Time-Resolved Transmission Measurements of Warm Dense Iron Plasma *

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Transmission measurements of warm dense iron plasma are reported over the photon energy range of 400–1200 eV, including the strong 2p–3d structures. One-dimensional hydrodynamic simulation is performed to estimate the plasma conditions: temperatures of several eV and densities of about 0.1 g/cm^3. By using the simulated temperature and density, the calculations of the transmission spectra are performed and compared with the time-resolved experimental results.

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Radiative opacity plays an important role in research such as inertial confinement fusion (ICF)[1–3] and astrophysics.[4] In recent years, hot plasma opacities have drawn much attention in the studies of ICF. With the development of diagnostic techniques, it is possible to provide high quality absorption spectra as well as reliable information concerning the plasma conditions. Among these works the opacity of iron plasma is particularly interesting due to both astrophysical needs[4] and validation for theoretical models. Many laboratory measurements of the opacity of iron plasma have been carried out in the past decades. Most of these experiments[5–13] have been limited to a maximum temperature of less than 100 eV and a density of approximately 0.01 g/cm^3. For hotter iron plasmas, measurements become more challenging due to the fact that the heat source must supply more energy and the backlight source must be brighter to overwhelm the sample self-emission. These opacities of iron plasmas are very important for astrophysics, especially for solar interior radiation transport. Such measurements were reported in Refs. [14–19]. Theoretical calculations on the opacities of iron plasmas can be found in Refs. [20–25].

In these aforementioned experiments, the plasmas were of high temperatures and low densities. However, measurements of iron plasma at low temperature (i.e., <10 eV) and high density have not been reported to our knowledge. This plasma state has an ion–ion coupling parameter, that is, the ratio of the Coulomb potential between two neighboring ions to their thermal energy closes to unity. This warm dense iron plasma is near the warm dense matter (WDM) region,[26] which is an important research field relevant to applied and fundamental sciences. Understanding the radiative properties of WDM is attracting considerable and rapidly increasing interest. However, until recently the opacities in the WDM regime have not been completely known. In the present work, we report transmission measurements of moderately coupled ($\Gamma_{ii} \simeq 1$) iron plasma near the WDM region over a photon energy range from 400 eV to 1200 eV. We adopt large area, long-pulse backlight for x-ray transmission measurements[12] in the experiments. At the same time, the x-ray backlight heated the CH tamped sample uniformly. The covered CH could depress the expansion of the central absorber and increase the spatial uniformity. The transmission spectrum of the iron absorber was obtained from the backlight and absorption spectra which were measured simultaneously in a single shot with a space-resolved flat-field grating (FFG) spectrometer coupled with a gated microchannel plate (MCP) detector. By varying the distance between the backlighter and the target, the backlight intensity and the MCP onset time, the transmission spectra under different plasma conditions can be obtained. One-dimensional (1D) hydrodynamic simulation has been performed to estimate the plasma conditions. We use the simulated temperatures and densities to calculate the transmission spectra by a detailed configuration accounting model in combination with the unresolved transition array method (DCA-UTA) and compare with the experimental results. The gross features agree with the experimental results. For the $2p$–$3d$ absorption peaks of iron plasma, there is a redshift about −10 eV of the calculated peaks with respect to the experimental results.

The experiments were performed on the SG-Ⅱ high-power laser facility at Shanghai. A sketch of the experimental setup is shown in Fig. 1. The samples, consisting of a mixture of iron and aluminum, were clad in a 50 μg/cm^2 (or 0.5 μm in thickness) plastic sandwich to tamp the expansion and to achieve uniformity in both temperature and density in the Fe/Al mixture. The sample for shot SN011 was made from 78 μg/cm^2 iron and 40 μg/cm^2 aluminum, while shot

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SN020 consisted of 156 μg/cm^2 iron and 40 μg/cm^2 aluminum. The half-sample design makes it possible to accomplish simultaneous measurements of the backlight spectrum and the absorption spectrum in one shot. The Fe/Al mixture was fabricated by simultaneous plasma spraying of Fe and Al ions. The Al doped in the Fe sample provides an opportunity to characterize the Fe plasma by its k-shell absorption line strengths in hot plasmas,[8,12,27–30] while only contributing weak continuum absorption backgrounds in the concerned energy range. The areal density of the sample was determined at the Beijing Synchrocyclotron Radiation Facility (BSRF) by comparing the measured transmission with the standard transmission data. The iron areal density uncertainty is about 10%, including contributions from measurement errors and the uncertainties of standard transmission data.[12]

