Imperial College London

Reduced-Dimension Multigroup Neutron Transport Code for ICF Experiments

Bryn Lloyd

Laboratory Astrophysics with ICF technology

- ICF is a unique platform for fundamental science
  - High energy density environment
  - Large neutron flux [1]

- Particularly suited to s-process experiments [2]
  - excited nuclear states present in HED environment [3]

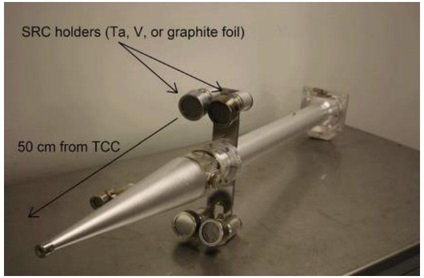

Fig.1 (top) Beryllium capsule, taken from [4]
(bottom) SRC from NIF, taken from [5]

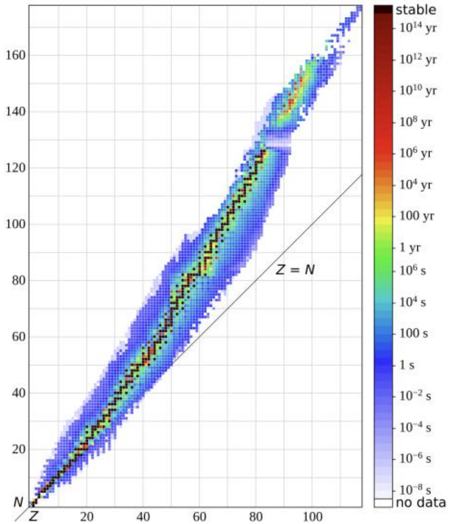

Fig.2 Chart of Nuclides, taken from [6]

[1] https://doi.org/10.1103/PhysRevLett.129.075001
[2] https://doi.org/10.1103/RevModPhys.29.547
[3] https://doi.org/10.1585/pfr.9.4404101
[4] https://www.osti.gov/biblio/909643
[5] https://doi.org/10.1063/1.4883186
[6] https://en.wikipedia.org/wiki/Table_of_nuclides

Aims

- Develop a neutron transport code
  - Focus on low energy
  - Customisable capsule structure and composition
  - Computational Simplicity is prioritised

- Validate model
  - Comparison with analytic solution and other simulation results

- Use the model
  - Investigate neutron moderation for use in nucleosynthesis experiments
  - Test assumptions required for nucleosynthesis experimental process

Neutron Transport

$$\boxed{\frac{1}{v}\frac{\partial\psi}{\partial t} + \boldsymbol{\Omega}\cdot\nabla\psi + n\sigma\psi = n\iint \frac{d^2\sigma}{dE\,d\boldsymbol{\Omega}}\psi\,dE\,d\boldsymbol{\Omega} + \mathrm{Q}}$$

Standard Form

$$\frac{1}{v}\frac{\partial\phi}{\partial t} + \iint \boldsymbol{\Omega}\cdot\nabla\psi\,dV\,d\boldsymbol{\Omega} + n\sigma\phi = n\int \frac{d\sigma}{dE}\phi\,dE + \mathrm{S}$$

$$\iint \boldsymbol{\Omega}\cdot\nabla\psi\,dV\,d\boldsymbol{\Omega} = \frac{1}{\mathrm{L}}$$

$$\frac{d\phi}{dt} = \left[-\frac{v}{L} - n\sigma v + nv\int \frac{d\sigma}{dE}dE\right]\phi + vS$$

Neutron Transport

$$\frac{1}{v}\frac{\partial \psi}{\partial t} + \boldsymbol{\Omega} \cdot \nabla \psi + n\sigma\psi = n\iint \frac{d^2\sigma}{dE\,d\boldsymbol{\Omega}}\psi\, dE\, d\boldsymbol{\Omega} + \mathrm{Q}$$

$\int dV$

$\int d\boldsymbol{\Omega}$

$$\boxed{\frac{1}{v}\frac{\partial \phi}{\partial t} + \iint \boldsymbol{\Omega} \cdot \nabla \psi\, dV\, d\boldsymbol{\Omega} + n\sigma\phi = n\int \frac{d\sigma}{dE}\phi\, dE + \mathrm{S}}$$

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Neutron Transport

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$$\frac{1}{v}\frac{\partial\phi}{\partial t} + \iint \boldsymbol{\Omega}\cdot\nabla\psi dVd\boldsymbol{\Omega} + n\sigma\phi = n\int \frac{d\sigma}{dE}\phi dE + \mathrm{S}$$

$$\boxed{\iint \boldsymbol{\Omega}\cdot\nabla\psi dVd\boldsymbol{\Omega} = \frac{1}{\mathrm{L}}}$$

Apply Approximation

$$\frac{d\phi}{dt} = \left[-\frac{v}{L} - n\sigma v + nv\int \frac{d\sigma}{dE}dE\right]\phi + vS$$

Neutron Transport

$$\frac{1}{v}\frac{\partial \psi}{\partial t} + \boldsymbol{\Omega} \cdot \nabla \psi + n\sigma\psi = n \iint \frac{d^2\sigma}{dE d\boldsymbol{\Omega}} \psi dE d\boldsymbol{\Omega} + \mathrm{Q}$$

$$\frac{1}{v}\frac{\partial \phi}{\partial t} + \iint \boldsymbol{\Omega} \cdot \nabla \psi dV d\boldsymbol{\Omega} + n\sigma\phi = n \int \frac{d\sigma}{dE} \phi dE + \mathrm{S}$$

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$$\boxed{\frac{d\phi}{dt} = \left[-\frac{v}{L} - n\sigma v + nv \int \frac{d\sigma}{dE} dE \right] \phi + vS}$$

