Electron Impact Excitation Cross Section Measurement for $n=3$ to $n=2$ Line Emission in Fe^{17+} to Fe^{23+}

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ABSTRACT

We have measured the electron impact excitation cross sections for the strong iron L-shell $3 \rightarrow 2$ lines of Fe XVIII to Fe XXIV at the EBIT-I electron beam ion trap using a crystal spectrometer and NASA-Goddard Space Flight Centers 6×6 pixel array microcalorimeter. The cross sections were determined by direct normalization to the well established cross section of radiative electron capture through a sophisticated model analysis which results in the excitation cross section for the strong Fe L-shell lines at multible electron energies. This measurement is part of a laboratory X-ray astrophysics program utilizing the Livermore electron beam ion traps EBIT-I and EBIT-II.

Subject headings: molecular data — molecular processes: photodissociation — stars: atmospheres

1. Introduction

The atomic data of iron are very important for interpreting virtually all types of observations since iron is the most abundant high-Z element and radiates profusely in many spectral bands. In specific, the spectral-rich emission from the iron L-shell has been one of the primary diagnostic tools of the high-resolution grating spectrometers on the $XMM - Newton$ and *Chandra* X-ray observatories. A great deal of theoretical modeling effort has been put forward to interpret these high-resolution X-ray spectra. Despite these efforts in improving

the atomic calculations, the need for laboratory measurements is clear: repeatedly, laboratory data have shown that calculations are inaccurate or incomplete because they miss crucial physics left out as part of necessary approximations (Beiersdorfer 2003). To address the need for validating the calculations using experimental data, our laboratory X-ray astrophysics program, utilizing the electron beam ion traps EBIT-I and EBIT-II at the University of California Lawrence Livermore National Laboratory has measured atomic data including ionization and recombination cross sections for charge balance calculations, emission line lists, excitation cross sections, and dielectronic recombination resonance strengths for interpreting X-ray line formation. On the iron excitation cross measurements, Gu et al. (1999a, 2001) have reported measurements for Fe XXI–Fe XXIV lines that were normalized to calculations in the high energy limit. Although such a normalization can be fairly reliable at high electron-ion collision energies, the accuracy of electron scattering calculations at these energies is estimated to be only to $15 - 30\%$ (Zhang et al. 1989), and may in fact be much worse (factors of two or more, see Section 4 of this paper), if the levels are affected by configuration interactions. A more accurate method is normalizing directly to radiative electron capture, i.e. radiative recombination (RR). Measurements of some Fe L-shell cross sections utilizing RR for normalization has been reported by Chen et al. (2002, 2005) and Brown et al. (2006). These measurements were made possible in part by the availability of a high-resolution, large-area, gain-stabilized microcalorimeter, the engineering spare microcalorimeter from the original $ASTRO-E$ satellite mission. Using this technique, we have recently measured all strong $n = 3 \rightarrow 2$ L-shell Fe lines from Fe^{17+} to Fe^{23+}. The results of these measurements are presented here.

2. Measurement and analysis

Our experiments were carried out on the EBIT-I device (Levine et al. 1988). Similar to the experimental setup described in our previous measurement on EBIT-II (Chen et al. 2005), we used a crystal spectrometer (Beiersdorfer & Wargelin 1994; Brown et al. 1999) together with the XRS/EBIT microcalorimeter detector (Kelley et al. 1999). The microcalorimeter has an energy resolution better than 10 eV and a dynamic range from 0.1 to 10 keV. The crystal spectrometer employed a flat Rubidium hydrogen phthalate (RAP) crystal, which has an energy coverage of about 150 eV per setting. To cover the L-shell Fe lines from different charge states (photon energies between 0.78 to 1.18 keV, equivalent to wavelengths between 10.5 and 15.9 Å), we set the Bragg angles to 30.5, 32, 36 and 40 degrees. The crystal spectrometer had a resolving power of 385 (FWHM of 2.6 eV at a photon energy of 1 keV). Most of the strong Fe 3 →2 L-shell lines observed with the crystal spectrometer were resolved, while only a few of those observed with the microcalorimeter were, illustrating the need to operate both instruments simultaneously. The L-shell lines were previously measured by Brown et al. (2002) and their labels and identifications are used in this paper. Our measurements were made at electron beam energies of 1.35, 1.46, 1.56, 1.7, 1.82, 1.94,

2.05, 2.45, and 2.93 keV, with beam currents ranging between 20 – 30 mA. These energies were slightly above the ionization threshold of individual ion charge states from F-like to Li-like, and they were high enough so that the contributions from dielectronic recombination radiation and resonance excitation to the direct excitation line intensities can be ignored. At these energies, however, cascades from higher levels may contribute to the line intensities. Our method determines the effective cross section that includes all possible cascade processes.

