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X-ray emissivities from well characterized underdense, laser-heated gas targets

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Maximizing the conversion efficiency (CE) of laser energy into multi-keV x-rays is a general concern to many areas of high-energy-density plasma physics. Bright x-ray sources are needed for backlighters in order to radiograph targets in inertial-confinement fusion (ICF) experiments. As the targets get larger, and as compression in the targets increases, the backlighter sources need to be brighter and the backlighter-photon energies must increase. To this end, for a given laser power, backlighters can become brighter by becoming more efficient at converting the drive beams to multi-keV x-rays. Volumetric heating of low-density gas targets has been shown to be a very efficient method of producing x-rays [1]. Recently, laser heating of an underdense aerogel target [2] has demonstrated efficient x-ray production. Ongoing experiments are optimizing these designs [3]; this paper reports on detailed calculations of the x-ray yield from L-shell Kr in laser-heated targets.

Many methods exist to compute the radiative cooling from highly charged ions in a plasma. Models that include a high level of detailed atomic structure and models that simplify the plasma description to a single 'average' ion can give widely different predictions for the x-ray output from a high-temperature plasma [4]. Predictions from such models need to be benchmarked against data obtained from plasmas where temperature and density conditions are known unambiguously. In these experiments, the ideal plasma would be stationary and homogeneous (i.e. gradient free). It would also need to be diagnosed with absolutely calibrated spectral detectors. To this end, Kr plasmas from laser-irradiated gasbags have been observed at the OMEGA laser (Laboratory for Laser Energetics, University of Rochester) with space- and time-integrating, absolutely calibrated crystal spectrometers. The plasma density is known from the initial-fill pressure of the bag, and the plasma temperature is monitored in a temporal window by Thomson scattering (TS). Up to 19 kJ of 3ω (351 nm) laser light were shot with a 1 ns square pulse into bags with 0.5 – 1.5 atm of Kr. The gradients in temperature are known by moving the TS volume from the centre to the skin of the bag. These experiments have produced record conversion efficiency of the laser light into Kr L-shell x-rays [3].

We have computed the steady-state collisional-radiative (CR) emissivity of x-ray transitions from all L- and K-shell Kr ions. Our models include the fine-structure levels from all singly excited configurations with $n \leq 5$ ($l \leq 4$) formed by promotion of an n=2 or an n=1 electron and some doubly excited configurations formed by permuting the n=2 spectator electrons. For some iso-electronic sequences (Mg- to F-like, B- to H-like), levels from configurations with $n \leq 6$ are considered. This results in models with up to > 1600 levels per ion. This significant level of description accounts for only a tiny fraction of the possible dielectronic recombination channels that determine the charge state distribution (CSD) in the Kr plasma. The method used to compute the CSD of the moderate-density plasmas in the present work is described in Ref. [5]. There, attention was paid to the collision limit above which levels with principal quantum number $\geq n$ can be neglected. The results in Ref. [5] were shown to converge to the earlier coronal result obtained for Kr by Fournier *et al.* [6]. The charge state distributions found for a range of temp-eratures of interest to the present OMEGA experiments are shown in Fig. 1.

