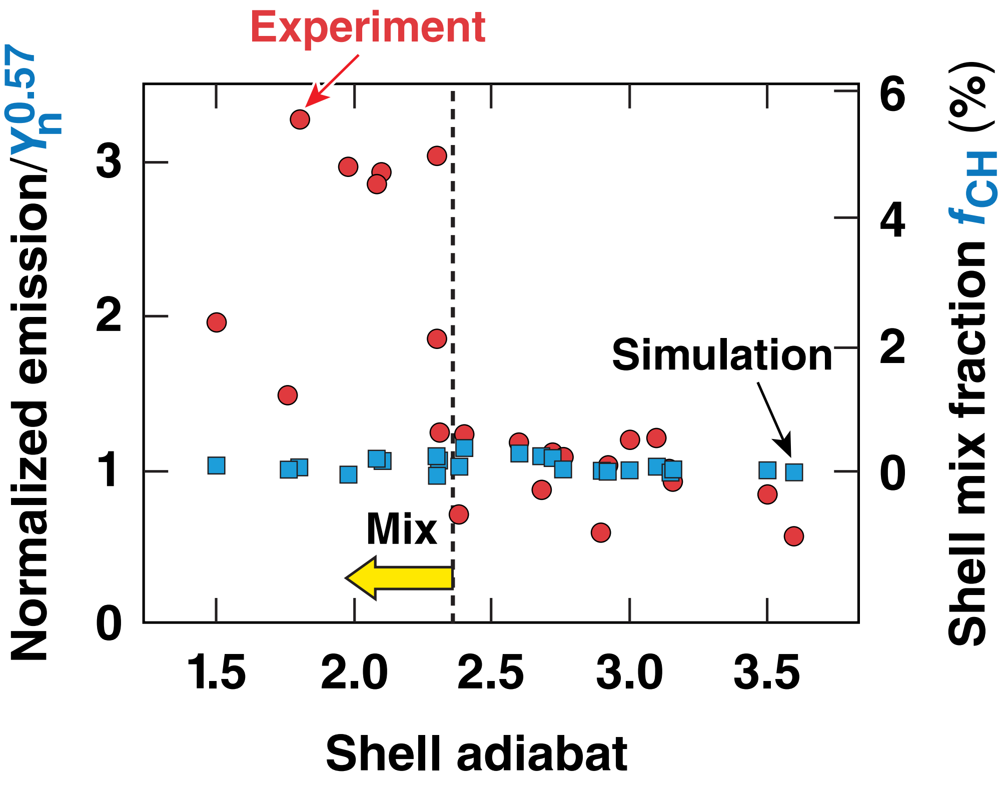
Fuel–Shell Mix Measurements Based on X-Ray Continuum Emission from Isobaric Implosion Cores on OMEGA



R. Epstein
University of Rochester
Laboratory for Laser Energetics

56th Annual Meeting of the
American Physical Society
Division of Plasma Physics
New Orleans, LA
27–31 October 2014

Summary

The x-ray emission of imploded cryogenic hot spots provides a diagnostic of fuel–shell mix*,**

- The photon-yield scaling with neutron yield is a consequence of the isentropic compression of isobaric hot spots
- The excess hot-spot x-ray emission relative to the scaled neutron emission serves as a fuel–shell mix diagnostic**
- The photon–neutron yield scaling and the appropriate x-ray yield normalization for the mix diagnostic is determined by the x-ray detector spectral response

---

*S. P. Regan *et al.*, Phys. Rev. Lett. 111, 045001 (2013).
**T. Ma *et al.*, Phys. Rev. Lett. 111, 085004 (2013).

