Abstract. Heating of thin foil targets by a high power laser at intensities of $10^{17} - 10^{19}$ W/cm² has been studied as a method for producing high temperature, high density samples to investigate X-ray opacity and equation of state. The targets were plastic (parylene N) foils with a buried microdot of a sample material, which was either aluminium, germanium or a mixture of germanium and titanium. L-shell and K-shell spectra were taken using crystal spectrometers recording onto film and an ultrafast X-ray streak camera coupled to a conical focusing crystal with a time resolution of 1 ps. The conditions in the microdot were inferred by comparing the measured spectra to synthetic spectra produced by the time-dependent collisional-radiative (CR) models FLY and FLYCHK. The data were also compared to simulated spectra from a number of opacity codes assuming local thermodynamic equilibrium (LTE). Temperature and density gradients were taken into account in the comparisons. The sample conditions, inferred from the CR modelling using FLYCHK, were 800±100 eV and 1.5±0.5 g/cc, in the germanium/titanium samples and 600±50/-150 eV, 3-4 g/cc in the pure germanium or aluminium samples. The higher densities were achieved by using a combination of long and short pulses to compress and heat the foils respectively. The experimental results and comparisons to predicted spectra are presented and discussed.
were microdot samples, 50μm in diameter 0.1μm thick and composed of 50% germanium and 50% titanium mixtures by particle number. The overcoat of parylene-N plastic between the laser and the buried dot was 1±0.5μm. The laser pulse was Gaussian, both spatially and temporally (0.5ps FWHM), at a wavelength of 0.53μm (2\textsuperscript{nd} harmonic) delivering typically 20J of energy to target, producing intensities of \(\sim10^{18}\) W/cm\(^2\). In order to mitigate prepulse conversion to second harmonic was employed. That is, since the conversion process is strongly intensity dependent, the lower intensity prepulse was not converted with high efficiency and the unconverted light was rejected at four 2\(\omega\) mirrors. In the second type of experiment a long pulse beam (represented in figure 1 by the dotted lines) was incident on one side of the target producing a shock compression of the buried layer. The compressed target was then irradiated with the short pulse beam thereby heating the compressed buried layer to high temperature. In this case experiments were done with the buried layer material made of either aluminium or germanium. The long pulse shape had a 100ps rise, a flat-top 700ps long and a fall of 200ps. The long pulse beam energy was typically 300J.

The results from experiments where the target was irradiated with the short pulse beam only show germanium emission spectra in the 1.3-2.5keV spectral range covering 2p-3d and 2p-4d transitions in charge states up to 29\(^+\). In the mixed germanium and titanium sample the plasma conditions were inferred from the titanium spectra by comparing the measurements of line ratios and widths to titanium spectra predicted by the time-dependent collisional-radiative model (CR) FLY [5] and from the germanium data by comparison to simulation predictions using the code FLYCHK [6]. In addition, to check the departure of the germanium sample from LTE the measured spectrum was compared to several LTE opacity codes with varying levels of spectral detail. In all cases experimental data were recorded using both time-integrated and time-resolved spectrometers. The time-resolved spectra show the pulse duration and emission history, whereas the time-integrated spectrometer allows absolutely calibrated data to be recorded for direct emissivity comparisons with collisional-radiative (CR) and LTE code predictions. The source size was measured with an X-ray pinhole camera with a ten micron diameter pinhole and a magnification of 30, recording onto X-ray film (Kodak Industrex C-type). The pulse duration was measured using an ultra fast X-ray streak camera –see Fig. 1 for the experimental schematic. The two time-integrated spectra were simultaneously recorded on calibrated X-ray film (Kodak Industrex CX-type) using a spectrometer that had two convex curved crystals each 200mm radius of curvature placed side by side. The crystals were PET, to cover the frequency range of the titanium K-shell (4.5-6.5keV) and CsAP to cover the germanium L-shell and aluminium K- shell (1.3-2.5keV) spectrum. Data from the time-integrating spectrometer is shown in Fig. 2a. Using curved crystals gives a greater frequency range than flat crystals and reduces source broadening. The streaked data were taken using a focussing conical CsAP
crystal coupled to an ultra-fast streak camera, with a Photonis P860X tube, at a streak rate of 3ps/mm and temporal resolution of 1ps. The camera used a solid potassium iodide photocathode (0.1µm KI/0.02µm Al/ 1µm plastic). The crystal spectrometer geometry, and camera slit length limited the spectral range of the streaked germanium measurement to 1.55-1.78keV. An example of the streaked data is shown in Fig. 2b. The duration of the observed spectrum is limited by the dynamic range of the streak camera.