To analyze the complicated Fe L-shell spectra, we developed a new method based on the atomic data calculated with the Flexible Atomic Code (Gu 2003). The model starts with a theoretical data base that includes thousands of lines, most of which were too weak to be measured experimentally but will contribute to the spectrum collectively. When comparing the theoretical model with the experimental data, we adjust the theoretical cross sections for a subset of strong lines in order to achieve acceptable agreement with measurement. This allows us to derive the measured cross sections for this subset of lines, and any possible contamination of weak lines in the determination of intensities of strong lines are accounted for in the analysis with theoretical calculations. More detailed description on the data analysis can be found in (Chen et al. 2006).

Overall the calculations agree to within 20% with the experimental results for all lines. For example, O-like Fe $2p_{1/2}2p_{3/2}^2 3d_{5/2}(J = 3) \rightarrow 2p_{3/2}^2(J = 2)$ has excitation cross sections of $2.60(\pm0.34) \times 10^{-20}\text{cm}^2$, $2.49(\pm0.34) \times 10^{-20}\text{cm}^2$, and $2.39(\pm0.35) \times 10^{-20}\text{cm}^2$, which compares to the theoretical numbers of $2.73\times10^{-20}\text{cm}^2$, $2.68\times10^{-20}\text{cm}^2$, and $2.60\times10^{-20}\text{cm}^2$, for electron energy of 1.46 keV, 1.56 keV and 1.70 keV, respectively. A few exceptions are a couple of F-like lines (F20a, F20b, F19a, and F17) at electron energies of 1.56 keV and 1.7 keV. The difference between theory and measurements in these few cases are about 30% or greater. The cause of this discrepancy is not clear.

Details of the measurement, results and discussions can be found in (Chen et al. 2006).

REFERENCES

Beiersdorfer, P., & Wargelin, B. J., 1994, Rev. Sci. Instrum. 65, 13

Beiersdorfer, P., 2003, Annu. Rev. Astron. Astrophys., 41, 343

Brown, G. V., Beiersdorfer, P., & Widmann, K., 1999, Rev. Sci. Instrum. 70, 280

Brown, G. V., Beiersdorfer, P., Liedahl, D. A., Widmann, K., Kahn, S. M. & Clothiaux, E. J., 2002, ApJS, 140, 589

Brown, G. V., Beiersdorfer, P., et al., 2006, submitted to Physical Review Letters.

Chen, H., Beiersdorfer, P., Scofield, J. H., Gendreau, K. C., Boyce, K. R., Brown, G. V., Kelley, R. L., Porter, F. S., Stahle, C. K., Szymkowiak, A. E., & Kahn, S. M., 2002, ApJ, 567, L169

Chen, H., Beiersdorfer, P., Scofield, J., K. C., Boyce, K. R., Brown, G. V., Kelley, R. L., Kilbourne, C. K., Porter, F. S., Gu, M. F.,& Kahn, S. M., 2002, ApJ, 618, 1086

Chen, H., Gu, M. F., Beiersdorfer, P. et al., 2006, ApJ, v646

Gu, M. F., Kahn, S. M., Savin, D. W., Beiersdorfer, P., Liedahl, Brown, G. V., Reed, K. J., Bhalla, C. P., & Grabbe, S. R., 1999a, ApJ, 518, 1002

Gu, M. F., Kahn, S. M., Savin, D. W., Bahar, E., Beiersdorfer, P., Brown, G. V., Liedahl & Reed, K., 2001, ApJ, 563, 462

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

Kelley, R. L., et al, 1999, SPIE, 3765, 114

Levine, M. A., Marrs, R. E., Henderson, J. R., Knapp, D. A., & Schneider, M. B., 1988, Physics Scripta, T22, 157

Zhang, H. L. & Sampson, D. H., 1989, Atomic Data and Nuclear Data Tables, 43, 1