Collaborators

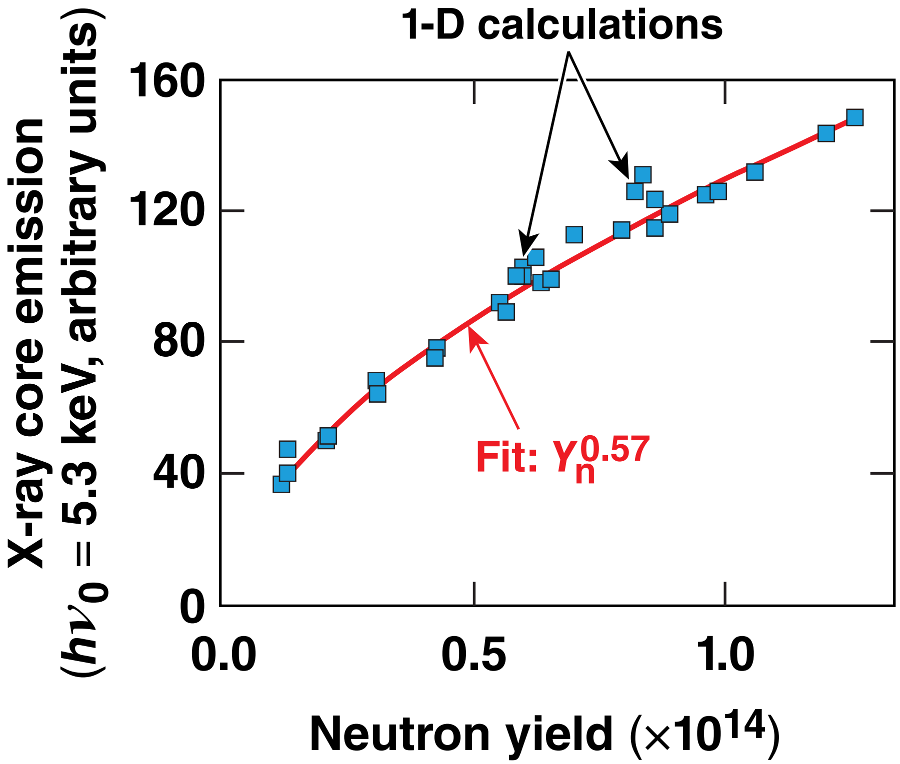
F. J. Marshall and V. N. Goncharov

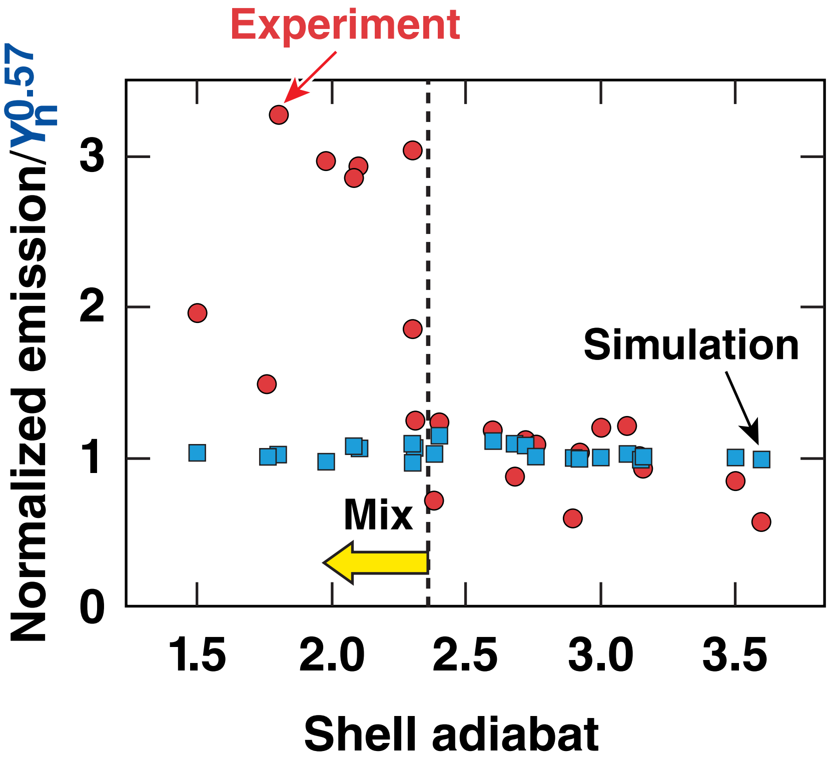
University of Rochester
Laboratory for Laser Energetics

