Charge Exchange Spectroscopy of Multiply Charged Ions of Industrial and Astrophysical Interest

Hajime Tanuma

Department of Physics, Tokyo Metropolitan University, 1-1 Minami-Ohsawa, Hachioji, Tokyo 192-0397, Japan

Abstract. As extreme ultra-violet (EUV) light sources for the next generation semiconductor lithography, laser produced plasmas (LPP) and discharge produced plasmas (DPP) of Xe and Sn have been investigated intensively in this decade. In these plasmas, multiply charged Xe and Sn ions emit the radiation near 13.5 nm. However, the emission lines from individual charge states of ions were understood until the emission spectra from charge-selected these ions with charge exchange spectroscopy were observed.

The solar wind charge exchange (SWCX) means the electron capture of multiply charged ions constituting the solar wind in collisions with neutral matters within the heliosphere and has been regarded as a dominant mechanism of the soft X-ray emission in the solar system. In order to analyze the X-ray spectra observed with satellites quantitatively in detail, the X-ray emission cross sections of the SWCX processes are needed by astrophysicists.

Multiply charged ions were produced in a 14.25 GHz electron cyclotron resonance (ECR) ion source with introduction of source gases, namely Xe, O_2, N_2, and C_2H_4 (or CH_4). For Sn ions, we inserted pellets of sintered tin oxide (SnO_2) into a plasma chamber in which oxygen plasma had been produced. The ions were fed into a collision chamber after the charge-state separation, and the photon emission following the charge exchange collisions of ions with He, H_2, and CH_4 gases was observed with spectrometers. A compact flat-field grazing-incident spectrometer (GIS) equipped with a liquid-nitrogen-cooled CCD camera had been used to observe optical radiation in the EUV region (5–38 nm) of Xe and Sn ions at a collision energy of 20 keV/charge. On the other hand, soft X-ray emission spectra in the photon energy range of 400–1000 eV had been observed with a window-less Si(Li) detector at 90° to the ion beam direction and a window-less silicon drift detector (SDD) at a magic angle of 54.7° for C, N, and O ions at collision velocity similar to that of the solar wind.

In the EUV spectra of lower charge Xe ions, individual emission lines have been identified, and it was found that four lines of Xe VII, eight lines for Xe VIII, and nine lines for Xe IX correspond to newly observed transitions. On the other hand, the unresolved transition arrays (UTAs) corresponding to 4d-4p, 4d-4f, and 4d-5p transitions have been observed in the EUV region for Xe X–Xe XVIII and Sn V–Sn XX, and a comparison with calculations using the Hebrew University Livermore Laboratory Atomic physics Code (HULLAC) has been carried out. The theoretical analysis indicates strong interactions between $4p^6 4d^{k-1} 4f$ and $4p^5 4d^{k+1}$ configurations, even though the experimental and theoretical results on the wavelengths of UTAs show significant discrepancy in the 4d–4f transition.

Soft X-ray emission spectra in collisions of bare and hydrogen-like C, N, and O ions with neutral target gases show dominant peaks corresponding to 1s–2p and $1s^2$–1s2p transitions, respectively. Also, the 1s–np and $1s^2$–1snp ($n = 3-5$) transitions have been observed with smaller intensities. According to both the classical over-the-barrier model and the quantal atomic orbital close coupling (AOCC) calculations, the dominant capture levels in highly charged ions are higher than $n = 3$. This fact means that the cascade processes from higher states to the 2p states are quite significant. We also measured the total single electron capture cross sections using a different experimental setup with the retarding method to separate the charge-state of ions after the collisions. Therefore the intensity ratios and the capture cross sections give the emission cross sections for each 1s–np and $1s^2$–1snp transition of hydrogen-like and helium-like ions.