performed with the well known K-Shell emission lines of N VI and N VII, commonly referred to as w and Lyman-α, respectively; see [7] for further details of spectrometer set-up and data acquisition. Both Ar and N_2 were introduced into the trap via gas injection.

Iron spectra were taken with a varied-line-spacing flat-field grating spectrometer with a mean spacing of 1200 lines/mm, a radius of 5.4 m, and an spectral resolution of 0.3 Å. Data were collected with a liquid nitrogen cooled CCD camera and an image size of 1024 $\times$ 1024 pixels. Wavelength calibrations were periodically performed with higher order nitrogen w and Lyman-α lines and with lines of O V and O VI; details of spectrometer set-up and data acquisition are described in [8]. Iron was introduced into the machine with a Metal Vapor Vacuum Arc (MeVVA), while N_2 and CO_2 were injected as gases. The electron density of the EBIT-I plasma was estimated via the ratio of the density-sensitive 1-2 N VI transition lines known as y and z [5].

Recently, additional spectra of iron were taken with an ultra high resolution spectrometer at LLNL. This instrument utilizes a varied-line-spacing flat-field grating with radius of 44.3 m and a mean spacing of 2400 lines/mm [9]. The spectral resolution of $\sim$0.025 Å corresponds to $\lambda/\Delta\lambda$ $\sim$4800 at the wavelengths studied here. Data were collected with a liquid nitrogen cooled CCD camera and an image size of 1300 $\times$ 1340 pixels [9]. Iron was introduced as $Fe(CO)_5$, which also provided oxygen for calibration.

Spectrometers from the LLNL electron beam ion trap facility have been installed on the NSTX tokamak, where they have been dubbed XEUS and LoWEUS, for laboratory astrophysics measurements on higher density plasmas [10]. XEUS, the X-ray and Extreme Ultraviolet Spectrometer, was installed in 2004 and has the 2400 lines/mm grating with radius 15.9 m and a spectral resolution of 0.1 Å. Data were collected with a CCD camera and an image size of 1300 $\times$ 1340 pixels [11, 12, 13]. Wavelength calibrations were performed using the K-shell Lyman-α and w lines of oxygen, nitrogen, carbon, and boron. LoWEUS, the Long Wavelength Extreme Ultraviolet Spectrometer, was installed in 2008 and has the same specifications as on EBIT-I: utilizing a varied-line-spacing flat-field grating with a mean spacing of 1200 lines/mm and a spectral resolution of 0.3 Å. Data were collected with a CCD camera and an image size of 1300 $\times$ 1340 pixels [14]. Similar to the experiments on EBIT-I, the wavelength calibrations were performed with higher orders of the C VI Lyman-α and C V w lines, as well as with strong lines of O V and O VI. The electron density of the NSTX plasma was measured directly with multi-point Thomson scattering. Argon was injected into NSTX as a gas, but in contrast to EBIT-I, iron in NSTX was an impurity that resulted from unwanted vaporization of stainless steel components in the tokamak vessel.

Iron measurements on the Alcator C-Mod tokamak at MIT were taken on a 2.2 m Rowland circle grating spectrometer with a micro-channel plate detector. Spectral resolution was lower than on EBIT and NSTX, but had time-resolution of $\sim$40 ms