R. Betti, R. Nora, and A. R. Christopherson

University of Rochester
Fusion Science Center and Laboratory for Laser Energetics

Core x-ray emission exhibits simple scaling with neutron yield in cryogenic implosion simulations*





- Measured yields are consistent with $Y_\nu \propto Y_n^{0.57}$ scaling for higher adiabats
- Excess x-ray emission for low adiabats suggests ablator mix in the hot spot

---

*T. C. Sangster *et al*., Phys. Plasmas 20, 056317 (2013).

The neutron-yield scaling of the photon yield is a property of isentropically compressed isobaric hot spots

- Neutron yield from the Bosch–Hale* reaction rate $\langle\sigma\nu\rangle \propto T^{4+\varepsilon}$:

  $Y_{\mathrm{n}} \propto P^2 T^{2+\varepsilon} Vt$

- Photon yield using Kulsrud** Gaunt factor $\varepsilon_{\nu}^{\mathrm{FF}} \propto P^2 T^{\eta}$

  $Y_{\nu_0} \propto P^2 T^{\eta} Vt$ near $h\nu_0 \approx 2\,\mathrm{kT}$

  - postulate a hot-spot adiabat $P \propto \alpha_{\mathrm{HS}} V^{-5/3}$
  - the inertial force of shell deceleration balanced by the core stagnation pressure† $M_{\mathrm{Sh}} R/t^2 = 4\pi R^2 P$ gives the Vt product

- Obtain scaling $Y_{\nu} \propto Y_{\mathrm{n}}^{q}$, where $q = \dfrac{5+2\eta}{9+2\varepsilon} \approx 0.56$ for $\varepsilon = 0$ and $\eta = 0$

---

*H.-S. Bosch and G. M. Hale, Nucl. Fusion 32, 611 (1992).

**R. M. Kulsrud, Astrophys. J. 119, 386 (1954).

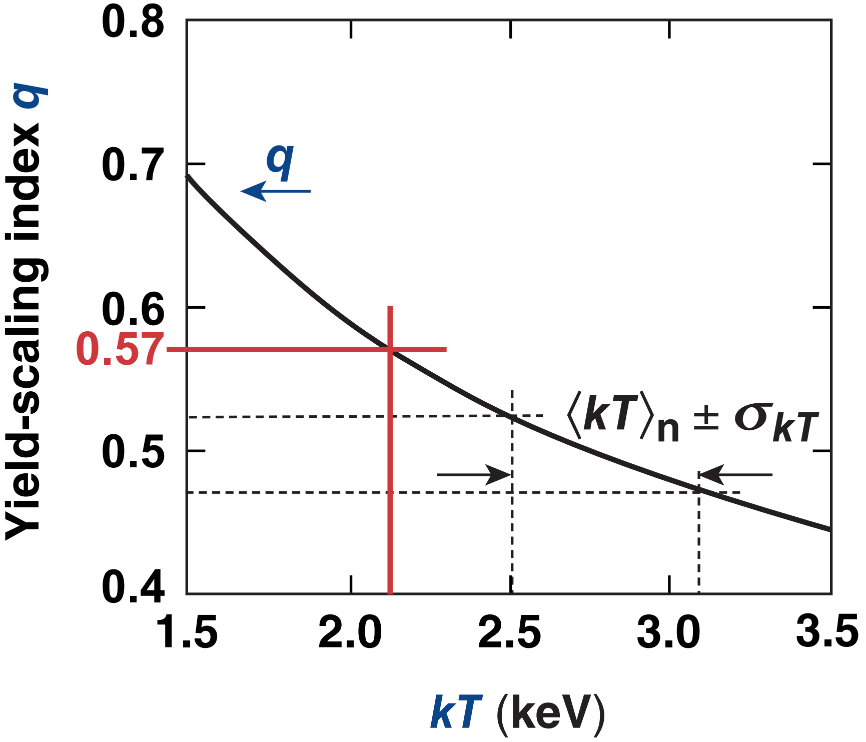
†R. Betti *et al.*, Phys. Plasmas 17, 058102 (2010).