Discretise energy

Computational Methods

1. Capsule Layers

2. Outside Layer

3. Target Layers

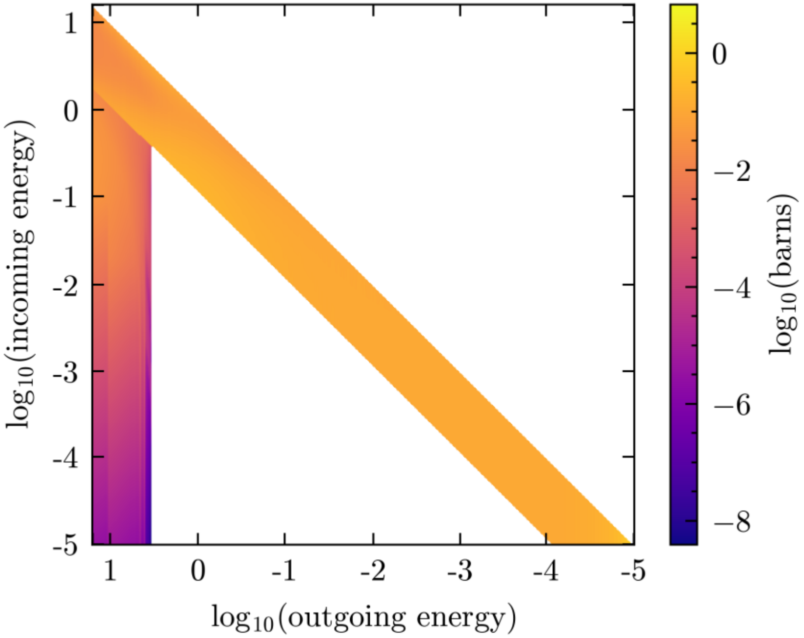

Fig.2 Scattering matrix for deuterium

Computational Methods

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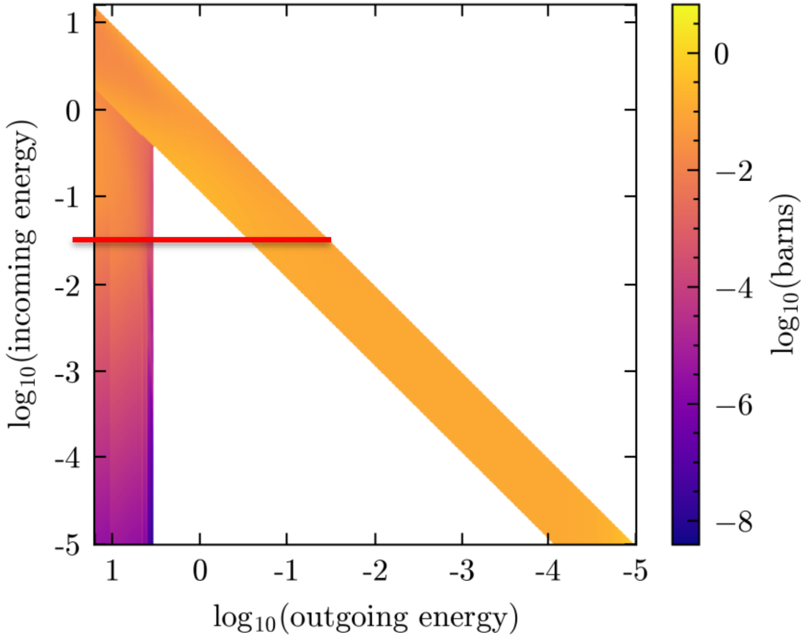

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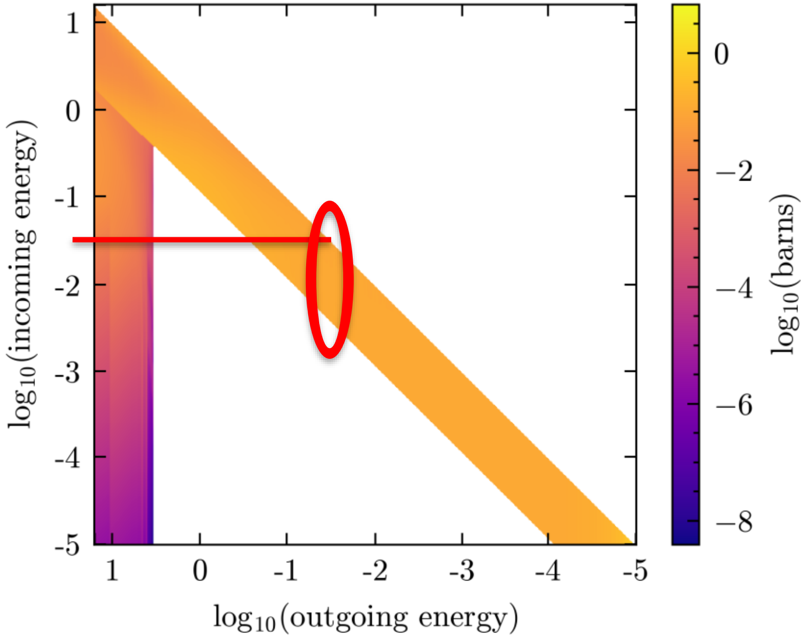

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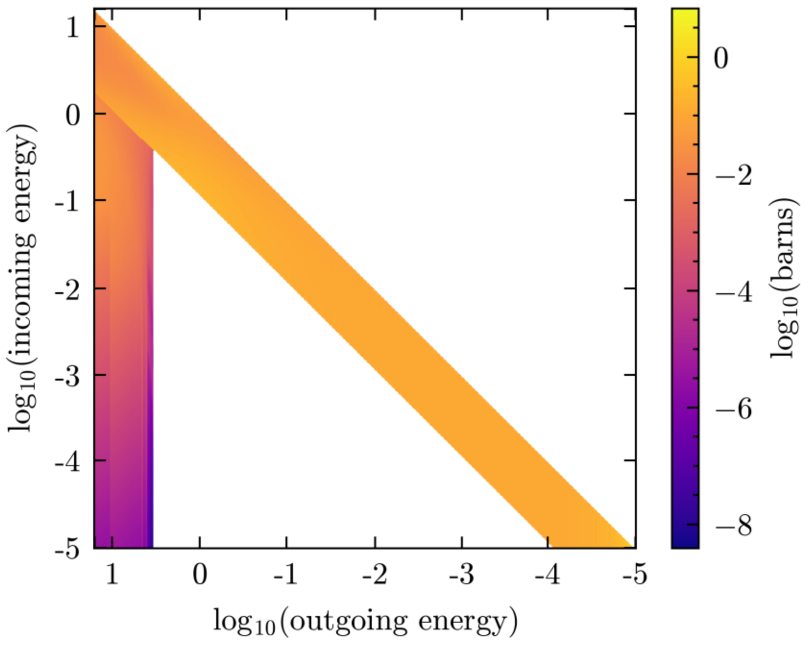

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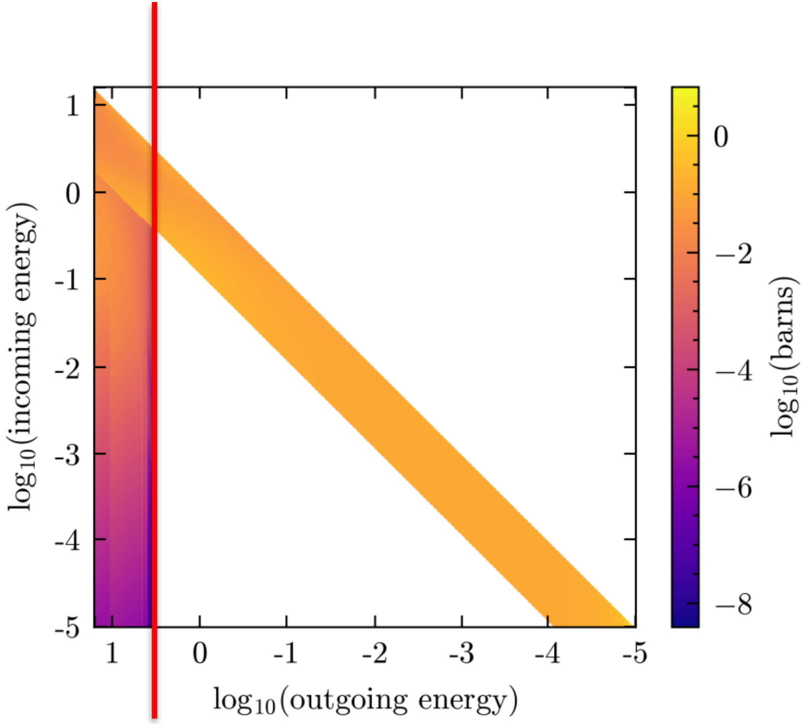

