Neutron and Charged Particle Data Needs for NIF Experiments

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Nuclear Data Needs and Capabilities for Applications

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Overview

Nuclear physics data is essential to characterize ignition-relevant implosion experiments.

- **Accurate temperature dependent fusion reactivity for light ions is of primary importance to describe thermonuclear burn.**
  - **— $D(t,\alpha)n$, $T(t,\alpha)2n$, $D(d,t)p$, $D(d,^3he)n$, $D(^3he,\alpha)p$**
  - **— DT, T_2, D_2, THD and D^3He gas fills are all used.**
- **Energy loss of fusion-generated alpha particles in hot dense plasmas must be accurately assessed (engine of ignition).**
  - **— Radiochemical neutron activation and neutron time-of-flight diagnostics validate stopping power models.**
- **Diagnostics for degraded implosion performance.**
  - **— Xe dopants to probe ablation front instabilities.**
  - **— Br(d,2n)Kr to probe ablator/cold fuel and ablator/hot core mix.**
  - **— Alpha particle induced reactions to probe hot core mix.**

Overview (continued)

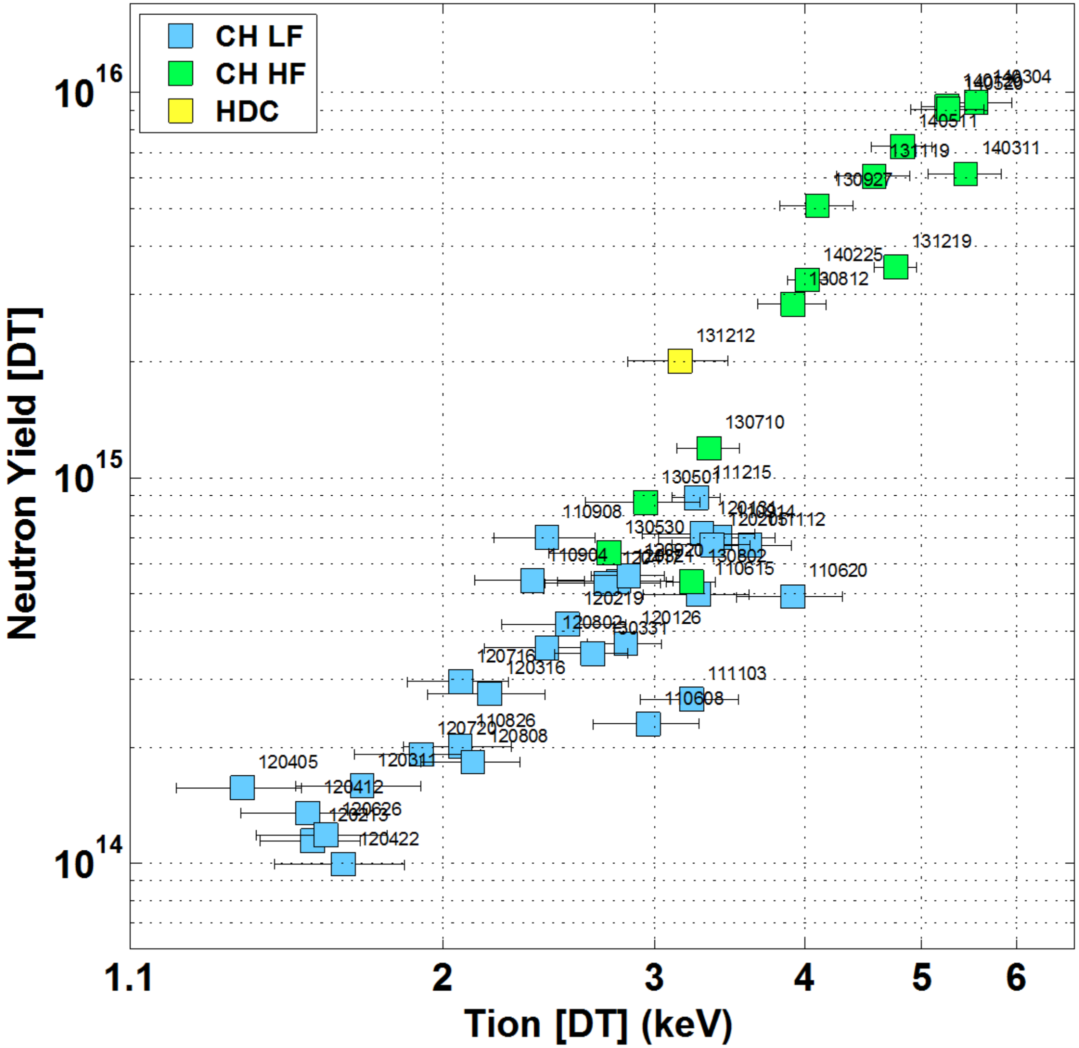
Nuclear physics data is essential to characterize ignition-relevant implosion experiments.

- **Gamma-ray diagnostics for performance and ablator/fuel instabilities.**
  - — **Total yield from DT-fusion γ branching ratio at 17.6 MeV.**
  - — **$^{12}C(n,n'\gamma)$ 4.4 MeV time-integrated emission provides hydrocarbon areal densities (remaining mass).**
    - – **Cross section at 14 MeV must be accurate.**
  - — **Does $^{13}C(n,n'\gamma)$ have strong emission near 4 MeV?**
    - – **If not, then a useful mix diagnostic is possible.**
- **Solid Radiochemistry Diagnostic (SRC) is currently a NIF diagnostic complementary to ^{12}C-γ GRH detection (CH ρr).**
  - — **Ratio of $^{198}Au/^{196}Au$ from the activated hohlraum.**
  - — **$(n,\gamma)/(n,2n)$: low energy neutrons/14 MeV neutrons.**
- **Fission product distribution experiments are not discussed.**
  - — **Capsule dopant and hohlraum foil placement.**

Qualitative description of an implosion experiment

- ***Indirect drive assumed throughout this discussion.***
- **Temporally and spatially shaped laser deposition onto hohlraum wall produces temporally and spatially varying x-ray drive.**
- **Ablator mass is ejected; shocks form and propagate; isentropic condition at peak implosion velocity on a low adiabat.**
- ***Transfer of incoming shell kinetic energy to PdV work on the capsule interior which leads to temperatures sufficiently large to initiate fusion reactions.***
- ***Ignition requires the generation of a propagating burn wave into the DT fuel by the stopping of fusion alpha particles in the hot core.***
- **Temperature rise also leads to pronounced increase in energy losses due to Bremsstrahlung and electron conduction.**
- **Balance between energy production (fusion reactions) and loss mechanisms characterizes the implosion performance.**

Summary of neutron yields from DT-cryogenic implosions versus measured ion temperature.



The high foot laser drive sacrifices compressibility for yield compared to the low foot laser drive.

This drive produces consistently smaller fuel densities but higher ion temperatures.

Plot courtesy of Pravesh Patel

Fusion reactivity and reaction-in-flight processes must be modeled accurately.

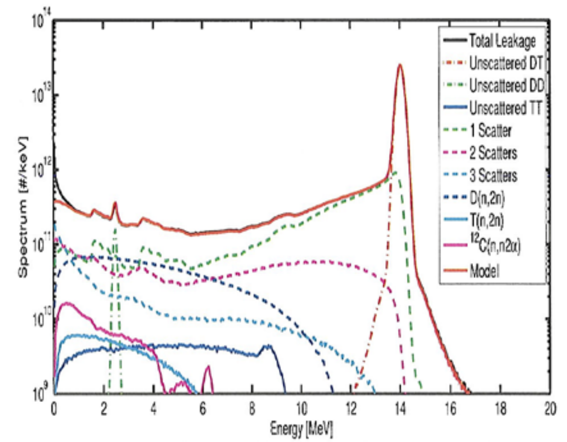
- **Light ion thermonuclear fusion reactivity parameterized as a function of temperature is necessary.**
  - **Accelerator experiments sample higher energies than ICF relevant energies and many reactivities are not available.**
    - **Example: ^{5}He resonance controversy in TT (Casey et al. PRL 2012; Sayre et al. PRL 2013)**
  - **ENDL parameterization.**
  - **Caughlan-Fowler parameterization (1988).**
  - **Specialized theoretical fits (Bosh-Hale).**
  - **Ab initio results are desirable.**
- **Cross sections for many in-flight reactions are needed to model neutron implosion spectra.**

DT Ignition

Fusion, Elastic Scatter, and In-Flight Reactions Explain the Data

- The complete set of physics
  - Unscattered DT, DD, TT.
  - Unscattered ${}^2_1H(n,2n)$, ${}^3_1H(n,2n)$, and ${}^{12}_6C(n,n2\alpha)$.
  - Singly, doubly, and triply scattered neutrons.
- DSR: 7.40%[7.40%]
- #(2–13 MeV): 1.26×10^{16} $[1.26 \times 10^{16}]$
- The model and calculated spectra now match well above 1 MeV. Below this, multiple scattering events dominate.
- **Including all aspects of this model explains the experimentally observed data.**

A Complete Model



The calculated neutron leakage spectrum and all of its components: fusion, elastic scattering to third order, and the in flight reactions ${}^2_1H(n,2n)$, ${}^3_1H(n,2n)$, and ${}^{12}_6C(n,n2\alpha)$