The full photon–neutron yield scaling expression includes stagnation parameter dependence

$$Y_{\nu_0} \propto \left[\frac{M_{\mathrm{Sh}}^{2/9}\, M_{\mathrm{HS}}^{10/9}}{\alpha_{\mathrm{HS}}^{4/9}}\right]^{p} Y_{\mathrm{n}}^{q}$$

$$q = \frac{5+2\eta}{9+2\varepsilon} \approx 0.57 \text{ at } kT = 2.1\ \text{keV}$$

$$p = \frac{1+(\varepsilon-\eta)/2}{1+2\varepsilon/9} \approx 1.0$$



- The scaling $q = 0.57$ is obtained for $kT = 2.21$ keV, which is marginally representative of hot-spot temperatures in the *LILAC* simulation ensemble

The yield-scaling index value obtained using the Zhou–Betti* hot-spot mass agrees with the *LILAC* result

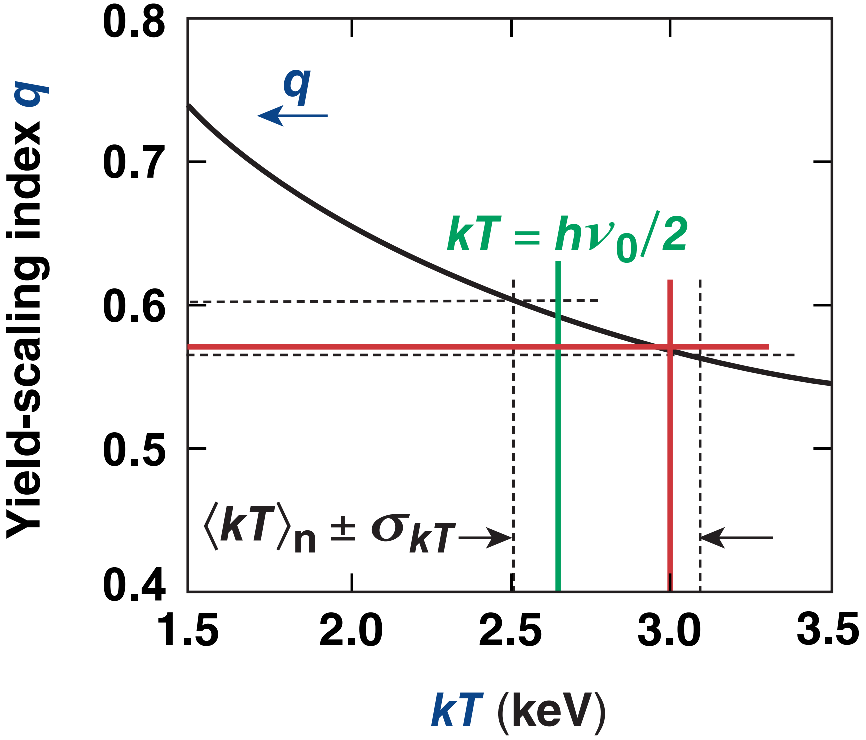
- **Zhou–Betti*** $M_{HS} \propto M_{Sh}^{1/7} P^{4/7} R^{16/7}$ from inner-shell mass ablation
- Alternative scaling