Fig.2 Scattering matrix for deuterium

Computational Methods

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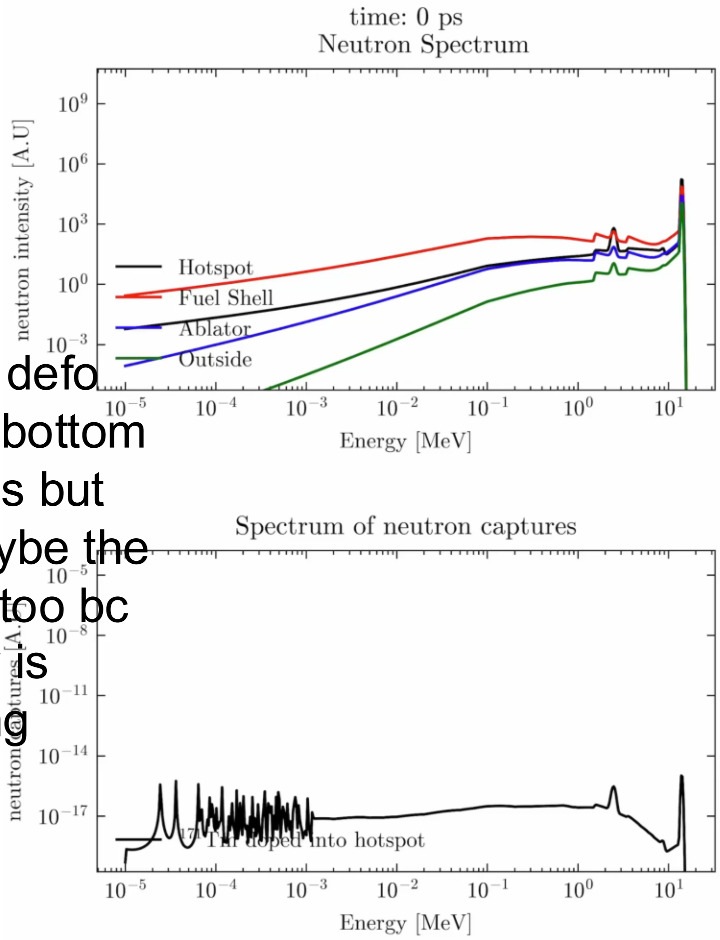
Need to defo multiply bottom by widths but also maybe the top one too bc intensity is confusing



Model Validation: High-Energy Behaviour

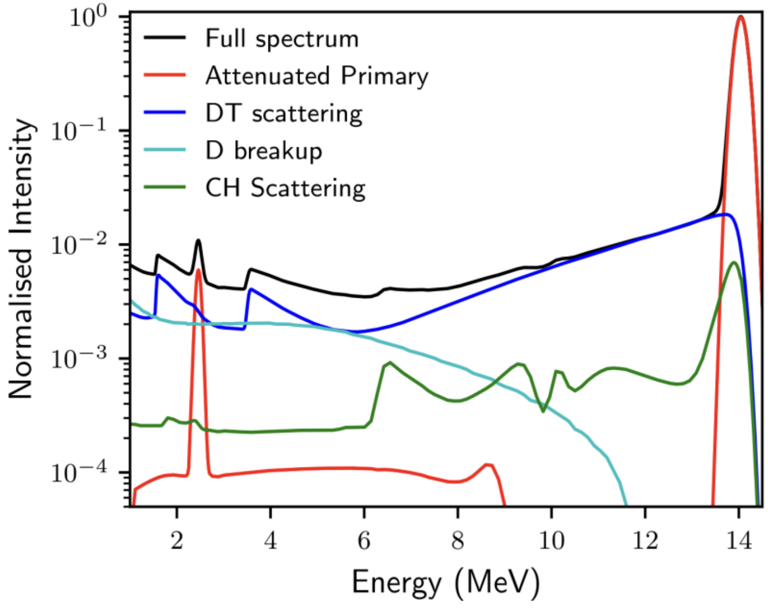


Fig.4 Neutron spectrum predicted by Minotaur, taken from [6]

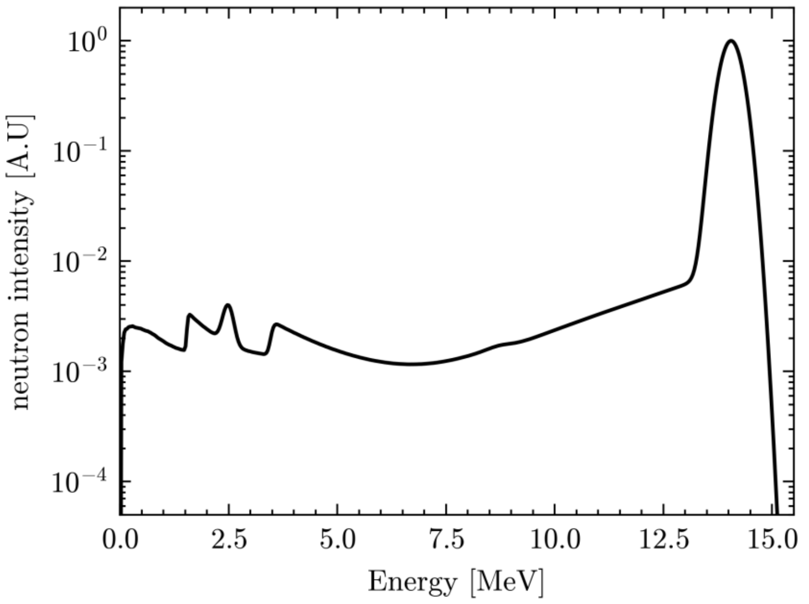


Fig.5 High-energy spectrum prediction

[6] A.Crilly https://doi.org/10.1063/1.5027462

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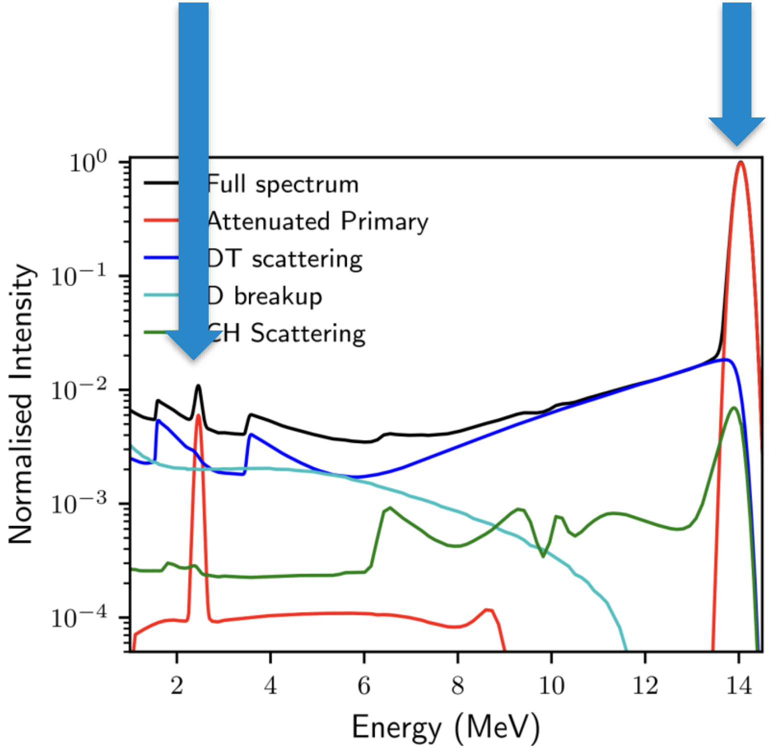