Slide courtesy of S. Sepke

DT Ignition

Twelve non-Fusion Reactions Generate Neutrons

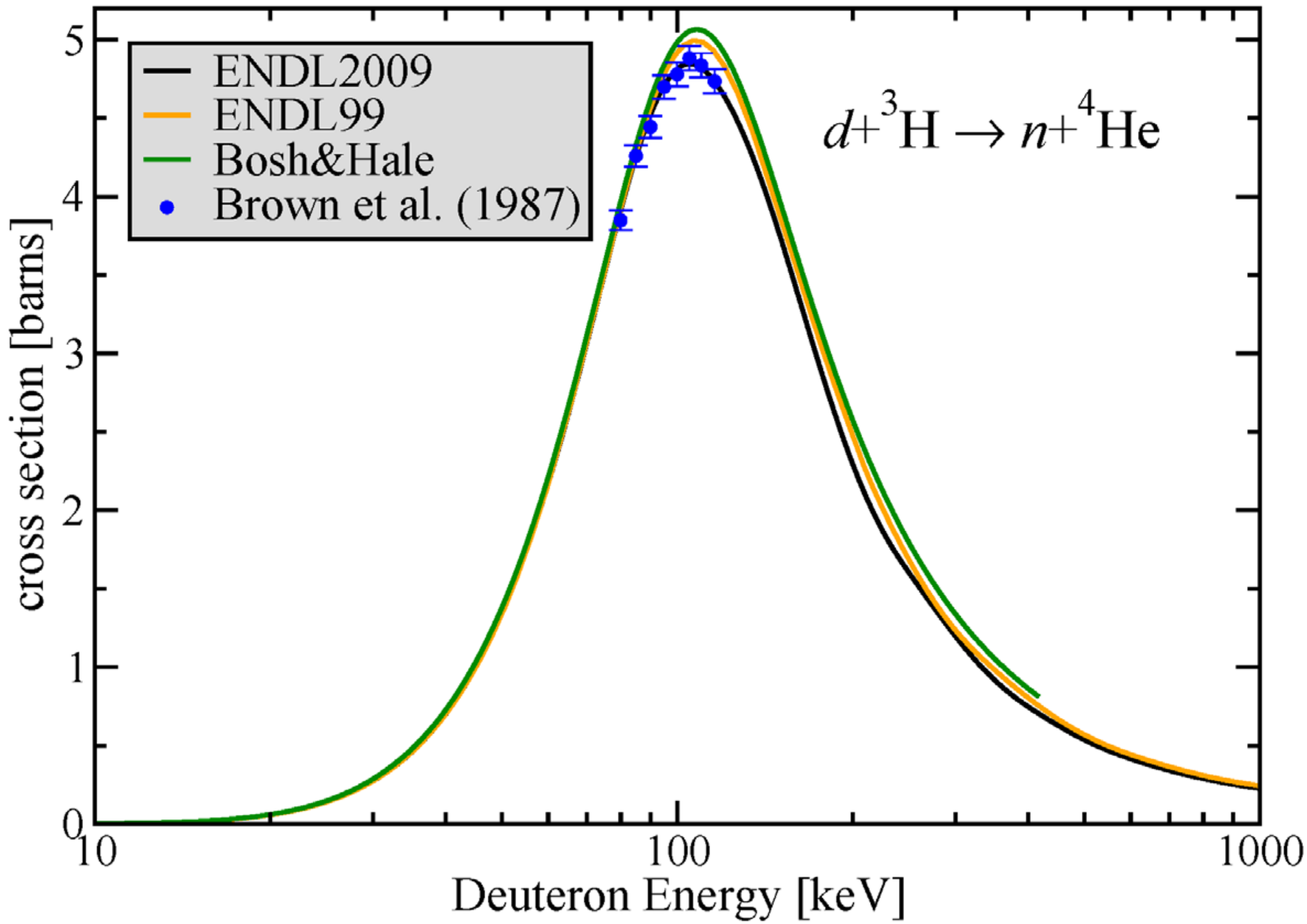
Twelve in-flight nuclear reactions generated neutrons in the simulation in addition to the DD, DT, and TT reactions.

Number of Escaped Neutrons Between 1 and 10 MeV			
$^{2}H(n,2n)$	4.87×10^{14}	$^{28}Si(n,np)$	1.27×10^{11}
$^{12}C(n,n2\alpha)$	3.40×10^{13}	$^{29}Si(n,2n)$	1.17×10^{11}
$^{3}H(n,2n)$	2.25×10^{13}	$^{2}H(p,pn)$	8.06×10^{10}
$^{13}C(n,2n)$	1.14×10^{12}	$^{30}Si(n,2n)$	6.92×10^{10}
$^{3}H(p,n)$	8.86×10^{11}	$^{28}Si(n,n\alpha)$	4.04×10^{10}
$^{16}O(n,n\alpha)$	3.32×10^{11}	$^{3}He(t,np)$	3.21×10^{10}

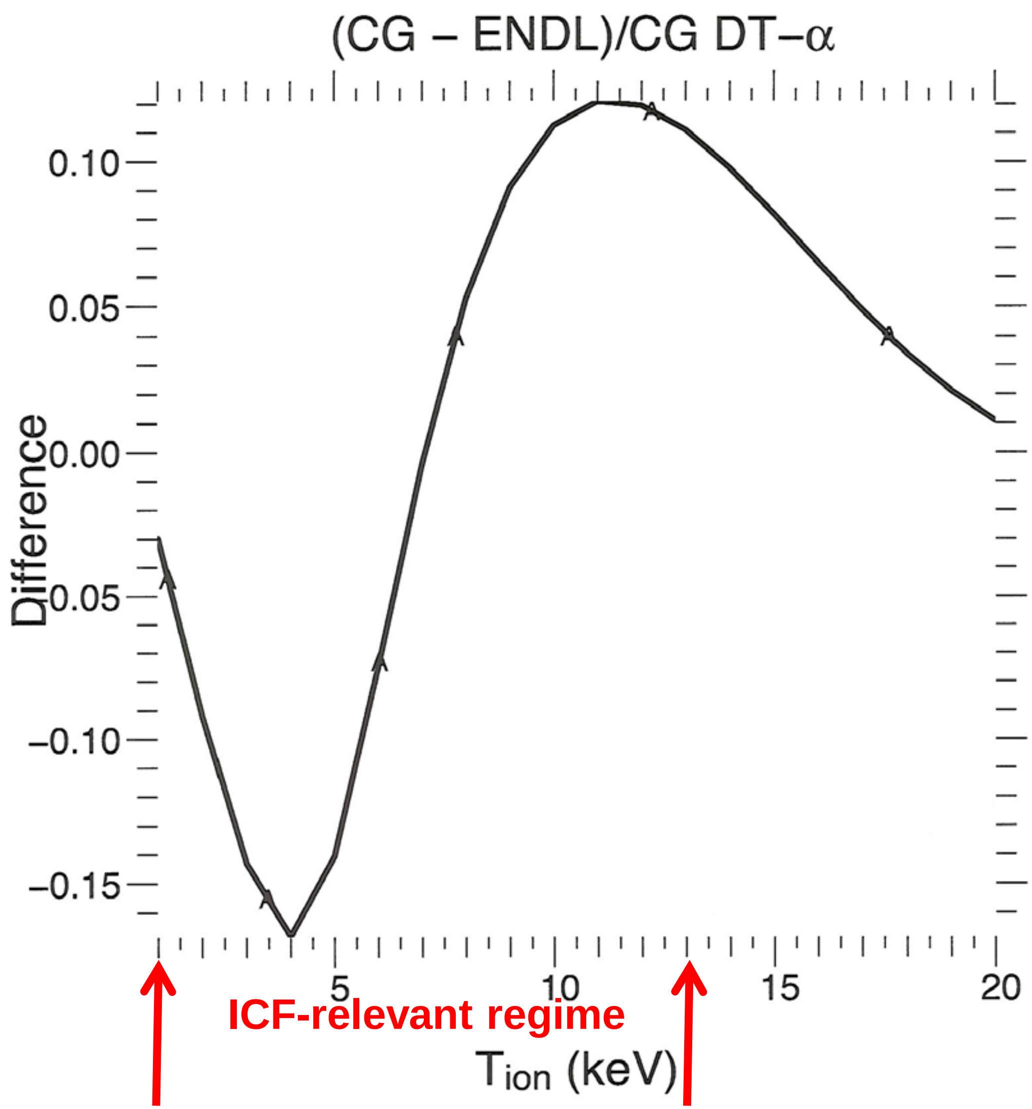
Notice that in this capsule $^{2}H(n,2n)$, $^{3}H(n,2n)$, and $^{12}C(n,n2\alpha)$ generated a number of neutrons on par with the DD and TT fusion reactions: 5.84×10^{13} and 5.15×10^{13}, respectively.

