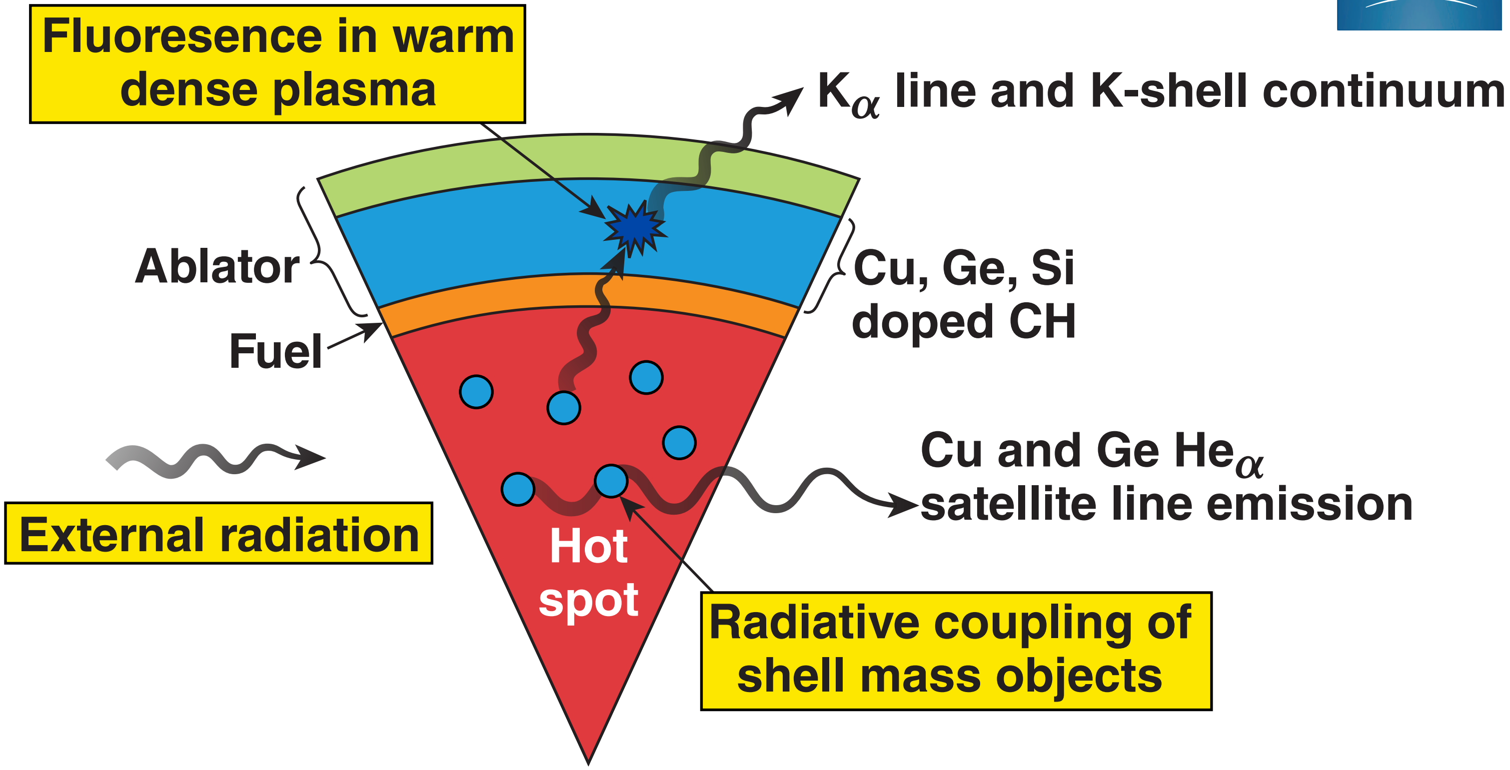
Spectroscopy of Mid-Z Shell Additives in Implosions at the National Ignition Facility