Both the germanium and titanium spectra from mixed titanium-germanium samples were used to infer the temperature and density. The titanium spectra were compared to synthetic spectra generated by the time-dependent collisional-radiative (CR) model FLY. FLY is a low atomic number (Z ≤26) K-shell spectral model and limited to H-like, He-like and Li-like ions. A recently developed generalised time-dependent CR model, FLYCHK, can model L-shell spectra and was used to analyse the germanium L-shell measurements. The germanium comparisons should ideally take the time-dependence of the plasma conditions into account but the first attempts at modelling shown here assume that the plasma is in a steady state. A measured germanium spectrum is shown in Fig. 3 plotted as emissivity, in J/kev/cm²/sr/s, versus X-ray energy in keV. The spectral unfold takes into account the source area (measured with the X-ray pinhole camera), X-ray pulse length (measured on the streak camera), crystal reflectivity, film response (calibrated off-line with the AWE Excalibur X-ray source [7]) and spectrometer geometry. The germanium L-shell spectrum is predominantly emission from 2p-3d transitions for ions up to 29⁺ (Li-like Ge). The streaked germanium spectra show a temporal variation in the emission. This late time emission which arises from the Ge/Ti mixture sample when it has decompressed was subtracted from the time-integrated data to minimize the effect on the spectrum due to under dense conditions.

A simulated spectrum calculated using FLYCHK for plasma conditions of 1g/cc, 800eV ±100eV is shown in Fig. 4. Four calculations at a density 1g/cc and electron temperatures of 700, 750, 800, 850 and 900eV were averaged to attempt to take into account the effect of spatial gradients. The FLYCHK data has been convolved with a Gaussian of FWHM 3eV to model detector resolution. The simulated spectra are in reasonable agreement with experimental data both in the spectral distribution and the absolute emissivity values. The LTE opacity code predictions using GRASP [8], CASSANDRA [9] and DAVROS [10], which incorporate different levels of detail, were also used to calculate synthetic Germanium L-shell spectra. Best fit was obtained in LTE at an electron temperature of 660 ± 60eV and density 1.5±0.5g/cc. CASSANDRA and DAVROS both use a DCA type (detailed configuration accounting) method; in the GRASP model detailed term calculations were performed to produce
energy levels and oscillator strengths which were then used to construct a spectrum using Saha-Boltzmann statistics.

Figure 3: Measured germanium spectra from the time-integrating spectrometer converted to intensity units at the source, and corrected for the late time emission.

These LTE spectra were also convolved with the instrument resolution. The results indicate that taking gradients into account yields reasonable agreement both with the absolute emissivity and the spectral features. The gradients of about $\pm 10\%$ in temperature and $30\%$ in density are similar to those used in the fit with the CR model.

Figure 4: Simulated spectrum from the collisional-radiative equilibrium model FLYCHK. The spectrum was obtained by averaging the contributions from plasma at $1g/cc$ and 700, 750, 800, 850 and 900eV with equal weighting.

The titanium spectrum was also compared to model prediction to infer the sample temperature and density. Titanium was chosen due to the relative simplicity of the K-shell spectrum compared to the L-shell spectrum for germanium, the large difference in the spectral ranges of the two materials, i.e., that one spectrum would not obscure the other, and the technical ease of mixing the two materials. Comparisons of the titanium results with the synthetic spectra from FLY allowed a density of $1.5\pm0.5g/cc$ to be inferred from the width of the spectral lines and a temperature of $1\pm0.1$ keV based on the line-intensity ratios. This is more than 100eV higher than the temperature inferred from FLYCHK comparisons to the germanium data. However, analysis of the spectra using FLYCHK
showed that the Ti Ly$\alpha$/He$\beta$ ratio used to obtain the temperature was susceptible to perturbation by background hot electrons. The germanium (and aluminium) spectra are predicted to be unaffected by the hot electron background suggesting the Ti spectra has some inaccuracies as a temperature diagnostic in this case, where the hydrogen-like population is comparatively low. The comparison of CR and LTE model calculations shows a significant departure of the germanium from LTE; with the non-LTE model giving best agreement at a temperature some 20% higher than the LTE calculations. In terms of the sample ionisation at 800eV calculations indicate a difference between non-LTE and LTE models of 0.8 of an ion stage. To obtain data at conditions closer to LTE several changes to the experiment were made. In a second set of experiments the target was compressed by a long pulse beam before being heated by the short pulse beam (see figure 1). To achieve LTE conditions the rates of collisional processes in the plasma must overwhelmingly dominate radiative processes. The sensitivity of the collisional rates and radiative rates to plasma conditions and transition energy can be shown by taking the ratio of collisional excitation to spontaneous radiative emission as in Eq. 1 [11].

