Contribution of Quantitative Spectroscopy to Fusion Plasma Research

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In fusion plasmas, different roles are required for impurities in terms of atomic number, Z; in low temperature peripheral (divertor) plasmas, enhancement of low Z impurity radiation is of importance for mitigating plasma heat load onto plasma-facing walls, while in high temperature core plasmas, suppression of impurity radiation, particularly by high Z impurity ions, is essential for maintaining high temperature. This talk discusses a mechanism, which enhances low Z impurity radiation in divertor plasmas and a method available for validating ionization and recombination rates of high Z impurity, tungsten (W) based on quantitative spectroscopy.

In the divertor plasma of JT-60U tokamak, we successfully provided a comprehensive picture of the carbon radiative cooling process [1]. In high-density divertor plasmas, typically an electron density above 1×10^{20} m^{-3}, strong radiation zone appeared, and intense line emissions from carbon ions, originating from the carbon divertor targets, were observed. It was found, in this radiation zone, that the C III line emission contributed 30% of the total radiation power, and C IV 60%, and that the C IV ions were produced by ionization of C III ions and at a higher rate by recombination of C V ions (He-like). These indicate that C III and C V ion flowed into the radiation zone, and were converted into the biggest radiator, C IV. In particular, a newly discovered channel [2], conversion of an inefficient radiator C V into an efficient C IV contributed to enhance the radiative cooling more than that of C III to C IV. Interestingly, in Ne-seeded plasmas, recombination of Ne IX (also, He-like ion) was observed in the Ne radiation zone [3], suggesting recombination of impurity He-like ion is one of common key processes to enhance the impurity radiation.

In the core plasma of JT-60U tokamak, W density was determined from the intensity of W^{45+} spectral line (4s-4p: 6.2 nm). The determined W density over electron density ranged from 1×10^{-5} up to 1×10^{-3} [4]. In addition, to investigate the validity of W^{44+} ionization rate and W^{45+} recombination rate, a density ratio of W^{45+} to W^{44+} calculated with an ionization equilibrium model was compared to that determined from an intensity ratio of W^{45+} to W^{44+} 4s-4p lines. One of the advantages of this method is cancellation-out of electron temperature dependence of excitation rates of 4s to 4p by taking the intensity ratio. This is due to similar transitions in simple systems; closed 3d shell + 4s electron, exciting to 4p level for W^{45+} and one additional 4s for W^{44+}. This analysis resulted in agreement between measurement and calculation within experimental uncertainty (~30%), showing the validity of the ratio of W^{44+} ionization rate to W^{45+} recombination rate. Similar analysis performed in the JET tokamak [5], but for the density ratio of W^{46+} to W^{45+} determined from the intensity ratio of W^{46+} to W^{45+} 3p-4d lines (0.52 nm), showed the measured W^{46+}/W^{45+} ratio was systematically higher by 16% than that calculated. This indicates a possibility that the calculated W^{46+} recombination rate is overestimated or the calculated W^{45+} ionization rate is underestimated. The reason for this deviation is not yet clear.

[1] T. Nakano, et al., J. Nucl. Mater. **390-391** 255 (2009).

[2] T. Nakano, et al., Nucl. Fusion **47** 1458 (2007).

[3] T. Nakano, et al., J Nucl. Mater. **438** S291 (2013).

[4] T. Nakano and the JT-60 Team, J. Nucl. Mater. **415** S327 (2011).

[5] T. Nakano, et al., J. Phys. B **48** 144023 (2015).