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September 1, 2011

APIP Conference
Belfast, Ireland
July 19, 2011 through July 22, 2011

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Diagnosing Implosions at the National Ignition Facility with X-ray Spectroscopy

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Abstract. X-ray spectroscopy is used on the National Ignition Facility (NIF) to diagnose the plasma conditions in the hot spot and the compressed shell of ignition-scale inertial confinement fusion (ICF) implosions. Ignition of an ICF target depends on the formation of a central hot spot with sufficient temperature and areal density. The concentric spherical layers of current NIF ignition targets consist of a plastic ablator surrounding a thin shell of cryogenic thermonuclear fuel (i.e., hydrogen isotopes), with fuel vapor filling the interior volume. A fraction of the ablator has a Ge dopant to minimize preheat of the ablator closest to the DT ice caused by Au M-band emission from the hohlraum x-ray drive. This paper concentrates on three spectral features of the implosion: Ge He α emission, Ge K α emission, and the Ge K-edge. Hydrodynamic instabilities seeded by high-mode ($50 < \ell < 200$) ablator-surface perturbations on ignition-scale targets can cause mixing of Ge-doped ablator into the interior of the shell at the end of the acceleration phase [1]. As the shell decelerates, it compresses the fuel vapor forming a hot spot. K-shell line emission from the ionized Ge that has penetrated into the hot spot provides an experimental signature of hot-spot mix. The amount of hot-spot mix mass is estimated from the brightness and spectral line shape of the Ge He α and satellite emission using a detailed atomic physics code. X-ray continuum from the hot spot is attenuated by the compressed shell, and the photoexcitation causes the shell to fluoresce in Ge K α emission. The contrast at the Ge K-edge and the brightness of Ge K α emission are used to diagnose the shell areal density. The highlighted spectral features measured in the 9.75-13.1 keV photon energy range are presented.

[1] B. A. Hammel *et al.*, High Energy Density Phys. **6**, 171 (2010).

Keywords: X-ray spectroscopy, inertial confinement fusion, hydrodynamic instability

PACS: 52.57.-z, 52.38.Ph, 52.38.Kd, 52.70.La

INTRODUCTION

X-ray spectroscopy is a valuable diagnostic on the National Ignition Facility (NIF) [1]. It is used to probe the plasma conditions of compressed inertial confinement fusion targets, which is crucial for hot-spot ignition [2]. The concentric spherical layers of current NIF ignition targets consist of a plastic ablator surrounding a thin shell of cryogenic thermonuclear fuel (i.e., hydrogen isotopes), with fuel vapor filling the interior volume [3]. The ablator is doped with Ge to minimize preheat of the ablator closest to the DT ice caused by Au M-band emission from the hohlraum x-ray drive [4]. A schematic of an ignition target highlighting the Ge-doped ablator surrounding the cryogenic DT layer and DT vapor is shown in Fig. 1(a). The ignition target has an outside diameter of 2.2 mm and a shell thickness of 258 μm . Liquid DT is directed inside the ablator shell using a fill tube and a DT ice layer is formed using the beta-layering technique [5]. The shell is accelerated via x-ray ablation inside a hohlraum [2]. As the shell decelerates, it compresses the fuel vapor, forming a hot spot. Ignition and energy gain are predicted to occur when the temperature and areal density of the hot spot reach 10 keV and 0.3 mg/cm^2 , respectively [2].

