Electron-impact excitation of \(2p^53l \rightarrow 2p^53l'\) line emission of Fe XVII

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Abstract.
We present theoretical investigations on the EUV line emission of Fe XVII in an electron-beam-ion-trap. Calculations of atomic data and the collisional-radiative model, used to study population kinetics of \(2p^53l\) levels of Fe XVII, are described. Intensities of the strongest EUV lines at 204.6 Å and 254.8 Å are found to be 2 orders of magnitudes smaller than the x-ray line intensities at 15 Å and 17 Å. Significant enhancement of the EUV lines around 250-400 Å due to resonance excitation is demonstrated.

1. Introduction
Ne-like Fe (Fe XVII) is abundant in many astrophysical and laboratory plasmas because of its L-shell closed electronic configuration of the ground state. Fe XVII lines of extreme ultraviolet wavelengths (EUV) have been observed in solar flares [1] and beam-foil spectra [2]. The lines were identified as transitions among \(2p^53l\) excited levels [2-4].

\(2p^53p (^1S_0) \rightarrow 2p^53s (1/2, 1/2)\) transition is known as an electron-impact pumping scheme to produce soft x-ray or EUV lasers. Laboratory experiments with laser produce plasmas [5, 6] have, however, shown very small gain of this transition for Se XXV; other transitions in the \(2p^53l\) levels exhibited the largest gain in the experiments. This result has been puzzling, since collisional excitation models predicted that the \(2p^53p (^1S_0) \rightarrow 2p^53s (1/2, 1/2)\) line should have one of the highest intensities. Later, Doschek et al. [7] reported that observed line intensities of Fe XVII in a solar flare were in good agreement with intensities calculated, taking account collisional excitations from the ground state of Fe XVII. In the both (observed and calculated) spectra, 204.6 Å and 254.8 Å lines, identified as \(2p^53p (^1S_0) \rightarrow 2p^53s (3/2, 1/2)\), and \(2p^53s (1/2, 1/2)\), respectively, had the strongest and almost the same intensities. They concluded therefore that inaccurate collision excitation rates in the model should not be the cause of the puzzle.

However, new observation of a solar flare by means of the EUV Imaging Spectrometer on Hinode satellite [8] has shown difficulty in reconciling observed Fe XVII line intensities with available atomic data. It was reported [9] that the observed intensity of the 254.8 Å line was factor of 2 smaller than that calculated by using CHIANTI code [10]. Although the discrepancy may be ascribed partially to
calibration issues, re-investigation of the relevant atomic data seems to be necessary for a better understanding.

In this paper, we describe excitation cross sections related to the EUV line emission of Fe XVII with emphases on resonance excitation effects and particularity of the $2p^5 3p (1S_0)$ state. To the best of our knowledge, the EUV line emission of Fe XVII has not been studied thoroughly with an electron-beam-ion-trap (EBIT), while there are studies on the x-ray lines at 15-17 Å [11-13]. We therefore present line emissivity and intensity ratios, calculated for experimental conditions of an EBIT.

2. Atomic data and collisional-radiative model of EBIT

In this section, we briefly describe calculations of atomic data and the collisional-radiative model used to study population kinetics of $2p^3 3l$ levels of Fe XVII in the EBIT.

2.1. Atomic data

HULLAC code [14] was used to obtain level energies, collision strengths of electron-impact excitation, and radiative-decay and auto-ionization rates. To account for strong valence-core correlation known for the $2p^5 3l$ excited states, configuration interaction with $2s2p^6nl^p$ states was included. Nevertheless, a large error remained in the calculated transition energy (wavelength) of $2p^5 3p (1S_0) \rightarrow 2p^5 3s (3/2, 1/2)$ and $2p^5 3s (1/2, 1/2)$. By taking account core polarization effects, the transition energy was improved to some extent, however the effects made the other transition energies less accurate. In earlier studies [15], multi-configuration Dirac-Fock calculations in the extended average mode gave inaccurate level energies of the $1S_0$ state. To improve this, a separate optimization of radial wavefunctions for this state was required, due to a particular radial dependence of this state. However, this pragmatic remedy can not be adopted with HULLAC code, since, in the HULLAC, every state of a given electronic configuration is represented by a common set of the radial wavefunctions obtained with a single parametric potential. For the sake of convenience, we just take correct transition energies from the NIST database [16].

