Nuclear Instruments and Methods in Physics Research B xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research B

journal homepage: www.elsevier.com/locate/nimb

Measurement of L-shell transitions in M-shell ions in the laboratory and identification in stellar coronae

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ARTICLE INFO

Article history:
Received 3 November 2016
Received in revised form 27 March 2017
Accepted 29 March 2017
Available online xxxx

Keywords:
Spectra
Extreme ultraviolet
Laboratory
Stars

ABSTRACT

Based on laboratory data from the Lawrence Livermore EBIT-I electron beam ion trap and calculations using the relativistic multi-reference Møller-Plesset (MRMP) perturbation theory approach, we identify L-shell transitions of M-shell iron ions in emission spectra of the nearby stars Capella and Procyon. These lines are weaker than the well known, prominent lines from Fe XVII. However, they need to be taken into account when modeling the spectra, especially of cool stars.

1. Introduction

Highly charged ions of iron provide important diagnostic tools for hot astrophysical plasmas via their K-shell and L-shell radiation. Although weak in emission, the L-shell transitions of M-shell iron ions, i.e., those charge states of iron that have a partially filled n = 3 shell in their ground state, have gained prominence in X-ray astrophysics because they are observed in the absorption spectra from active galactic nuclei [1–3]. However, in order to fit such absorption spectra and to extract the crucial information, such as the motion of the absorbing plasma and the abundance fraction of the emitters, it is necessary to know the transition energies with very high accuracy [4–7].

The measurement of the L-shell lines of the M-shell ions of iron in the laboratory has been difficult, and few such measurements exist in emission. Fe^{15+} is the simplest M-shell ion, with only one valence electron in the M shell, and we have already reported measurements of Fe XVI L-shell transitions using the Livermore electron beam ion trap [8,9]. In addition, we have recently reported the measurement of two L-shell transitions of the Fe XV spectrum [10]. The magnesiumlike Fe^{14+} ion is the next simplest M-shell ion of iron with two valence electrons in the M shell.

In parallel to experimental efforts, there have been theoretical developments to produce wavelengths that match those produced by laboratory measurements and required by astrophysical observations. A combination of the Many-Body Pertubation Theory (MBPT) method and the configuration-interaction (CI) method was used by Gu [5] and Gu et al. [3] to produce wavelengths of L-shell transitions in iron and nickel that were shown to be superior to earlier results using the CI method alone, as employed, for example, by the Hebrew University Lawrence Livermore Atomic Code (HULLAC) [11] or by the Flexible Atomic Code (FAC) [12]. In addition, the relativistic multi-reference Møller-Plesset (MRMP) perturbation theory [13,14] has been shown to produce exceptionally accurate wavelengths of the L-shell transitions of Fe XVII, Fe XVI, and Fe XV [10,15,16].

In the following, we discuss measurements of high-resolution L-shell spectra of iron near 15 and 17 Å performed at the Lawrence Livermore EBIT-I electron beam ion trap that exhibit transitions from autoionizing levels in M-shell iron ions. These were analyzed with the help of modeling based on the Flexible Atomic Code, augmented with accurate transition energies produced by calculations using the relativistic MRMP method. These successful comparisons of experimental and theoretical reference data give us confidence to apply our analysis to the iron features in stellar spectra recorded with the grating spectrometers of the *Chandra X-ray Observatory*. In particular, we present evidence of L-shell emission lines from

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http://dx.doi.org/10.1016/j.nimb.2017.03.152
0168-583X/© 2017 Published by Elsevier B.V.

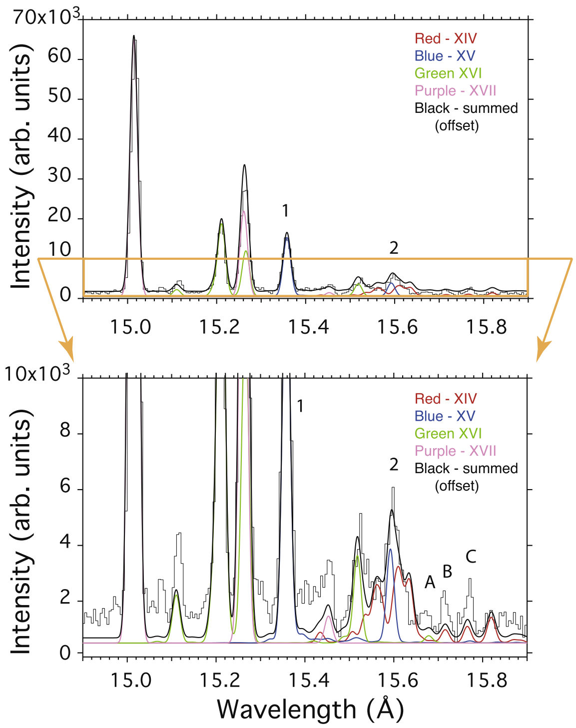

Fig. 1. Comparison of iron measurements with new calculations in the 14.9–15.9 Å region. The iron spectrum was taken with the Lawrence Livermore EBIT-I machine at a beam energy of 1.5 keV. Calculated lines are based on MRMP (for wavelength) and FAC (for intensity) and have been normalized to the strongest observed line in each charge state for each wavelength region. Black trace for the sum of the calculated lines has been slightly offset to allow the constituent lines to be seen. Scale in the bottom inset has been expanded to show the weaker lines. Fe XIV lines labeled A-C are identified in Table 1. Fe XV lines labeled 1–2 are identified in Table 2.