Slide courtesy of S. Sepke

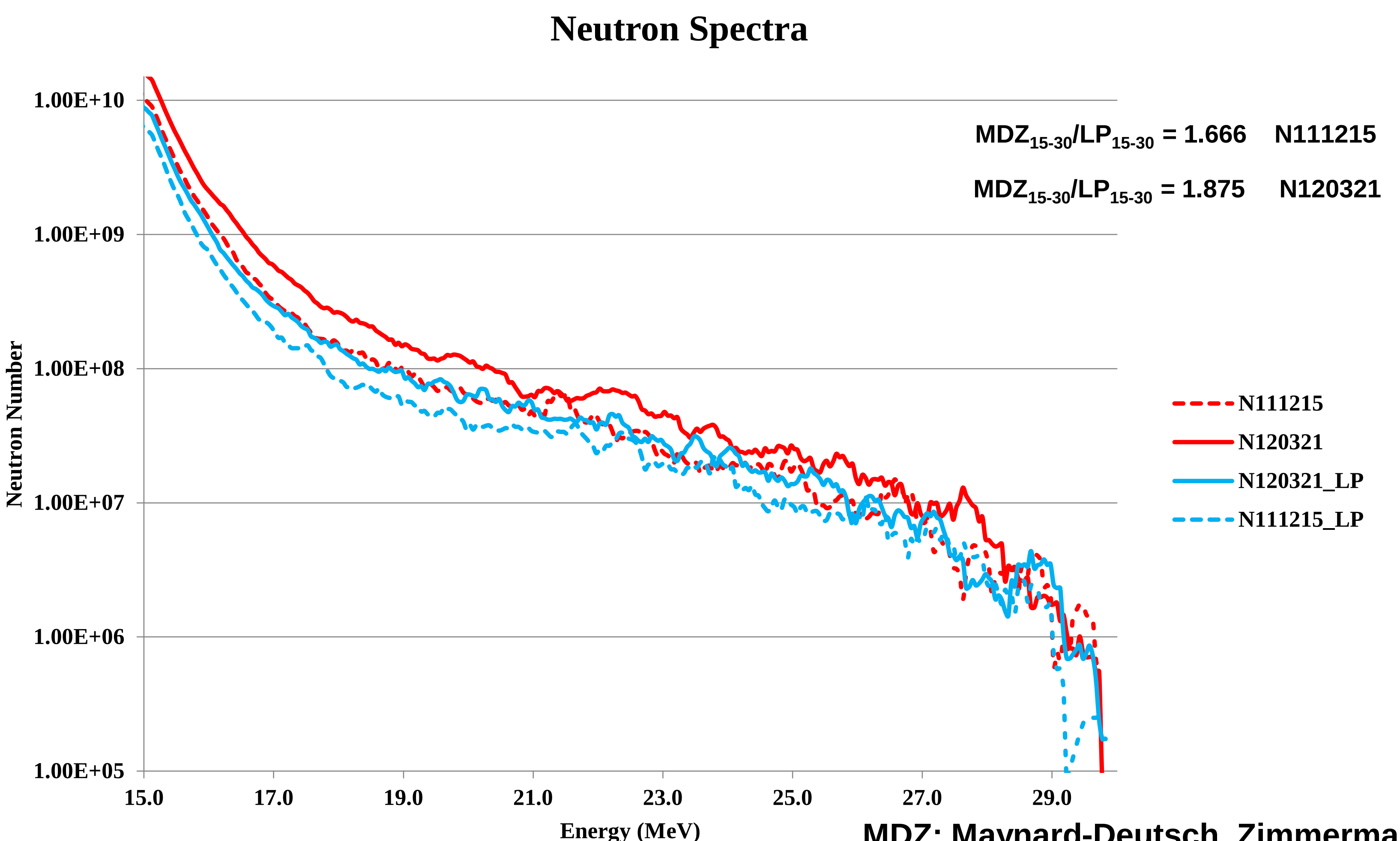
Comparison of DT fusion rates
Experimental data at high deuteron energies only



Comparison of DT fusion rates
Different fits lead to 15% relative variation



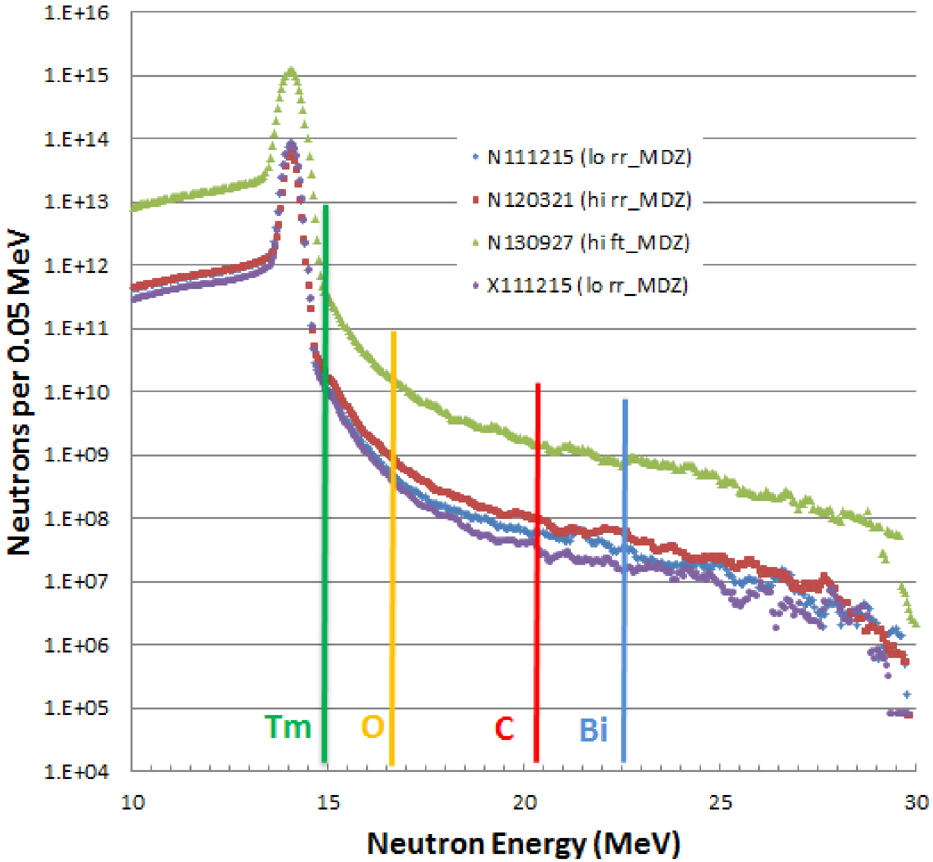
Different alpha particle stopping power models have reaction-in-flight neutron spectral signatures. Observable?



MDZ: Maynard-Deutsch_Zimmerman
LP: Li-Petrasso-Zylstra

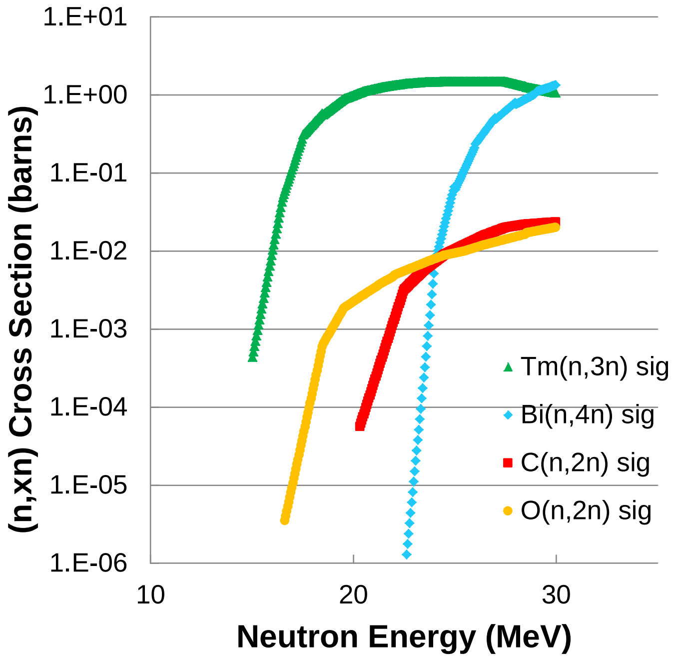
Selected NIF neutron spectra with (n,xn) detector thresholds and cross sections

Slide courtesy of E. Henry



Neutron spectra from Cerjan; thresholds from NNDC

Tm(n,3n) NIF measurement
Hayes, Tonchev, Wilhelmy et al.
(Phys. Plasmas, submitted)