R. Epstein
University of Rochester
Laboratory for Laser Energetics

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Summary

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

Collaborators

S. P. Regan[1], T. C. Sangster, and J. L. Tucker[2]
University of Rochester
Laboratory for Laser Energetics

R. L. McCrory, D. D. Meyerhofer
University of Rochester
Laboratory for Laser Energetics, and
Departments of Mechanical Engineering and Physics and Astronomy

**B. A. Hammel, L. J. Suter, H. Scott, D. A. Callahan, C. Cerjan, N. Izumi,
M. H. Key, O. L. Landen, N. B. Meezan, B. A. Remington**
Lawrence Livermore National Laboratory

I. E. Golovkin, and J. J. MacFarlane[3]
Prism Computational Sciences

R. C. Mancini
University of Nevada, Reno

K. J. Peterson
Sandia National Laboratories

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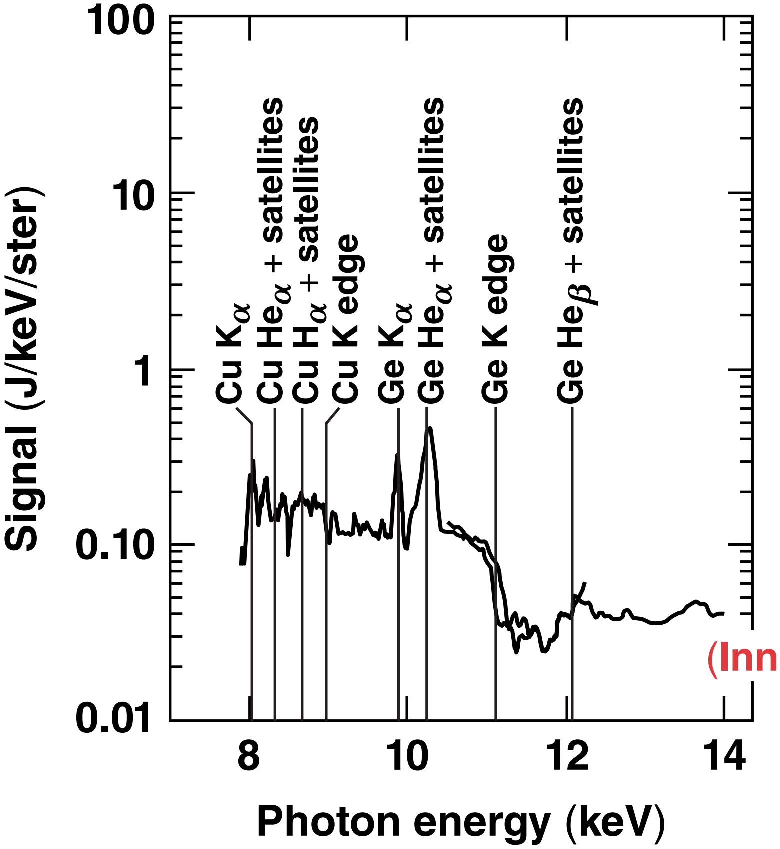
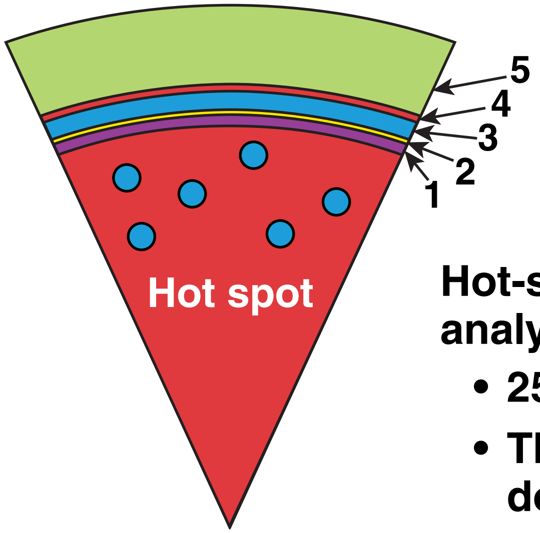
[1] PO4.00009, this conference
[2] LLE Summer High School Research Program
[3] CP8.00069, this conference

