Australian Government
Defence

Background Compensated Neutron Spectrum Unfolding with an NNS and the Shadow-Cone Technique

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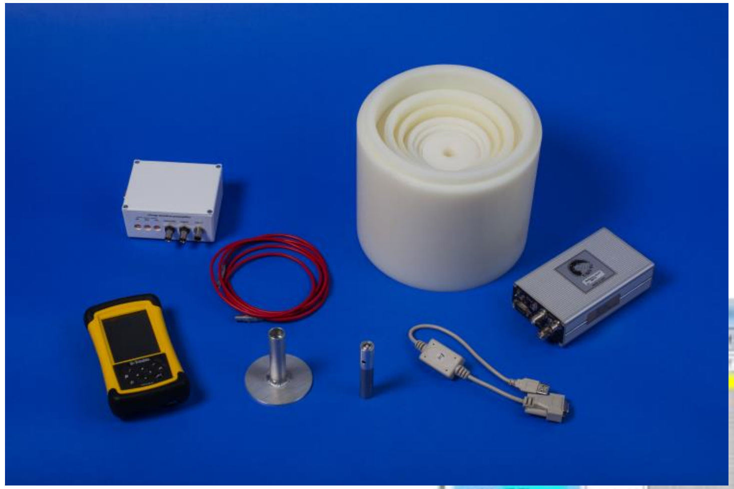
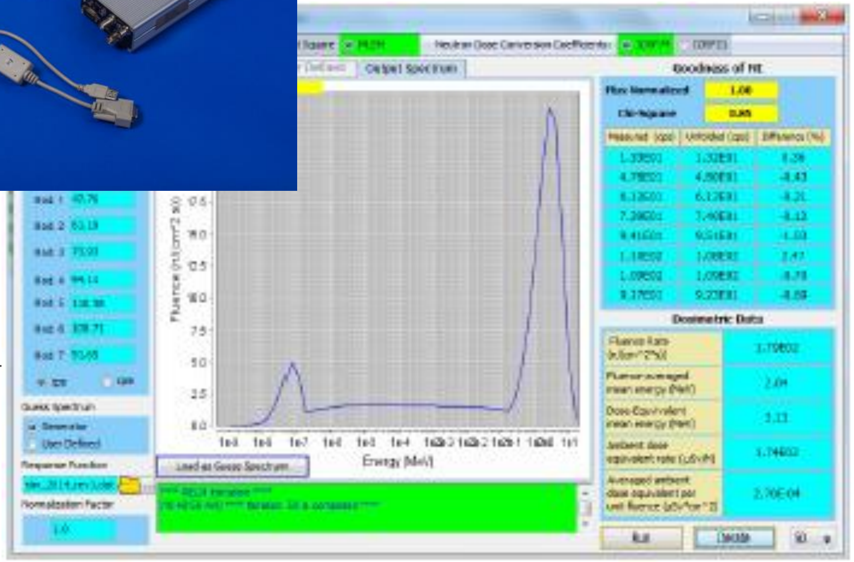
Introduction

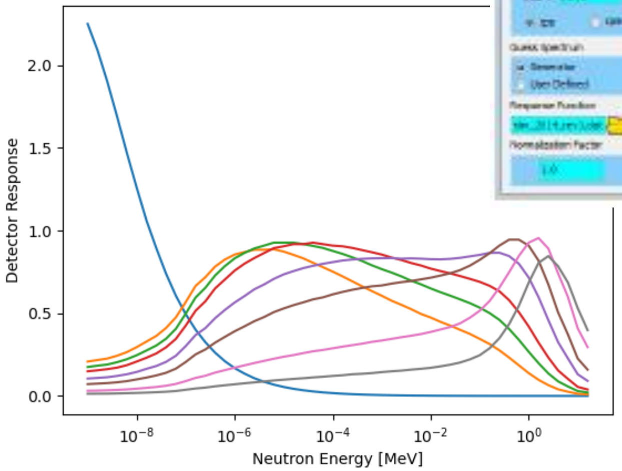
- DSTG are developing capability in radiation transport modelling and detection using Geant4
  - This has focused primarily on γ transport and interactions, for which we have calibrated and well characterised sources
- Neutrons are another possible target for detection, identification and dose-risk assessment
  - Direct detection is difficult due to the nuclear reactions of neutrons, making direct detection and measurement of neutron energies difficult
  - Bonner Sphere Systems (moderation based)
  - Time of Flight Systems (velocity based)
  - Fast Neutron Scattering Systems (momentum based)
  - Neutron Induced Reaction Systems (nuclear reaction based)