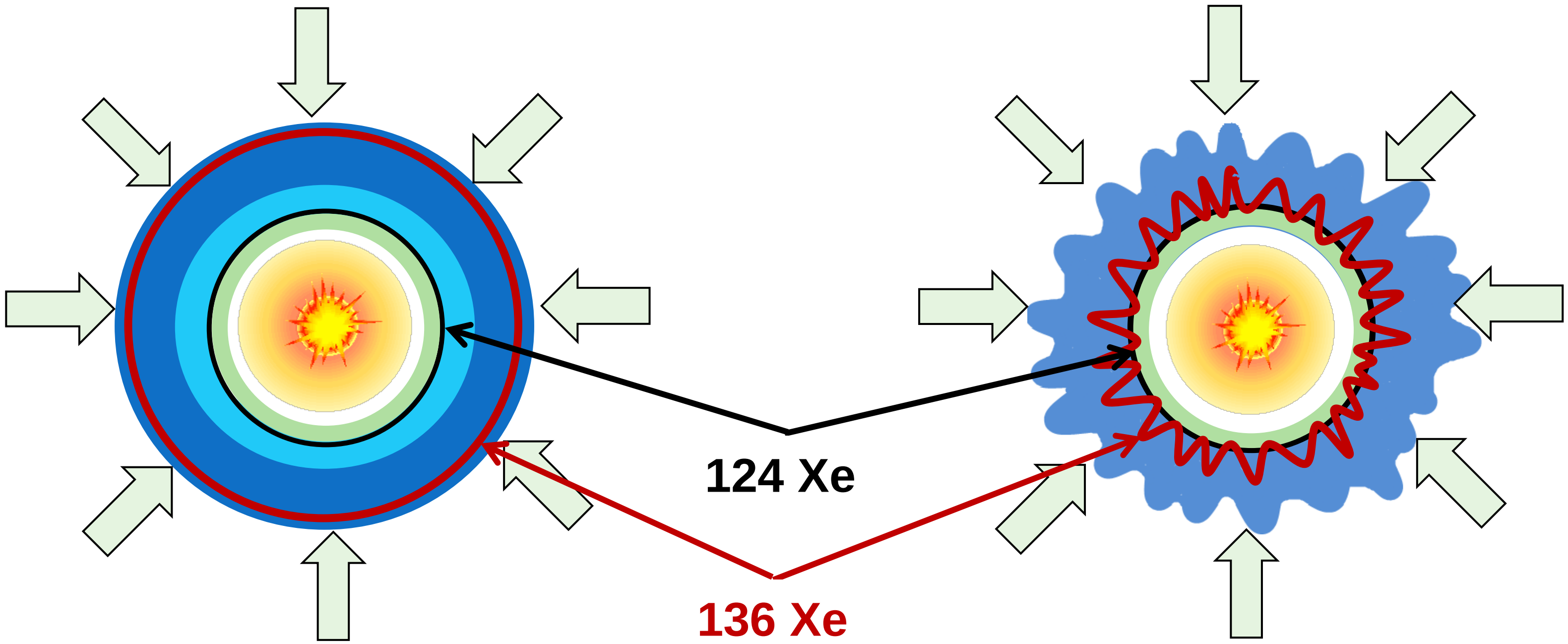
Cross sections for Bi, C, and O are estimates

Nuclear reaction signatures for cold shell mix diagnostics are programmatically important.

- X-ray emission diagnostics are typically used to quantify cold material mix into the hot core.
  - This approach is essentially limited to the hot (emitting) regions.
- Neutron and charged particle reactions are not limited to the hot core region.
  - The relevant (n,2n), (p,n), (d,2n) and (t,3n) cross sectional data is needed.
  - Examples: ^{124}Xe(n,2n)^{123}Xe and ^{79}Br(d,2n)^{78}Kr detected with RAGS.
    - TUNL data for ^{124}Xe acquired (Bhike, Phys. Rev. C 2015).
  - Possible validation with x-ray spectroscopy.
- Xe-doped SymCap experiments ready to be fielded in FY15/FY16.
  - Two regions of a CH/Si SymCap have been doped with ^{136}Xe (outer region) and ^{124}Xe (inner region) by D. Hoover (GA) and S. Kucheyev (LLNL).
  - In-line radiochemical simulations in HYDRA predict a small ratio of the (n,2n) activation products ^{135}Xe/^{123}Xe due to ablative stabilization.
    - First experimental test of this prediction.
    - Demonstration of RAGS capability with neutral atom AMS detection.

Xe isotope tracers will measure the amount of ablator penetration into the fuel and identify its location in the ablator. Accurate (n,2n) cross sections are needed.

No-mix implosion	High mix implosion



The outer tracer with ^{136}Xe is far from the hot spot at bang time; the 14 MeV neutron fluence (neutrons/cm^2) and consequent (n,2n) interactions it experiences will be low; so the ^{135}Xe activation level detected by RAGS will be low compared to the inner ^{123}Xe activation level

The outer tracer, ^{136}Xe, will be closer to the hot spot, the 14 MeV neutron fluence (neutrons/cm^2) and consequent (n,2n) interactions it experiences will increase, so the ^{135}Xe activation level detected by RAGS will increase compared to the inner ^{123}Xe activation level

Detection of DT-fusion α reactions would provide a direct test of shell material mixed into the hot core.

Candidate (α,n) detector materials

- The $^{10}B(\alpha,n)^{13}N$ reaction has nearly the best energetics
- The half-life is reasonable
- The product is a gas
- The decay mode is not distinctive
- diborane (B_2H_6) is a gas

Target	Product	Q-Value (MeV)	Threshold (MeV)	Coul. Bar. (MeV)	Half Life (s)	Radiation	Chem. Form
^{6}Li	^{9}B	-3.98	6.62	1.6	8.00E-19	p,2a	Solid
^{9}Be	^{12}C	5.70	0.00	2.0	Stable		Solid, Gas?
^{10}B	^{13}N	1.06	0.00	2.4	598	β+	Gas
^{12}C	^{15}O	-8.50	11.34	2.8	122	β+,e	Gas
^{14}N	^{17}F	-4.35	6.09	3.2	65	β+	Gas
^{16}O	^{19}Ne	-12.14	15.17	3.5	17	β+,γ	Gas
^{19}F	^{22}Na	-1.95	2.36	3.8	8.22E+07	β+,e,γ	Solid
^{20}Ne	^{23}Mg	-7.22	8.66	4.2	11	β+,γ	Solid
^{23}Na	^{26}Al	-2.97	3.48	4.5	2.27E+13	β+,e,γ	Solid
^{24}Mg	^{27}Si	-7.20	8.40	4.8	4	β+,γ	Solid
^{27}Al	^{30}P	-2.64	3.03	5.1	150	β+,e,γ	Solid

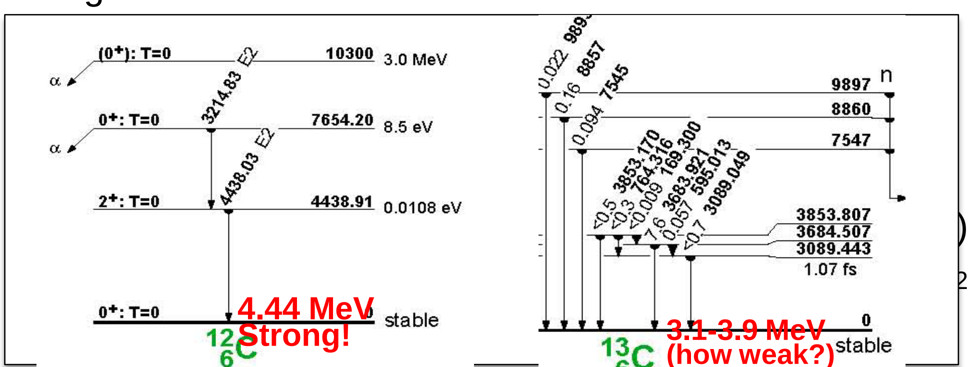
National Nuclear Data Center

Slide courtesy of E. Henry.

Ablator-cold shell mix diagnostic using ^{12}C–γ 4.4 MeV emission from a buried layer ^{12}CH layer in a ^{13}CH capsule.

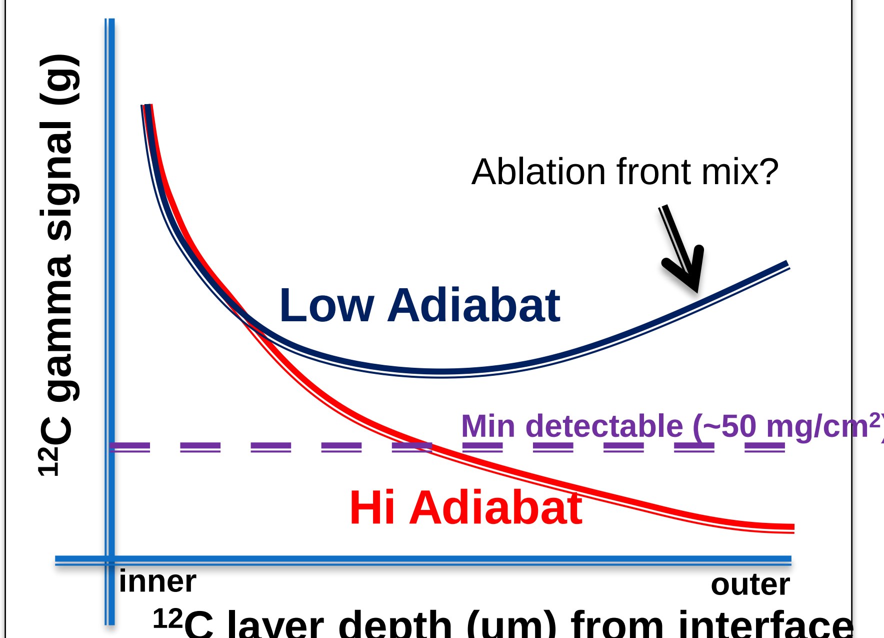
- **Physics Goal- (1)** demonstrate lack of n-induced γ signal from ^{13}C (as compared to strong 4.44 MeV ^{12}C (n,n')γ). **(2)** If true, ^{12}C buried layers in ^{13}C-based HDC (or CH) capsules could be used to infer origin of C mix through GRH ρR measurements (and eventual imaging). Can combine with Xe &/or Ge-doping.