Mix mass is modeled as multiple spheres of ablator mass with uniform plasma conditions and areal density



Cu, Ge, Si-doped CH ablator



	Layer	Dopant (atm. %)
(Inner)	1	Cu (0.1%)
	2	Si (0.7%) Ge (0.15%)
	3	Si (1.7%) Ge (0.15%)
	4	Si (1%)
(Outer)	5	None

Hot-spot mix-mass analysis assumes:

- 250-ps emission
- The original shell dopant concentration
- Shell transmission based on simulations

Atomic model fit gives estimates of:
T, ρ, and ρR

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 ρR 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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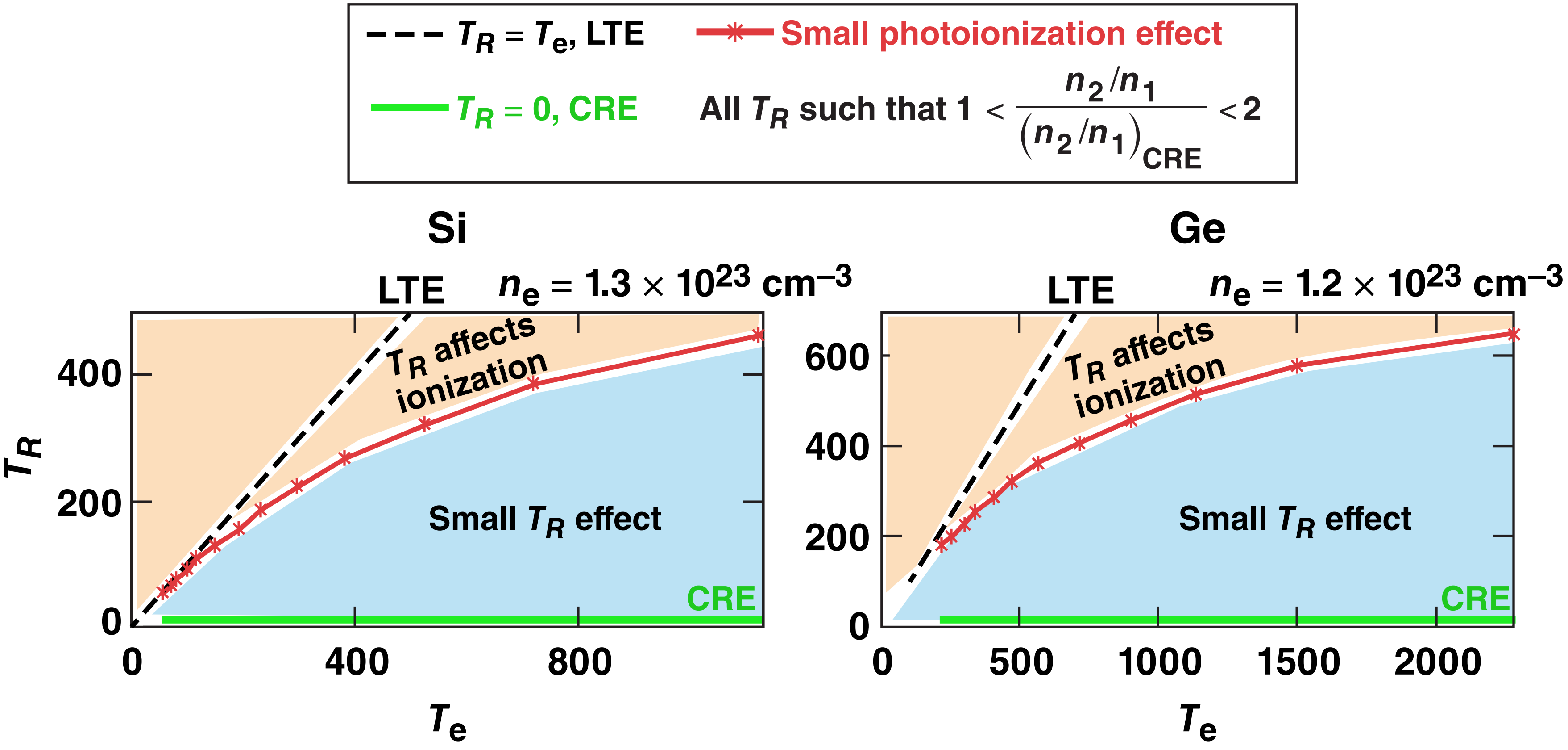
[*] S. P. Regan *et al.*, Phys Plasmas 19, 056307 (2012).