$$Y_{\nu_0} \propto M_{Sh}^{4p/11} Y_n^q$$

$q = \dfrac{7+2\eta}{11+2\varepsilon} \approx 0.57$ at

$kT = 3.0$ keV

$$p = \frac{1+(\varepsilon-\eta)/2}{1+2\varepsilon/11} \approx 1.0$$



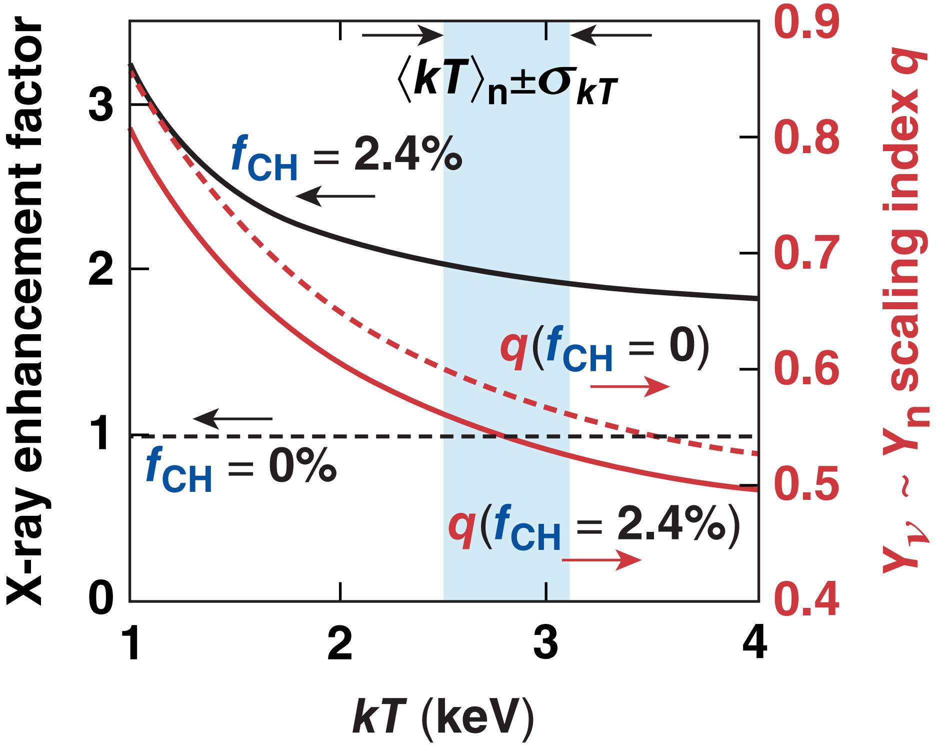
- The scaling $q = 0.57$ is consistent with the range of neutron-averaged temperatures in the *LILAC* simulation ensemble

---

*C. D. Zhou and R. Betti, Phys. Plasmas 14, 072703 (2007).

Small CH atomic fractions account for the observed excess hot-spot x-ray emission at low adiabats

- Free-free $Y^{FF}_{Z,\nu} \propto n_i n_e Z^2 Vt$ plus free-bound $Y^{FB}_{Z,\nu} \propto n_i n_e Z^4 \left(\frac{\chi_H}{kT}\right) Vt$ x-ray "yield" for each atomic fraction f_Z*