- **Experimental concept**
  - Expose ^{13}C & ^{12}C pucks to n-flux at OMEGA and measure γ's with GRH & Super GCD. **Continue if >10x difference** at ~3 MeV threshold.
  - Implode pure ^{13}C capsule on NIF for Hohl/TMP bkgnd
  - Then ^{12}C layers buried in ^{13}C capsules to infer Mix origin



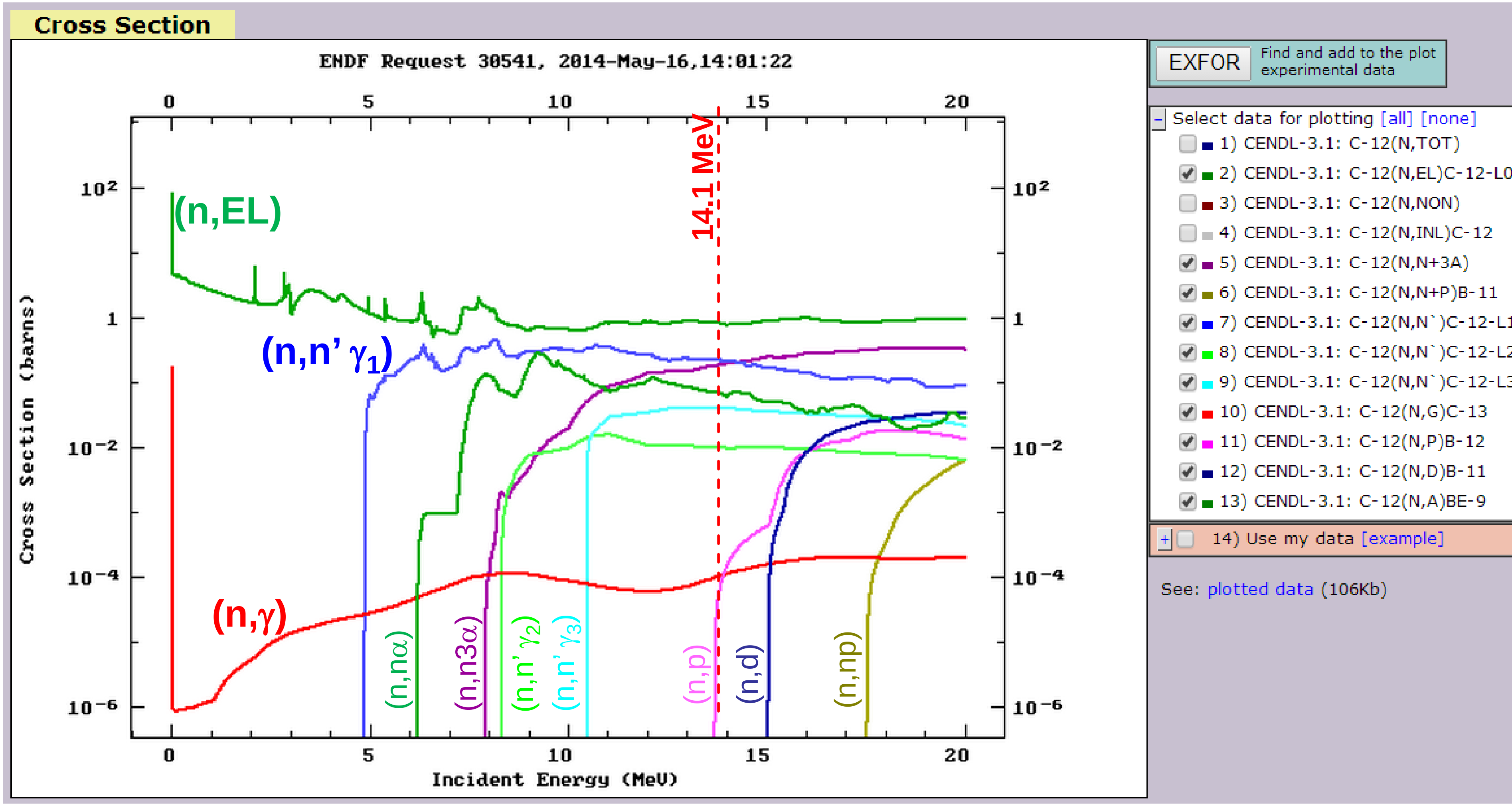
Energy Level Diagrams

Carbon gammas may illuminate Dark Mix

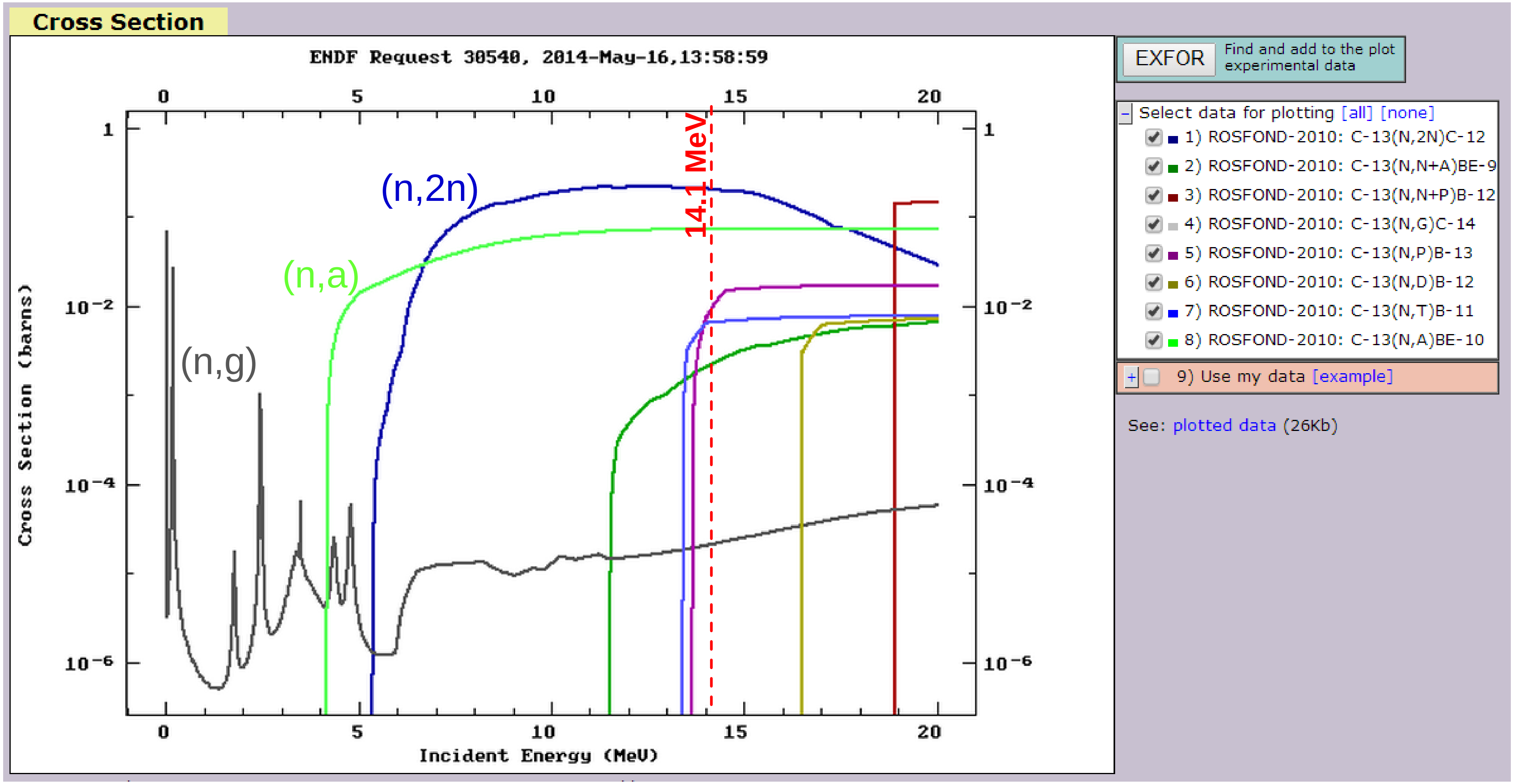


This will help us determine where carbon ablator mix is coming from and when; sensitive to Dark Mix (unlike x-rays & separated reactants)

