§5. Spectroscopic Measurements and Database Development for Highly Charged Rare Earth Elements

Koike, F. (Sophia Univ.),
Suzuki, C., Murakami, I., Sakaue, H.A., Goto, M., Kato, D., Kato, T., Morita, S., Funaba, H.,
Sasaki, A. (JAEA)

The spectra of photoemissions due to the transitions between the sub-shell levels in N-sub-shell open atomic ions are of interest for the strong influence from the interactions between the electronic state configurations with different constituent orbitals. Modifications in unresolved transition array (UTA) spectral profile has been pointed out[1,2], and this effect is advantageous to the development of practical extreme ultraviolet (EUV) light sources. The wavelengths of the 4*d* - 4*f* transitions are reported to be, for example, 7.9 nm for Nd (Z=60), 7.0 nm for Eu (Z=63) , and 6.8 nm for Gd (Z=64)[3]. The 4*d* - 4*f* transitions of Tb(Z=65) at 6.5 nm has been investigated theoretically by Sasaki et al[4].

To study the EUV light emissions from highly charged heavy ions in connection to their atomic structures, it is quite worthy to study in thin plasma conditions. We have proposed the use of the LHD plasmas for the spectral measurement of lanthanide elements. In the fiscal year 2011, we measured the emission spectra of Gd(Z=64) and Nd(Z=60) in detail[5,6]. We further measured Tb(Z=65) and Dy(Z=66) in 2012, Yb(Z=70), Er(Z=68), and Sm(Z=62) in 2013. We extended, in the fiscal year 2014, our measurement to the elements Ce (Z=58), Ho (Z=67), Tm(Z=69), Lu(Z=71), and Hf (Z=72)[5,6]. We have presently covered almost the whole range of the atomic number in lanthanide atoms, say, for atoms with Z=58, 60, 62, 64, 65, 66, 67, 68, 69, 70, 71, and 72. The present accumulation of the spectral data is now enabling our investigation on the Z-dependence of the spectral features in lanthanide elements.

We compared those spectra to our elaborate atomic structure calculations based on a Multi-Configuration Dirac-Fock (MCDF) approximation. We employed the General purpose Relativistic Atomic Structure Program 92 (GRASP92)[7] for the electronic structure, and the Relativistic Atomic Transition and Ionization Properties (RATIP) code[8] for transition wavelengths and strengths. By using these programs, we can properly evaluate the electron correlations through the interactions between the relevant configuration state functions (CSF's) in a sophisticated manner. The complex spectra from UTA are generated theoretically. We have made the MCDF calculations for all the lanthanide atomic species for ions with the number of electrons from 27 to 59. We have investigated, firstly, the Z- dependence of the 4*d*-4*f* UTA spectral features, and, secondly the charge state dependence of the 4*d*-4*f* UTA spectral features for individual elements.

Figure 1 gives the synthesized EUV spectra in the 4*p* - 4*d*, 4*d* - 4*f* UTA region for all the lanthanide elements from Ce to Lu. We find that the general trend of the spectra agrees well with our experimental LHD spectra.

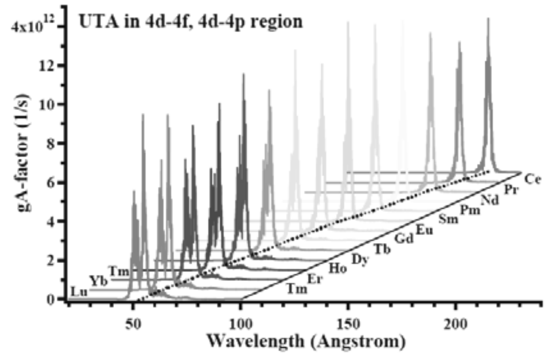

Fig 1. Synthesized EUV spectra of lanthanide atomic ions for the region of 4*p* - 4*d*, 4*d* - 4*f* UTA. The distribution of weighted Einstein coefficients (gA-factors) for transitions between N sub-shell states of Ce(Z = 58) to Lu (Z = 71) for ions with a configuration [Ni]4s24p64d^{w}(w = 2 ~ 8) in the ground state. Horizontal axis: Wavelength of the emitted photons in units of Angstrom. Vertical axis: Sums of the weighted Einstein coefficients in units of 1/s. The sums of all the calculated gA-factors have been convoluted by the Lorentzian function of full width at half maximum (FWHM) 0.10 Angstrom and the triangular function of FWHM 0.10 Angstrom. The dotted line under the curves indicate the wavelengths of the spectral peak position.

In Fig.2, we show the charge state dependence of the EUV spectra in the 4*p* - 4*d*, 4*d* - 4*f* UTA region for Yb(Z=70). We find the UTA shows a dual peaked nature mainly in the wings of lower charges.

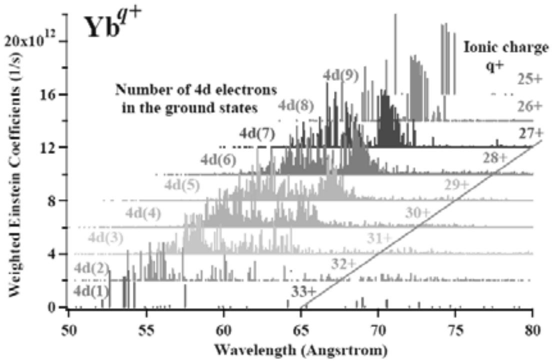

Fig. 2. Ionic charge dependence of the distribution of gA-factors in Yb ions. Vertical bars: the weighted Einstein coefficients for 4*d* - 4*f* and 4*p* - 4*d* transitions for individual ionic charges from Yb^{25+} with $4d^9$ to Yb^{33+} with 4*d*. Horizontal axis: wavelength of emitted photons in units of Angstrom. Vertical axis: weighted Einstein coefficients in units of 1/s.

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