[**] J.J. MacFarlane *et al.*, High Energy Density Phys. 3, 181 (2006).

[†] R. C. Mancini *et al.*, Comput. Phys. Commun. 63, 314 (1991).

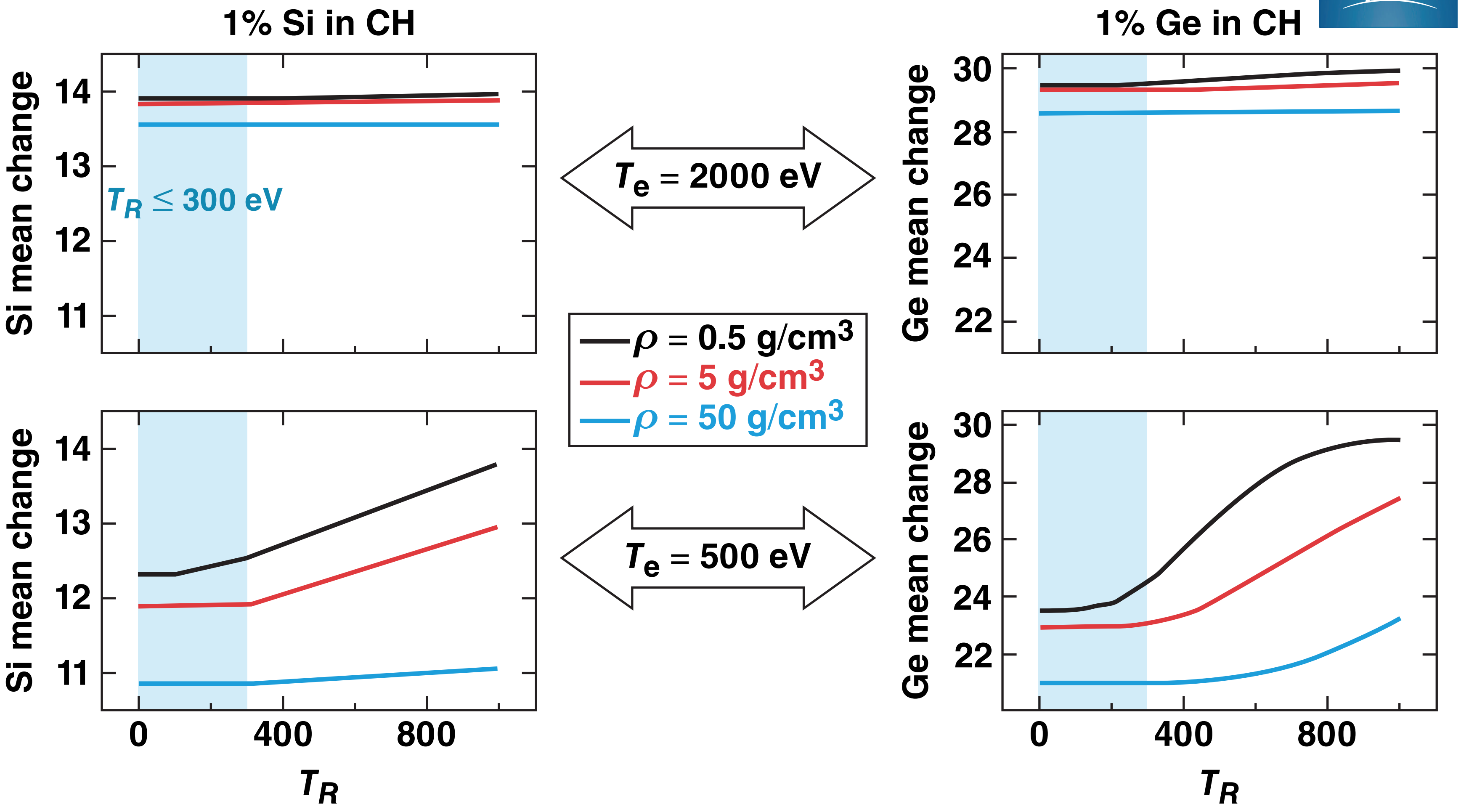
A T_R-modified Saha equation estimates the effect of external radiation on the ionization state of additive ions

