

Reexamination of collisional ionization cross sections including double ionization processes

Collisional ionization and recombination rates remain a major source of uncertainty in the spectroscopic modelling of solid-density plasmas. X-ray free-electron lasers (XFELs) provide a unique platform to generate warm dense matter with well-defined density and ultrafast energy deposition, enabling K-shell emission spectra to be used as sensitive diagnostics of ionization dynamics. However, the interpretation of these spectra depends critically on the treatment of non-thermal electron distributions, degeneracy effects, and competing atomic processes that may produce similar spectral signatures.

In this work, we revisit previously reported K-shell emission spectra from XFEL-irradiated solid-density aluminium. The experiment used 3 keV, 35 fs XFEL pulses to photoionize aluminium foils, producing K-shell vacancies and subsequent fluorescence emission. We analyse these data using the collisional-radiative model BigBarT, which self-consistently evolves the electron continuum, including non-thermal electron populations and Fermi–Dirac degeneracy effects [1, 2].

We further include shake-off processes following primary photoionization. These processes create additional L-shell vacancies and generate satellite emission features that can mimic those usually attributed to collisional ionization [3]. Our simulations show that shake-off contributes significantly to the observed satellite structure. Nevertheless, when standard collisional cross sections are used, the calculated spectra underestimate the satellite emission, mainly because rapid three-body recombination refills L-shell vacancies on too short a timescale.

To assess the sensitivity of the spectra to these rates, we performed simulations with reduced collisional cross sections. Lowering these rates by an order of magnitude substantially improves agreement with the experimental data, as longer-lived L-shell holes allow shake-off-driven configurations to contribute more effectively to the emitted spectrum. These results suggest that commonly used IPD-scaled collisional models may overestimate three-body recombination rates in low-temperature, solid-density XFEL-driven plasmas.

References

- [1] Ansia L. et al., Phys. Rev. E 112, 025201 (2025).
- [2] A. G. de la Varga, P. Velarde, High Energy Density Physics 9, 542–547 (2013).
- [3] G. O. Williams et al., arXiv, 2501.16970 (2025).