The Nested Neutron Spectrometer

- Manufactured by Detec, headquartered in Quebec, Canada
- He3+ neutron detector
- Several polyethylene cylinders which fit together like Russian dolls
- Characterized response functions and software provided by the manufacturer
- Unfolds neutron spectrum using iterative algorithms including Maximum Likelihood Estimation Maximisation (MLEM)

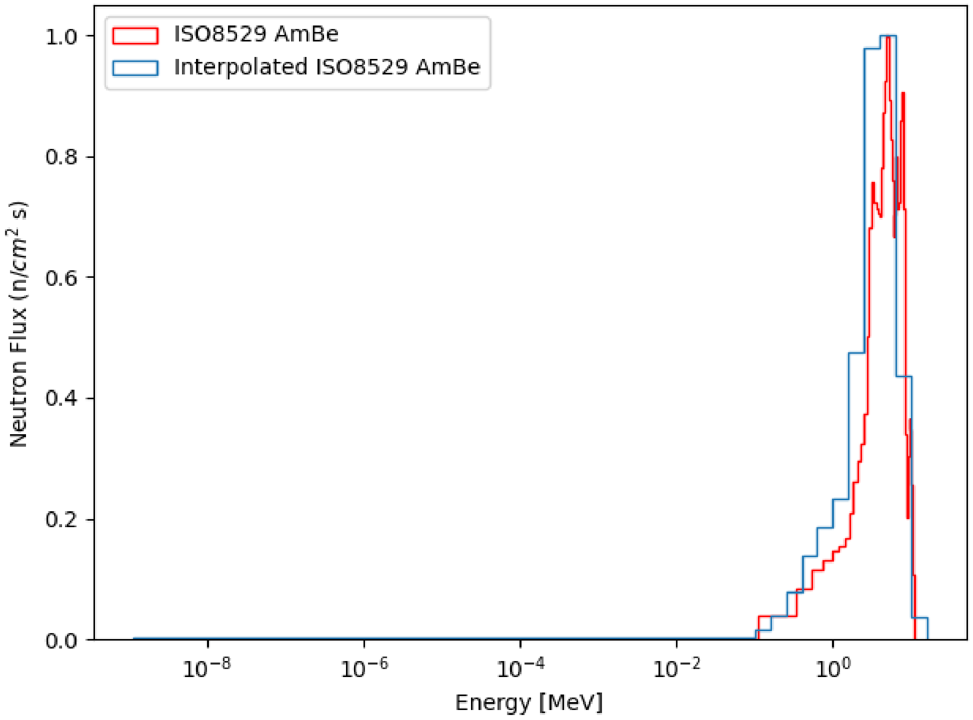






Neutron source characterization

- AmBe neutron source
- ~145 GBq, $1.1 \times 10^{7}\ n/s$
- Am-241 decays producing an α particle
- ${}^{9}_{4}Be + \alpha \rightarrow {}^{12}_{6}C^{*} + n$
- The emitted neutrons have energies < ~12 MeV, with important features above 1 MeV