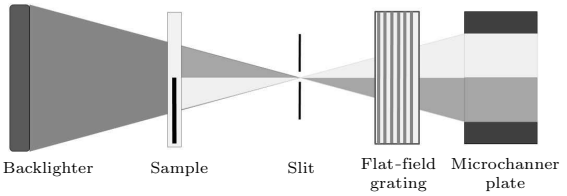

Fig. 1. The experimental setup for the transmission measurement.

The iron plasma opacity is obtained from the transmission of an x-ray probe beam (or backlight) through the sample. The required uniform backlight in the experiment was produced by irradiating a 2-μm-thick CsI foil which was attached to a 10-μm-thick gold foil with the beam-smoothed ninth laser light of the SG-Ⅱ laser facility. This frequency-tripled laser light delivered about 1000 J energy in a 2.0 ns square pulse. The focal area was about 450 μm × 450 μm and the distance between the backlighter and the sample was 7 mm. A space-resolved FFG spectrometer with low higher-order diffractions was coupled with a gated MCP detector to record the spectral signal during a ∼150 ps period. The spectral resolution was about $\lambda/\Delta\lambda \sim 200$, primarily restricted by the limited spatial resolution of the MCP detector. The space-resolved spectrum consists of two spectral portions that represent, respectively, the backlights either passing through the Fe/Al mixture or not, and was imaged and diffracted with the spectrometer coupled with a slit. The backlight also plays the role of heat source. By varying the delay of the MCP onset time relative to the backlight pulse, the spectra can be recorded at different time windows corresponding to different iron plasma conditions. It is worth noting that this method can be used to study the evolution of plasma conditions. We show in Fig. 2 the space-resolved transmission spectra measured in two separate shots SN011 and SN020. The delays are about 1.7 ns in shot SN011, and 0.5 ns in shot SN020.

The procedure for obtaining the transmission spectrum is shown in the following. Assuming that $\tau_{\mathrm{Fe/Al}}$ and τ_{CH} are the optical depths of the Fe/Al absorber and the CH tamper, the intensities of the two spectra $I_{\mathrm{A}}(\nu)$ and $I_{\mathrm{B}}(\nu)$ recorded on the detector plane can be written as

$$I_{\mathrm{A}}(\nu) = I_0(\nu) \cdot \exp[-\tau^{\mathrm{Fe/Al}}(\nu) - \tau^{\mathrm{CH}}(\nu)], \quad (1)$$

$$I_{\mathrm{B}}(\nu) = I_0(\nu) \cdot \exp[-\tau^{\mathrm{CH}}(\nu)] \quad (2)$$

where $I_0(\nu)$ is the backlight intensity. Due to the high brightness of the backlight source and the low temperature of the plasma, the contribution of self-emission was sufficiently small to be ignored in our experiments. From Eqs. (1) and (2), the Fe/Al transmission can be obtained as

$$T(\nu) = \exp[-\tau^{\mathrm{Fe/Al}}(\nu)] = \frac{I_{\mathrm{A}}(\nu)}{I_{\mathrm{B}}(\nu)}. \quad (3)$$

The response of the spectrometer as a function of the x-ray intensity has been calibrated[31] and taken into account during the procedure.

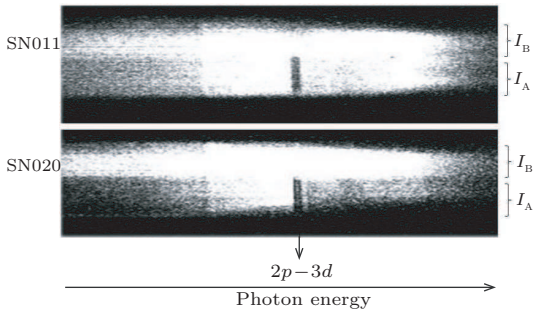

Fig. 2. The measured space-resolved Fe/Al absorption spectra from two shots SN011 and SN020. Here I_{A} and I_{B} represent the backlights either passing through the Fe/Al mixture or not, respectively.

