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Spatially-resolved X-ray scattering measurements of a planar blast wave

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ABSTRACT

We present X-ray scattering measurements characterizing the spatial temperature and ionization profile of a blast wave driven in a near-solid density foam. Several-keV X-rays scattered from a laser-driven blast wave in a carbon foam. We resolved the scattering in high resolution in space and wavelength to extract the plasma conditions along the propagation direction of the blast wave. We infer temperatures of 20–40 eV and ionizations of 2–4 in the shock and rarefaction regions of the blast wave. This range of measured ionization states allows for a detailed comparison between different models for the bound–free scattering. FLYCHK simulations of the temperature-ionization balance generally agree with the experimental values in the shocked region while consistently underestimating the ionization in the rarefaction.

1. Introduction

Warm dense matter (WDM) is a state of matter that is thought to be common to massive bodies in the solar system and beyond. It spans a physical range of conditions intermediate to solid-density condensed matter and high temperature, low density classical plasmas. At pressures above 1 Mbar and temperatures on the order of 10 eV, the atoms may experience significant collisional or pressure ionization leading to a partially degenerate electron population and strongly coupled ions. A rigorous understanding of the equation of state of these materials is essential to the validity of models for planetary interiors [1], which sheds light on the origin of planetary magnetic fields [2] and the formation and distribution of extrasolar planets [3].

Spectrally resolved X-ray scattering is a non-invasive diagnostic technique that may be used to measure the material conditions of WDM created in laboratory astrophysics experiments [4]. In many cases these experiments involve depositing large amounts of energy onto a sample of matter, driving a shock or related phenomenon which creates large 1D gradients in the plasma conditions. Previous X-ray scattering experiments have used spatially integrating crystal spectrometers, which has limited these efforts to characterizing approximately homogeneous plasmas [6,7,9,10]. Here we report the analysis of X-ray-scattering data obtained using a high-resolution imaging spectrometer. This allowed us to test competing models for the scattered spectrum and to compare measurements of the temperature and ionization of warm dense carbon with density-constrained simulations.

We developed the Imaging X-ray Thomson Spectrometer (IXTS) [11] for the Omega laser [12] at the Laboratory for Laser Energetics, University of Rochester to extend the utility of X-ray scattering to diagnosing spatially nonuniform plasmas. For this experiment, a relevant scale length is the width of the heated and compressed material swept up by the blast wave. This region is approximately 100 μm wide for nanosecond-long laser irradiation at intensities of order 10^{14} W/cm^2 [5]. The IXTS uses a toroidally curved germanium crystal to simultaneously spectrally disperse and image X-rays along one dimension with a spatial resolution of <50 μm [13]. Using an imaging approach, it is possible to measure a range of plasma conditions along the gradient in the plasma heating for direct comparison to equation of state codes.

In the present experiment, intense laser irradiation drove a blast wave in a carbon foam. This created WDM conditions behind the shock front with large spatial heating gradients throughout the blast wave. A collimated X-ray beam scattered from the foam at 90° and was spectrally and spatially resolved. We analyzed this scattering data to extract the temperature and ionization state of the foam at multiple positions along the axis of the flow. The inferred plasma conditions straddle a largely unmeasured regime for carbon where there is a significant contribution to the scattering from

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weakly bound electrons. High quality scattering data allowed us to evaluate models for the computation of the scattering profile from weakly bound electrons, validating an approach based on the impulse approximation. Comparing the measurements of the ionization balance to the predictions of the FLYCHK code [14], we find good agreement except in the high-temperature, low-density rarefaction region of the blast wave.

2. X-ray scattering

Following the method of Chihara [15,16], the scattered spectrum is modeled using the dynamic structure factor

$$S(k,\omega) = |f_I(k)+q(k)|^2 S_{ii}(k,\omega) + Z_f S^0_{ee}(k,\omega) + Z_c \int \tilde{S}_{ce}(k,\omega-\omega')S_s(k,\omega')\mathrm{d}\omega'. \quad (1)$$

The three additive terms on the right hand side denote elastic scattering from electrons bound to ions, inelastic scattering from kinematically free electrons, and inelastic scattering from bound electrons. The inelastic bound electron term includes excitations of core electrons [17] and Compton scattering from weakly bound electrons that are lifted into the continuum. This latter process is only possible when the Compton shift is greater than the electron binding energy. The correlation functions are weighted by terms proportional to the charge in each state. For large values of the scattering wavenumber k, $|f_I(k)+q(k)|$ is approximately equal to the number of inner shell electrons that coherently scatter X-rays, Z_c is the total number of bound electrons, and Z_f is the number of free electrons.

For large scattering angles and small wavelengths, the X-rays scatter non-collectively from the motion of the individual electrons. The free-electron Compton peak is broadened by the momentum distribution of the electrons. This includes Doppler broadening from thermal motion and electron degeneracy effects. Through the width of the inelastic peak, the scattering spectrum is sensitive to the electron temperature and density and, through the ratio of the intensity of the elastic to inelastic scattering, the ionization state.