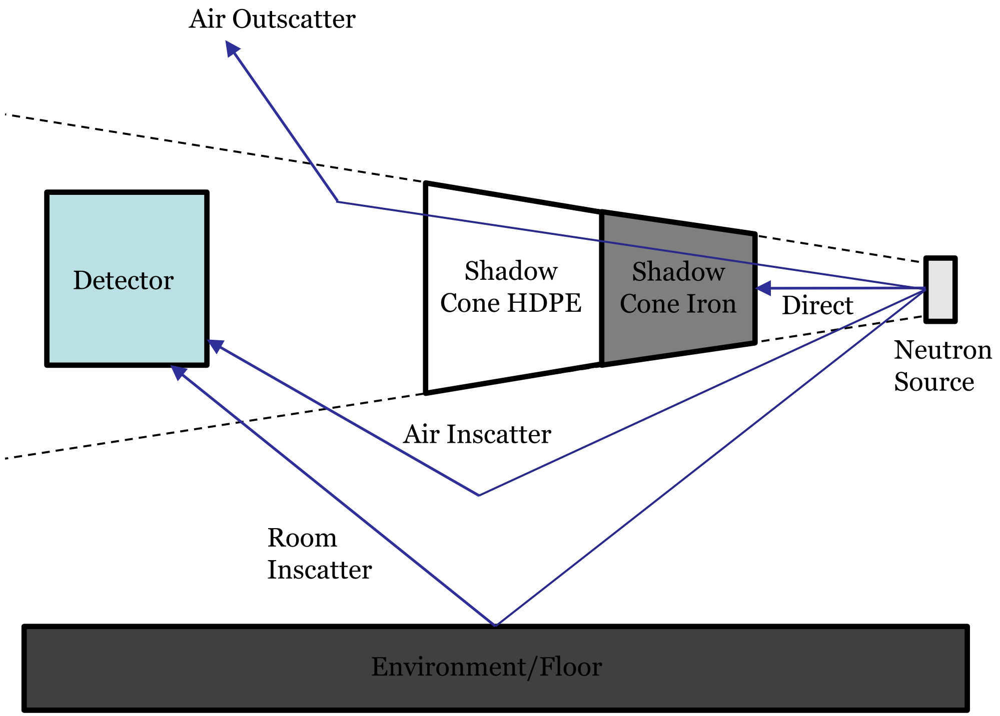
ISO8529 AmBe neutron spectrum and NNS energy bin interpolated AmBe spectrum

Problem Statement

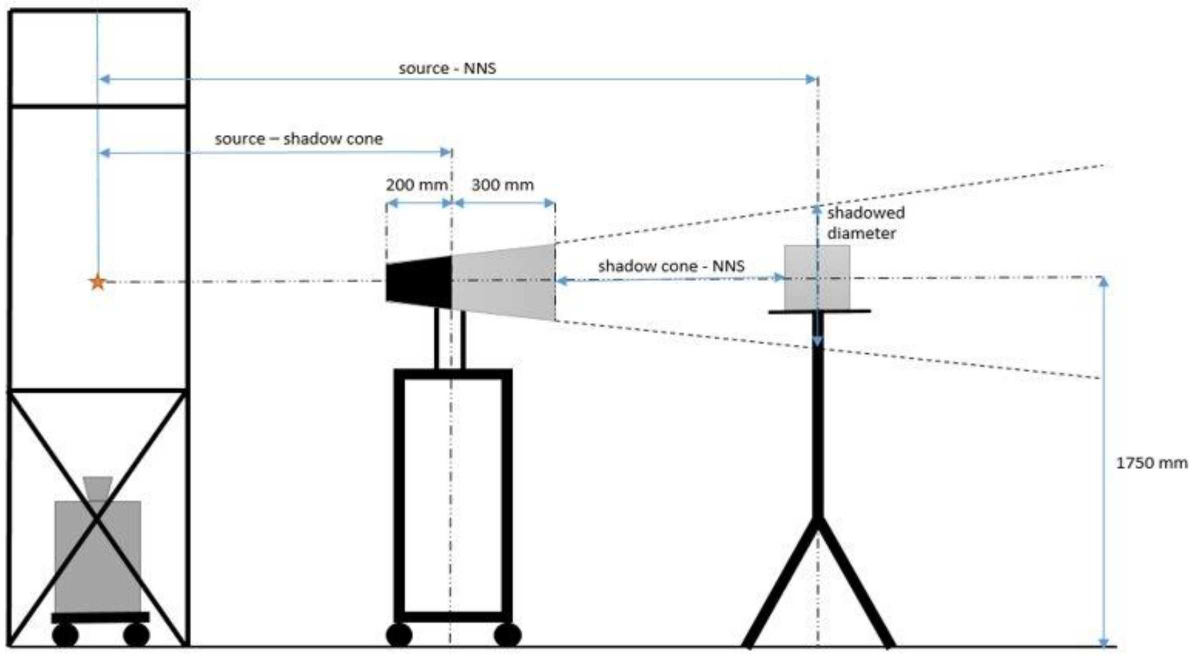
- We need measurements of the direct AmBe neutrons from our source to define our neutron source model in our Geant4 simulation environment
- The DSTG Radiation Laboratory is not a low scattering environment, and our AmBe source is not well characterized
- We can't confirm our source model without a simulated detector model
- Which we can't ensure is well simulated without a well characterized source
- So how do we disentangle direct neutrons from problematic background and scattered neutrons?

