Opacity Measurements in a Hot Dense Medium

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The first measurements of the opacity in a well characterized, hot, dense, laser-produced plasma are reported. Measurements of the absorption of x rays by 1 to 2 transitions in Al XII through Al VIII have been made in a laser heated slab plasma at the measured temperature and density of 58 ± 4 eV and 0.020 ± 0.007 g/cm^3. The conditions in the plasma were determined to be reproducible, spatially uniform, and in nearly complete local thermodynamic equilibrium. The absorption spectra and the temperature-density data obtained provide an improved means for comparison with detailed atomic physics and opacity calculations.

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Experimental and theoretical determinations of the x-ray opacities of hot, dense materials have long been of interest. In astrophysics, for instance, the use of incorrect opacities might be partly responsible for the differences between calculations and observations of the period ratios of Cephid variables, the solar neutrino flux, and the analysis of the solar interior by helioseismology [1]. Opacities are also important for terrestrial plasmas such as in the inertially and magnetically confined fusion programs. High-quality experimental measurements [2,3] of the x-ray opacities of highly ionized materials are difficult. The opacity must be accurately measured with experimental errors clearly specified, and the plasma conditions, e.g., the temperature and density, must be precisely determined. In order to make a good measurement that could be readily compared with theory we also wanted the plasma to be uniform, reproducible, and in local thermodynamic equilibrium (LTE). In this paper we describe techniques that can reliably and reproducibly determine the x-ray-absorption opacities of hot, dense materials and also determine the plasma density and temperature. The measurements are of sufficiently high quality that the data can be compared to detailed atomic physics and opacity calculations.

The absorption experiments were performed using point projection spectroscopy [4–8] at the Lawrence Livermore National Laboratory (LLNL) NOVA ten beam laser system [9]. Figure 1 shows a schematic diagram of the experimental arrangement. X rays, produced by a short, tightly focused laser beam on the backlight target, passed through the heated sample and were spectrally dispersed by a PET crystal onto x-ray photographic film. Point projection spectrometry gives both spectral and spatial information simultaneously and provides temporal resolution equal to the duration of the backlighter pulse. The apertures and collimators shown in Fig. 1 allow quantitative analysis of the recorded spectrum. Backgrounds from film chemical fog, sample emission, and crystal x-ray fluorescence can all be separately determined from the film record.

The sample consisted of two thicknesses (500 and 1500 Å) of aluminum foil which were clad in a 2-μm plastic sandwich to tamp the foil expansion and produce a more uniform density in the sample material. The samples were heated [6] by x rays from a gold target (not shown in the figure) irradiated by eight of NOVA's ten beams. Each of these beams had a 3ω energy of 2 kJ in a 1-ns square pulse. The backlight target was a 100×25 μm samarium fiber; samarium was used because of its relatively featureless spectrum in the measured spectral range. The fiber was hit by a 500-J laser pulse that had a 200-ps full width at half maximum (FWHM) Gaussian profile and which was delayed 2 ns after the start of the heating beams. The uncorrected x-ray film image from this experiment is shown in Fig. 2.

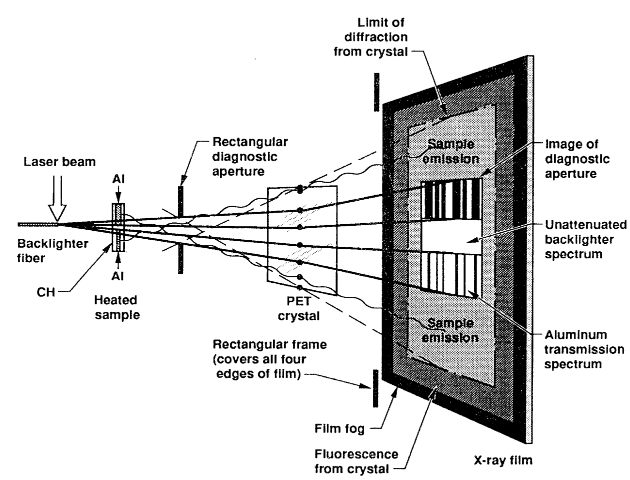

FIG. 1. Schematic experimental arrangement for the point projection absorption measurements.

