Collisional-radiative models for water-window emission spectra from 4f-shell highly charged ions of heavy elements

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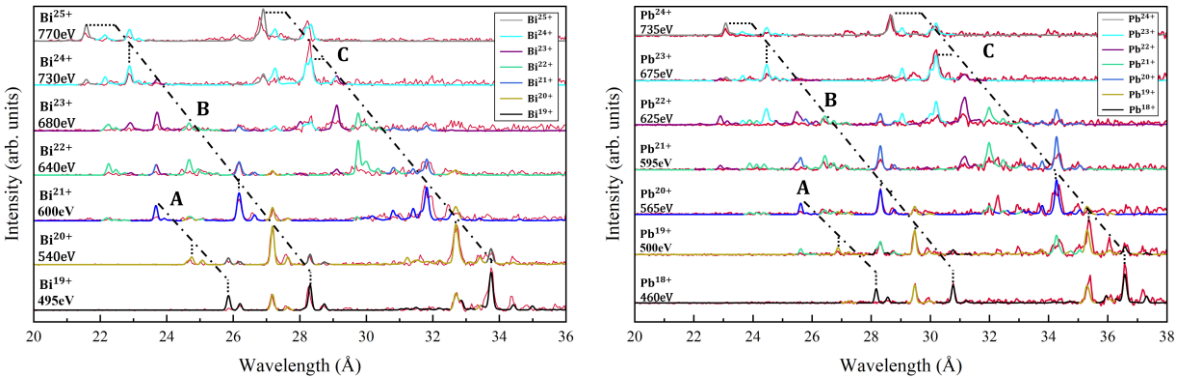

The emission line spectra of Ce- to Gd-like Bi (left) and Pb (right) ions, shown in red for CoBIT and in colored for the calculated spectra, fall within the water-window range. Black, gold, blue, green, purple, light blue, grey for Ce- to Gd-like ions, respectively. Peaks A, B, and C correspond to the $4f - 7g$, $4f - 6g$, and $4f - 5g$ transition arrays, respectively. The wavelength scales of the calculated spectra from Bi^{19+} to Bi^{24+} are shifted +0.18, +0.14, +0.15, +0.31, +0.2 and +0.08 Å, from Pb^{18+} to Pb^{22+} are shifted +0.23, +0.19, +0.17, +0.16, +0.13 Å, respectively. The calculated spectra have been convoluted with Gaussian distribution functions with a full width at half-maximum of 0.12 Å.

The water-window emission lines (20–40 Å) [1] of highly charged bismuth (Bi) and lead (Pb) ions generated in laser-produced plasmas have long been regarded as promising light sources for biological microscopy of living cells [2]. However, in laser plasmas the presence of broad charge-state distributions and strongly overlapping transition arrays makes reliable line identification extremely difficult. To overcome these limitations, we employed a compact electron beam ion trap (CoBIT) [3] to isolate individual charge states of Bi and Pb and identify their strong emission lines in the water-window wavelength range[4][5].

To interpret the measured spectra, we developed a collisional–radiative (CRM) model accounting for detail atomic processes of the highly charged Bi and Pb ions interacting with mono-energetic electron beams. Each strong transition array observed in the experimental spectra was carefully identified with the present calculations. Distributions of the observed peaks show distinct features depending on charge state abundance in the CoBIT. As shown in the figure, the calculated spectra for Ce- to Gd-like Bi and Pb ions (colored) show excellent agreement with the CoBIT measurements (red) after applying appropriate wavelength shifts and charge state abundances. Three prominent groups A, B, and C of emission lines are consistently observed. These correspond to the $4f - 7g$, $4f - 6g$, and $4f - 5g$ transitions, respectively, all arising from the open 4f shell. Furthermore, we found that line emissions mediated via meta-stable excited states play an important role.

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