Shadow Cones

- Enables the direct measurement of the scattered neutron contribution
- Two datasets:
  - Unshadowed: Direct + scattered neutrons
  - Shadowed: Scattered neutrons
- Limited previous work in literature using shadow cones with NNS



Experimental Overview

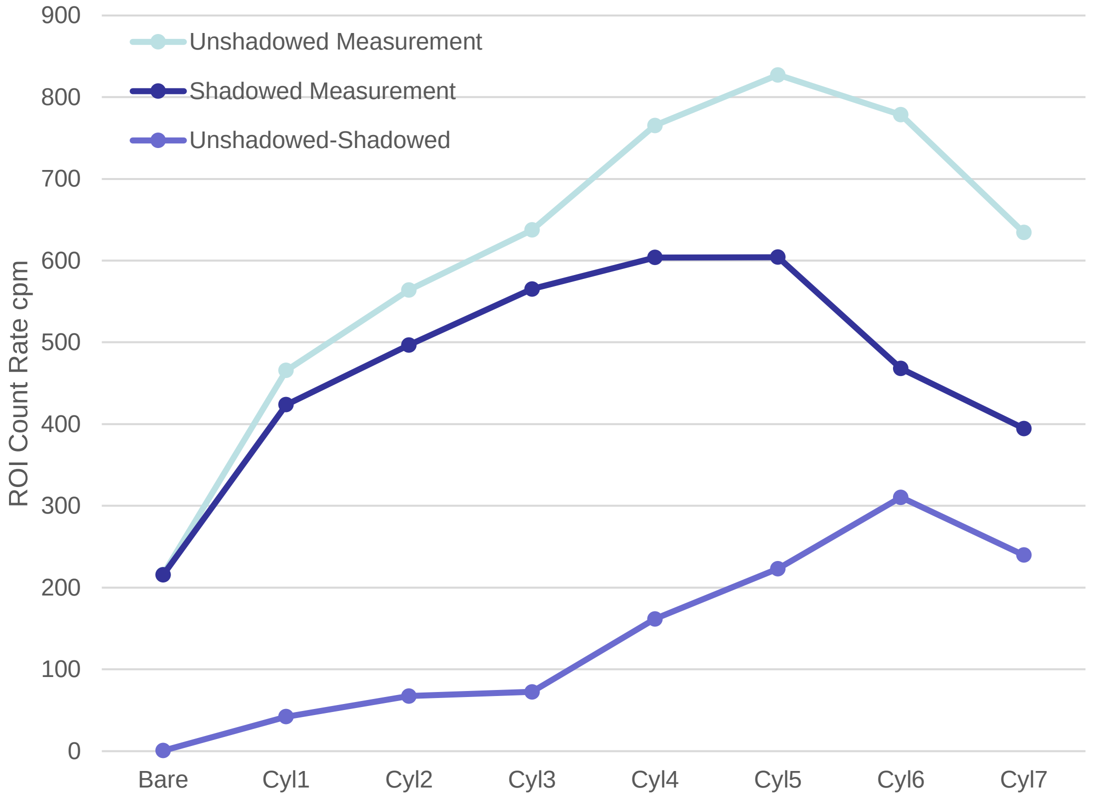


Diagramatic representation of the NNS, Shadow Cone and AmBe source locations during experimental measurements conducted in 2021