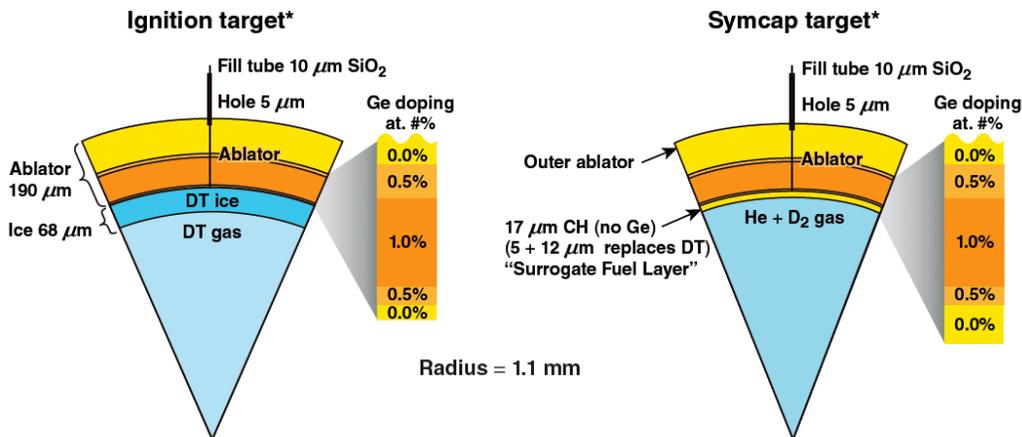


FIGURE 1. Schematic of ignition target in (a) and symcap target in (b). The cryogenic fuel of the ignition target and the D^3He gas fill of the symcap are delivered to the interior of the Ge-doped, plastic ablator using a fill tube. The radial distribution of the Ge atomic doping level in the plastic ablator is shown.

This paper concentrates on three spectral features of an imploding ICF target: Ge He_α emission, Ge K_α emission, and the Ge K-edge. Hydrodynamic instabilities seeded by high-mode ($50 < \ell < 200$) ablator-surface perturbations on ignition-scale targets can cause mixing of Ge-doped ablator into the interior of the shell at the end of the acceleration phase [6]. The amount of hot-spot mix mass is estimated from the brightness and spectral line shape of the Ge He_α and satellite emission using a detailed atomic physics code [7]. Simulations set surface finish requirements to keep hot-spot mix less than 100 ng. The Ge emission from tritium–hydrogen–deuterium (THD) and DT cryogenic targets and gas-filled plastic-shell capsules, which replace the cryogenic fuel layer with a mass-equivalent CH layer as shown in Fig. 1(b), was examined. The

latter is called a symmetry capsule or symcap, which is imploded to investigate the symmetry of the hohlraum x-ray drive by measuring the spatial distribution of the x-ray emission from the hot spot around the time of peak compression [8]. Ignition targets have an equimolar mixture of D and T. Tritium-rich layered targets with H and D were imploded to exploit the lower neutron yields for diagnostic purposes. X-ray continuum from the hot spot is attenuated by the compressed shell, and the photoexcitation causes the shell to fluoresce in Ge K_{α} emission. The contrast at the Ge K-edge and the brightness of Ge K_{α} emission are used to diagnose the shell areal density. The paper is organized as follows: the first section shows the measured one-dimensional (1-D) spectral image and calibrated spectrum of an ICF implosion, and the second and third sections highlight the shell and hot-spot spectral features, respectively.

X-RAY SPECTROSCOPY ON NATIONAL IGNITION FACILITY

The supersnout containing the hot-spot x-ray spectrometer (HSXRS) was developed to diagnose hot-spot mix in NIF implosions [9]. The time-integrated x-ray spectra in the 9.75-13.1 keV range of an ignition-scale implosion target with Ge-doped ablators shown in Fig. 2 were recorded along the hohlraum axis using the HSXRS. The spectral image has one-dimensional spatial imaging with 100- μm resolution, which is limited by the entrance slit on HSXRS. The slit width is dictated by photon throughput considerations. The spectral resolution is 12 eV. The Ge He_{α} emission is emitted from the mix mass in the hot spot and provides a spectroscopic signature of hot-spot mix. The Ge K_{α} emission is from the cold, dense shell, and compressed-shell conditions can be diagnosed with Ge K_{α} emission and by the Ge K-edge attenuation. The Ge K_{α} emission is photopumped by x-ray continuum from the hot spot. The x-ray continuum and shell opacity are assumed to scale as $e^{-h\nu/kT}$ and $1/h\nu^3$, respectively. The 1-D spatial profile of the shell emission (Ge K_{α} emission) is broader than the spatial