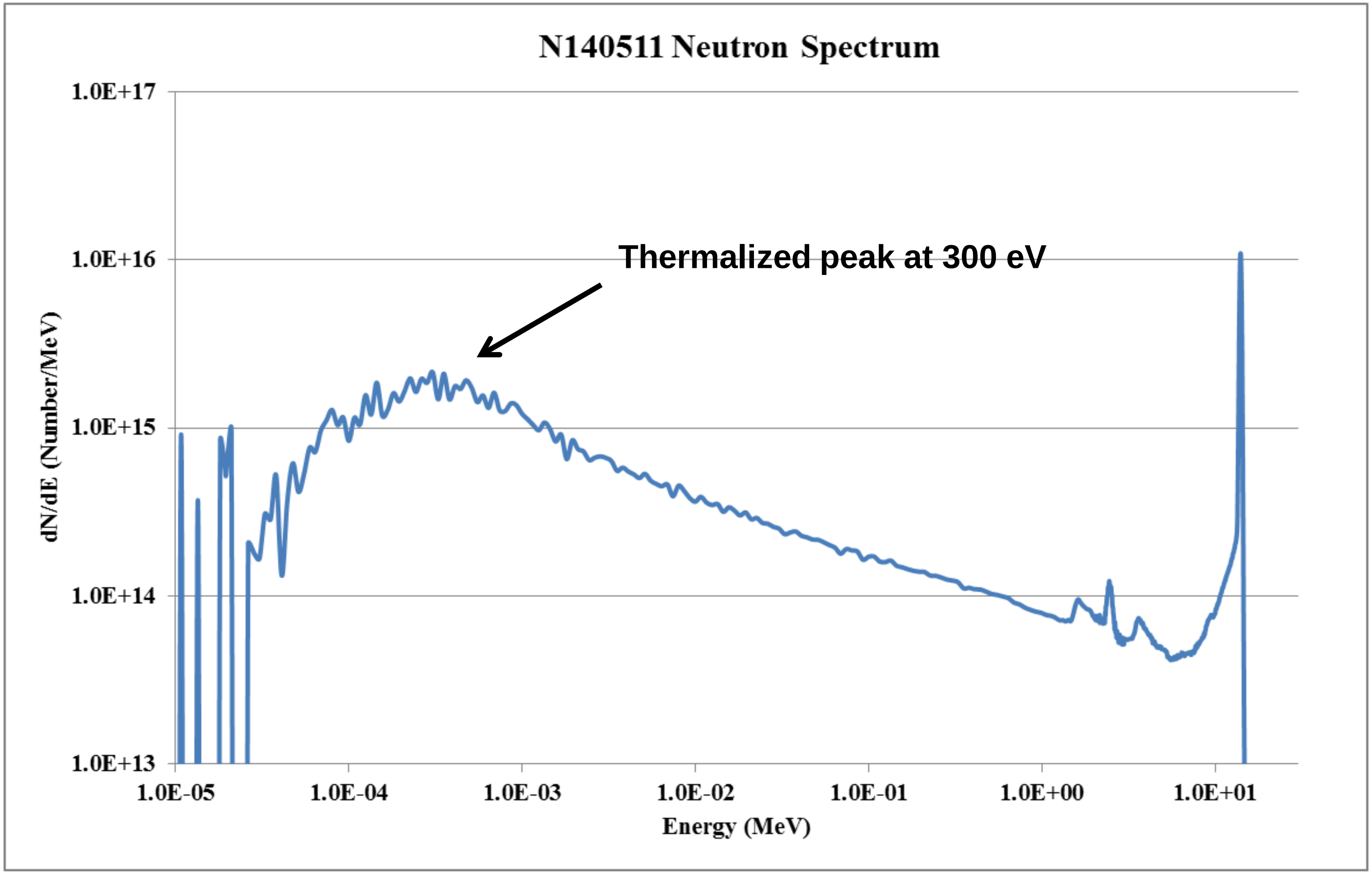
^{12}C has a large $\sigma(n,n'\gamma_1)$ producing the 4.44 MeV γ



Corresponding ^{13}C data is required. ENDF doesn't list σ for $^{13}C(n,n')$, and (n,γ) is exceedingly small (<0.1 mb). Correct?

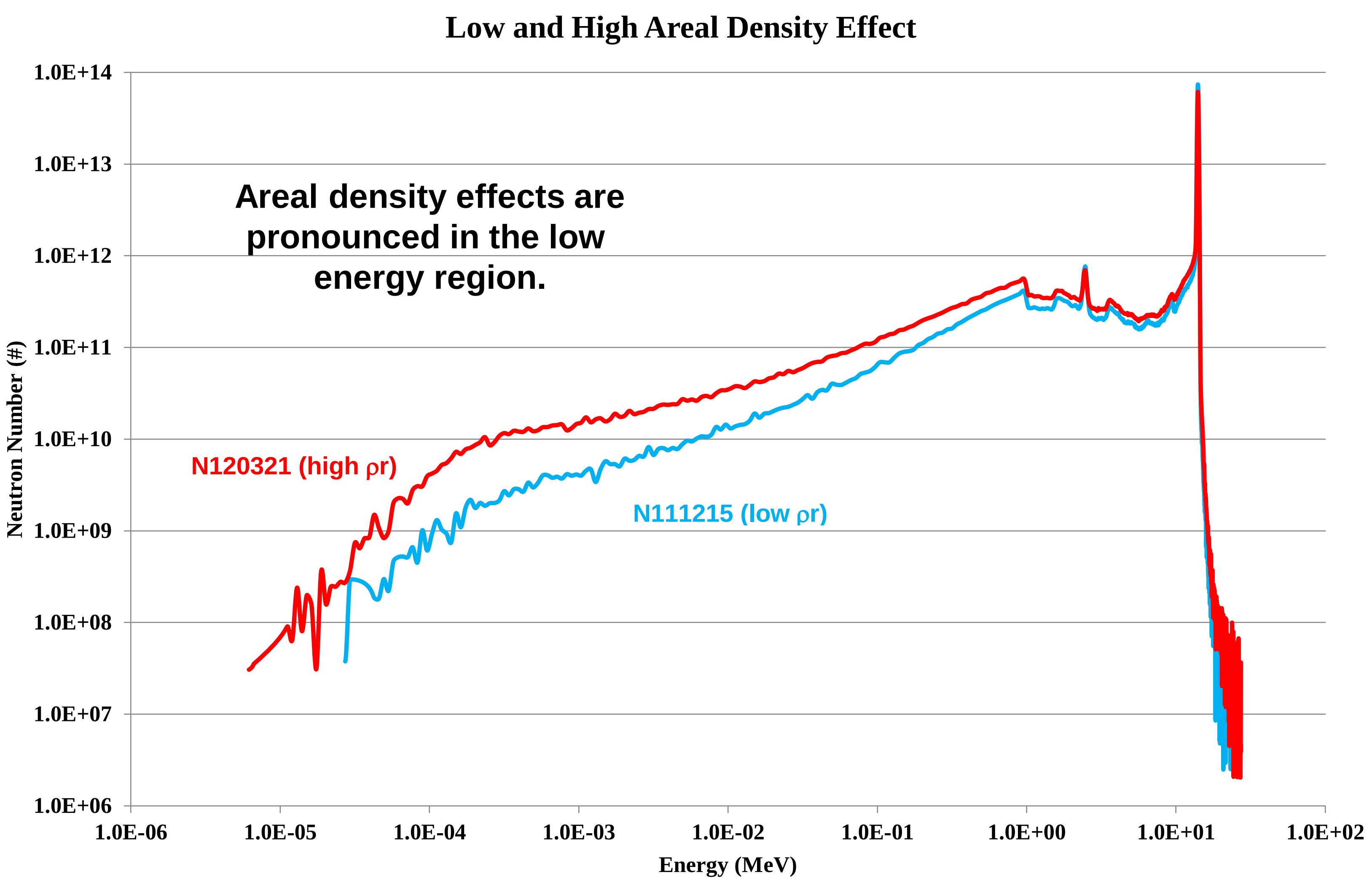


N140511 (high foot) low energy neutron spectrum Characterization requires (n,γ) capture cross sections (SRC diagnostic).



Total yield = 7.4 x 10^{15}

Experimental characterization of the thermalized neutron spectrum is necessary for capture reactions. Diagnostic information available but not currently understood.



