Identification of Auger electron heating via XUV emission of hollow ions induced by irradiating solids with FLASH at intensities up to $10^{16}$ W/cm$^2$


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Abstract: The transition from solid-to-plasma has been studied by irradiating Al foils with the FLASH XUV free electron laser at intensities up to $10^{16}$ W/cm$^2$. Intense XUV self-emission has been observed showing spectral features of hollow ions that go beyond single inner-shell photo-ionization of solid. Simulations of the XUV spectral distribution indicate that efficient heating of electrons in the conduction band has taken place after photoionisation. A simple model of electron heating that occurs immediately after the decay of the crystalline order, induced by ionization of core electrons, followed by Auger electron heating is proposed.

The rapid heating of solids is of intense interest to many researchers in the fields of plasma physics, warm dense matter, fusion sciences, planetary and astrophysical sciences [1, 2]. Theoretically, matter in this state is difficult to address, with electrostatic and thermal energies being of equivalent importance, so perturbative approaches of either solid-state or classical-plasma physics are inapplicable. Further, in this regime it is difficult to obtain quantitative experimental data. A promising way forward is the use of the new generation of short-wavelength XUV and X-ray Free Electron Lasers (XUV-FEL and X-ray) to irradiate solid samples.

The experiment was performed at the FLASH XUV-Free Electron Laser Facility at DESY in Germany. Solid Al-foils were irradiated with intense pulses of 13.5 nm radiation 92 eV operating at 5 Hz. The pulses were of 15 fs duration and focussed to 1 µm with a multilayer optic with a focal length of 269 mm. The micro-focussing has led to intensities larger than $10^{16}$ W/cm$^2$ creating experimental conditions that are distinctly different from those created at synchrotrons, where photoionization of core electrons and associated X-ray transitions have been studied. The spectrometer employed a Hitachi 1200 lines/mm variable line spacing grating which creates a flat spectral focal plane on a CCD camera providing a spectral coverage from 10 to 30 nm. The harmonic efficiency of the grating in $2^{nd}$ and $3^{rd}$ order is 9.5 (2.7) % and 1.9 (1.8) % of 1$^{st}$ order at wavelengths between 11.8 nm and 18.2 nm, respectively. An Al edge filter was used to establish that the spectral resolution achieved was 0.1 nm. The samples were composed of 10 µm thick Al foils that were continuously moved transverse to the FEL beam to expose a fresh surface to each FEL pulse at 5 Hz repetition rate.
Figure 1 shows the emission spectra (solid black line) taken at best focus, Z=0 integrated over 2000 shots. The dominant spectral features are identified as Al IV emission. The hatched areas indicate the discrepancy between the data and the simulation including only the configuration K^2L^4M^1. The lower curves in Fig. 1 show the fit of the spectral distribution including also multiple excited L-shell states K^2L^8M^3. We note that emission from the states for x=2, 3 are not sensitive to radiative recombination [3]. Moreover, their time scale is determined by autoionization rather than radiative decay [4]. Therefore the emission corresponds to the high density phase after laser irradiation and we therefore employ the x=2, 3 configuration for the determination of the temperature.

The best fit (lower curves in Fig. 1) is obtained for an electron temperature of about 25 eV indicating strong heating of electrons in the conduction M-band. A temperature larger than 20 eV, however, will lead to rapid destruction of the solid on a ps-time scale. The density falls below solid 2.7 g/cc, distinct atomic states appear at densities lower than about 2 g/cc and the ionization of M-shell electrons leads to different ionization stages. Also the inverse channel of autoionization, namely dielectronic capture comes into play that should leave its signatures in the spectra as dielectronic satellite emission. This temperature is considerably larger than those driven by photoionized electrons (about 8 eV). The temperature of about 8 eV represents an excited transient state of a solid that will relax after 40 fs either by radiative decay (fluorescence) or by autoionization.

As the branching ratio favours autoionization by 99.8 % the energy of the decaying electron (Auger electron) is shared with the three remaining conduction band electrons. Simulations show that the energy difference of 70 eV, e.g., between the configuration K^2L^8M^3 and K^2L^4M^4, is equivalent to the kinetic energy of the Auger electrons [5]. Assuming that all the Al atoms in the intense laser beam are photoionized [6] this excess energy of 70 eV will rapidly thermalize with the remaining 8 eV electrons in the conduction band resulting in a temperature of about 25 eV. The transient evolution is characterized as follows: first, 2p-hole states are produced by photoionization of the cold solid, then they are refilled due to the Auger effect on a time scale of about 40 fs. The Auger electrons then lead to a rapid heating of the electrons in the conduction band and a subsequent destruction of the solid on a ps time scale then takes place. Second the heating driven by Auger electrons allows the inverse Auger channel (dielectronic capture) to efficiently create holes in the 2s- and 2p- shells with corresponding transitions.

In conclusion we have characterized independent of plasma simulations via spectroscopic analysis, important steps in the sub-ps evolution of matter when high intensity short pulse XUV Free Electron Laser radiation interacts with solid matter. Photoionisation and thermalization between the electrons in the conduction band transforms the system from the cold solid to warm dense matter. The relaxation of almost all photoionized hole states via Auger effect leads to important heating of the conduction band electrons. Subsequently there is decay of crystalline order and the transition from warm dense matter to a dense plasma-like state occurs with corresponding marks in the spectral emission.

References