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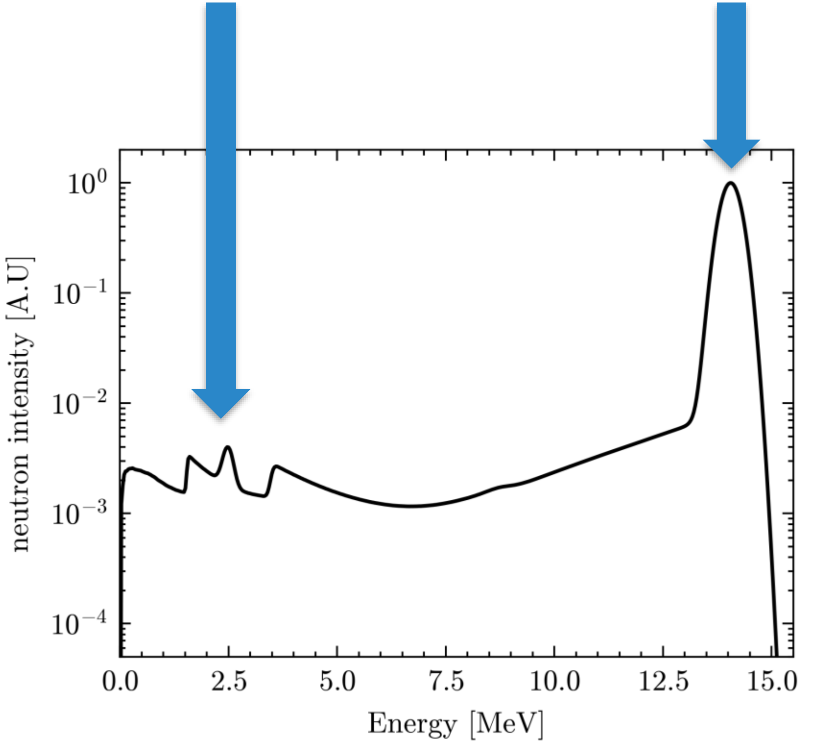

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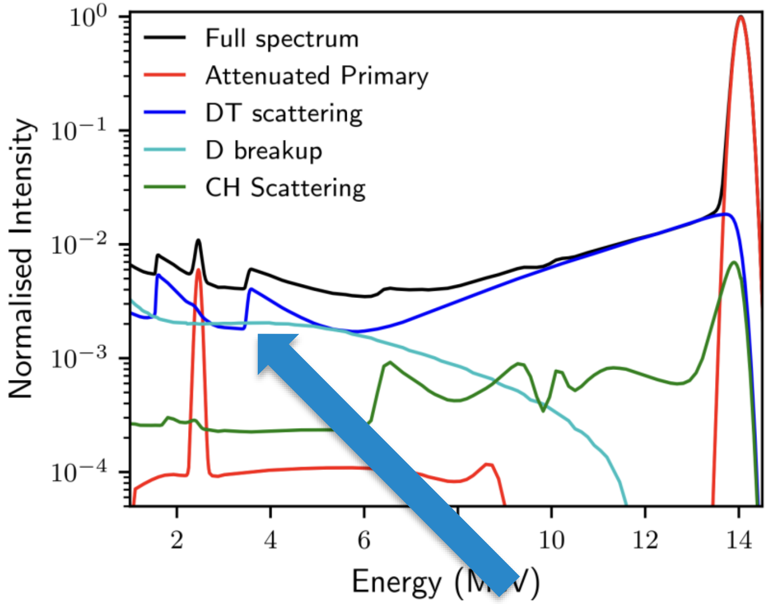

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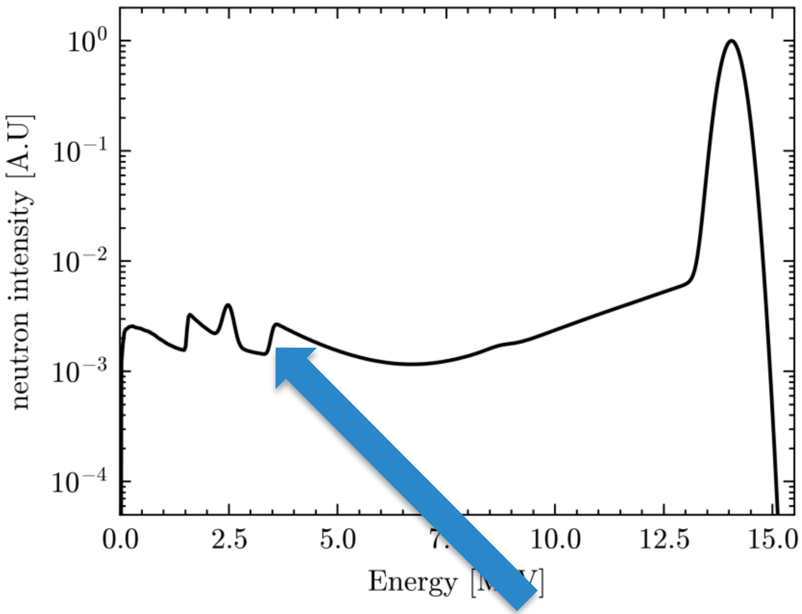

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Results: Example Nucleosynthesis Experiment

- Measurement of capture cross-section of excited nuclear states
- Use ground-state capture cross-section as a first guess

- Perform two separate experiments:
    1. Neutron moderation
    2. Target mixing

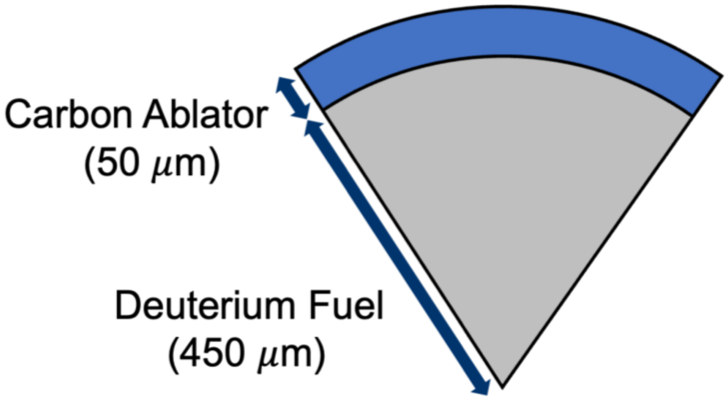


Fig.6 Schematic of PDXP capsule

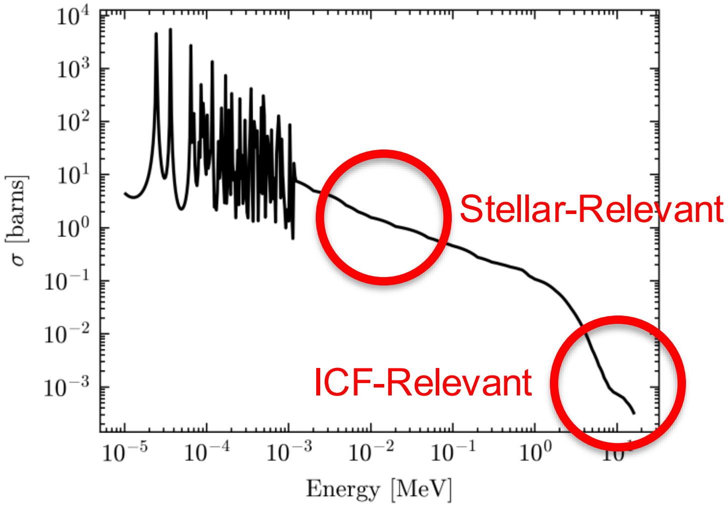
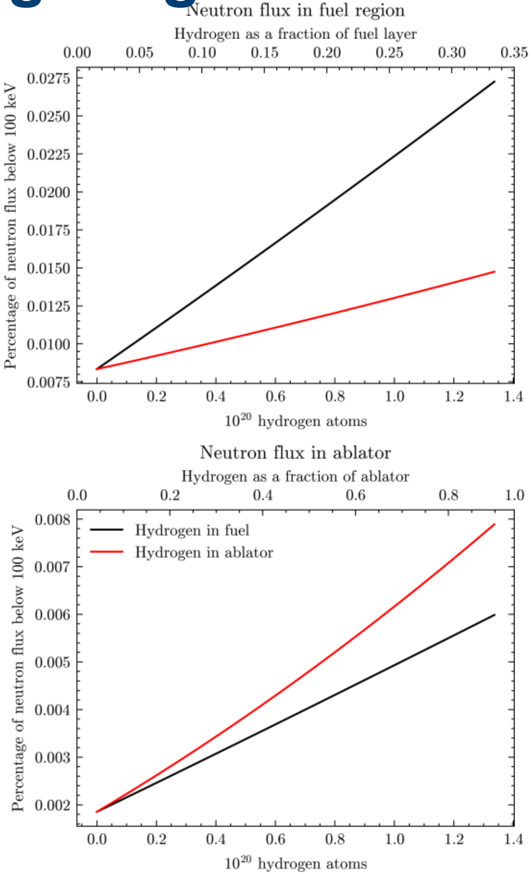


