Dielectronic satellite lines of Fe XVII

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Abstract. We have been measuring the L-shell x-ray emission produced by dielectronic recombination of neonlike Fe\(^{16+}\) ions populating doubly excited levels of the form \(1s^22l^23n\ell n'\ell'\) in Fe\(^{15+}\). The measurements are carried out at the Livermore electron beam ion trap facility, where we isolate dielectronic resonances by choice of the electron beam energy. We utilize crystal spectrometers to record the x-ray lines generated in the radiative deexcitation of the \(1s^22l^23n\ell n'\ell'\) upper levels. The measurements aim to support the identification of such lines in low-density astrophysical plasmas.

1. Introduction

L-shell dielectronic satellite lines can play an important role in the spectra of stellar coronae because of the potential to use such lines as temperature diagnostics [1]. Dielectronic satellite lines to the well known characteristic Fe XVII L-shell lines are produced by electron capture and subsequent radiative decay:

\[
1s^22s^22p^6 + e^- \rightarrow 1s^22s^22p^5n\ell n'\ell' \rightarrow 1s^22s^22p^6n'\ell' + h\nu
\]

or

\[
1s^22s^22p^6 + e^- \rightarrow 1s^22s^22p^6n\ell n'\ell' \rightarrow 1s^22s^22p^6n'\ell' + h\nu'.
\]

The strongest such satellite lines \(h\nu, h\nu'\) are those with \(n = n' = 3\), i.e., those produced by LMM resonances. However, even the strongest resonances do not produce lines that are easily detected in typical astrophysical or laboratory plasmas. Moreover, some of the upper levels produced by dielectronic recombination can also be produced by collisional excitation. In fact, most of the Fe XVI x-ray lines detected so far in low-density coronal plasmas are collisionally excited lines [2]. Similarly, Graf et al. have measured multiple Fe XVI lines using an electron beam ion trap [3]; again, these lines were exclusively produced by collisional excitation.

Identification of dielectronic satellite lines, i.e. Fe XVI lines that are produced exclusively or nearly exclusively by dielectronic recombination, are now possible because of the low-noise, high-resolution spectra provided by some of the astrophysical x-ray observatories. In particular, Fe XVI lines with a so-called spectator electron \(n'\ell\) and \(n' = 4\) have recently been identified in the spectrum of Capella observed with the Chandra X-ray Observatory [4]. These lines were used to infer a formation electron temperature of \(\log(T) = 6.67 \pm 0.03\) K. There has also been a search for dielectronic satellite lines with \(n' = 3\) in the spectrum of Capella based on theoretical predications [5].

Here we report on using an electron beam ion trap to specifically excite and observe the dielectronic satellite lines of Fe XVII in order to guide the search for such lines from low-density astrophysical plasmas.
2. Experiment
Dielectronic recombination is a resonant process, because the energy of the free electron \( e^- \) must be such that upon capture into a level \( n'\ell' \) it gives off the correct energy to promote a bound electron from an \( n = 2 \) level to a level \( n\ell \). We can use this fact to excite specific resonances by appropriate selection of the energy of the electron beam interacting with the ions trapped in an electron beam ion trap, as illustrated in innumerable such experiments before, e.g., [6, 7, 8].

For the present measurements we employ the Livermore electron beam ion trap facility [9]. It was equipped with two crystal spectrometers [10], which together cover the iron L-shell emission between about 12.0 and 17.5 Å. Individual x rays diffracted by the crystals are detected with thin-window proportional counters [11]. A window-less SiLi detector was used to monitor the trap conditions in real time. Although the SiLi detector has a relatively poor energy resolution of more than 100 eV, it has a much higher count rate than the EBIT x-ray microcalorimeter [12, 13], which has a more than ten times better energy resolution than the SiLi detector. All data from the crystal spectrometers and the SiLi detector have been acquired fully time resolved using an event-mode data acquisition system [14]. Each x-ray event is tagged with the energy of the electron beam and the time.

3. Results and Discussion
By sweeping the electron beam energy from well below the LMM resonance energy, which is located at about 400 eV, to well above the threshold excitation energy of the Fe XVII lines, which varies from about 700 eV for the \( 3s \rightarrow 2p \) transitions to about 900 eV for the \( 3p \rightarrow 2s \) transitions, we can map out all \( 1s^22\ell'3\ell n'\ell' \) resonances with \( n' \geq 3 \). The resultant x-ray emission recorded with the SiLi detector as a function of beam energy is shown in Fig. 1.

As Fig. 1 shows, our measurements clearly resolve the resonances with spectator electrons \( n' = 3 \) and 4. The resonances with \( n' \geq 5 \) are not resolved. This is in part because the electron beam energy is not truly mono-energetic; instead, it has an energy spread of about 30 to 50 eV, as demonstrated before [15, 16]. In addition, the resonances of each complex cover a large,

![Figure 1. Fe L-shell emission as a function of electron beam energy. The data were recorded with a windowless SiLi detector. The location of the LMM and LMN resonances, as well as those merging with the excitation thresholds, are marked.](image-url)
Figure 2. Fe XVII x-ray emission as a function of electron beam energy. The data were recorded with a crystal spectrometer. The emission labeled 3A, 3B, 3C and 4D are transitions in Fe XVII. The dashed line marks the location of the threshold for electron impact-excitation. X rays emitted below this line are from dielectronic recombination.

overlapping range of electron energies.

The x-ray emission observed using one of the two crystal spectrometers as a function of beam energy is shown in Fig. 2. This spectrometer covers the range of the $3p_{1/2,3/2} \rightarrow 2s_{1/2}$ lines 3A and 3B, the $3d_{3/2} \rightarrow 2p_{1/2}$ line 3C, and the $4d_{5/2} \rightarrow 2p_{3/2}$ line 4D in Fe XVII [17]. A lineout of the spectral emission at beam energies above the threshold for electron impact-excitation is shown in Fig. 3(a), while the emission covering the LMN resonances is shown in Fig. 3(b).

An analysis of the full data set is now in progress. From Fig. 2 we can already note that there are no $n' = 3$ dielectronic satellite features in this spectral range. However, we find that there are several dielectronic satellite features with $n' = 4$, as illustrated in Fig. 3(b). Moreover, line 3C is associated with a continuous set of high-$n$ dielectronic satellites that form a smooth transition as the electron energy crosses the excitation threshold. This is reminiscent of what has been observed for the K-shell x-ray lines of heliumlike ions [18, 19].

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References

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Figure 3. Fe XVII spectral emission in the 12–15 Å range. (a) spectrum formed by direct electron-impact excitation; (b) dielectronic satellite lines from the decay of 1s22ℓ3ℓ′4ℓ″ excited levels.