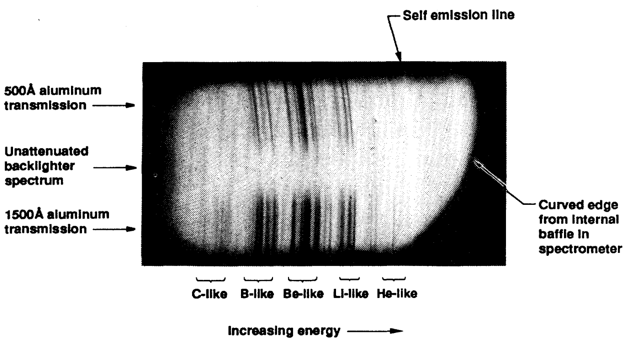

FIG. 2. Raw spectrometer data for the two-thickness aluminum shot showing the absorption spectrum for the 1500-Å (lower) and 500-Å (upper) samples with the unattenuated backlighter spectrum between.

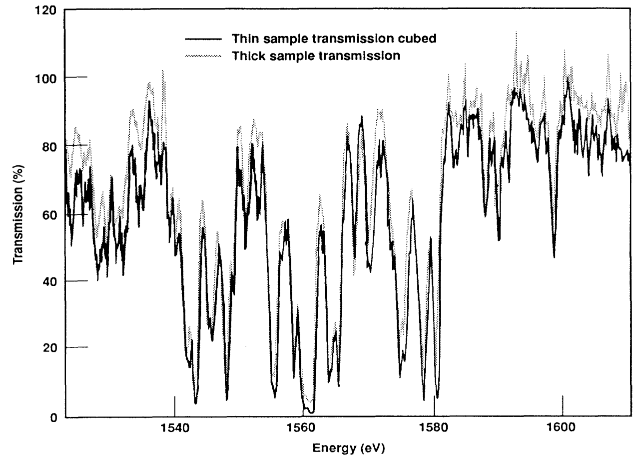

FIG. 3. Transmission comparison between the thick and thin samples. The cube of the thin-sample transmission is shown.

The film was scanned with a photodensitometer. The digitized data were numerically corrected [10] to remove curvature introduced by the spectrometer geometry and then backgrounds were subtracted. Since each type of background was recorded on all sides of the image, it was possible to do more than simply assume a constant background level. For each type of background a two-dimensional background image was formed by interpolation from the edges and this spatially varying background image was subtracted. The first background to be subtracted was film chemical fog, and then film density was converted to measured intensity, I_m, using the measured x-ray response of Kodak type-C x-ray film. Next backgrounds from the self-emission of the sample, I_s, and fluorescence from inside the spectrometer, I_f, were subtracted. As shown in Fig. 1, there was a space between the two thicknesses of aluminum that only contained the 2-μm plastic tamper. Through this gap the backlighter x rays passed unattenuated by the aluminum. Dividing the image by this wavelength-dependent, unattenuated backlighter spectrum, I_b, gave the transmission, T, of the samples,

$$T(\lambda)=e^{-\kappa(\lambda)w}=(I_m-I_s-I_f)/I_b\,,$$

where $\kappa(\lambda)$ is the wavelength-dependent absorption coefficient in cm^2/g and w is the path length in g/cm^2 through the plasma.

Internal consistency of the data reduction was provided by a comparison of the data obtained from the 500- and 1500-Å portions of the target. As can be seen from the above equation, since the thick sample was 3 times the thickness of the thin sample, the cube of the thin-sample transmission should be equal to the thick-sample transmission. This is true only if there was no instrumental broadening, the backgrounds were properly removed, the two samples were heated to the same temperature, and they had the same ionization level and density. The agreement that can be seen in Fig. 3 shows that the measured transmissions from the two thicknesses are consistent and thus indicates a successful data-reduction technique and also implies that the expanded sample density and temperature were the same for both thicknesses.