Fig.7 Ground-state neutron capture cross-section of ^{171}Tm

Investigating Neutron Moderation



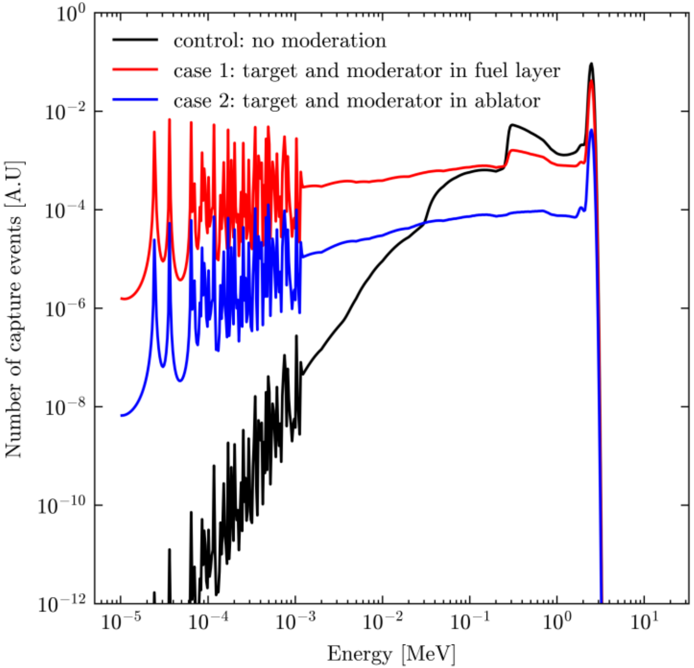
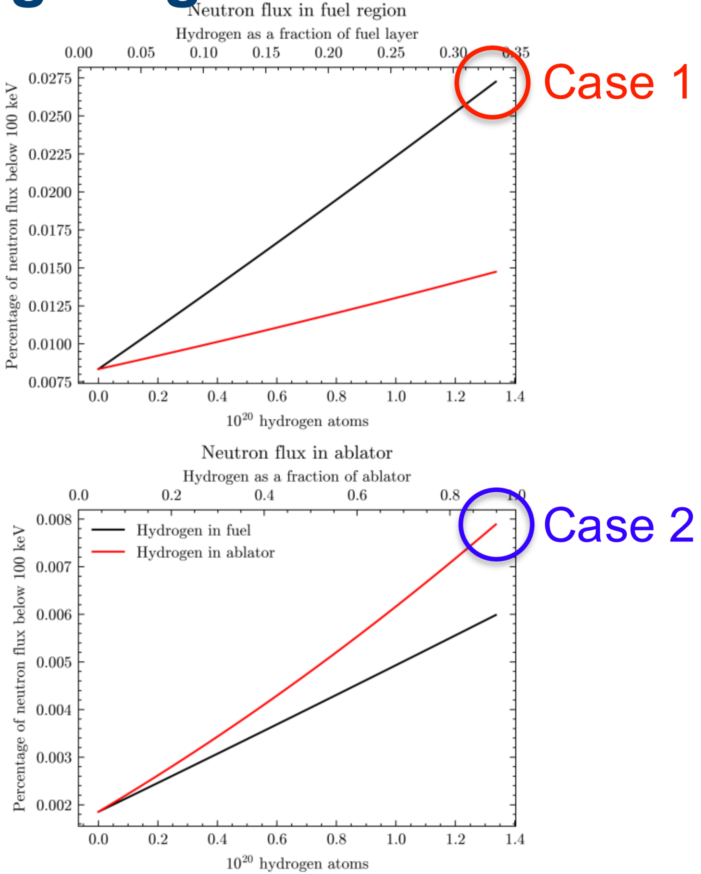
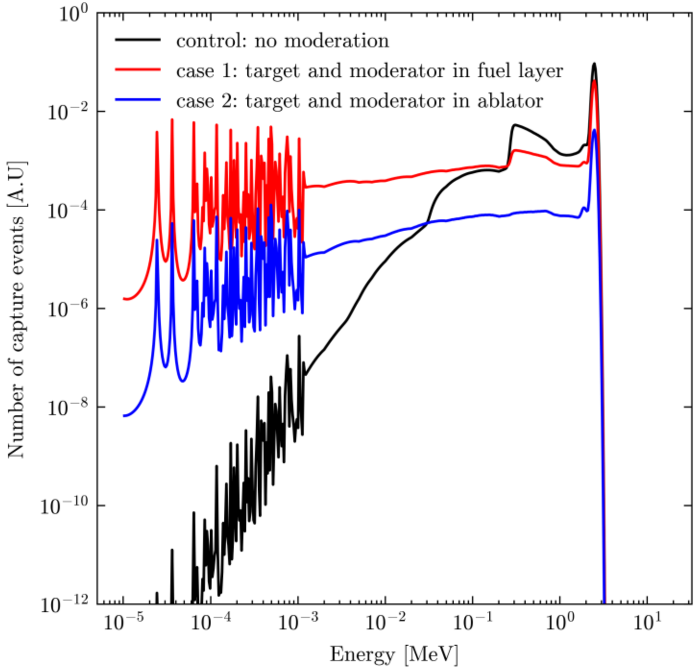


Fig.9 Spectrum of neutron capture events

Fig.8 Effect of moderation by addition of hydrogen on low-energy neutron flux

Investigating Neutron Moderation





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Investigating Experimental Procedure