Acknowledgements

Nuclear Physics

L. Bernstein, R. Bionta, D. Bleuel, J. Caggiano, D. Casey, D. Fittinghoff, G. Grim, R. Hatarik, A. Hayes (LANL), E. Henry, H. Herrmann (LANL), J. Knauer (LLE), F. Merrill (LANL), D. Sayre, D. Shaughnessy, W. Stoeffl, A. Tonchev, J. Wilhelmy (LANL), C. Yeamans

HYDRA

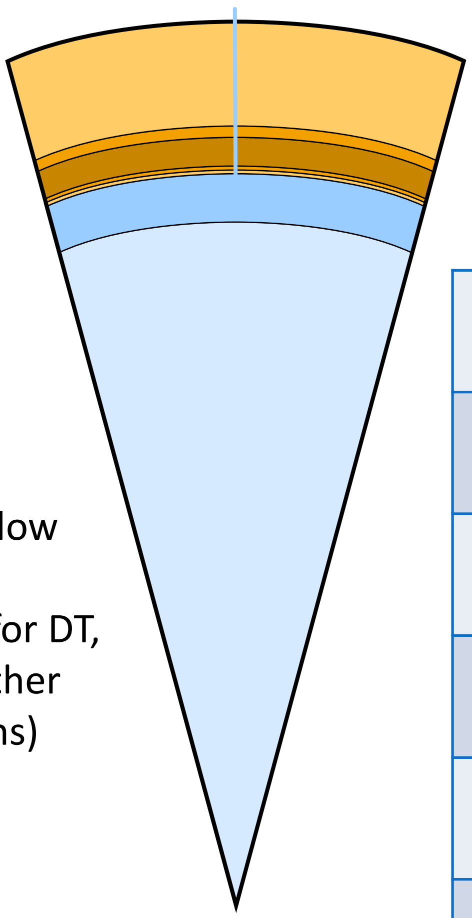
M. Marinak, M. Patel, S. Sepke

BACKUP

CH(Si) THD Design v3.3 (from Haan 8/15/11, updated 9/28/11, densities updated 9/13/11)

(all dimensions and densities at cryogenic temp)

Inner CH radius = 935 (± n/a) um
Outer radius = 1130 ± 5 um
Wall 195 ± 3 um
CH density(cryo) = 1.034 +0.025*Si% +0.029*Ox%
Densities below assume 0.5 at% oxygen
Thermal contraction taken to be 1/1.0127

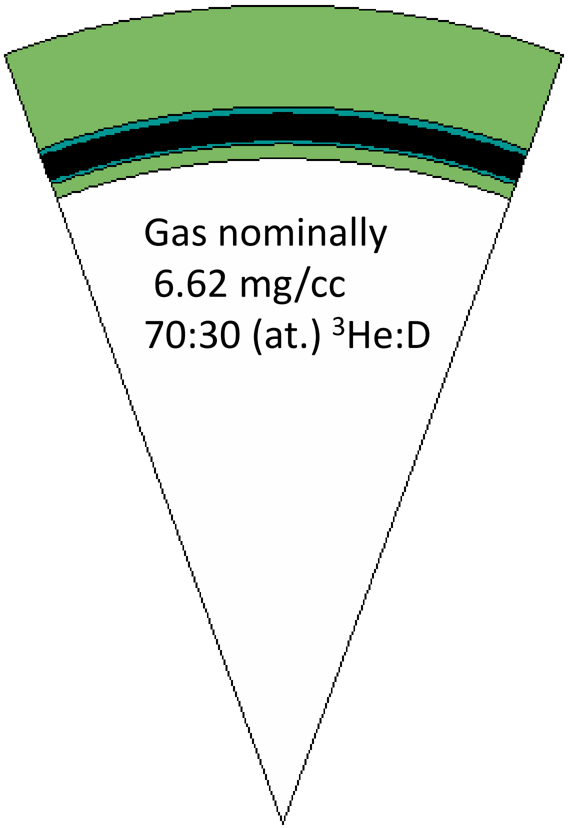


Fuel layer
69 microns

Gas density
set 1.5 K below
triple point
(0.3 mg/cc for DT,
varies for other
compositions)

Layer	Thickness (um)	Si dopant (at%)	Cryo density (g/cc)
1 (inside)	6±2	Nominally 0, req't <0.1	1.049
2	6±2	1±0.2	1.074
3	35±2	2±0.2	1.099
4	10±2	1±0.2	1.074
5 (outside)	(balance)	Nominally 0, req't <0.05	1.049

CH(Si) Symcap Design v3.2 (from Haan 7/1/11, densities updated 9/13/11)
(all dimensions and densities at cryogenic temp)



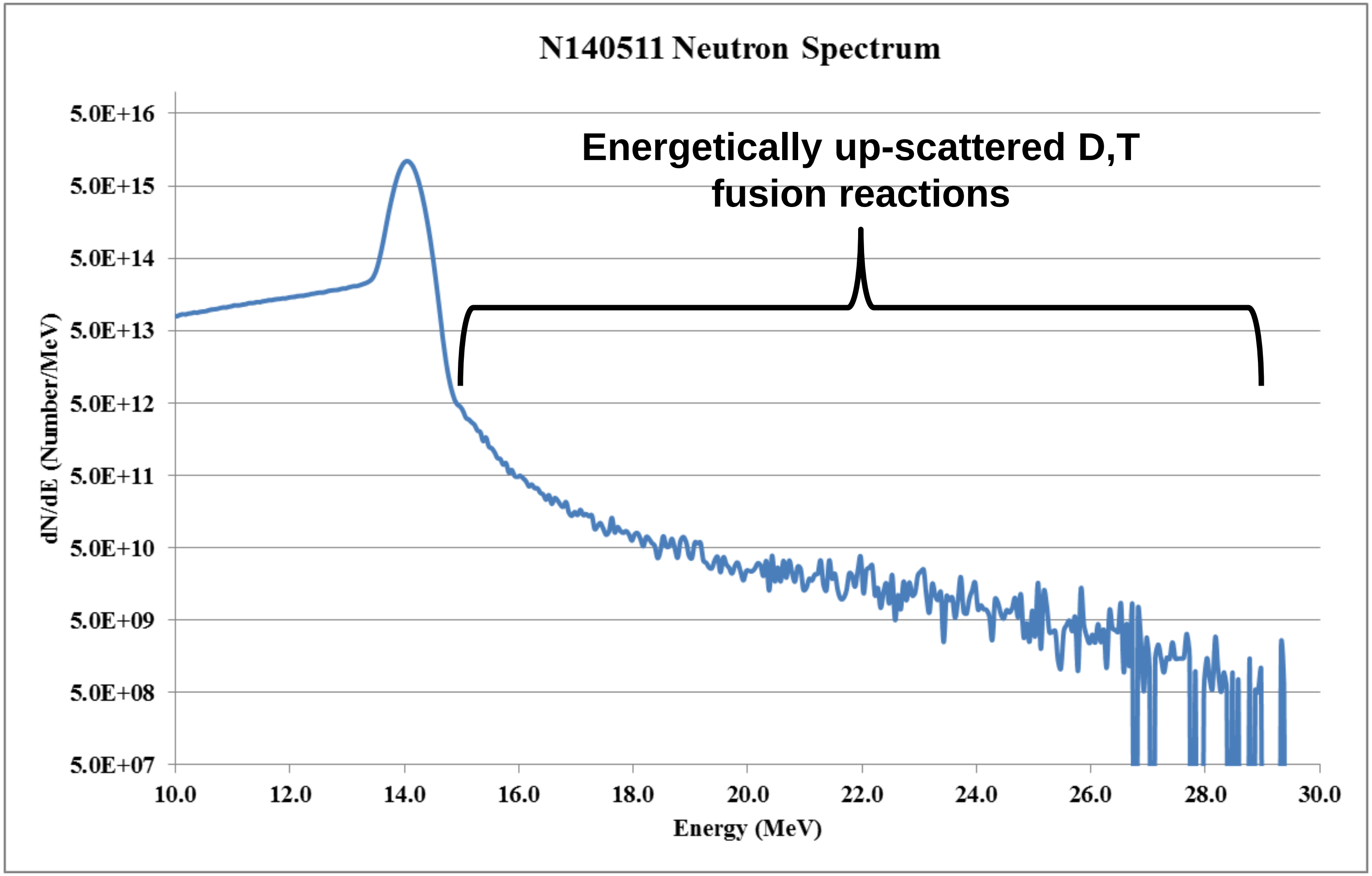
Inner radius = 928 (± n/a) um
Outer radius = 1137 ± 5 um
Wall 209 ± 3 um
CH density(cryo) = 1.034 +0.025*Si% +0.029*Ox%
Densities below assume 0.5 at% oxygen
Thermal contraction assumed to be 1/1.0127

Layer	**Thickness (um)**	**Si dopant (at%)**	**Estimated density (g/cc)**
1 (inside)	20±2	Nom. 0, req't <0.1	1.049
2	6±2	1±0.2	1.074
3	35±2	2±0.2	1.099
4	10±2	1±0.2	1.074
5 (outside)	(balance)	Nom. 0, req't <0.05	1.049

Higher neutron yield with larger DT fuel areal density provides a wider neutron spectral range.