Another feature of $2p^5 3p (1S_0)$ is the large direct excitation cross section and then the small resonance excitation effect compared with the other states involved in the EUV line emission. This is clearly demonstrated in Fig. 1. The resonance excitation cross sections were obtained with a Gaussian energy distribution function using FWHM of 10 eV.

2.2. Collisional-radiative model of EBIT

In the EBIT, ions are excited with a quasi mono-energy electron beam. Recombination from higher ionization states can be avoided by setting the electron energy below the ionization threshold of Fe XVII (about 1260 eV). A collisional excitation model can therefore be used for the population kinetics of the excited levels. Because of low electron number densities ($N_e = 10^{10-11} \text{ cm}^{-3}$) in the EBIT, the
corona model is also applied. In the quasi stationary condition, the fractional populations of the excited levels $n_i$ are written,

$$n_i = N_e \left( \alpha_{DE} + \alpha_{RE} \right) n_g \sum_{j \leq i} A_{ji},$$

where $\alpha_{DE}$ and $\alpha_{RE}$ are the direct excitation and resonance excitation rate coefficients, respectively, $A_{ji}$ is the Einstein’s coefficients of spontaneous decay, and the population of the ground level $n_g = 1$.

3. Line emissivity and intensity ratio

In Fig.2, the line emissivity divided by the electron number density, $\Delta E_{ji} A_{ji} n_i / N_e$, is plotted for the electron beam energy of 850 eV. The lines in x-ray region are also shown for comparison. The strongest EUV lines at 204.6 Å and 254.8 Å have intensities 2 orders of magnitudes smaller than the x-ray line intensities at 15 Å and 17 Å. It suggests that the EUV lines are generally more difficult to observe in laboratory plasmas of low electron densities like the EBIT. It is seen in the figure that the two lines at 204.6 Å and 254.8 Å have almost the same intensities, because of strong intermediate coupling in the lower levels, for the two lines is the electric-dipole branching ratio close to unity. It is noted that many other EUV lines also appear around 250-400 Å as strong as the two lines. The resonance excitation contribution dominates these line emissions. The resonance excitation effect manifests itself more clearly in the energy dependence of line intensity ratios.

![Fig. 2 Line emissivity of Fe XVII in EBIT at electron energy of 850 eV.](image)

The line intensity ratios of 269.4 Å /254.8 Å are plotted at electron energies for 800-950 eV in Fig.3. In the figure, the intensity ratios, calculated by accounting for the direct excitation only, are also shown for comparison. It is quite obvious that the resonance excitation enhances the intensity ratio significantly. This is easily understood by recalling that the resonance excitation effect of the upper level of the 269.4 Å line, 2p$^3$3d ($^2F_3$), is much larger than that of the upper level of the 254.8 Å line, 2p$^3$3p ($^1S_0$) (see Fig. 1). Due to the narrow energy width of the electron beam, the intensity ratio shows rapid variation along the electron energy. At the highest peak, the intensity ratio is enhanced by about a factor of 3. It is noted that a similar enhancement of the intensity ratio of x-ray lines at 17 Å to the 15 Å line (3F+3G+M2 and 3C, respectively, as designated in Fig. 2) has been reported in earlier measurements with an EBIT [11].

4. Summary

Although the EBIT is known as the one of the best apparatus to examine detailed electron collision processes of highly charged ions, no observation of the EUV lines of Fe XVII has been reported with
the EBIT to date. We investigated theoretically the EUV line emission in the EBIT by using the
collisional excitation model with atomic data from HULLAC code. The intensities of the strongest
EUV lines at 204.6 Å and 254.8 Å were found to be 2 orders of magnitudes smaller than the x-ray line
intensities at 15 Å and 17 Å, suggesting that the EUV lines would be more difficult to observe with the
EBIT. The present results demonstrate significant enhancement of other EUV lines in 250-400 Å due
to resonance excitation.

Acknowledgment
This work is supported by the NIFS/NINS project of Formation of International Network for Scientific
Collaborations.

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