$$\frac{n_2}{n_1} = \frac{n_e C_{12}(T_e) + R_{12}(T_e, T_R)}{n_e^2 C_{21}(T_e) + n_e\left[R_{21}^{\text{spontaneous}}(T_e) + R_{21}^{\text{stimulated}}(T_e, T_R)\right]}$$



A radiation temperature of $T_R < 300$ eV does not substantially change the ionization of dopants at T_e above ~500 eV

PrismSPECT* results



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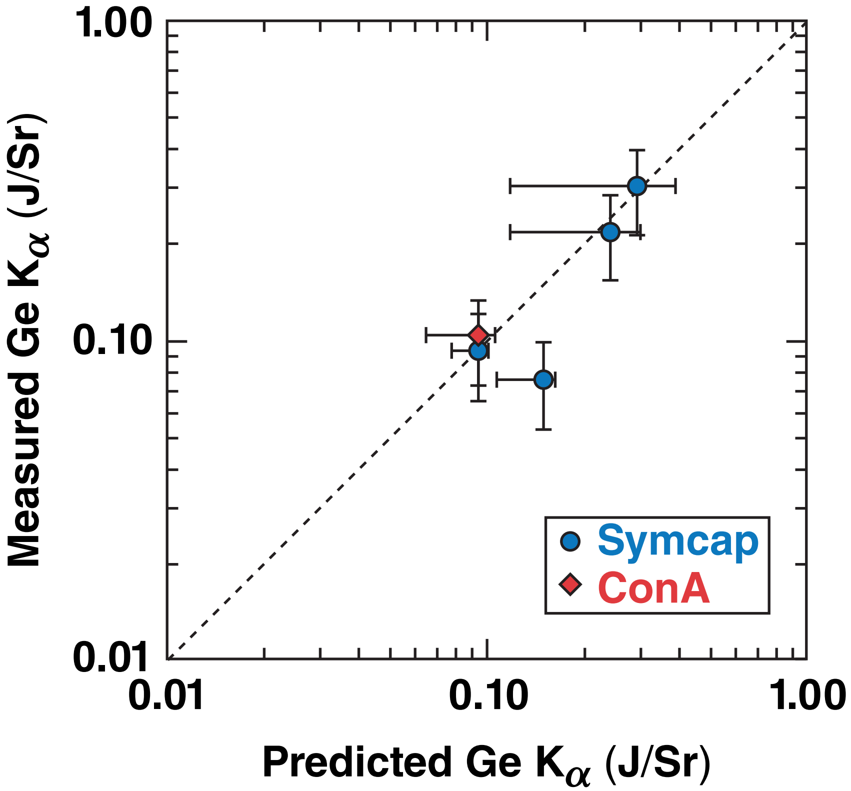
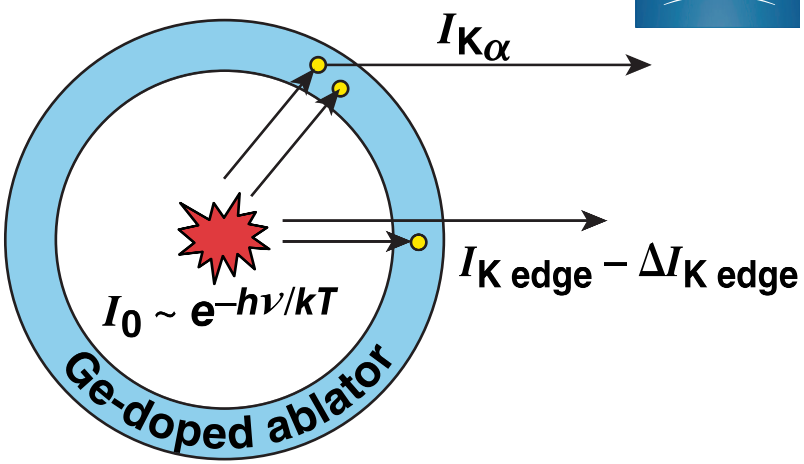
*PRISM Computational Sciences, Inc., Madison, WI.