$$\frac{n_eC_{ij}}{A_{ji}} = \frac{n_e}{1.3 \times 10^{13} \Delta E_{ij} 3 \sqrt{T_e}}$$  \hspace{1cm} (1)

Where $n_eC_{ij}$ is the collisional excitation rate coefficient; $A_{ji}$ is the spontaneous radiative decay coefficient; $n_e$ electron density (/cc); $\Delta E_{ij}$ is the transition energy (keV) and $T_e$ is the electron temperature (keV).

In the second type of experiment the sample density was increased by shock compression as described above and the position of the buried layer was moved so that there was a plastic coating of 4µm between the buried layer and the side of the foil irradiated with the short pulse beam. The change in position lowered the temperature of the buried layer. From Eq. 1 it can be seen that increasing the density and reducing the electron temperature should produce sample conditions closer to LTE. Initially, measurements were made using aluminium as the buried layer in these experiments. The aluminium measurements confirmed that the sample was at higher density when using a combination of long and short pulses than with the short pulse alone. From comparisons of the streaked experimental spectra to predicted spectra from FLY, a peak temperature of 650 ±50eV and density 3g/cc were inferred. Radiation-hydrodynamics simulations using the NYM [12] code were used to predict the conditions in a germanium layer, buried at the same place in the foil, when subjected to shock compression and heating by the short pulse. The effect of the short pulse heating was simulated by energy deposition over the 0.5ps timescale of the laser pulse to reproduce the temperature and density history observed in the time resolved data from the streak camera. The energy deposition as a function of depth was determined in extensive measurements of peak temperature as a function of depth for a wide variety of laser parameters [13]. The resulting time history and detection threshold of the time integrating spectrometers was then used to establish the conditions in the time integrated data. The conditions predicted for the radiation-hydrodynamics simulations were a gradient in temperature of 450-650eV at 4g/cc density. Figure 5 shows the FLCHK predicted mean ionization for LTE and NLTE simulations for a 4g/cc germanium sample over a range of temperatures from 400-800eV. The sample is predicted to depart from LTE by between 0.15 and 0.35 ion stages over the 450-650eV range of temperatures. Figure 5 shows a measured emission spectrum from a shock-compressed, short-pulse heated germanium buried layer compared to predictions from FLYCHK for both LTE and NLTE taking into account gradients in the sample as predicted by the radiation-hydrodynamics simulations. Figure 6 shows the effect of the departure from LTE on the predicted spectrum of germanium. However, this difference is now similar to the uncertainty in the sample conditions.
In summary, experiments using buried layer targets have shown that sample plasmas at high temperatures and high densities can be produced to study opacity and high temperature equation of state. Germanium emission data have been obtained at high density 1.5±0.5 g/cc and high temperature 825±75 eV with the conditions inferred from comparisons of the data to the CR model FLYCHK. Reasonable agreement with the spectral shape and absolute emissivity was obtained when spatial gradients in the sample are incorporated into the analysis. Comparison of the data to the predictions of several LTE models also shows good agreement but at a temperature 20% lower (660±60) than the CR modelling, using similar gradients. To obtain data at conditions closer to LTE a combination of long and short pulse laser beams was used to shock compress and heat buried layer samples. Data from aluminium samples was obtained at 650±50eV and 3g/cc and from germanium at 550±100eV, 3.5±0.5g/cc. The higher density germanium data was within 0.4 of an ionization stage of the LTE value. Reasonable agreement was obtained with the absolute emissivity but the gradients in the sample conditions are large. Future work will extend the technique to higher densities using multiple beams to produce coalescing shocks at the buried layer and will aim to reduce gradients.

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