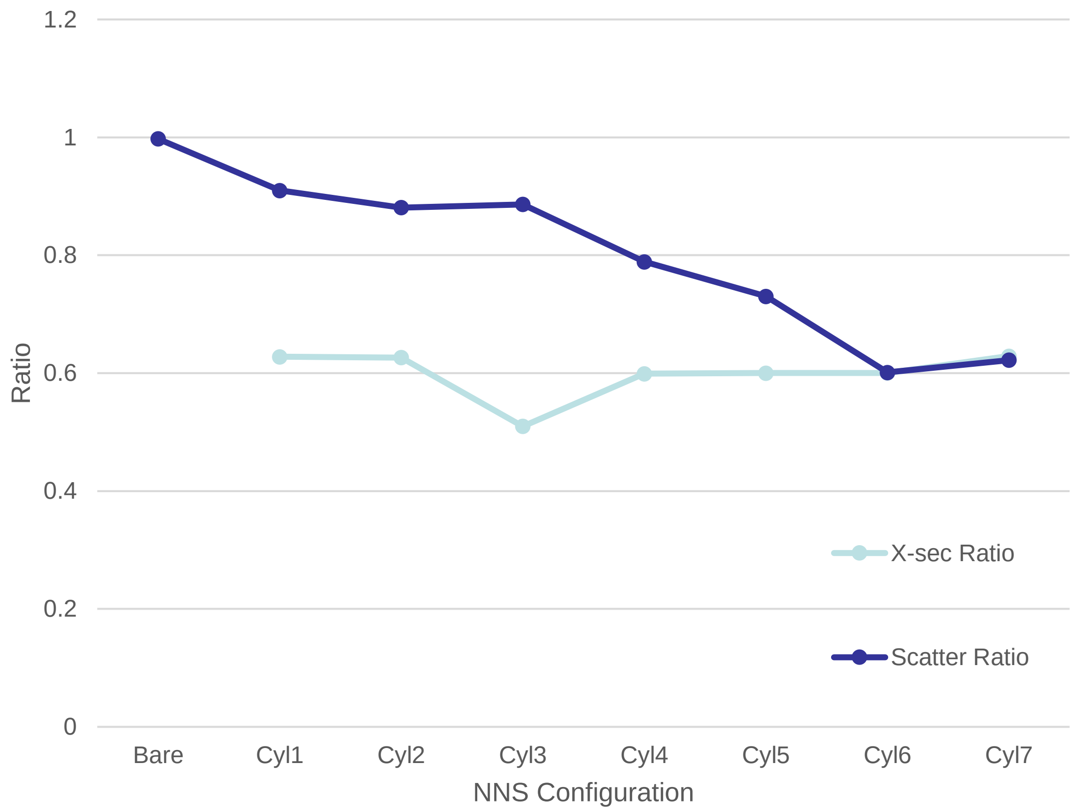
Cylinder	Cone	Shadow cone – NNS [cm]
7	M1	110
6	M1	75
5	M2	110
4	M2	75
3	M2	50
2	M3	195
1	M3	130

Shadow cone positioning required to maintain that the shadowed area is no greater than twice the cross section of the NNS

Results



Results from experimental measurements, with unshadowed, shadowed and the implied unshadowed-shadowed values



Detector area to shadowed area cross section ratio and direct counts to shadowed counts scatter ratio