In these experiments, x-ray transmission errors are largest in spectral regions where the sample is transparent, the errors are relatively small in regions of intermediate transmission, and the errors increase again where the transmission is comparable to the backgrounds. Photon noise, uncertainties in sample thickness, subtraction of backgrounds, and the conversion of film response to x-ray intensity all contribute to errors in the absolute transmission. Convolving our estimates of these errors results in a standard deviation of $\pm 5\%$ in the transmission which is consistent with the rms difference of the two transmissions in Fig. 3.

Sample density and the heating-radiation temperature were independently measured on separate shots. Laser energies were closely monitored to insure that conditions were identical from shot to shot and reproducibility of conditions was also tested by repetition of the experiments. To determine the expanded plasma-slab thickness, and consequently its density, point projection spectrometry was used on a sample viewed from the side. The experimental arrangement shown in Fig. 1 was changed by rotating the sample 90° about a line normal to the plane of the figure. In this geometry the length of the aluminum absorption lines on the film and the known magnification of the experiment give the expanded sample thickness. On this experiment a single, initially 3000-Å-thick aluminum sample was used in order to increase the expanded plasma thickness to a dimension that could be adequately measured with the spatial resolution available with our present backlighter. We made use here of hydrodynamic calculations that showed that the plasma density and temperature (over this thickness range) were approximately independent of initial target thickness. This was also consistent with the above results which implied that the 500- and 1500-Å samples had the same density. A plot of intensity versus film position along one of the aluminum lines is shown in Fig. 4. Comparison with the lengths of other lines showed the density to be uniform to within 15%. After convoluting with the uncertainty caused by the finite size of the backlighter and the uncertainty introduced by shot-to-shot variations we found the density to be 0.020 ± 0.007 g/cm^3.

In a separate experiment the aluminum sample was replaced by an optically thick foil and measurements of the radiation temperature from the surface of this sample [11] were made using the Dante [12] ten-channel K- and L-edge filtered x-ray diode system. This measurement was repeated twice and the temperature at 2-ns delay, corresponding to when the absorption experiments were performed, was 58 ± 2 eV in both cases. Consideration of timing uncertainties, shot-to-shot variations, and the differences between this sample and our aluminum samples increase the error bars implying a temperature of 58 ± 4 eV for our aluminum samples.

Having determined the temperature and density we calculated the expected aluminum transmission. The theoretical calculation assumed LTE and followed the method of Abdallah and Clark [13] which uses atomic physics data calculated by the method of Cowan [14]. The theoretical transmission was folded with a Gaussian of FWHM =0.6 eV which was the spectrometer resolution. The x-ray transmission through our thin aluminum sample and the theoretical transmission spectrum calculated at 58 eV and 0.020 g/cm^3 are shown in Fig. 5.

To assess if our plasma was in LTE we used the formulas of Griem [15]. We found that the electron density, N_e, was sufficiently high that collisional processes are dominant in the plasma. Specifically, the ion balance of the He-like and less ionized species are given by the Saha equations. The only species that are possibly not in LTE are bare Al ions, H-like ions, and excited states of He-like and less ionized species that are missing a K-shell electron. But even in LTE, at the measured temperature and density these species would be present only in insignificant quantities in the plasma and x-ray absorption from these ions would be too small to be detected by our instruments. Thus having the abundances of these ions depressed as was implied by our calculations would not affect the measured spectrum. All excited states from ions having two K-shell electrons are in LTE, and thus the ground states and excited states that comprise virtually all the plasma are in LTE. Confirmation of these LTE calculations can also be seen by the good agreement shown in Fig. 5 which shows our measurement compared to an LTE calculation.