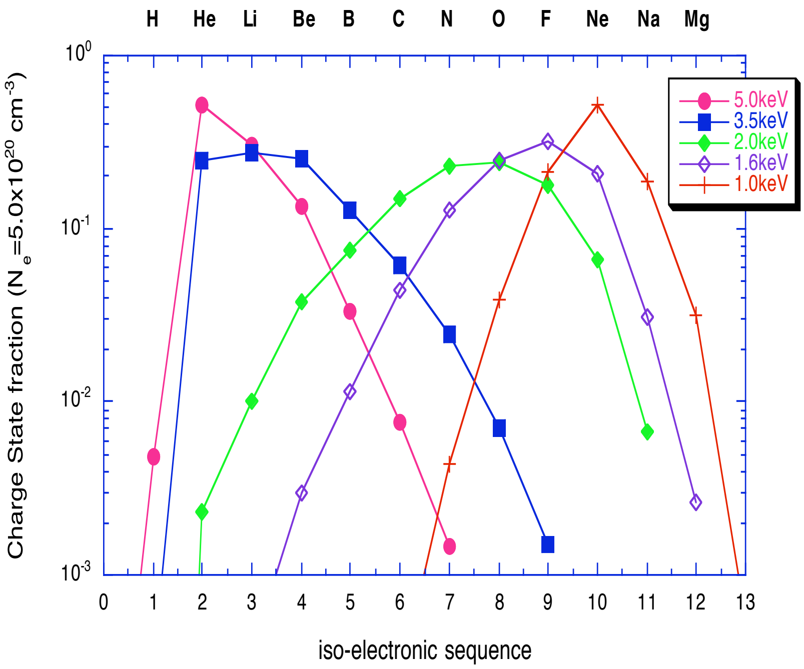

Figure 1 The calculated CSD for Kr at 1.0, 1.6, 2.0 3.5 and 5.0 keV, computed for N_e = $4.5\text{x}10^{20}$ cm^{-3}. The calculations were done as described in Ref. [5].

We have computed the steady state CR level populations for all the above-mentioned Kr ions. The atomic structure and rate coefficient data were generated with the relativistic, multi-configuration HULLAC suite of codes [7]. The present models include more than 8000 levels for the sets of ions shown in Fig. 1. Our CR spectrum is compared with data from OMEGA shot 29674 in Fig. 2. We note that the TS data from two series of shots indicate the temperature at the centre of the gas bag is 3.5 – 4.0 keV while the laser beams are on, and drops to ≤ 1.6 keV near the edge of the bag. Our spectral data are space and time integrated; the observed temperature gradient is reflected in the simulation in Fig. 2 by superposition of spectra from several individual-temperature spectra. The data show emission from all L-shell ions Kr^{26+} to Kr^{33+}. The data also show a strong recombination phase in the anomalous strength of the 3G and 3F Ne-like lines. This recombination phase is not accounted for in our steady-state calculations.

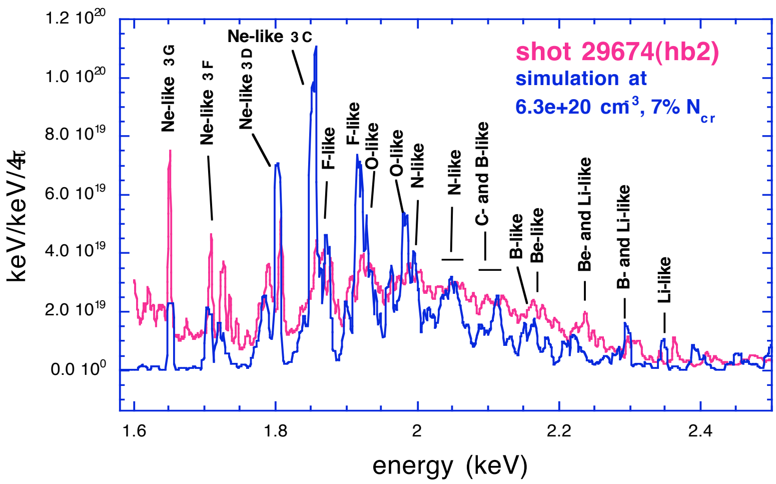

Figure 2 L-shell Kr spectrum for OMEGA shot 29674 as measured with the HENWAY spectrometer, and a simulated spectrum for a range of temperatures from 1.0 to 4.0 keV using HULLAC atomic data. Features from all L-shell ions (Kr^{26+} to Kr^{33+}) are visible.

The line emissivities in Fig. 2 can be summed to yield the total soft-x-ray output for L-shell Kr ions at a given temperature. We have computed the emission in all spectral bands from M-, L- and K-shell Kr ions, including DR-fed line emission, and free-bound and