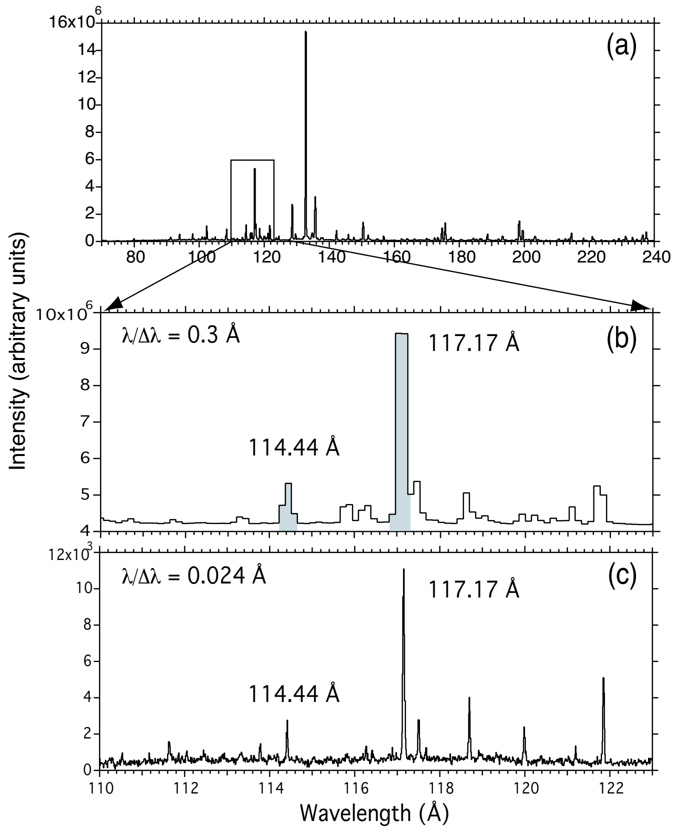

FIGURE 1. Measurement of B-like Fe XXII at lower electron density ($N_e \sim 10^{11}$ cm^{-3}) on EBIT-I. (a) Overview spectrum with area of interest outlined. (b) Inset showing the two density-sensitive lines studied. Spectrum taken with LoWEUS-type spectrometer with $\lambda/\Delta\lambda \sim$400. (c) Spectrum of the same region taken with new ultra high-resolution spectrometer with $\lambda/\Delta\lambda \sim$4800

[15]. Argon measurements were taken with AXEUS, the Alcator X-ray and Extreme Ultraviolet Spectrometer, which also comes from the LLNL electron beam ion trap facility [16]. Specifications are the same as XEUS [13], but data were collected on a CCD camera with image size of 1340 $\times$ 100 pixels and had time resolution of $\sim$5 ms [16]. Like at NSTX, the electron density at Alcator was measured directly with multi-point Thomson scattering. Argon was also introduced into Alcator via gas injection, while iron was an intrinsic impurity resulting from stainless steel components in the tokamak vessel.

Observations of Capella (α Aurigae) were taken with the *Chandra X-Ray Observatory*'s Low Energy Transmission Grating Spectrometer. We used a co-added data set summed from several observations totalling $\sim$500 ksec to measure the line ratios of Fe XXII. The ArXIV line pair was not observed because Capella is too hot for this charge state to exist in large quantities and because stellar argon emission is typically much weaker than iron. We used the previously published density (determined from a variety of line ratios) for Capella of $N_e \sim 10^{12}$ cm^{-3} [1] for the purpose of this analysis.

Data were analyzed using the programs IPLab for image processing, which included filtering out hard x rays, and IGOR for further analysis, which included wavelength

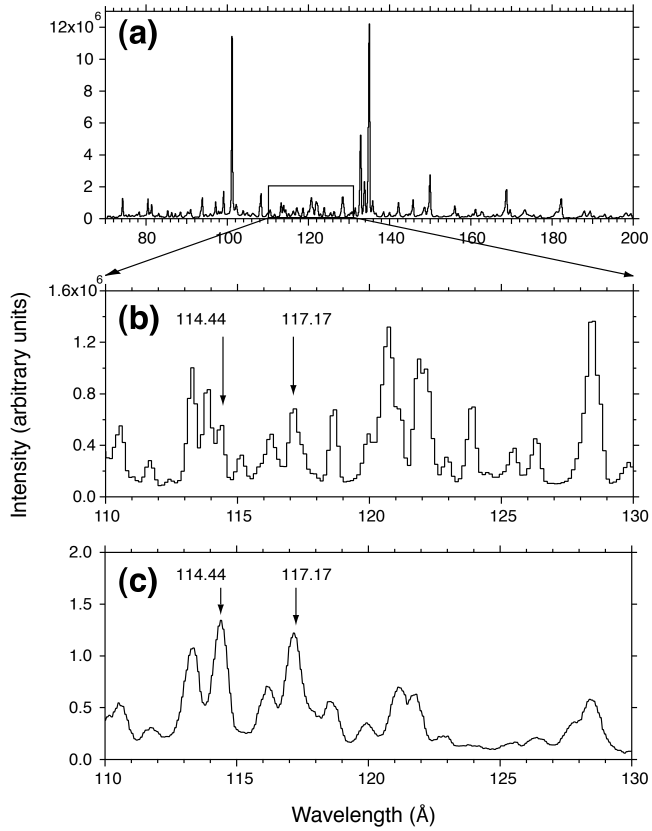

FIGURE 2. Measurement of B-like Fe XXII at higher electron density ($N_e \sim 10^{13} - 10^{14}$ cm^{-3}) on tokamaks. (a) LoWEUS spectrum from NSTX with area of interest outlined. (b) Inset showing the two density-sensitive lines studied. (c) Spectrum of the same region taken with the grating spectrometer at Alcator C-Mod.

calibrations and Gaussian fits of the lines we studied.