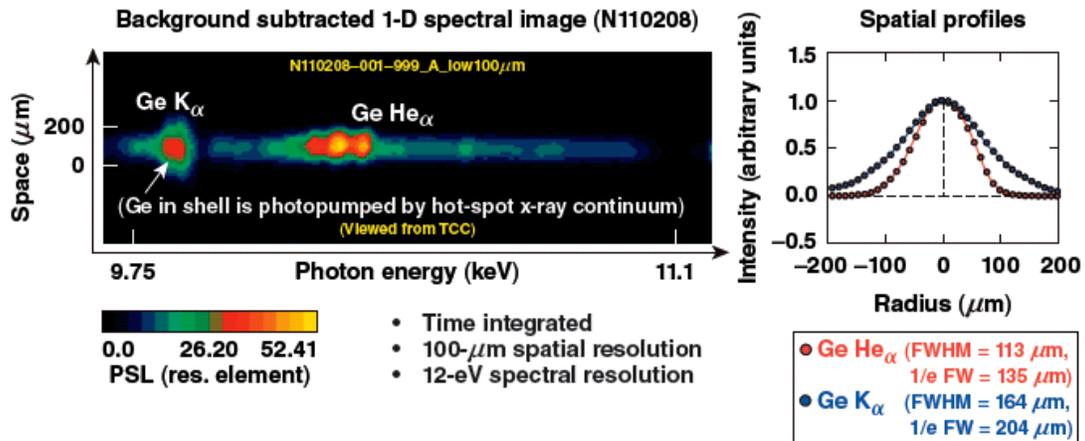


FIGURE 2. Time-integrated, 1-D spectral image of ignition-scale implosion recorded with the Hot-Spot X-ray Spectrometer (HSXRS) on the National Ignition Facility (NIF). The spatial resolution is 100 μm and the spectral resolution is 12 eV. The one-dimensional (1-D) spatial profile of Ge K_{α} emission from the compressed shell is broader than the Ge He_{α} emission from hot spot, as expected.

profile of the hot-spot emission (Ge He $_{\alpha}$ emission), as expected. The absolutely calibrated x-ray spectrum is spatially integrated and the x-ray continuum is modeled in Fig. 3.

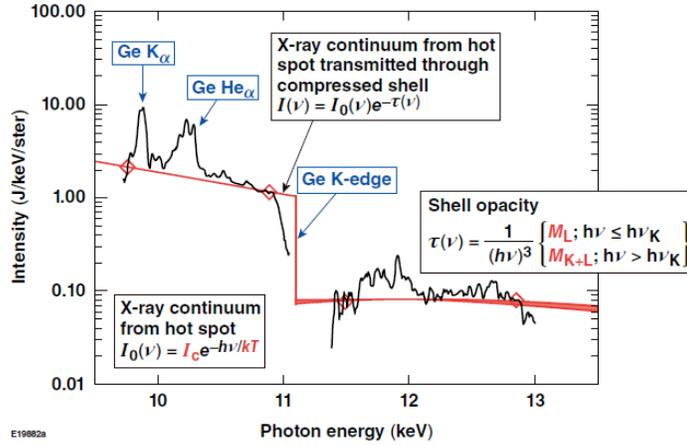


FIGURE 3. Spatially-integrated and photometrically calibrated spectrum showing Ge He $_{\alpha}$ and Ge K $_{\alpha}$ emissions and the Ge K-edge. The x-ray continuum from the hot spot transmitted through the compressed shell is modeled assuming the x-ray continuum and the shell opacity scale with photon energy ($h\nu$) as $e^{-h\nu/kT}$ and $h\nu^{-3}$, respectively. I_c , M_L , M_{K+L} are fitting constants and $h\nu_K$ is the Ge K-edge photon energy.