In contrast to previous studies which have mainly focused on carbon ionized to $Z_f \sim 4$ [18], the presently considered region spanning $0 > Z_f > 4$ has a significant bound–free contribution. At 90° scattering, the experimental Compton shift of 117 eV is greater than the binding energy of the four electrons in the L-shell. Consequently, all four L-shell electrons may participate in bound-free scattering. The total intensity in the inelastic peak from free and weakly bound Compton scattering is roughly constant until the K-shell electrons start to be ionized. The Compton peak from weakly bound electrons is broadened by the initial momentum distribution of the bound states. This broadening reveals no information about the state of the plasma and so acts as a background to the signal from the free electrons. Noncollective X-ray scattering measurements of plasmas are feasible only when the free electron scattering is significantly stronger than weakly bound scattering. For carbon, this condition is $Z_f > 2$ [19], a constraint that limits the applicability of X-ray scattering in this experiment to regions downstream of the shock.

In many non-collective X-ray scattering experiments the bound–free contribution is negligible because the accessible valence electrons are stripped from the ions. This is either because the final density is high enough to lower the continuum past the valence electrons [25,26], the experiment starts with a low density material that is strongly heated and ionized [18,27], or a metal is investigated in which the valence electrons are initially delocalized [10,28].

The XRS code [20,21], which has been used to interpret much of the data from high energy density scattering experiments, has two approaches to model the bound–free scattering. The first is based on the impulse approximation (IA) [22,23]. The IA assumes that the Compton shift is large compared to the electron binding energy so that the transition to the continuum is instantaneous. The bound electrons are approximated as free with a momentum distribution equal to that of the bound states. The form factor approximation (FFA) uses the Born approximation with hydrogenic wave functions to include the effects of the electron binding energies [24]. The latter method has been used to analyze nearly all of the published experimental data. Gregori et al. have indicated that the IA approach is superior to the FFA in the presence of significant bound–free scattering [7]. We present evidence confirming the validity of the IA for scattering from carbon in ionization states from approximately neutral to fully stripped of the valence electrons.

3. Experiment

We performed an X-ray scattering experiment on the Omega laser to measure spatially-resolved X-ray scattering in a simple geometry. A diagram of the experiment is given in Fig. 1(a). A set of ten Omega beams delivered 4.5 kJ ± 1% of 0.351 μm laser light in a 1 ns full-width-at-half-maximum (FWHM), nominally flat-topped pulse with a rise and fall time of 100 ps. The laser beams were smoothed with distributed phase plates (SG-8) to a spot size of 860 μm FWHM resulting in an irradiance of 7×10^{14} W/cm^2 ± 10%. The beams were incident onto a 1 mm thick block of carbonized resorcinol formaldehyde (CRF) foam at a density of 340 mg/cc. The ablation of material from the laser irradiated surface of the foam drove a strong shock which transitioned to a blast wave after the end of the laser pulse.

After a delay of 8.2 ns, a second set of twelve beams heated a thin (5 μm) nickel foil with 5.4 kJ of energy in a 1 ns pulse to create a

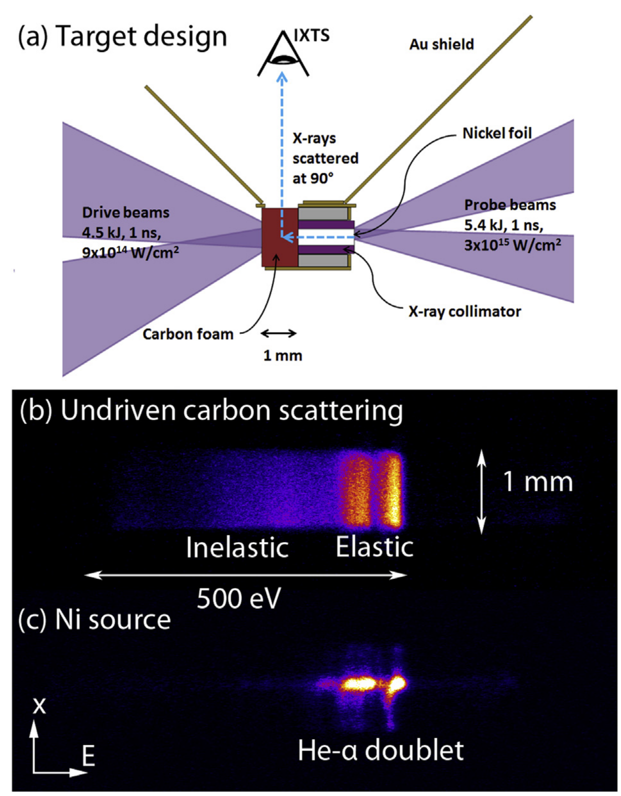

Fig. 1. (a) A diagram of the target used for the X-ray scattering experiments. (b) A sample scattered image from a shot in which the blast wave was not driven. The vertical axis is the spatial dimension and the horizontal is spectral. The spectrum from the nickel source is given in (c).