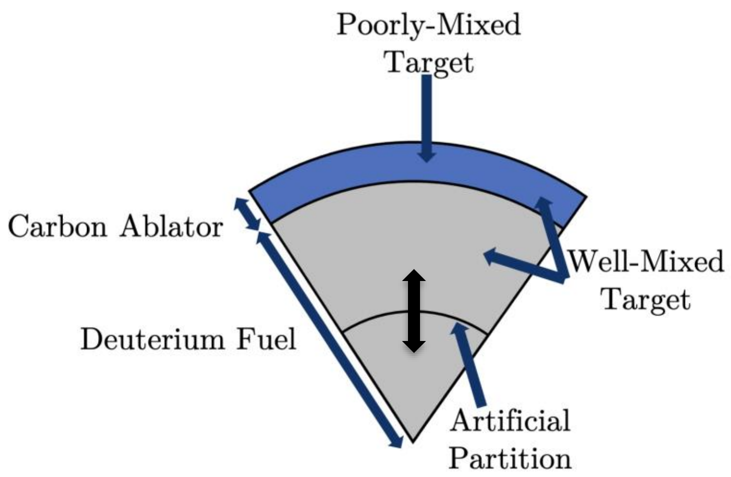


Fig.10 Schematic of experiment design

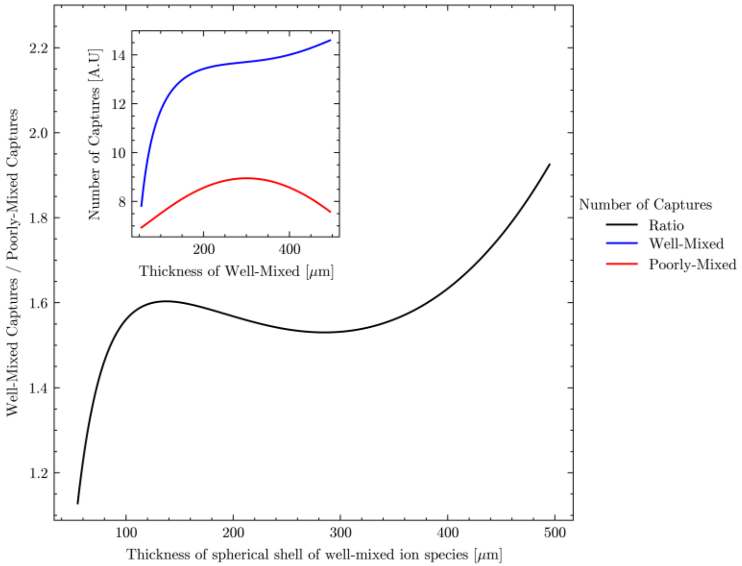


Fig.11 Ratio of neutron captures for an increasingly well-mixed species with a poorly-mixed species

Investigating Experimental Procedure

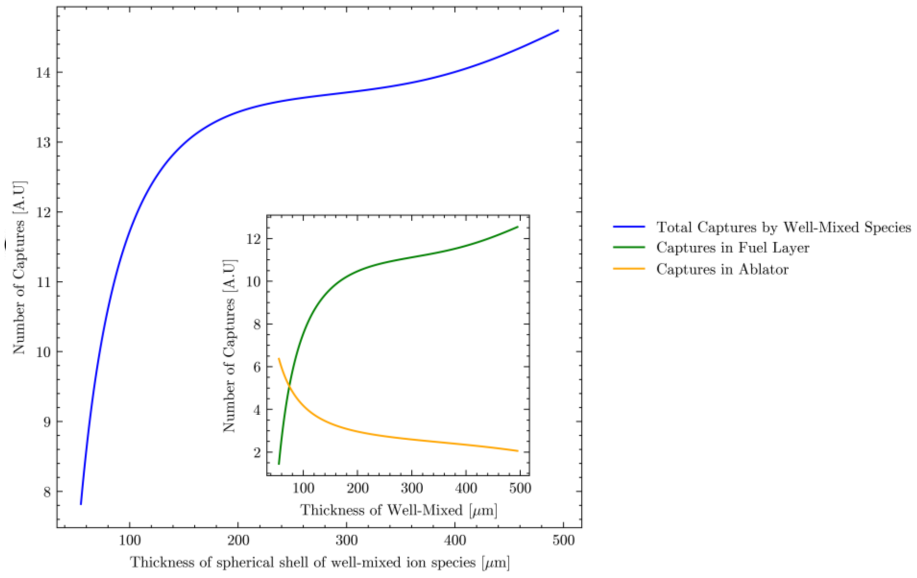
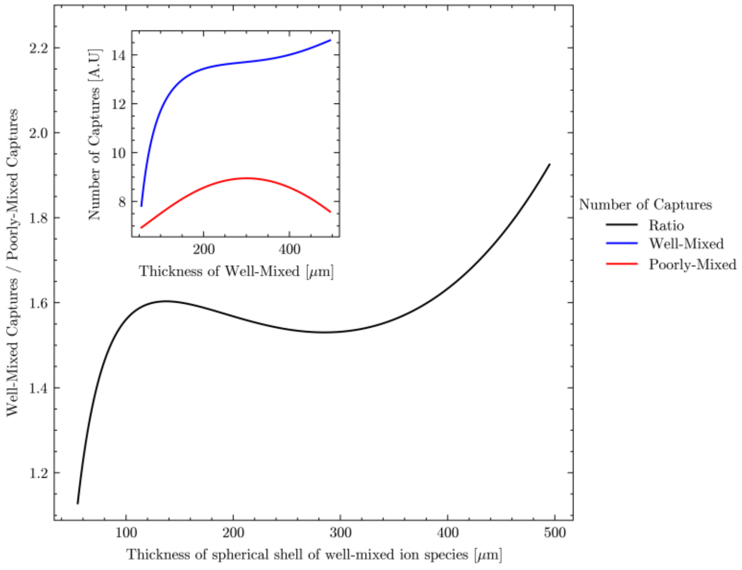


Fig.12 Dissection of well-mixed captures by layer



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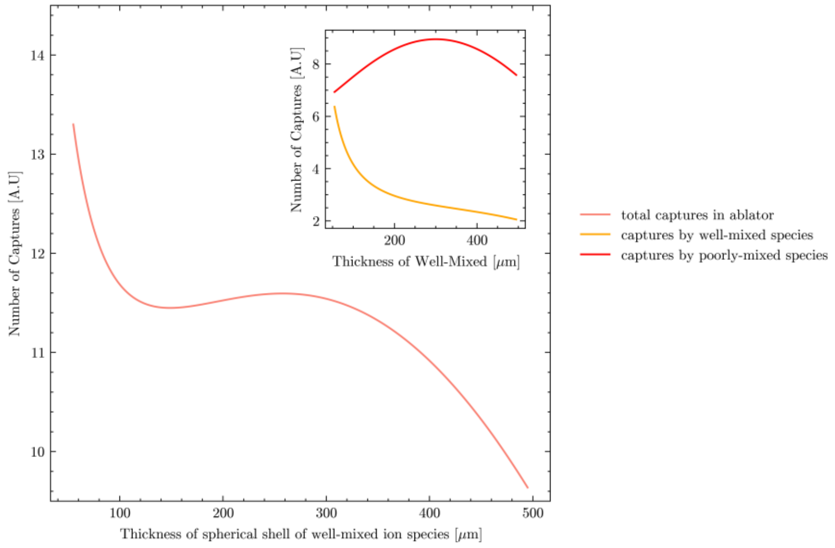

Fig.13 Dissection of captures in ablator by species

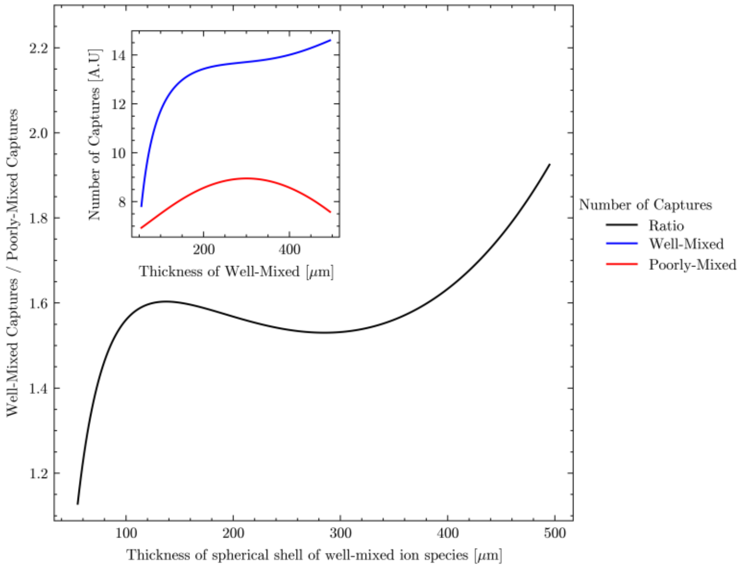

Fig.11 Ratio of neutron captures for an increasingly well-mixed species with a poorly-mixed species

