Soft X-ray spectroscopy and atomic physics of highly charged lanthanide ions in plasmas

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Soft X-ray emissions from highly charged ions of lanthanide elements (Z=57–71) are of interest in terms of basic atomic physics as well as potential applications for industrial light sources. However, available experimental data are still limited for these ions. Magnetically confined torus plasmas can be exploited for producing such data because of their properties favorable for spectroscopic studies. Therefore, we have systematically observed soft X-ray spectra of lanthanide ions in the Large Helical Device (LHD) plasmas at the National Institute for Fusion Science (NIFS) [1–4].

In the series of experiments, a small number ($\simeq 10^{17}$ atoms) of lanthanide elements were injected into high-temperature ($\simeq$2–3 keV) hydrogen plasmas using the tracer encapsulated solid pellet (TESPEL) [5]. Soft X-ray spectra were recorded with three different grazing incidence spectrometers to cover the various wavelength regions. In the last decade we have injected all the lanthanide elements except for promethium to investigate atomic number (Z) dependence in detail. As reported in previous papers [1–3], the spectral features are mainly composed of quasi-continuum bands of 4d-4f transitions in low temperature conditions, while discrete lines in high temperature conditions due mainly to ions with 4s or 4p outermost electrons (Cu-, Zn-, Ga-like, etc.).

The discrete spectra in high-temperature LHD plasmas are compared with the past experimental data taken in tokamaks, laser-produced plasmas and electron beam ion traps (EBITs) to assign known lines as many as possible. Then we make comparisons with detailed atomic structure calculations and collisional-radiative models to identify unknown lines. Also, we use the interpolation of Z dependence of the transition wavelengths.

The EBIT experiments are helpful as we can distinguish an ion stage for each line by gradually changing the electron beam energy. We performed a new experiment in Tokyo EBIT [6] for europium to make a comparison with the LHD spectra as shown in Fig. 1, where the spectra for two different beam energies (1.45 keV and 1.50 keV) are plotted together with the LHD spectrum. Figure 2 shows Z dependences of the measured wavelengths of four different resonance lines of Ga-like ions. The detailed theoretical calculation revealed that the crossing of the wavelengths for the two transitions observed between Z=62 and 63 originates from large configuration mixing and spin-orbit splitting [7].

Consequently, these analyses lead to some new experimental identifications of spectral lines as well as deeper understanding of atomic physics issues specific to highly charged heavy ions.

References
[1] C. Suzuki *et al*, Plasma Phys. Control. Fusion **59** 014009 (2017)
[2] C. Suzuki *et al*, Atoms **6** 24 (2018)
[3] C. Suzuki *et al*, J. Phys. B: At. Mol. Opt. Phys. **54** 015001 (2020)
[4] C. Suzuki *et al*, Atoms **9** 46 (2021)
[5] S. Sudo and N. Tamura, Rev. Sci. Instrum. **83** 023503 (2012)
[6] N. Nakamura *et al*, Phys. Scr. **T73** 362 (1997)
[7] F. Koike *et al*, Phys. Rev. A **105** 032802 (2022)

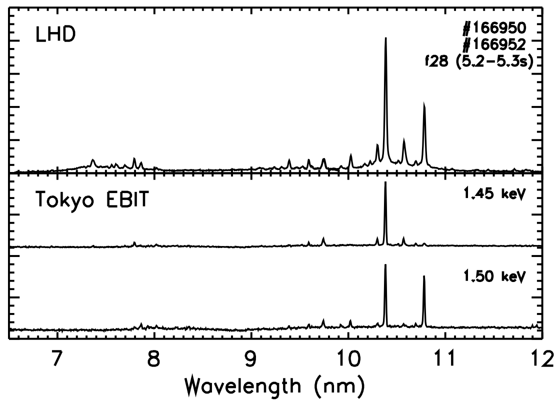

Figure 1. Soft X-ray spectra of europium ions observed in LHD (top) and Tokyo EBIT (bottom).

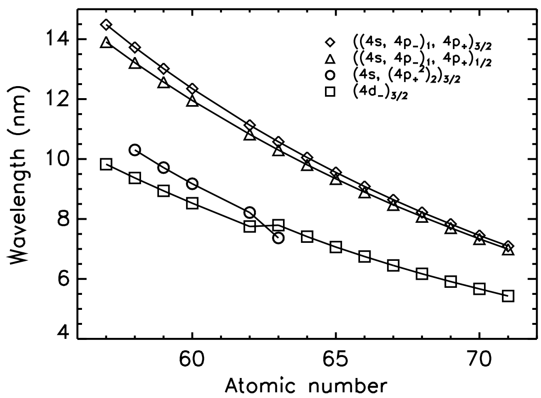

Figure 2. Z dependence of the measured wavelengths of several resonance lines of Ga-like lanthanide ions.