We used the Flexible Atomic Code [17, 18] to calculate emission strengths of two boron-like line pairs in iron and argon known to be sensitive to the electron density. In iron, we examined the Fe XXII line pair $(2s2p^2)_{3/2} \rightarrow (2s^2 2p)_{3/2}$ at 114.44 Å and $(2s2p^2)_{1/2} \rightarrow (2s^2 2p)_{1/2}$ at 117.17 Å, which was also previously used as part of an analysis of the corona of Capella [1]. For argon we examined the Ar XIV line $(2s^2 3d)_{3/2} \rightarrow (2s^2 2p)_{1/2}$ at 27.47 Å and the blend $(2s^2 3d)_{5/2} \rightarrow (2s^2 2p)_{3/2}$ and $(2s^2 3d)_{3/2} \rightarrow (2s^2 2p)_{3/2}$ at 27.63 Å [5]. We calculated ratios for both monoenergetic (relevant to EBIT-I) and Maxwellian plasmas (relevant to the tokamaks).

RESULTS AND DISCUSSION

Spectra of iron emission are shown in Figures 1 and 2 for EBIT-I, NSTX, and Alcator C-Mod, with the Fe XXII line pair indicated. The change in relative line strength is obvious between the low-density regime of EBIT-I and the high-density regime of

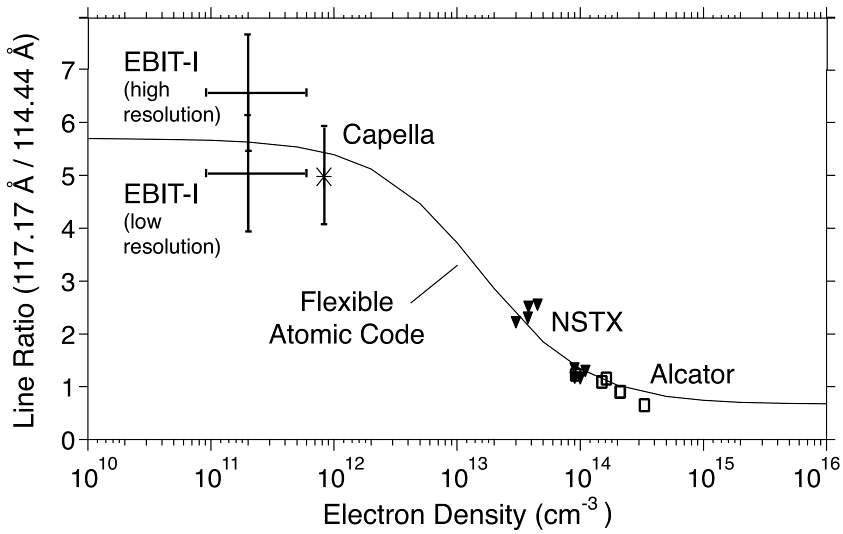

FIGURE 3. Ratio curve calculated for the boron-like Fe XXII line pair 117.17 Å / 114.44 Å. Experimental measurements and errors are plotted. Crosses are from EBIT-I, star is from *Chandra* LETGS observations of Capella, filled triangles are from NSTX, and open squares are from Alcator C-Mod.

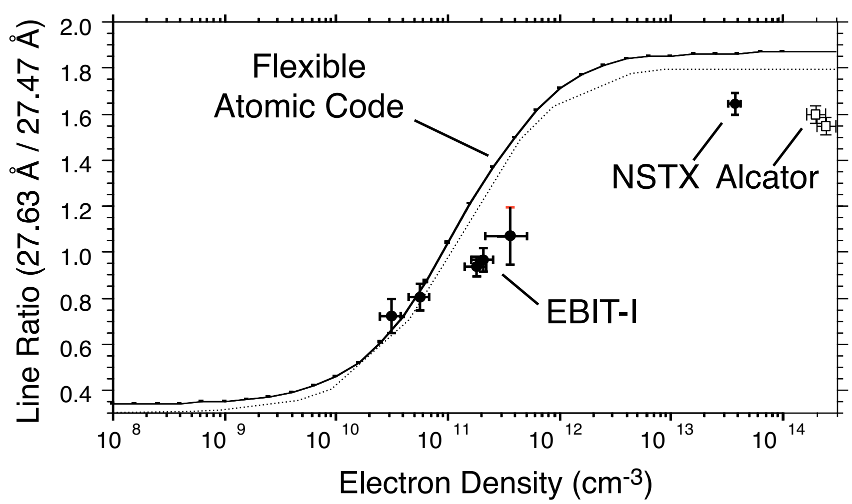

FIGURE 4. Ratio curve calculated for the boron-like Ar XIV line pair 27.63 Å / 27.47 Å. Solid line is calculated for a Maxwellian distribution with electron energy of 0.3 keV for tokamaks; dotted line is calculated for a monoenergetic beam with an electron energy of 1.0 keV appropriate for EBIT-I. Experimental measurements and errors are plotted.