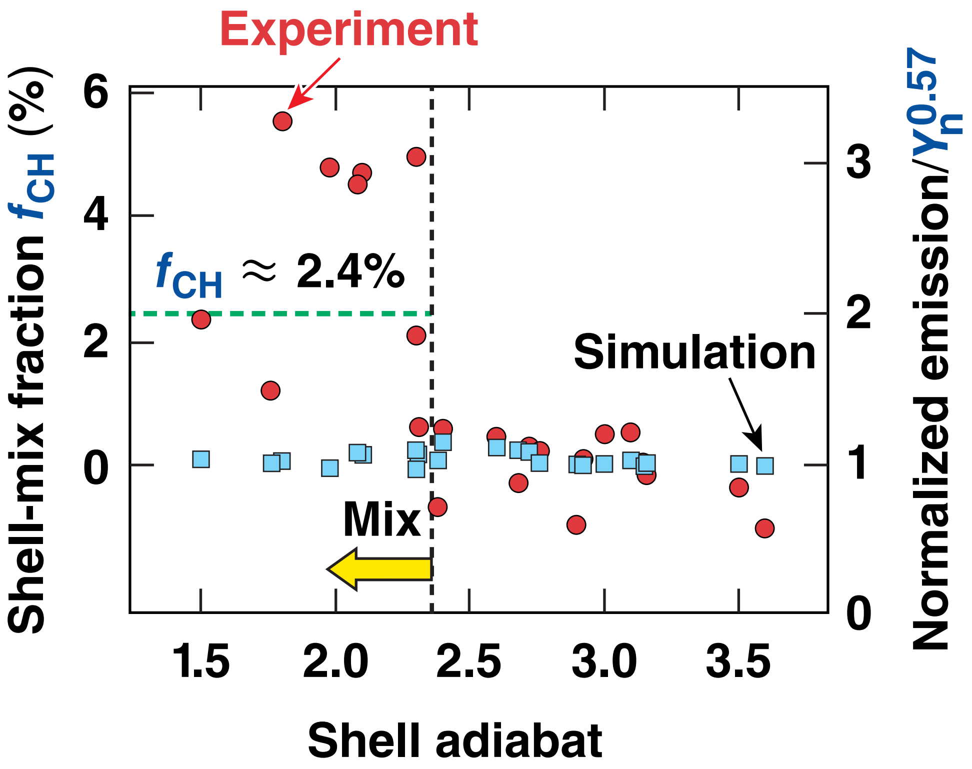


- X-ray enhancement and scaling index q resulting from $f_{CH} \approx 2.4\%$ hot-spot contamination are plotted
- A CH atomic fraction $f_{CH} \approx 2.4\%$ would double the hot-spot x-ray emission
- Adding FB emission lowers the yield-scaling index slightly; $q(f_{CH} = 2.4\%) \approx 0.54$

---

*Gaunt factors $g_{Z,FF}$ and $g_{Z,FB}$ from W. J. Karzas and R. Latter, Astrophys. J. Suppl. Ser. 6, 167 (1961).

Excess x-ray emission, relative to the scaled neutron yield in cryogenic implosions, provides a mix-mass estimate*



- Mix fraction $f_{CH} \approx 2.4\%$ doubles the hot-spot emission - - - - -

- For $\langle M_{HS} \rangle \approx 2.1$-$\mu$g hot spots, $f_{CH} \approx 2.4\%$ represents $\Delta M_{CH} \approx 125$ ng

---

*T. Ma *et al.*, Phys. Rev. Lett. 111, 085004 (2013).

Summary/Conclusions

The x-ray emission of imploded cryogenic hot spots provides a diagnostic of fuel–shell mix*,**

- The photon-yield scaling with neutron yield is a consequence of the isentropic compression of isobaric hot spots
- The excess hot-spot x-ray emission relative to the scaled neutron emission serves as a fuel–shell mix diagnostic**
- The photon–neutron yield scaling and the appropriate x-ray yield normalization for the mix diagnostic is determined by the x-ray detector spectral response

---

*S. P. Regan *et al.*, Phys. Rev. Lett. 111, 045001 (2013).

