Analysis of Dielectronic Recombination Transitions for Highly Charged Iron Ions

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(Received 14 November 2001 / Accepted 21 November 2001)

The X-ray spectra emitted from highly charged Fe ions impacted by an electron beam with an energy ranging from 4.3 to 8.5 keV were measured in the Tokyo Electron Beam Ion Trap (EBIT). To analyze the observed spectra, cross sections for dielectronic recombination of KLn states were calculated for the range 4.3 ~ 6.6 keV by the use of the distorted wave method. By comparing the convoluted cross sections with the experimental spectra, close agreement was obtained, and we identified He-like Fe as a dominant component (74%) in a mixture also containing Li-like ions (18%) and Be-like ions (8%). The ion density was estimated to be $6.5 \sim 8.5 \times 10^8$ cm^{-3}.

Keywords: dielectronic recombination, highly charged iron ion, plasma spectroscopy, ebit

The study of iron ions is of interest to astrophysics, due to the high abundance of iron in a wide variety of astrophysical objects. Furthermore, iron is commonly used in the construction of various ion confinement devices such as the TOKAMAK. Recently, using the Tokyo Electron Beam Ion Trap (EBIT) [1-3], X-ray spectra of highly charged Fe ions were observed [4] for electron beam energies ranging from 4.3 keV to 8.5 keV. In this energy range, radiative recombination (RR), dielectronic recombination (DR), resonance excitation (RE), resonance recombination (RER), direct excitation (DE), and radiative transition processes may take place. The energy range passes across the joining point of DR and DE, which corresponds to the ionization limit of doubly excited high Rydberg states that are formed by electron capture. Since the beam density is approximately $10^{10} \rightarrow 10^{12}$ cm^{-3}, the RR spectrum is very weak and will not be discussed in this paper, with our interest focused only on the energy range of 4.3 → 6.6 keV.

The excitation energy of $1s \rightarrow 2l$ is approximately 6.6 keV. For the beam energy below this, DR transitions take place. For the purpose of analyzing the experiment, cross sections of the processes concerned were calculated in the isolated resonance approximation. In the calculation, the Auger decay rates and radiative decay rates were obtained by using the multi-configuration Hartree-Fock method with relativistic corrections [5, 6]. The continuum states were described by distorted waves with the potential chosen to be the same as that for the bound states.

Since the emitted photons were detected at 90^{o} to the direction of the electron beam, for DR transitions of He-like, Li-like and Be-like ions, we calculated the polarization degree for each radiative decay from doubly excited eigen states. The expression of polarization degree is given in [7] for pure LS-coupling states. For intermediate states, the expression should be weighted by the square of the transition matrix elements in the calculation. From the calculation we noticed that for strong transitions, the polarization degrees were approximately the same as those calculated from pure LS-coupling basis sets states. In the case where the detector system is not sensitive to the polarization direction, photon numbers at 90^{o} observation, $N(90^{\text{o}})$, may have a relation with cross sections as follows:

$$\begin{aligned} N(90^{\text{o}}) &= 4\pi I_0(90^{\text{o}})\sigma^{\text{Conv}}(90^{\text{o}}) \\ &= 4\pi I_0(90^{\text{o}}) \sum_j \frac{3}{3 - P_j} \frac{\sigma_j^{\text{Conv}}}{4\pi} \qquad (1) \end{aligned}$$

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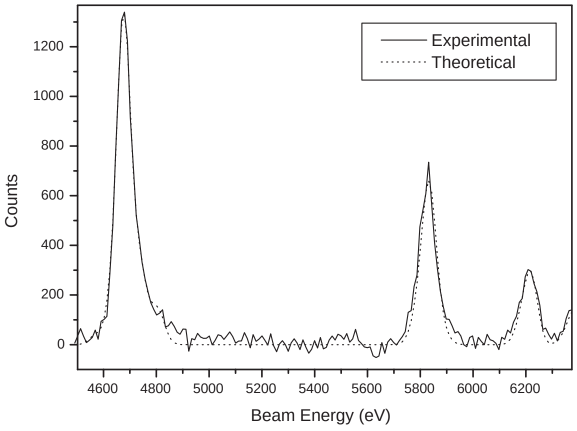

Fig. 1 Simulated DR spectra fitting to the experiment result for 90^{o} observation