SPECTRAL FEATURES OF COMPRESSED SHELL

The contrast in the measured x-ray continuum signal around the Ge K-edge can be used to diagnose the areal density of Ge-doped ablators. The opacity of the shell is

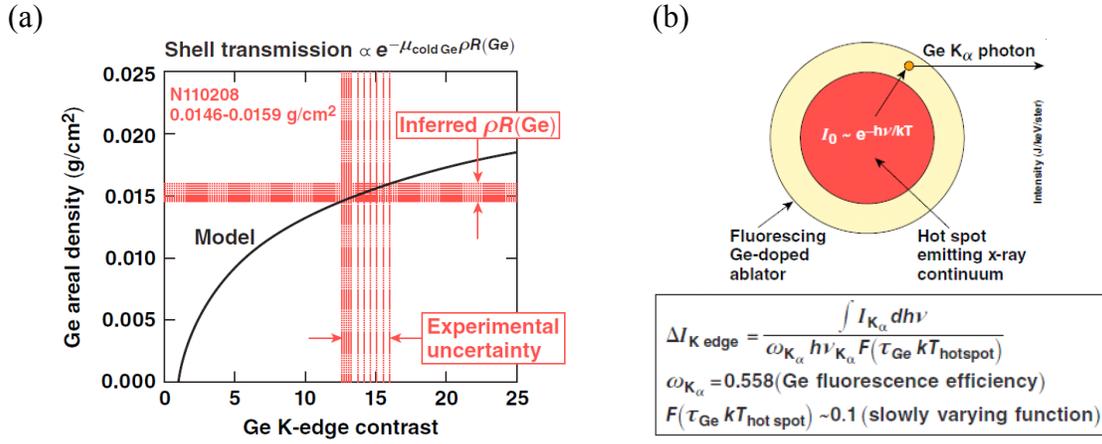


FIGURE 4. (a) The Ge areal density and the contrast in the measured x-ray continuum signal around the Ge K-edge. Shell transmission is modeled assuming opacity of the shell is $\mu_{\text{cold Ge}}\rho R(\text{Ge})$, where $\mu_{\text{cold Ge}}$ is the mass absorption coefficient of neutral Ge. The inferred $\rho R(\text{Ge}) = 0.0146\text{-}0.0159 \text{ g/cm}^2$. (b) X-ray continuum from the hot spot photopumps the surrounding compressed shell containing Ge dopant producing Ge K $_{\alpha}$ emission with spectral brightness $I_{K_{\alpha}}$, which is related to the Ge K-edge contrast $\Delta I_{K_{\text{edge}}}$. $\omega_{K_{\alpha}}$ is the Ge fluorescence efficiency and F is a slowly varying function.

assumed to be $\mu_{\text{cold Ge}} \rho R(\text{Ge})$, where $\mu_{\text{cold Ge}}$ is the mass absorption coefficient of neutral Ge and $\rho R(\text{Ge})$ is the areal density of the Ge-doped ablator. The dependence of the $\rho R(\text{Ge})$ on the Ge K-edge contrast is plotted in Fig. 4(a) and is used to infer $\rho R(\text{Ge}) = 0.0146\text{-}0.0159 \text{ g/cm}^2$ in the compressed ablator. The intensity of Ge K_{α} emission can be used to diagnose the compressed shell areal density. X-ray continuum from the hot spot photopumps the surrounding compressed shell containing Ge dopant and produces Ge K_{α} emission with spectral brightness $I_{K_{\alpha}}$, which is related to the Ge K-edge contrast $\Delta I_{K_{\text{edge}}}$ as shown in Fig. 3(b). The Ge fluorescence efficiency is defined as $\omega_{K_{\alpha}}$ and F is a slowly varying function.

SPECTRAL FEATURES OF HOT SPOT

The ablator material mixed into the hot spot is ionized and emits Ge K-shell x rays. A detailed atomic physics model including Stark broadening of the line shapes is used to estimate the amount of mix mass from the Ge K-shell line brightness [10]. As shown in