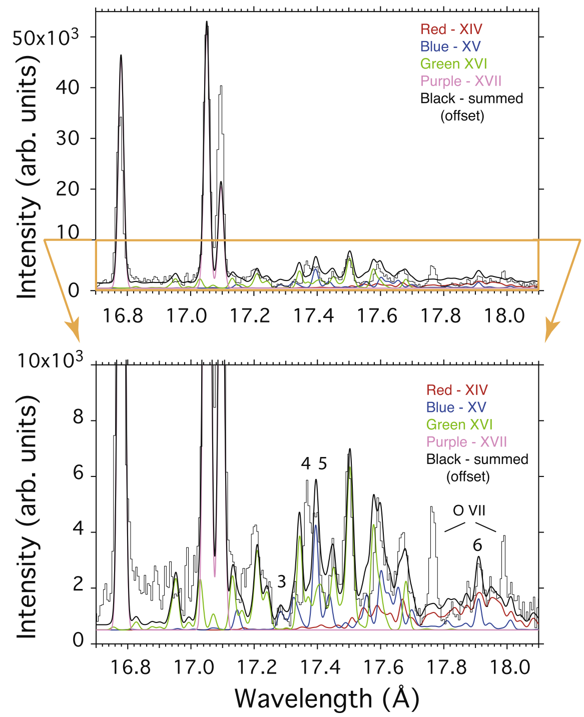

Fig. 2. Comparison of iron measurements with new calculations in the 16.7–18.1 Å region. The iron spectrum was taken with the Lawrence Livermore EBIT-I machine at a beam energy of 1.5 keV. Calculated lines are based on MRMP (for wavelength) and FAC (for intensity) and have been normalized to the strongest observed line in each charge state for each wavelength region. Black trace for the sum of the calculated lines has been slightly offset to allow the constituent lines to be seen. Scale in the bottom inset has been expanded to show the weaker lines. Fe XV lines labeled 3–6 are identified in Table 2.

M-shell iron ions in the spectra of the nearby stars Capella and Procyon.

2. Laboratory measurements

In Fig. 1 we show L-shell emission spectra recorded on the Livermore EBIT-I device using a high-resolution grating spectrometer [17]. The emission of lower charge states of iron was enhanced by injection of iron pentacarbonyl at high injection pressure and by employing short trapping times. Even under such favorable conditions the emission from the M-shell ions of iron is rather weak. The spectra are dominated by the Fe XVII emission, i.e., by the emission from neonlike Fe^{16+}, which in its ground configuration has no electrons in the M shell.

An overlay of theoretical spectra onto the experimental data is shown in Fig. 1. The theoretical spectra were calculated using excitation data from FAC calculations and wavelength data from MRMP calculations. We find excellent agreement in most cases between theory and observations. This allows us not only to identify the better known features associated with Fe XVI [9,16], but also several Fe XV and some Fe XIV features in the laboratory spectra. While most of the lines from these two charge states are blended, a few lines are reasonably well resolved. In Fe XV, we note five such lines, which are labeled a thorough e in Figs. 1,2. In Fe XIV, we note three resolved features labeled A, B, and C. A summary of these lines is given in Table 1. Only two of the Fe XV lines (a and b) have been previously reported [10]. Note that the spectrum shown in Fig. 2 also contains K-shell emission from oxygen, It is an unavoidable presence when injecting iron in the form of iron pentacarbonyl. (See Table 2).

3. Stellar measurements

Using the experimentally validated theoretical wavelengths, Beiersdorfer et al. [16] were able to identify features associated with the L-shell emission of Fe XVI in the spectra of the star Capella (α Aurigae) observed with the *Chandra* High Energy Transmission Grating Spectrometer (HETGS). Indeed, they were able to find many unassigned features in the spectrum of Capella that corresponded to the locations predicted for Fe XVI lines, as shown in Fig. 2. Using our new identifications of Fe XV and Fe XIV transitions, we have searched for features from these charge states of iron in the Capella observations. We could only find one weak feature, which we believe corresponds to the strongest Fe XV line at 15.356 Å (see Fig. 2). We conclude that Capella is too hot to identify further L-shell transitions of M-shell iron lines.

The spectra of stars cooler than Capella may contain more emission from lower charge states of iron M-shell ions. We have investigated this notion by looking at the spectrum of Procyon (α Canis Minoris), which is a much cooler star (about 2 MK) than Capella (about 5 MK).

In Fig. 3, we show the emission of L-shell iron near 15 Å of Procyon observed with Chandra's Low Energy Transmission Grating Spectrometer (LETGS). Although the LETGS resolution is poor and the noise in the spectrum is high, we can identify the well known Fe XVII line at 15 Å (cf. blue trace in Fig. 3). It is accompanied by prominent emission on its long-wavelength side, which extends to about 15.5 Å. We modeled the Procyon spectrum using the spectral models we developed to fit the laboratory data in Fig. 1. The fit of the LETGS spectrum of Procyon (red trace in Fig. 3) requires flux from Fe XVI, Fe XV, and Fe XIV. Like the laboratory spectra from EBIT-I, the Procyon spectrum shows K-shell lines of oxygen, which we also included in our model. (See Fig. 4).