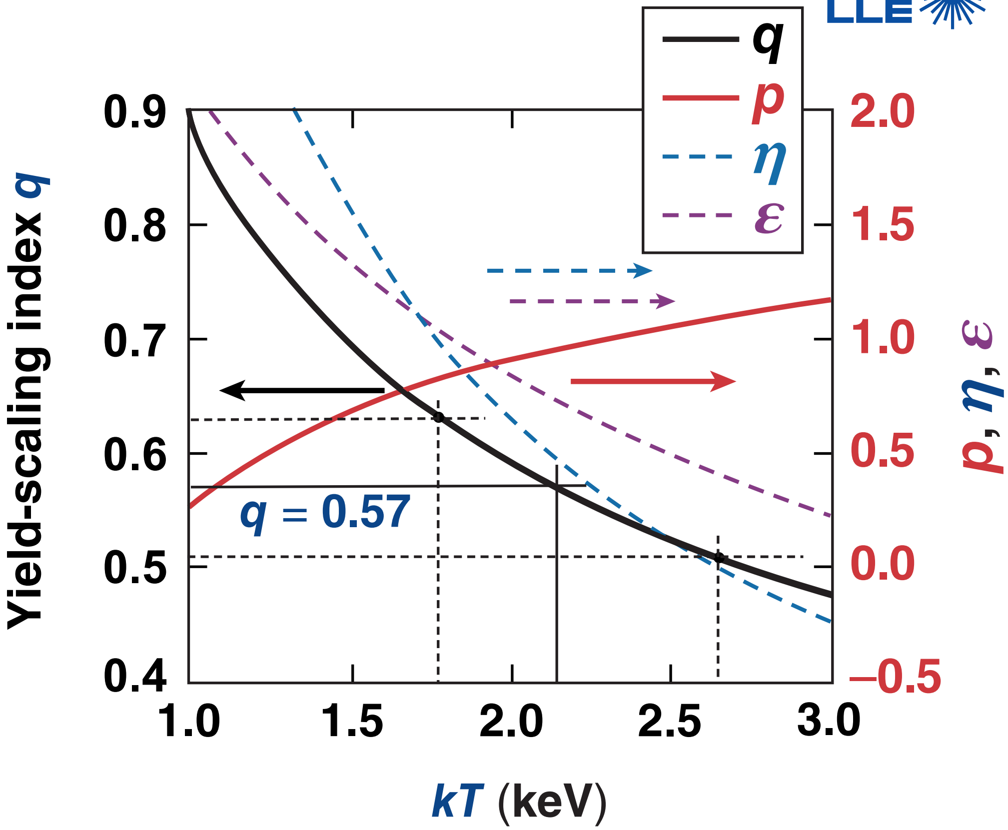
**T. Ma *et al.*, Phys. Rev. Lett. 111, 085004 (2013).

The photon–neutron yield scaling obtained from scaling arguments agrees with 1-D *LILAC* results over a broad temperature range

$$Y_{\nu_0} \propto \left[\frac{M_{\mathrm{Sh}}^{2/9}\, M_{\mathrm{HS}}^{10/9}}{\alpha_{\mathrm{HS}}^{4/9}}\right]^{p} Y_{\mathrm{n}}^{q}$$

$$q = \frac{5+2\eta}{9+2\varepsilon} \approx 0.57$$

$$p = \frac{1+(\varepsilon-\eta)/2}{1+2\varepsilon/9} \approx 1.0$$



- The scaling $q = 0.57 \pm 0.06$ is obtained for $kT = 2.21 \pm 0.43$ keV and is to be compared with $q = 0.57$ from *LILAC* results

Excess hot-spot x-ray emission above the expected clean DT level gives the mix fraction of shell C in the hot spot[1]

- Free-free (FF) plus bound-free (BF) x-ray "yield"

$$Y_\nu \propto n_I n_e \left[\langle Z^2 \rangle_I \left(\frac{\chi_H}{kT} \right)^{1/2} + 2 \langle Z^4 e^{\chi_Z/kT} \rangle_I \left(\frac{\chi_H}{kT} \right)^{3/2} \right] e^{-h\nu/kT} Vt$$

- The composition is DT $n_D = n_T$, with a trace $f_Z = n_Z/(n_D + n_T + n_Z)$ of a contaminant, e.g., C ($Z = 6$)

- Using $n_e = (n_D + n_T)(1 + f_Z Z)$ $n_I \langle Z^n \rangle = (n_D + n_T)(1 + f_Z Z^n)$ and the neutron yield:

$$Y_n \approx n_D n_T \langle \sigma\nu \rangle Vt$$

- Obtain

$$Y_\nu / Y_n \approx f(T)(1 + f_Z Z)(1 + f_Z j_Z / j_{DT})$$

- The shell-mix fraction x is obtained[1] from Y_ν/Y_n ratio measurements and emissivity j_Z, j_{DT} values from optical parametric chirped-pulse amplification (OPAL)[2] and detailed-configuration accounting (DCA)[3] tables

