Recent Developments in Modeling Atomic Processes in Dense Plasmas

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Recent experiments using intense laser pulses on thin targets have produced spectra in which it has been speculated that certain features are due to multiple ionization or recombination events [1]. To explore this possibility, a program of work has begun to add the rate coefficients for collisional double ionization and its inverse process, four-body recombination, to the collisional rate matrix computed within the Los Alamos plasma kinetics code ATOMIC.

First of all, the required collisional double ionization cross sections were obtained from semiempirical fits to experimental measurements, since there is no reliable theoretical method that can produce collisional double ionization cross sections in a timely manner for a wide range of atoms or atomic ions [2]. The semiempirical fits were designed to be reliable over a wide range of incident electron energies, and to be sufficiently versatile to describe cross sections from few-electron ions to larger atomic systems. These semiempirical fits were implemented in the Los Alamos multipurpose ionization code GIPPER [3]. Of course, in any rate matrix, one must also include the corresponding inverse processes so that ion populations may be properly obtained. In this case, the corresponding inverse process is four-body recombination, where three electrons interact with an ion such that two electrons recombine with the ion. We have derived the four-body recombination rates from detailed-balance considerations, for cases where the electron distributions are Maxwellian or non-Maxwellian.

The resulting collisional rate matrix is then solved as part of the Los Alamos plasma kinetics code ATOMIC [4]. We have examined emission spectra produced from solving the coupled rate equations, including the double ionization and four-body recombination rate coefficients, for an Ar plasma in which various fractions of hot electrons are present. We find that inclusion of these multiple-electron effects can make appreciable differences to the average ionization stage of the plasma and the resulting emission spectra at relatively high electron densities, for plasma conditions that contain appreciable fractions of hot electrons.

For example, in Fig. 1, we present emission spectra of Ar at various electron densities. The electron temperature is 120 eV with a 50% fraction of hot electrons, at various temperatures (10, 20, and 30 keV) as labeled in the heading. At this temperature and density, the dominant spectral peak is due to transitions in the He-like stage of Ar (at around 3.96 Å); peaks from lower (more electrons) ion stages with lower emissivities are also present. At lower electron densities the inclusion of the collisional double ionization and four-body recombination rates (labeled as CDI/4BR) make little difference to the emission spectra. However, as the electron density is increased to $10^{23}/cm^3$, the spectra including the CDI/4BR are quite different from that without CDI/4BR. The spectra at a density of $10^{23}/cm^3$ show peaks corresponding to ions containing more electrons (even up to C-like and N-like Ar), indicating that the CDI/4BR allows the ions to recombine more quickly in this region. This effect is also seen in the average ionization stage, which is almost two units lower when CDI/4BR is included at a density of $10^{23}/cm^3$. Similar effects are also observed when lower fractions of hot electrons are included.

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[2] B. Streufert and J. Colgan, *Los Alamos Summer School Research Reports* **8** 129, Los Alamos National Laboratory report LA-UR-06-5939 (2006).
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[4] N.H. Magee, et al., "Atomic Processes in Plasmas," in *14th APS Topical Conference Proceedings*, (J.S. Cohen, S. Mazevet, and D.P. Kilcrease, Eds.), Santa Fe, NM, pp. 168–180 (2004).

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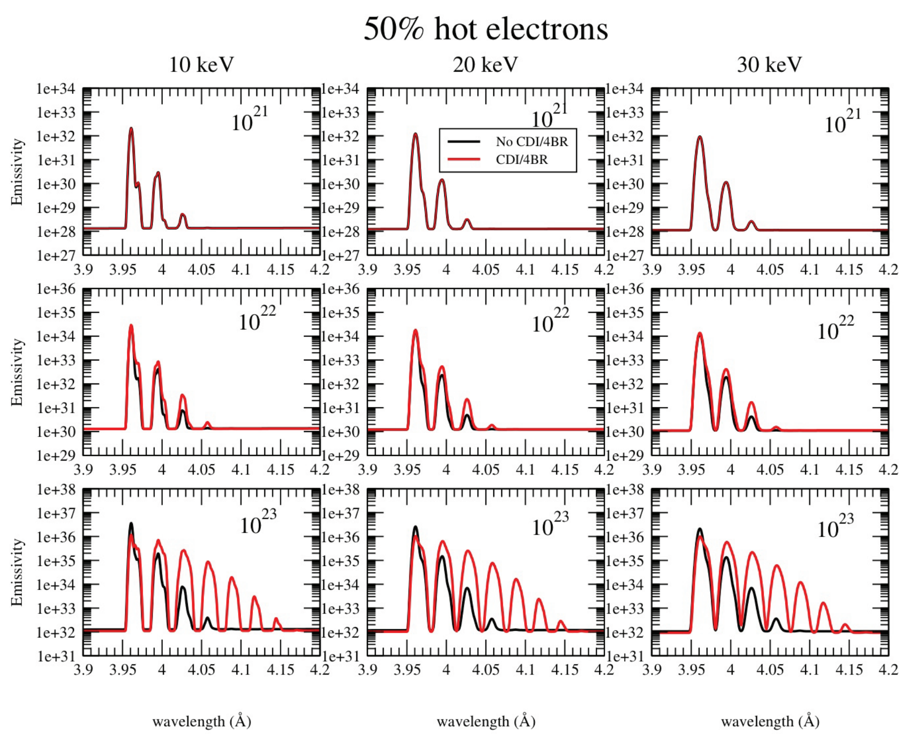

Fig. 1.
Emission spectra of Ar at various electron densities.