Spectroscopy of Mid-Z Shell Additives in Implosions at the National Ignition Facility

Fluorescence in warm dense plasma

Kα line and K-shell continuum

Cu, Ge, Si doped CH

Cu and Ge Heα satellite line emission

Radiative coupling of shell mass objects

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Our NIF shell-dopant spectrum analysis takes several important issues into account:

- The atomic-kinetic radiation-transport effects on He$_\alpha$ satellite line emission from dopants are treated adequately in a model representing the shell material mixed into the core as small, independently radiating objects.

- External radiation within the hohlraum temperature range will not significantly affect the dopant ionization or line emission.

- Cu and Ge cold-material values of K$_\alpha$ fluorescence efficiencies will be sufficiently accurate under warm dense shell conditions.
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Mix mass is modeled as multiple spheres of ablator mass with uniform plasma conditions and areal density.

- Hot-spot mix-mass analysis assumes:
  - 250-ps emission
  - The original shell dopant concentration
  - Shell transmission based on simulations

<table>
<thead>
<tr>
<th>Layer</th>
<th>Dopant (atm. %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Cu (0.1%)</td>
</tr>
<tr>
<td>2</td>
<td>Si (0.7%) Ge (0.15%)</td>
</tr>
<tr>
<td>3</td>
<td>Si (1.7%) Ge (0.15%)</td>
</tr>
<tr>
<td>4</td>
<td>Si (1%)</td>
</tr>
<tr>
<td>5</td>
<td>None</td>
</tr>
</tbody>
</table>

Atomic model fit gives estimates of: \( T, \rho, \) and \( \rho R \)
Mix mass is estimated from the absolute brightness of the Ge He$_\alpha$ line satellites*

- The total Ge ion number is obtained from the total He$_\alpha$ satellite line emission and a PrismSPECT** model of the line intensity per Ge ion

- Modeling includes term-split spectral detail, accurate line profiles,† and radiation-kinetic coupling for a sphere of areal density $\rho R$ and mass $m = 4\pi(\rho R)^3/(3\rho^2)$

- The Ge concentration and ion number give the total mix mass $M$

- With a number of spheres $N = M/m$ occupying a fraction $f$ of the hot-spot volume, the probability that an escaping dopant photon will encounter a second sphere is $N^{1/3}f^{2/3} \sim 0.1$. Therefore,

  *the shell-material spheres radiate independently.*

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A $T_R$-modified Saha equation estimates the effect of external radiation on the ionization state of additive ions:

$$\frac{n_2}{n_1} = \frac{n_e C_{12}(T_e) + R_{12}(T_e, T_R)}{n_e C_{21}(T_e) + n_e [R_{21}^{\text{spontaneous}}(T_e) + R_{21}^{\text{stimulated}}(T_e, T_R)]}$$

- $T_R = T_e$, LTE
- Small photoionization effect
- $T_R = 0$, CRE
- All $T_R$ such that $1 < \frac{n_2/n_1}{(n_2/n_1)_{\text{CRE}}} < 2$

For Si:
- $n_e = 1.3 \times 10^{23} \text{ cm}^{-3}$
- $T_R$ affects ionization
- Small $T_R$ effect

For Ge:
- $n_e = 1.2 \times 10^{23} \text{ cm}^{-3}$
- $T_R$ affects ionization
- Small $T_R$ effect
A radiation temperature of $T_R < 300$ eV does not substantially change the ionization of dopants at $T_e$ above $\sim 500$ eV.

PrismSPECT* results

1% Si in CH

1% Ge in CH

$T_e = 2000$ eV

$T_e = 500$ eV

$\rho = 0.5$ g/cm$^3$

$\rho = 5$ g/cm$^3$

$\rho = 50$ g/cm$^3$
The measured $K_\alpha$ emission is consistent with the K-shell absorption of the core continuum*

\[
\int I_{K_\alpha} \frac{d\nu}{\nu} \sim \omega_{K_\alpha}
\]

\[
\mu_K \rho_{Ge} R = \ln \left[ \frac{I_{K\text{ edge}}}{I_{K\text{ edge}} - \Delta I_{K\text{ edge}}} \right]
\]

Ge fluorescence efficiency: $\omega_{K_\alpha} = 0.539**$

The cold $\omega_K$ is a good approximation for the Ge K$\alpha$ fluorescence efficiency for ionization below Ne-like.