Radiative hydrodynamic simulation was used to determine the plasma conditions. The simulation uses the 1D version of the MULTI code developed by Ramis *et al.*[32] The sample foil simulated consists of a 0.1-μm-thick Fe layer and a 0.15-μm-thick Al layer and is tamped on both sides by two 0.5-μm-thick CH layers. The backlight x-ray heats the target from one side of the sample foil. In the simulation, the temporal history of radiation temperature was measured by a soft x-ray spectrometer consisting of four x-ray diodes. The simulated temporal history of the density and temperature in the sample is plotted in Fig. 3. As the sample is heated only from one side, there are large gradients of density and temperature. An analysis of the shot SN020 at the probe window with heating time of 0.5 ns has given the electron temperature 2 ± 1 eV and the density 0.2 ± 0.1 g/cm^3. For shot SN011 at the probe window with heating time of 1.7 ns, the electron temperature is 6 ± 2 eV and the density is 0.05 ± 0.02 g/cm^3.

An opacity code DCA-UTA was used to calculate the transmission spectra and the results were compared with the measurements. This opacity code

adopts the DCA with term structures treated by the UTA model, to calculate the opacities of hot dense plasmas in local thermodynamic equilibrium. In this code, the atomic data are calculated by self-consistent potentials for isolated atoms. When solving the Boltzmann–Saha equations, the continuum lowering is considered. The details of this code have been discussed elsewhere.[33–35] The transmission was obtained from the calculated opacity $\mu(\nu)$ by means of Beer's law ($T(\nu) = \exp[-\mu(\nu) \cdot \rho l]$). As the transverse scale of the sample is much larger than the sample thickness, the expansion of the sample can be considered as 1D with areal density unchanged. The calculations use the initial areal density of the sample, which was inferred from the x-ray transmission measurements at the BSRF.

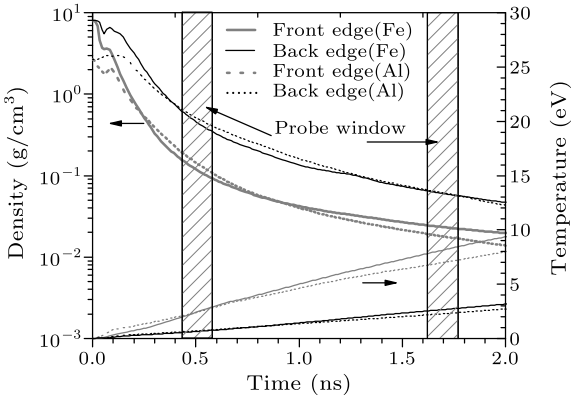

Fig. 3. The simulated temperature and density of the Fe layer (solid) and the Al layer (dotted) in the CH/Fe(Al)/CH multilayer foil.

In Fig. 4, we display the DCA-UTA calculations of the transmission and compared with the experimental results. The spectral resolution is about $\lambda/\Delta\lambda \sim 200$. The measured wavelengths were calibrated by the K-shell emission lines of a CF_4 plasma under the same experimental setup, which were identified by the theoretical results of atomic code Cowan. As shown in Fig. 4(a), the transmission calculations performed at a temperature of 2 eV and a density of 0.10 g/cm^3 fit the experimental data well for shot SN020 by a 10 eV blue shift. The absorption feature near 720 eV belongs to the $2p$–$3d$ ($2p^l 3s^{l'} 3p^{l''} 3d^{l'''} - 2p^{l-1} 3s^{l'} 3p^{l''} 3d^{l'''+1}$) transitions. The two sub-peaks come from the $2p_{3/2}$–$3d_{5/2}$ and $2p_{1/2}$–$3d_{3/2}$ transitions of mainly Fe I and Fe II ions. For shot SN011 with heating time of about 1.7 ns, the electron temperature is much higher. As shown in Fig. 4(b), the two sub-peaks merge together due to the line broadening with higher temperature. The center of the $2p$–$3d$ absorption feature shifts to higher energies of about 7 eV and this can be readily understood such that the average ionization stages increase with the temperature. With the influence of the area density variation considered, it is found that the absorption structure in Fig. 4(b) is still deeper than that in Fig. 4(a), which reveals that the temperature of shot SN011 is higher than that of shot SN020. The calculated temperature and density for shot SN011 are 6 eV and 0.05 g/cm^3, respectively. By a 15 eV blue shift of the calculated spectrum, the experimental results can be fitted quite well. The atomic data calculations are based on the self-consistent potentials. As the configuration interactions are not included adequately, the $2p$–$3d$ transition energies for neutral iron atoms and low ionization state ions have a large red shift with respect to the experimental results. The ion–ion coupling parameters $\Gamma_{ii} = (Z^* e)^2/dk_B T$ obtained in our experimental condition are about 1, and the plasmas are moderately coupled. When solving the Boltzmann–Saha equations to obtain the population density, the continuum lowering is considered. Though the UTA-DCA calculations provide good descriptions about the gross features of the $2p$–$3d$ absorption peaks, there are discrepancies for the sub-peaks. Such detailed structures result from the electron correlations and can be treated by a configuration interaction calculation.[35]