In future experiments we desire to use the aluminum transmission spectrum by itself as a temperature diagnostic. As in this experiment, a separate density measurement will still be required. The calculation shown in Fig. 5 represents an aluminum plasma with an average of 4.9 bound electrons. Moving along a line in temperature-density space such that the average ionization remains constant leaves the calculated spectrum virtually unchanged. In this region of temperature and density the calculations show that the ionization remains constant when the density is doubled and the temperature is increased by 5 eV. This means that the spectrum is more sensitive to temperature than to density. In our experiment we measured density to $\pm 35\%$. This corresponds to a ± 2-eV error in temperature. When using this technique as a temperature diagnostic, theoretical uncertainties [16] in calculating the ion balance as a function of temperature and density increases the error to ± 4 eV.

In conclusion, the experiment presented here marks the first time that a high-energy density laboratory plasma has been *reproducibly* created and diagnosed in detail. The temperature of the plasma has been measured to within 7% while the density of the plasma has been determined within 30%. This plasma has the unique property that the sample of interest, in this case aluminum, is contained in a region essentially *free of gradients,* thus pro-

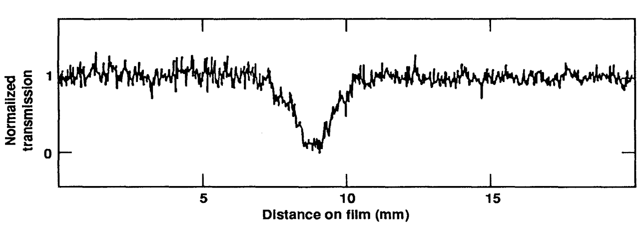

FIG. 4. Transmission along the length of the aluminum line from an experiment in which the sample was rotated 90° from the orientation in Fig. 1. The length of the line gives the sample density. Because of the finite size of the backlighter the transmission does not fall and rise abruptly but changes over a distance consistent with the size of the backlighter.

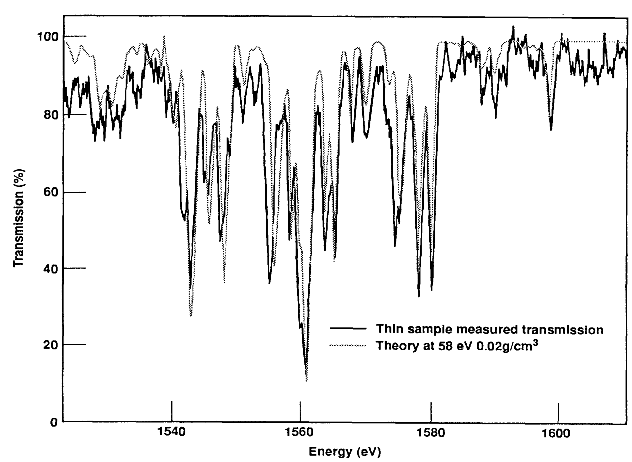

FIG. 5. Measured thin-sample transmission vs calculation.

viding a single temperature and density LTE environment. An extension of the point projection spectroscopy method has been perfected to allow the first measurements of the spectroscopic details of the LTE opacity of a moderate Z sample. Further, the experimentally determined opacity has been shown to be in excellent agreement with a detailed spectroscopic prediction. The methods illustrated in the present Letter can also be extended to experiments on non-LTE plasmas and thus will be useful in determining the detailed LTE and non-LTE optical properties of materials of importance in, e.g., astrophysical plasmas and fusion research. Finally, the capability to create and diagnose the temperature of this sample suggests that the current technique can, in the future, be used as a temperature diagnostic in other similar experiments.

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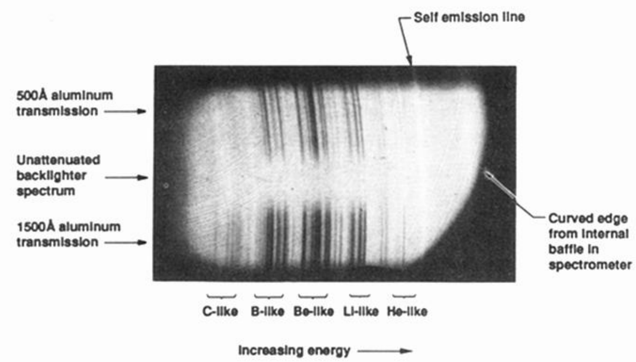

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