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# Numerical Investigation of Highly Charged Tin Ions through Electron Impact Excitation with Collisional-Radiative Model

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The development of laser produced plasma (LPP) driven extreme ultraviolet (EUV) light sources is imperative for the progression of next-generation lithography technologies [1-5]. Tin (Sn) is an optimal atomic light source element, as highly charged Sn ions in dense LPPs emit radiation near 13.5 nm. In this view, hot plasma is generated when molten Sn microdroplets are irradiated by energetic laser pulses. The ions responsible for emitting EUV photons near 13.5 nm are $Sn^{8+}$-$Sn^{15+}$. The radiation emitted near 13.5 nm appears in unresolved transition arrays (UTAs) originating from adjacent charge states, leading to spectral line blending from neighboring ionic charge states [1-2]. These transition arrays are unresolved due to the high number of possible transitions in the open-4d sub shells of the ions considered. Consequently, spectroscopic investigation of these plasmas is challenging due to the numerous, densely-packed transitions in these open-4d subshell Sn ions.

The atomic structure of Sn ions can be investigated using the measurements from different experimental techniques, such as laser-produced plasmas, vacuum spark discharge, charge-exchange recombination spectroscopy, and electron-beam ion traps (EBIT) [1]. However, plasma diagnostics are impeded due to the complexity of highly charged Sn ions. Present study explores the spectral properties of highly charged Tin ions, employing electron impact excitation and plasma model calculations.

The calculation of electron impact excitation of $Sn^{8+}$-$Sn^{15+}$ presents a formidable challenge due to its intricate structure. As heavy ions, highly charged Sn ions exhibit significant relativistic effects, including spin-orbit interaction and j-j coupling, resulting in considerable fine structure splitting of the excited states. For detailed investigation of highly charged Sn ions, this study focuses on electron excitation from the ground state of $Sn^{15+}$, i.e., $4p^5$ (J=3/2). The following set of odd configurations is considered for the preliminary calculation: $4s4p^54d$, $4s4p^44d4f$, $4s^24p^44f$, $4s^24p^34d^2$, $4s^24p^34f^2$, $4p^54d^2$,$4p^54f^2$, and $4p^64f$. The set of even configurations such as $4s^24p^44d$, $4s^24p^34d4f$, $4s^24p^24d^3$, $4s^24p^24d4f^2$, $4s4p^6$, $4s4p^54f$, $4s4p^34d^24f$, $4s4p^44d^2$, $4s4p^44f^2$, $4p^64d$, $4p^44d^3$, and $4p^54d4f$ is included [1-2]. To compute electron-ion atomic structure parameters, we employ a fully relativistic multiconfiguration Dirac-Fock (MCDF) method [6] integrated into the flexible atomic code (FAC) [7] and calculated the excitation energies of the considered fine structure levels, transition parameters such as oscillator strengths and transitions probabilities. Further, the resulting wave functions are then used to construct the transition matrix (T-matrix) for excitation cross-sections computations. Moreover, a fully relativistic distorted wave (RDW) method is utilized to calculate the excitation cross-sections for incident electron energies up to 3.5 keV. The electron impact excitation coefficients for all transitions are calculated using the obtained cross-sections. These coefficients are crucial in developing a collisional-radiative (CR) plasma model for $Sn^{15+}$ ions.

In the present collisional-radiative plasma model, we meticulously consider the fine structure levels, including the ground and upper excited states, in addition to the ionization state of $Sn^{15+}$. These levels are interconnected through various collisional and radiative transitions in plasmas. Consequently, present CR model comprehensively integrates various papulation transfer processes among fine structure levels, including electron impact excitation, ionization, and radiative decay, along with their respective reverse processes, such as electron impact de-excitation and three-body recombination. To ensure the robustness of our calculated atom-ion structure and electron-ion collision parameters, we examine the EBIT $Sn^{15+}$ measurements conducted by Scheers et al. [1]. Comparisons were made between the measured line emissions from $Sn^{15+}$ within the wavelength range of 13-15 nm and the corresponding intensities derived from our present theoretical CR model. This comparative analysis serves to validate the reliability of our atom-ion structure and electron-ion collision data. Detailed electron impact excitation results for electron-ion structure and electron-ion collision parameters will be presented and discussed in the conference.

References

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