From level population $(P_L, P_M)$ scaling:

$$\omega_K = \frac{[A_\alpha P_L + A_\beta P_M]}{[A_\alpha P_L + A_\beta P_M] + [A_{K,LL}P_L^2 + A_{K,LM}P_LP_M + \text{etc.}]}$$

$\omega_K$ vs. Ion charge $Z$

**Emission:** $A_\alpha, A_\beta$

**Autoionization:** $A_{K,LL}, A_{K,LM}$

$$\frac{\omega_{K_\beta}}{\omega_{K_\alpha}} = \frac{A_\beta P_M}{A_\alpha P_L}$$

Free-electron effects alter the isolated-atom $K_\alpha$ fluorescence efficiency of Ge and Cu only slightly.

- Collisional decay ($C_\alpha$), recombination ($C_{R,K}$), and radiative recombination ($R_{R,K}$) compete with autoionization and $K_\alpha$ emission and reduce the isolated-atom value of $\omega_{K_\alpha}\!^*$

$$\omega_{K_\alpha}^{\text{corrected}} = \frac{A_\alpha}{A_\alpha + A_{\text{auto}} + C_\alpha + C_{R,K} + R_{R,K}} = 1 + (C_\alpha + C_{R,K} + R_{R,K})(\omega_{K_\alpha}/A_\alpha)$$

Correction terms for $n_e = 10^{25}$ cm$^{-3}$ and $kT_e = 100$ eV:

$$\omega_{K_\alpha} C_\alpha/A_\alpha \leq 5.9 \times 10^{-2}$$
$$\omega_{K_\alpha} C_{R,K}/A_\alpha \leq 9.2 \times 10^{-4}$$
$$\omega_{K_\alpha} R_{R,K}/A_\alpha \leq 3.1 \times 10^{-2}$$

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For Ge:

- $A_{K,LL} = 1.08 \times 10^{15} \text{ sec}^{-1}$
- $A_{K,LM} = 2.90 \times 10^{14} \text{ sec}^{-1}$
- $A_\alpha = 1.65 \times 10^{15} \text{ sec}^{-1}$
- $A_\beta = 2.64 \times 10^{14} \text{ sec}^{-1}$

$$\frac{\omega_{K\beta}}{\omega_{K\alpha}} = \frac{A_\beta P_M}{A_\alpha P_L}$$

* E. J. McGuire, Phys. Rev. 185, 1 (1969);
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$$\omega_{K_\alpha}^{\text{corrected}} = \frac{A_\alpha}{A_\alpha + A_{\text{auto}} + C_\alpha + C_{R,K} + R_{R,K}} = 1 + \left(\frac{\omega_{K_\alpha}}{0.54}\frac{\eta_e}{10^{24}}\right) \left(\frac{h\nu_\alpha}{9.8 \text{ keV}}\right)^3 \left(\frac{kT}{0.1 \text{ keV}}\right)^{1/2}$$

$$\frac{\omega_{K_\alpha} C_\alpha}{A_\alpha} = 5.9 \times 10^{-3} \left(\frac{h\nu_\alpha}{9.8 \text{ keV}}\right)^3 \left(\frac{kT}{0.1 \text{ keV}}\right)^{1/2}$$

$$\frac{\omega_{K_\alpha} C_{R,K}}{A_\alpha} = 9.2 \times 10^{-6} \left(\frac{h\nu_\alpha}{9.8 \text{ keV}}\right)^3 \left(\frac{kT}{0.1 \text{ keV}}\right)$$

$$\frac{\omega_{K_\alpha} R_{R,K}}{A_\alpha} = 3.1 \times 10^{-3} \left(\frac{h\nu_\alpha}{9.8 \text{ keV}}\right)^{3/2} \left(\frac{kT}{0.1 \text{ keV}}\right)^{1/2}$$