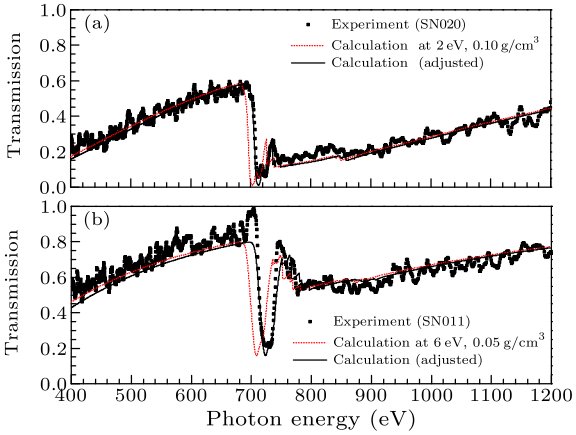

Fig. 4. Comparisons between the measured transmission spectra and the DCA-UTA calculations. The dotted line represents the original calculated data, and the solid line represents a blue shift of the original spectra to align the absorption peaks. (a) Shot SN020 at temperature 2 eV and at density 0.10 g/cm^3. (b) Shot SN011 at temperature of 6 eV and at density 0.05 g/cm^3.

The doped Al in our experiments contributed only weak bound–free and free–free continuum absorptions in the concerned photon energy range. The transmission uncertainties, determined mainly by the backlight brightness and spectrometer sensitivity variations, are accurate to approximately ∼10% over the 400–800 eV photon energy range, and about ∼15% in the energies above 800 eV. Experimental problems, such as plasma uniformities, areal density uncertainty due to sample non-1D expansion, disregard of higher order diffractions, and the backlight nonuniformity, though estimated to be relatively less important, still remain to be resolved.

In summary, we have performed the transmission measurement of warm dense iron plasma on the SG-

Ⅱ high power laser facility. The large area, long pulse backlight for x-ray transmission measurement also play the role of heat source. The transmission is measured with a space-resolved flat-field grating spectrometer coupled with a gated microchannel plate detector. The spectral resolution is about $\lambda/\Delta\lambda \sim 200$ and the time resolution is about 150 ps. The 1D hydrodynamic simulation has been performed to estimate plasma parameters. Based on the simulations, the inferred iron plasma conditions are temperature 6 ± 2 eV, density $0.05\pm0.02\,\mathrm{g/cm^3}$ for shot SN011, 2 ± 1 eV and $0.2\pm0.1\mathrm{g/cm^3}$ for shot SN020. By using the simulated temperature and density, the DCA-UTA calculations of the transmission spectra are performed. In the calculation, the continuum lowering due to the influence of the neighbors is considered. Due to the accuracy of the atomic data, the positions of the $2p$–$3d$ absorption peaks are lower than the experimental results. By a blue shift of the calculated spectra, the experimental results can be fitted quite well. These warm dense plasmas have ion–ion coupling parameters close to unity and the opacity measurements of the present work would be valuable for research of WDM opacities.

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