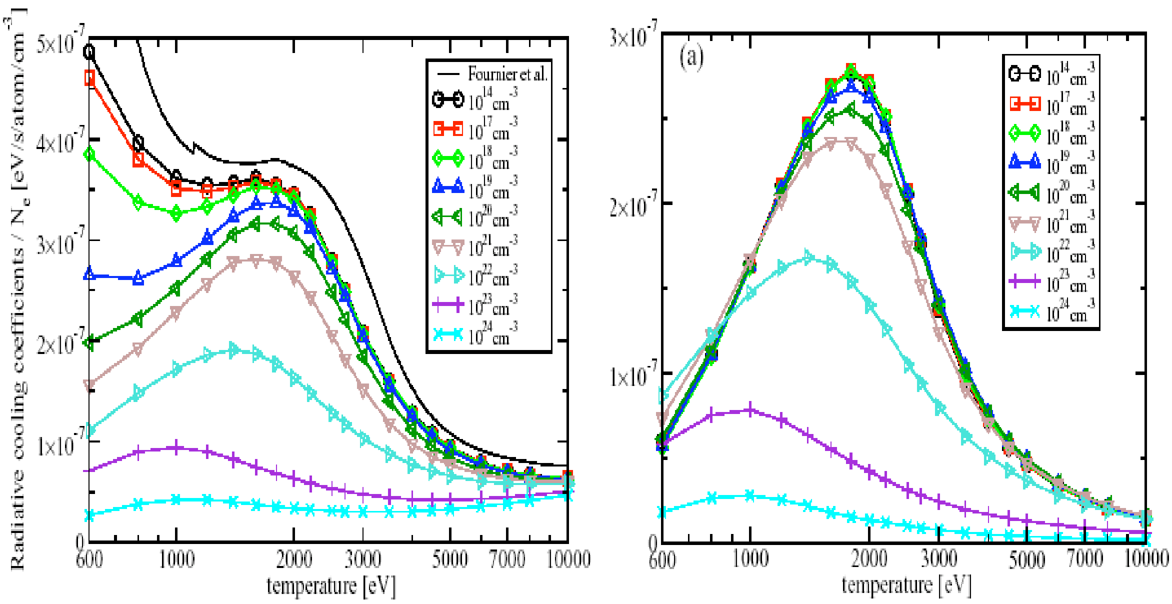

Figure 3 Total (right) and soft x-ray line-emission (left) cooling curves as computed in Refs. [5,6] with HULLAC atomic data.

free-free continuum emission [5,6]. The results for the total radiative loss rate per atom, and the CR line emission in the soft-x-ray band (1 – 12 keV) are shown in Fig. 3. The curves in

Fig. 3 have been normalized by the electron density; one sees that above a threshold density, the CR result is suppressed compared to the coronal result of interest to tokamak impurity radiation studies [4, 6]. These density-dependent emissivities have been tabulated for easy use in large-scale radiation-hydrodynamic simulations.

Figure 4 shows the integral of the energy in the observed spectrum in Fig. 2 as a function of photon energy. Shot 29674 was filled with 0.9 atm Kr, which results in an electron density of 6.3×10^{20} cm^{-3} (7% critical for 3ω light). The result from our spectrometer is that 3.07 kJ of soft x-rays are output into 4π. This is 16.2% of the incident laser energy. The integral of the simulation in Fig. 2 is also shown in Fig. 4 (increased by 28% to account for the continua and additional cooling channels included in the *total* cooling curves in Fig. 3). The agreement is excellent. The assumed gradient used in making the simulation for shot 29674 is admittedly crude, and the temporal window (2.2 ns) over which it is assumed the x-rays are integrated is found with an uncalibrated spectrometer coupled to a streak camera. Work is underway to improve this analysis. These experiments saw a record 40% conversion of the laser energy to x-rays for targets with 1.5 atm fill pressures (20% critical density). This work was preformed under the auspices of the U.S. Department of Energy by the University of California Lawrence Livermore National Laboratory under contract No. W-7405-ENG-48.

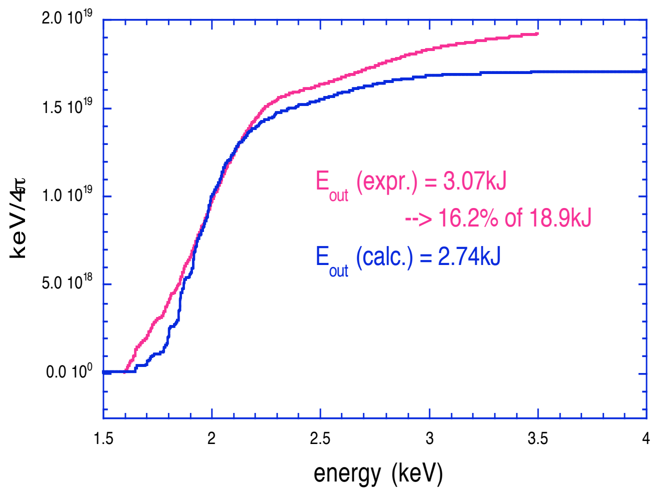

Figure 4 Integrated energy from the two spectra shown in Fig. 2.

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