Here P_j is the polarization degree for radiative decay j [7], $I_0(90^{\mathrm{o}})$ represents photon number densities (cm^{-2}), and σ_j^{Conv} stands for convoluted space integrated cross sections (cm^2) for radiative decay j. We fit to the observation with $4\pi I_0(90^{\mathrm{o}})(c_{\mathrm{He}}\sigma_{\mathrm{He}}^{\mathrm{Conv}}(90^{\mathrm{o}}) + c_{\mathrm{Li}}\sigma_{\mathrm{Li}}^{\mathrm{Conv}}(90^{\mathrm{o}}) + (1 - c_{\mathrm{He}} - c_{\mathrm{Li}})\sigma_{\mathrm{Be}}^{\mathrm{Conv}}(90^{\mathrm{o}}))$, then c_{He}, c_{Li}, and $(1 - c_{\mathrm{He}} - c_{\mathrm{Li}})$ are the abundance of ions. Based on the experimental condition, we can assume that the charge balance was kept constant during the observation. By using the nonlinear least-square method shown in [8], we got $c_{\mathrm{He}} = 0.740 \pm 0.001$, $c_{\mathrm{Li}} = 0.177 \pm 0.008$. Then c_{Be} can be obtained from $c_{\mathrm{Be}} = 1 - c_{\mathrm{He}} - c_{\mathrm{Li}} = 0.082 \pm 0.009$. The FWHM of the beam energy is 57.4 ± 1.5 eV. Then, we obtained $I_0(90^{\mathrm{o}}) = (1.59 \pm 0.02) \times 10^{23}\ \mathrm{cm}^{-2}$. The fitting for 90^{o} observation is shown in Figure 1. When comparing Figure 1 with the figure fitted with space integrated cross sections we find, the relative amplitudes of KLL, KLM, and KLN are almost the same. This means that average polarization degrees are very close for KLL, KLM, and KLN, which verifies the discussion in [4].

Since $N(90^{\mathrm{o}})$ is the count for the detection of emitted photons by collision, it is equal to the number of ions which have reacted. Considering $\frac{\partial n_{\mathrm{i}}}{\partial t}\tau \ll n_{\mathrm{i}}$, we have

$$\begin{aligned} I_0(90^{\mathrm{o}}) &= p\int_{\mathrm{V}} n_{\mathrm{i}} n_{\mathrm{e}} \overline{v} \tau \mathrm{d}\mathbf{r} \frac{\mathrm{d}\Omega}{4\pi} \\ &= p n_{\mathrm{i}} L \tau \frac{I_{\mathrm{e}}}{e} \frac{\mathrm{d}\Omega}{4\pi} \end{aligned} \tag{2}$$

Here n_{e} and n_{i} are the densities of electrons and ions, respectively, in the interaction region. I_{e} is the electron beam current, τ is the observation time, $\overline{v}$ is the averaged velocity of the electron beam during the observation time, L is the reaction length in the trap visible to the detector, and p is the efficiency of the detector system.

In the experiment, the electric current intensity was 100 mA, the observable electron-ion interaction length was 1 cm, the observation time was 1.9 s for each electron energy channel, and the solid angle for the observation is $\mathrm{d}\Omega = 4.01 \times 10^{-3}$. Taking account of the total efficiency of the detector system, which is estimated to be $p = 0.5 \sim 0.6$ for $h\nu \simeq 6$ keV from the transparency [9] of the window in the front of the detector and the quantum efficiency of detector (EURISYS MESURES, EGP500-15), the average ion density is estimated to be $6.5 \sim 8.5 \times 10^8\ \mathrm{cm}^{-3}$.

A detailed description of the present calculation and comparison will be published elsewhere in future.

The authors are grateful to the members of the Tokyo EBIT group for their helpful discussion. One of the authors (Yueming Li) is supported by the Scholarship of Mombu-Kagaku-sho in Japan. Fred Currell thanks the Royal Society for travel support facilitating this collaboration.

[1] F. J. Currell *et al.*, J. Phys. Soc. Japan **65**, 3186 (1996).
[2] H. Watanabe *et al.*, J. Phys. Soc. Japan **66**, 3795 (1997).
[3] H. Kuramoto *et al.*, Rev. Sci. Instrum. **71**, 687 (2000).
[4] H. Watanabe *et al.*, *to be published in* J. Phys. B.
[5] R. D. Cowan, *Theory of Atomic Structure and Spectra* (University of California Press, Berkley, CA, 1981), p. 327.
[6] Y. M. Li and S. C. Li, J. Korean Phys. Soc. **32**, 312 (1998).
[7] A. S. Shlyaptseva, R. C. Mancini and P. Neill, Phys. Rev. A **57**, 888 (1998).
[8] W. H. Press *et al.*, *Numerical Recipes in Fortran 77* (Cambridge University Press, NY, 1989), p. 675.
[9] B. L. Henke, E. M. Gullikson and J. C. Davis, At. Data Nucl. Data Tables **54**, 181 (1993).