Conclusions & Future Work

- Moderation of neutron spectrum by hydrogen is not effective enough
- Understanding target mixing is important for nucleosynthesis experiments

- Extend investigation with additional moderators and target ions
- Use results to inform more powerful simulations such as Minotaur

Conclusions & Future V

- Moderation of neutron ... ctive enough
- Understanding targ ... is experiments

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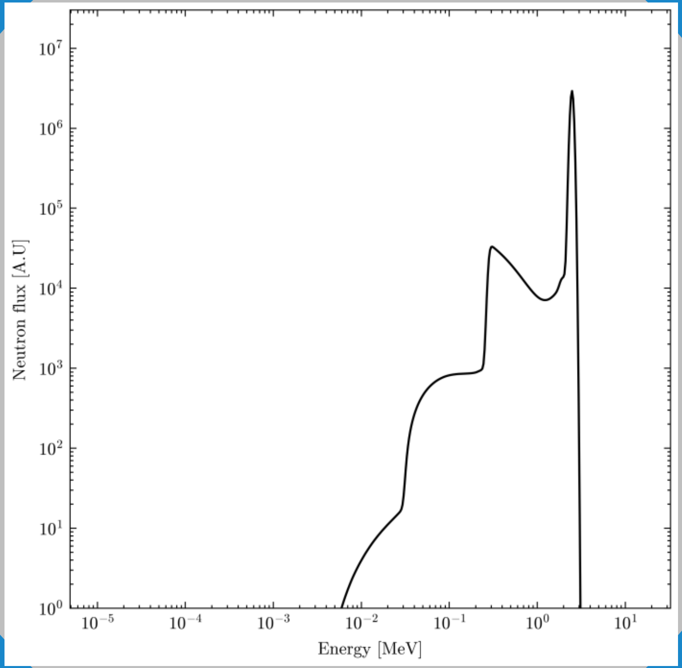

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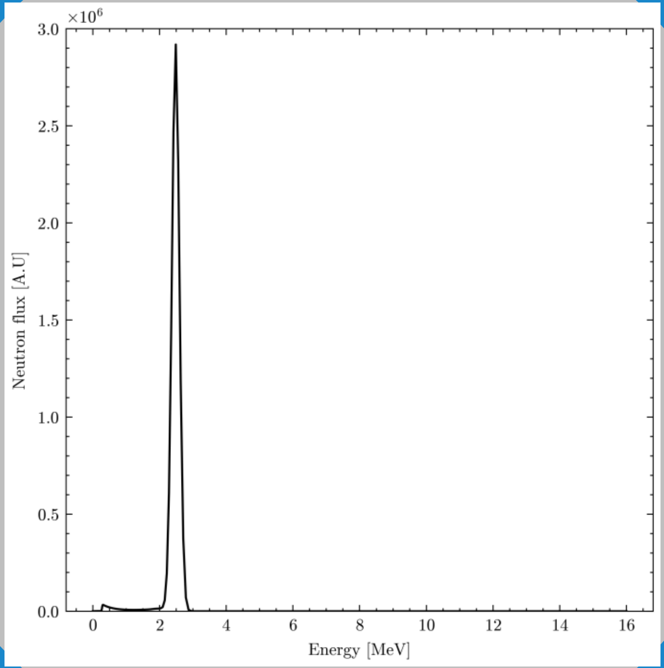


Model Validation: Analytic vs Numerical

- Elastic scattering of a monoenergetic neutron source by a uniform cross-section in an infinite volume

- NTE: $\frac{1}{v}\frac{d\phi}{dt} = -nv\sigma + n\int \frac{d\sigma}{dE}\phi dE$

- Analytic Solution : $\phi_s = \frac{1}{\sigma}\int \frac{d\sigma}{dE}\phi_{s-1}\, dE$

- Numerical Solution: $\phi_{s+1} = \phi_s + \frac{d\phi}{dt}|_{\phi=\phi_s}$

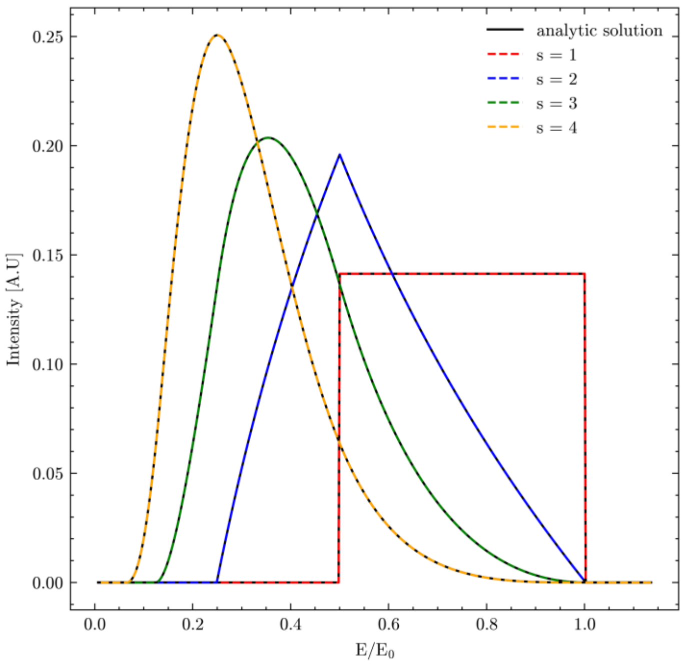
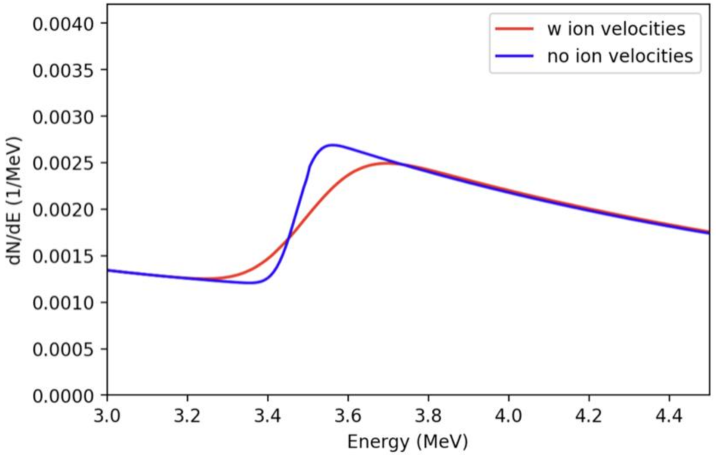
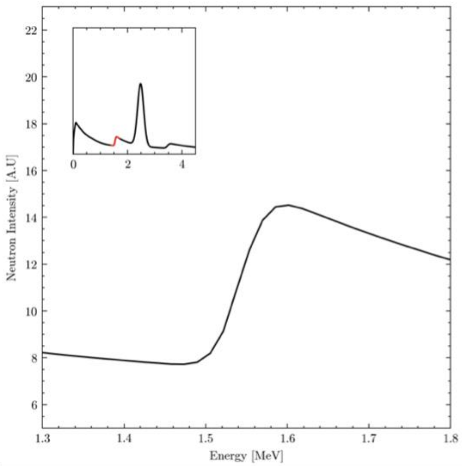
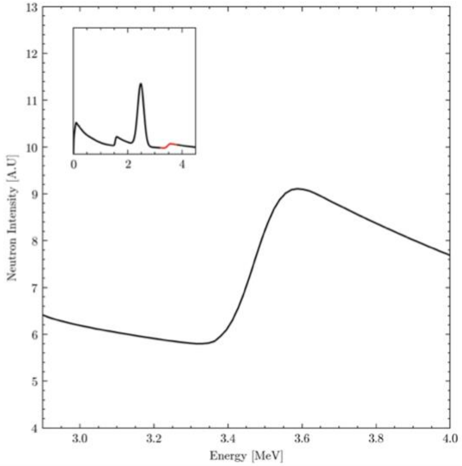