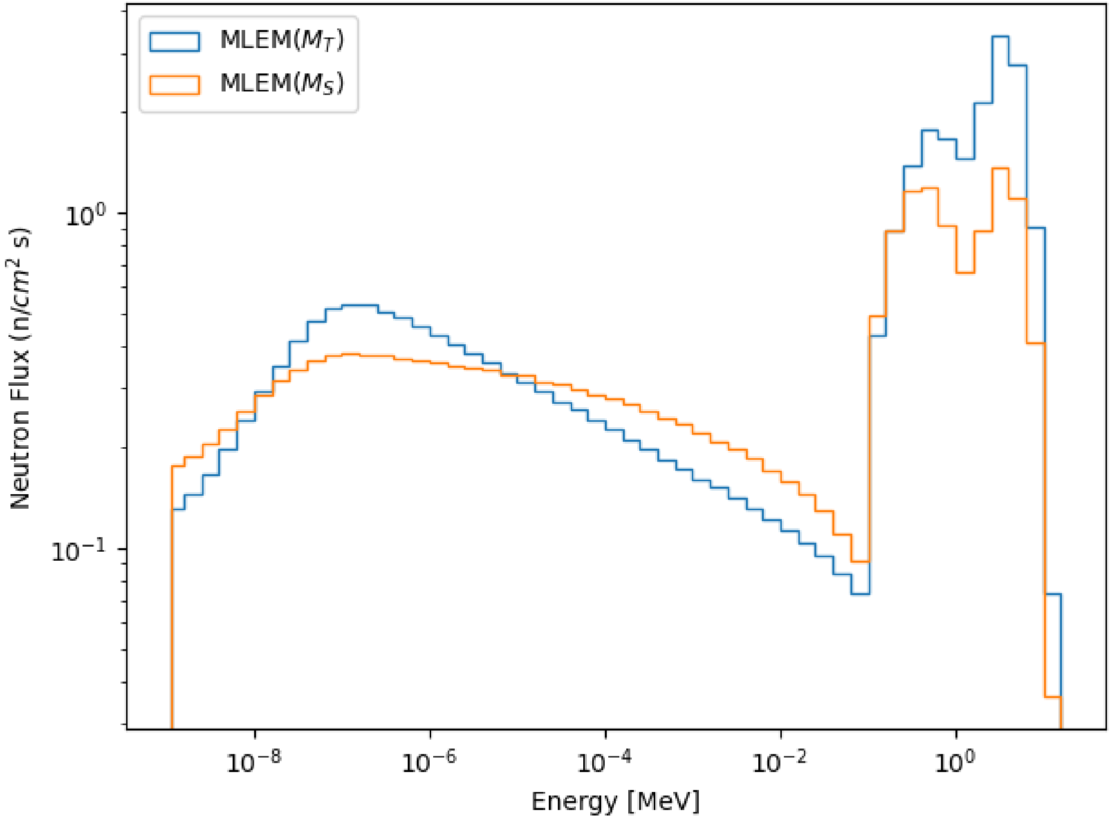
Spectrum Unfolding with MLEM

Measured count rate
= NNS Response · Neutron Spectrum

$$c_i = \sum_{j=1}^{J} a_{i,j} \cdot n_j$$

$$New\ Spectrum = \frac{Old\ Spectrum}{Sensitivity} \cdot \mathrm{BP}\left(\frac{Measured\ Data}{\mathrm{P}(Old\ Spectrum)}\right)$$

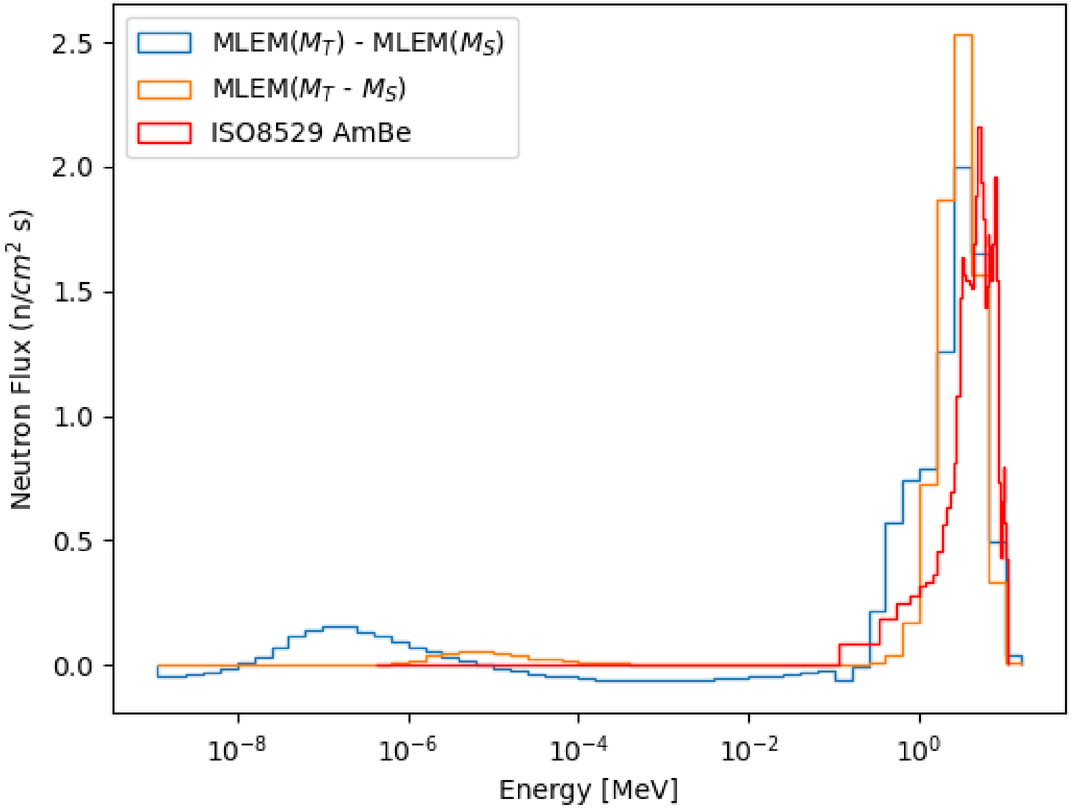
$$n_j^{k+1} = \frac{n_j^k}{\sum_{i=1}^{I} a_{ij}} \sum_{i=1}^{I} a_{ij} \frac{m_i}{\sum_{j=1}^{J} a_{ij} n_j^k}$$