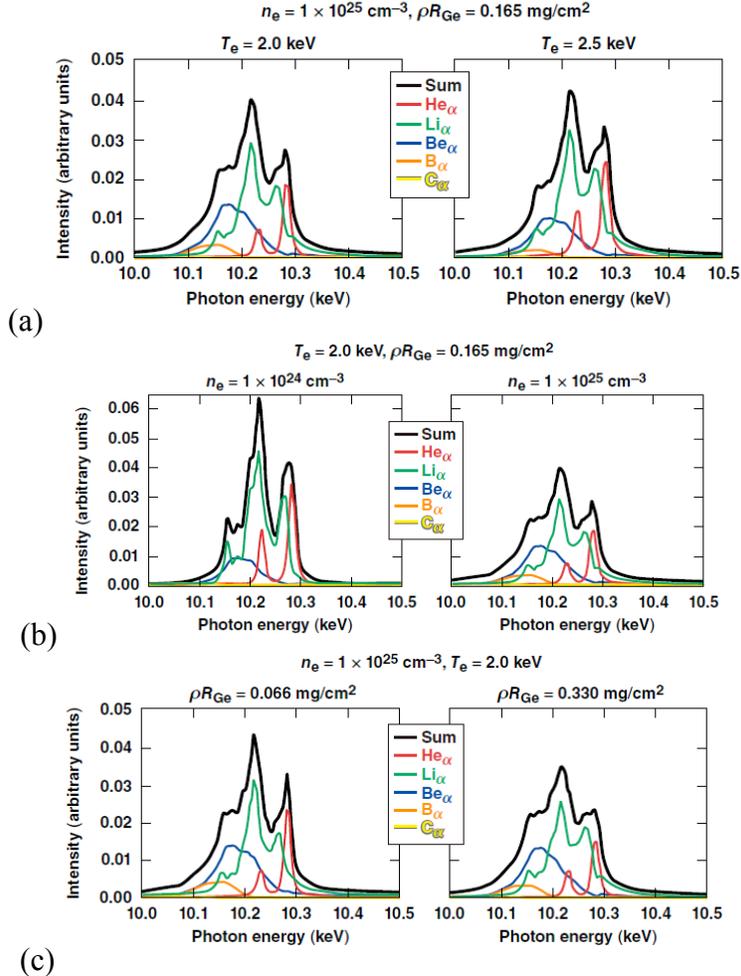


FIGURE 5. The calculated spectral components of the Ge He_{α} + satellite emission for (a) $T_e=2.0 \text{ keV}$ and 2.5 keV and $n_e=1 \times 10^{25} \text{ cm}^{-3}$ and $\rho R_{\text{Ge}}=0.165 \text{ mg/cm}^2$, (b) $n_e=1 \times 10^{24} \text{ cm}^{-3}$ and $1 \times 10^{25} \text{ cm}^{-3}$ and $T_e=2.0 \text{ keV}$ and $\rho R_{\text{Ge}}=0.165 \text{ mg/cm}^2$, (c) $\rho R_{\text{Ge}}=0.066 \text{ mg/cm}^2$ and 0.330 mg/cm^2 and $n_e=1 \times 10^{25} \text{ cm}^{-3}$ and $T_e=2.5 \text{ keV}$. The spectral shape of the sum is sensitive to variations in the plasma conditions.

Fig. 5 the calculated spectral line shapes are sensitive to variations in n_e , T_e , ρR_{Ge} for the range of plasma conditions under consideration. The calculated spectrum includes self-absorption-coupled level kinetics, which gives an estimate of the areal density of Ge in the mix mass. This estimate of ρR_{Ge} is related to the emitting Ge mass and density assuming a spherical spatial Ge distribution. Measured spectra are compared with modeled spectra for several thousand combinations of n_e , T_e , ρR_{Ge} and the best match is determined based on a least squares fit [7, 10].

CONCLUSION

X-ray spectroscopy is a valuable diagnostic on the National Ignition Facility. Hot-spot mix and compressed-shell areal density in ignition-scale implosions on the National Ignition Facility are diagnosed using x-ray spectroscopy.

ACKNOWLEDGMENTS

This work was supported by the U.S. Department of Energy Office of Inertial Confinement Fusion under Cooperative Agreement No. DE-FC52-08NA28302, the University of Rochester, and the New York State Energy Research and Development Authority. The support of DOE does not constitute an endorsement by DOE of the views expressed in this article.

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Prepared by LLNL under Contract DE-AC52-07NA27344.