---

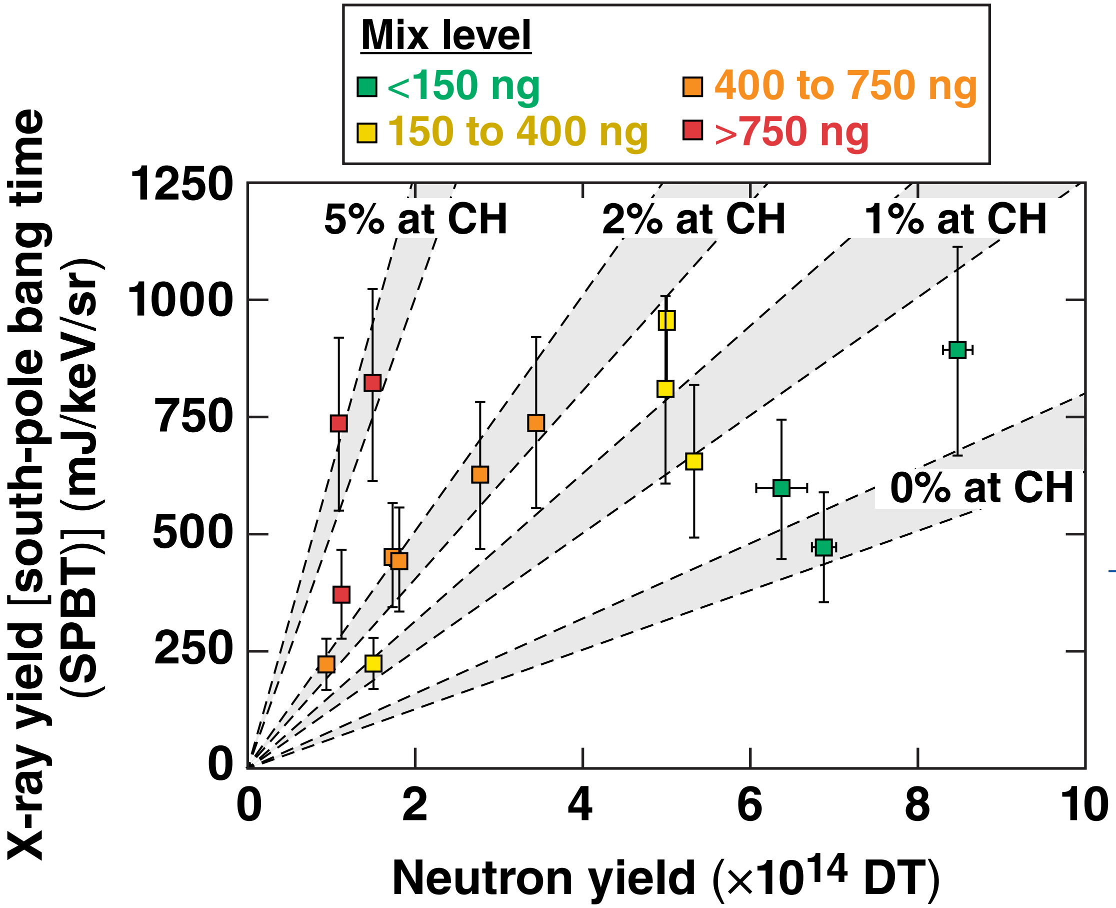
[1] T. Ma *et al.*, Phys. Rev. Lett. 111, 085004 (2013).

[2] F. J. Rogers, F. J. Swenson, and C. A. Iglesias, Astrophys. J. 456, 902 (1996).

[3] H. A. Scott and S. B. Hansen, High Energy Density Phys. 6, 39 (2010).

The level of mix is inferred from the ratio of x-ray yield to neutron yield*

NIF cryogenic Si-doped CH shells through 2012*



- Bands represent $1.7 < kT < 3.9$ keV and $h\nu_0 \approx 10.85$ keV
- Measurements made near $h\nu/kT = 4$, which is ideal for

$$\frac{Y_\nu}{Y_n} \propto \frac{P^2\left(\frac{e^{-h\nu/kT}}{T^2}\right)Vt}{P^2T^2Vt} = \frac{e^{-h\nu/kT}}{T^4}$$

---

*T. Ma *et al.*, Phys. Rev. Lett. 111, 085004 (2013).