The measured K_α emission is consistent with the K-shell absorption of the core continuum*





$$\frac{\int I_{K\alpha}\,\frac{dh\nu}{h\nu}}{\int \Delta I_{\text{K edge}}\,\frac{dh\nu}{h\nu}} \sim \omega_{K\alpha}$$

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

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

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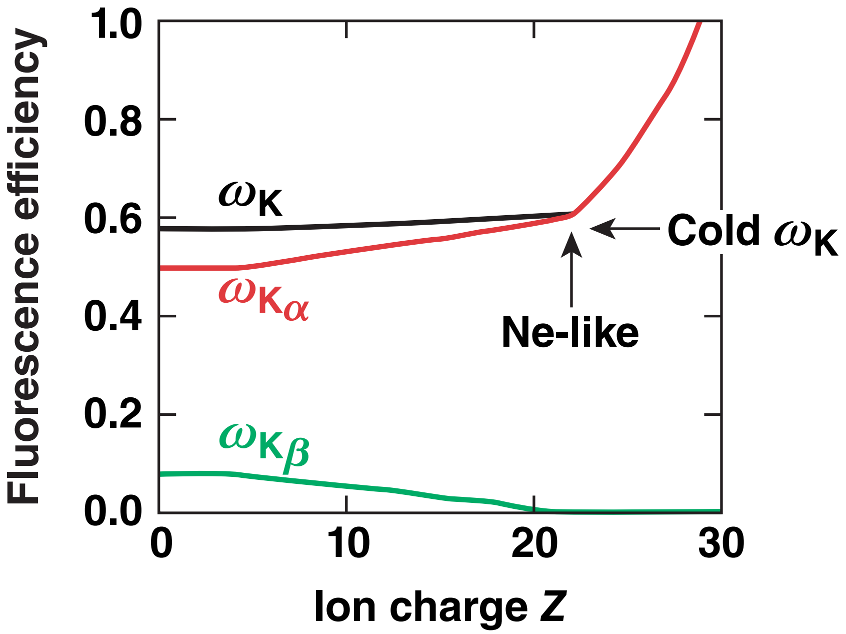
[*] S. P. Regan *et al.*, Phys Plasmas 19, 056307 (2012).

[**] J. Hubbell *et al.*, J. Phys. Chem. Ref. Data 23, 339 (1994).

The cold ω_K is a good approximation for the Ge K_α fluorescence efficiency for ionization below Ne-like

From level population (P_L, P_M) scaling:*

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



Emission: A_α, A_β

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

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

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* E. J. McGuire, Phys. Rev. 185, 1 (1969);
E. J. McGuire, Phys. Rev. A 2, 273 (1970).