tokamaks. Similar differences in the spectra from EBIT-I and NSTX were found for Ar XIV (not illustrated due to space limitations). Figures 3 and 4 show the line ratio curves of the boron-like density-sensitive lines calculated with the Flexible Atomic Code for Fe XXII and Ar XIV and the ratios measured on EBIT-I, NSTX, and Alcator C-Mod [5, 14, 15]. For Fe XXII (Fig. 3), excellent agreement is found between theory and tokamak measurements near the high density limit. Agreement from EBIT-I data at lower density is not as good, but measurements overlap within the error limits. We are now attempting measurements around the critical density of 10^{13} cm^{-3}, where the rate of change is greatest. For Ar XIV (Fig. 4), agreement between theory and measurements is reasonable at low densities but poor at high densities. It is evident that the density dependence of this line pair is not fully established; the upper limit is clearly lower than calculated while the lower limit has not yet been tested. Improved atomic models are needed, particularly in the case for Ar XIV.

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REFERENCES

1. R. Mewe, A. J. J. Raassen, J. J. Drake, J. S. Kaastra, R. L. J. van der Meer, and D. Porquet, *A&A* **368**, 888 (2001).
2. C. W. Mauche, D. A. Liedahl, and K. B. Fournier, *ApJ Lett*. **588**, L101 (2003).
3. J. Sanz-Forcada, A. Maggio, and G. Micela, *A&A* **408**, 1087 (2003).
4. N. S. Bickhouse and A. K. Dupree, *ApJ* **502**, 918 (1998).
5. H. Chen, P. Beiersdorfer, L. A. Heeter, D. A. Liedahl,K. L. Naranjo-Rivera, E Träbert, M. F. Gu, and J. K. Lepson, *ApJ* **611**, 598 (2004).
6. P. Beiersdorfer, *Can. J. Phys*. **86**, 1 (2008).
7. J. K. Lepson, P. Beiersdorfer, G. V. Brown, D. A. Liedahl, S. B. Utter,N. S. Brickhouse, A. K. Dupree, J. S. Kaastra, R. Mewe, and S. M. Kahn, *ApJ* **578**, 648 (2002).
8. J. K. Lepson, P. Beiersdorfer, E. Behar, and S. M. Kahn, *ApJ* **590**, 604 (2003).
9. P. Beiersdorfer, E. W. Magee, E. Träbert, H. Chen, J. K. Lepson M.-F. Gu, and M. Schmidt, *Rev. Sci. Instrum* **75**, 3723 (2004).
10. A. T.Graf, S. Brockington, R. Horton, S. Howard, D. Hwang, P. Beiersdorfer, J. Clementson, D. Hill, M. May, M. Mclean, R. Wood, M. Bitter, J. Terry, W. L. Rowan, J. K. Lepson, and L. Delgado-Aparicio *Can. J. Phys*. **86**, 307 (2008).
11. P. Beiersdorfer, M. Bitter, L. Roquemore, J. K. Lepson, and M. F. Gu, *Rev. Sci. Instrum* **77**, 10F306 (2006).
12. P. Beiersdorfer, J. K. Lepson, M. Bitter, K. W. Hill, and L. Roquemore, *Rev. Sci. Instrum* **79**, 10E318 (2008).
13. J. K. Lepson, P. Beiersdorfer, M. Bitter, M., and S. M. Kahn, *Can. J. Phys* **86**, 175 (2008).
14. J. K. Lepson, P. Beiersdorfer, J. Clementson, M. F. Gu, M Bitter, L. Roquemore, R. Kaita, P. G. Cox, and A. Safronova, *J. Phys. B* **43**, 142010 (2010).
15. M. L. Reinke, P. Beiersdorfer, N. T. Howard, E. W. Magee, Y. Podpaly, J. E. Rice, and J. L. Terry, *Rev. Sci. Instrum* **81**, 10D376 (2010).
16. P. Beiersdorfer, G. V. Brown, J .B. Kamp, E. W. Magee, J. K. Lepson, Y. Podpaly, and M. L. Reinke, *Can. J. Phys* **89**, 653 (2010).
17. M. F. Gu, *ApJ* **582**, 1241 (2003).
18. M. F. Gu, *Can. J. Phys* **86**, 675 (2008).