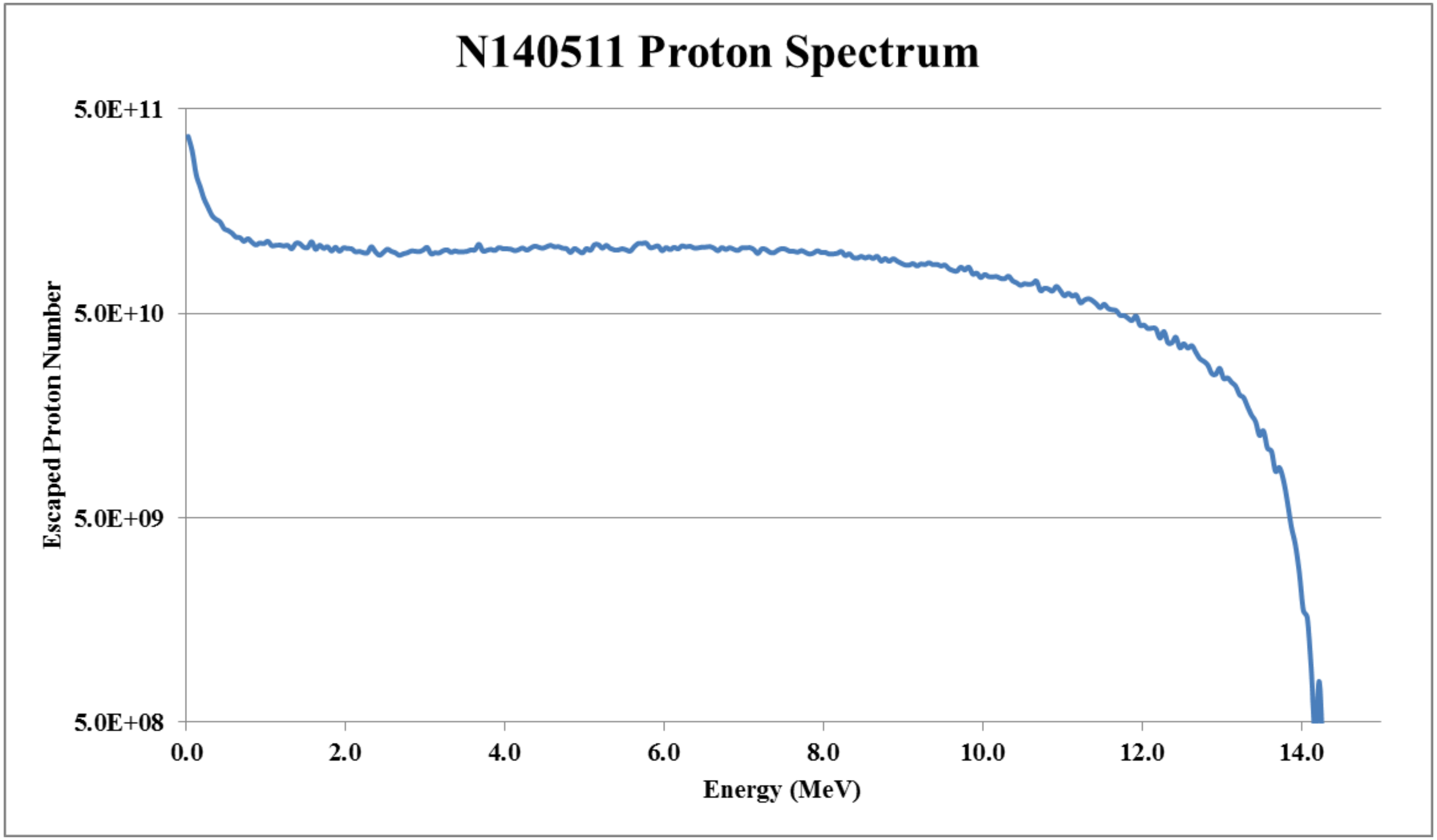
- High foot laser drive with a conventional CH ablator capsule represents an improvement upon the performance of the Symcap platform.
  - Stable, repeatable platform with ~5 x 10^{15} neutrons in 150 ps.
  - Higher doping levels possible (?).
  - Dopant loading during fabrication must be demonstrated.
- High energy neutron spectrum (> 14 MeV)
  - Reaction-In-Flight (RIF) neutrons populate this energy range.
  - Stopping power experiments require larger neutron yields to reduce experimental uncertainties.
- Thermalization neutron spectrum (< 1 MeV)
  - Larger DT areal densities required to produce sufficient low-energy signal.
  - SRC diagnostic probes this energy range and provides late-time ablator areal density and remaining shell temperature dependence.
  - Low Energy Neutron Spectrometer (LENS) would be very desirable.

N140511 (high foot) high energy neutron spectrum



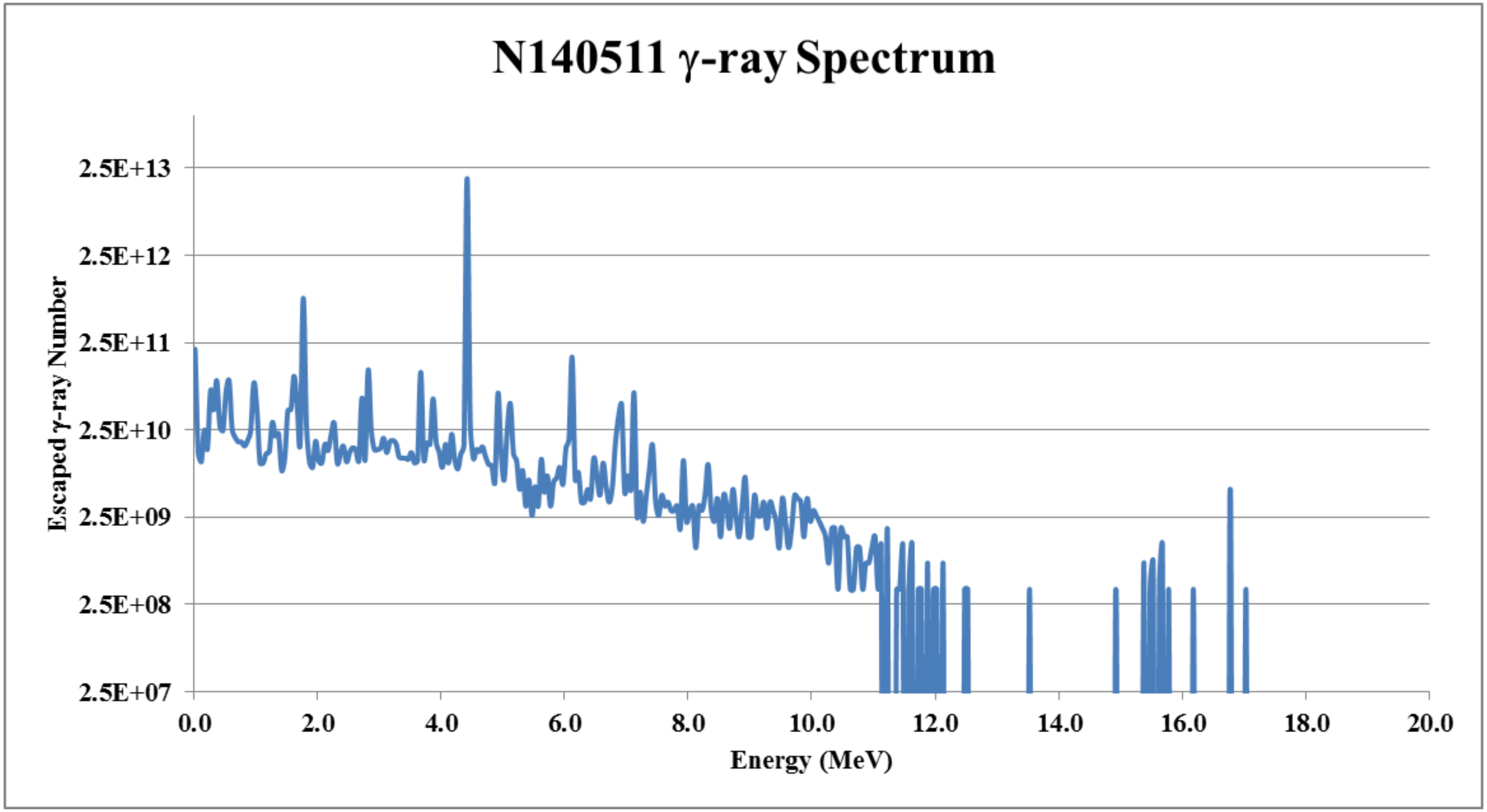
Total yield = 7.4 x 10^{15}

N140511 (high foot) escaped protons from n-p scattering in the remaining CH ablator.



Total yield = 2.5 x 10^{13}

N140511 (high foot) γ-ray spectrum dominated by $^{12}C(n,n'\ \gamma)$ scattering.



Total ^{12}C-γ yield = 2.0 x 10^{13}

HYDRA (very briefly)

- The primary implosion experiment simulation tool used for NIF experimental design and analysis.
  - ALE (Adaptive Lagrange-Euler)
  - Finite element based (quadrilateral in 2D or hexahedral elements in 3D)
  - Massively parallel
  - PYTHON user scripts may be readily linked.
- Physics capabilities are extensive.
  - Consistent numerical treatment of the hydrodynamic equations, diffusive radiation transport, and diffusive electron conduction.
  - Substantial flexibility exists for different EOS and conductivity model choices.
  - Implicit Monte Carlo photon transport.
  - Particle Monte Carlo neutron, charged particle, and gamma-ray generation and transport.
  - In-line or post-processing radiochemistry available (KUDU).
- A static three-dimensional model exists that correlates implosion diagnostics and quantifies the stagnation properties.

Noteworthy nuclear physics-based capabilities at the NIF not discussed.

- **Proton Time-of-Flight (pTOF)**
  - Fielded and analyzed by Hans Rinderknecht/MIT.
  - Shock flash bang time in D/^{3}He gas fills.
- **Wedge Range Filters (WRF)**
  - Fielded and analyzed by Alex Zylstra/MIT
  - Capsule areal density at shock flash bang time in D/^{3}He gas fills.
- **Both techniques probe charged particle stopping power.**
  - Both are limited to low areal densities currently.