Fig.3 Comparison with analytic as verification of scattering implementation

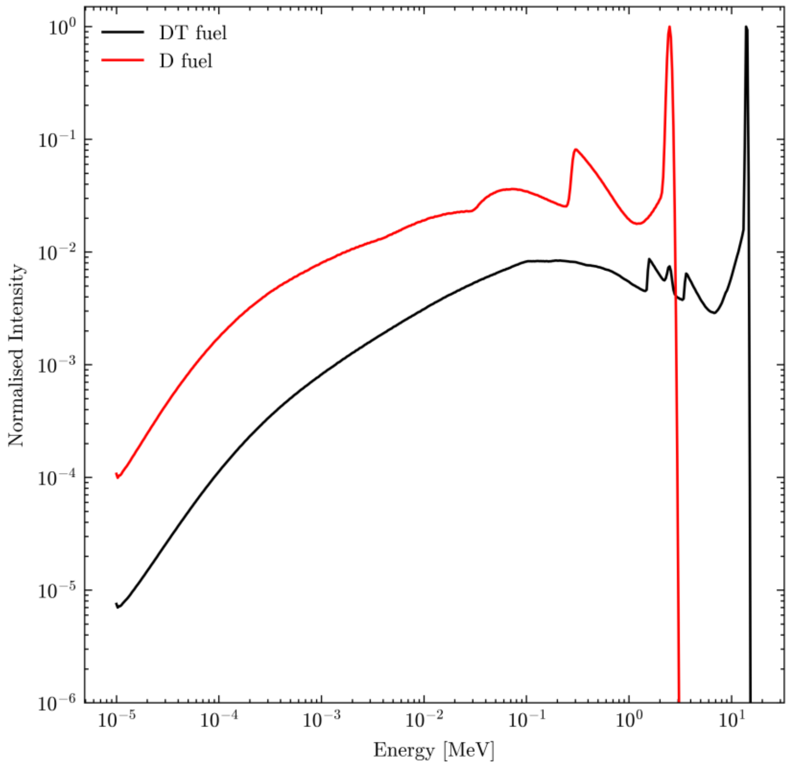
Appendices: Minotaur Comparison

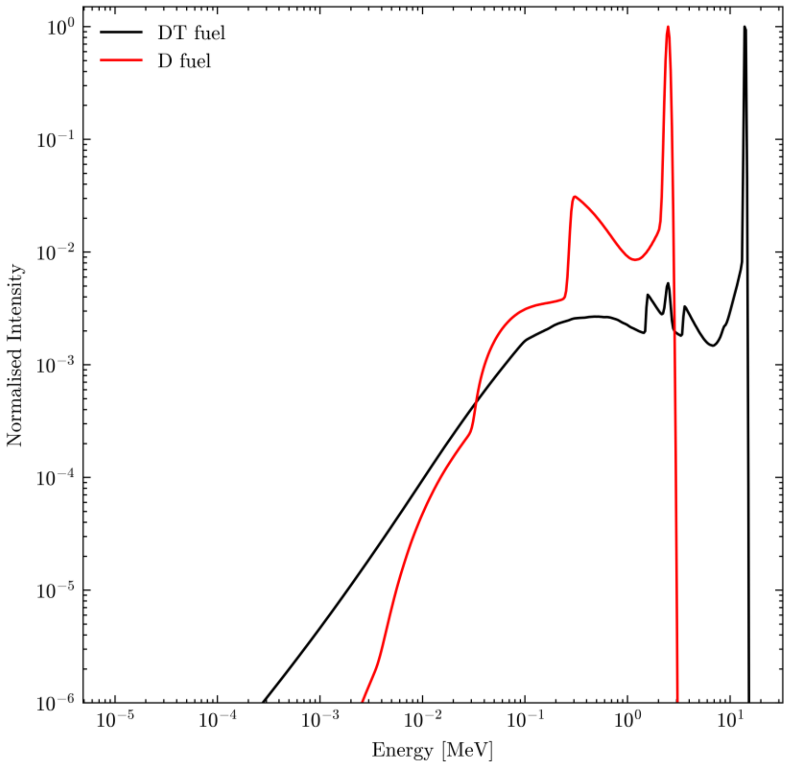






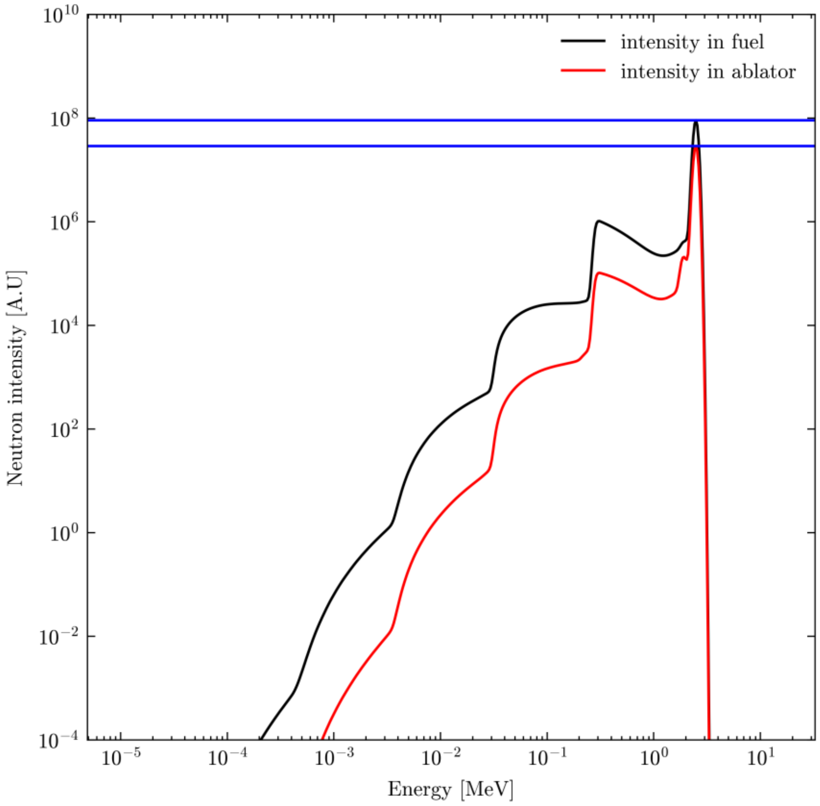
Appendices: Fuel Comparison





(left) DT vs D for a cryogenic ignition capsule. (right) DT vs D for a PDXP capsule

Appendices: Flux varying by layer



Appendices: moderation in a cryogenic capsule

Appendices: streaming term