Free-electron effects alter the isolated-atom K_{α} fluorescence efficiency of Ge and Cu only slightly

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

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

Correction terms for $n_e = 10^{25}\ \text{cm}^{-3}$ 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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*R. Epstein and B. Yaakobi, Phys. Rev. A 44, 5111 (1991).

Summary/Conclusions

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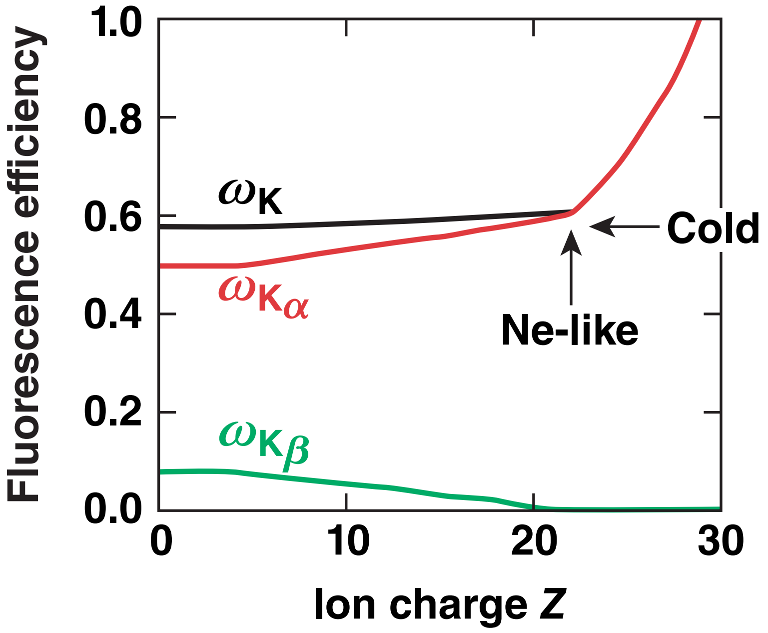

$$\frac{\omega_{K_\beta}}{\omega_{K_\alpha}} = \frac{A_\beta P_M}{A_\alpha P_L}$$

For Ge:**

$A_{K,LL} = 1.08 \times 10^{15}\ \text{sec}^{-1}$

$A_{K,LM} = 2.90 \times 10^{14}\ \text{sec}^{-1}$

$A_\alpha = 1.65 \times 10^{15}\ \text{sec}^{-1}$

$A_\beta = 2.64 \times 10^{14}\ \text{sec}^{-1}$

$A_{K,LL}$, etc., …

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

$$\omega_{K_\alpha} C_\alpha / A_\alpha = 5.9 \times 10^{-3} \, \frac{\left(\dfrac{\omega_{K_\alpha}}{0.54}\right)\left(\dfrac{\eta_e}{10^{24}}\right)}{\left(\dfrac{h\nu_\alpha}{9.8\text{ keV}}\right)^{3}\left(\dfrac{kT}{0.1\text{ keV}}\right)^{1/2}}$$

$$\omega_{K_\alpha} C_{R,K} / A_\alpha = 9.2 \times 10^{-6} \, \frac{\left(\dfrac{\omega_{K_\alpha}}{0.54}\right)\left(\dfrac{\eta_e}{10^{24}}\right)^{2}}{\left(\dfrac{h\nu_\alpha}{9.8\text{ keV}}\right)^{3}\left(\dfrac{kT}{0.1\text{ keV}}\right)}$$

$$\omega_{K_\alpha} R_{R,K} / A_\alpha = 3.1 \times 10^{-3} \, \frac{\left(\dfrac{\omega_{K_\alpha}}{0.54}\right)\left(\dfrac{\eta_e}{10^{24}}\right)}{\left(\dfrac{h\nu_\alpha}{9.8\text{ keV}}\right)^{3/2}\left(\dfrac{kT}{0.1\text{ keV}}\right)^{1/2}}$$

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