Reconstructed neutron spectra from unshadowed (M_T) and shadowed (M_S) datasets using MLEM

Options?

- Subtract the unfolded spectra?
- Unfold the subtracted count-rate data?



Reconstructed neutron spectra using available manufacturer supplied tools to account for shadowed and unshadowed datasets

Options?

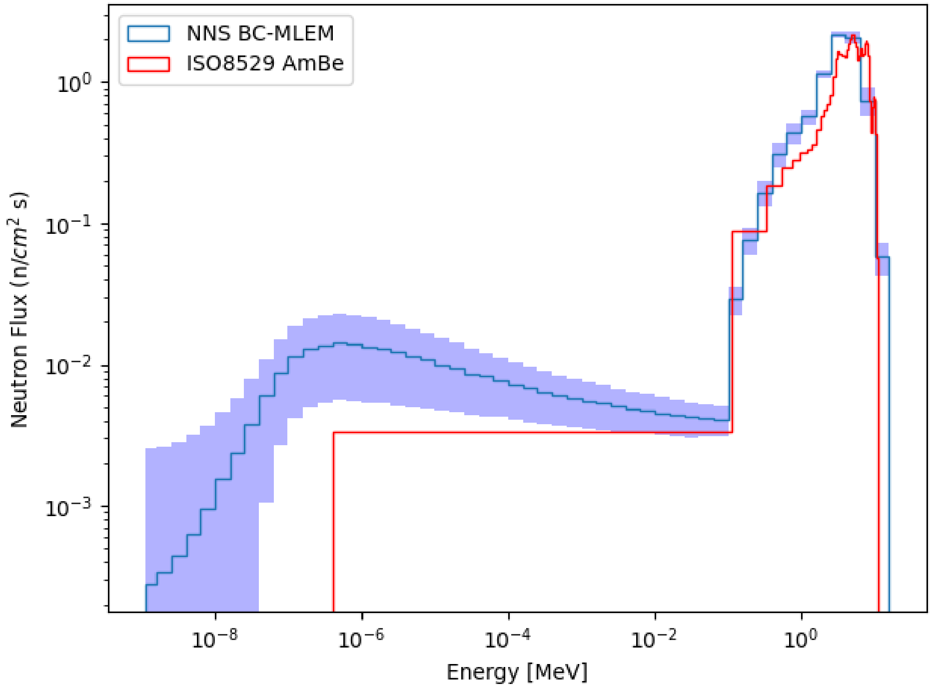
- Subtract the unfolded spectra?
  - Simplest solution, but the two MLEM solutions aren’t necessarily physically compatible
- Unfold the subtracted count-rate data?
  - This may work, however this formulation of MLEM requires data that is Poisson distributed
- Implement a new algorithm?

Background Compensated MLEM

$$\textit{New Spectrum} = \frac{\textit{Old Spectrum}}{\textit{Sensitivity}} \cdot \mathrm{BP}\left(\frac{\textit{Unshadowed Data}}{\mathrm{P}(\textit{Old Spectrum}) + \textit{Shadowed Data}}\right)$$

$$n_j^{k+1} = \frac{n_j^k}{\sum_{i=1}^{I} a_{ij}} \sum_{i=1}^{I} a_{ij} \frac{m_i}{\sum_{j=1}^{J} a_{ij} n_j^k + b_i}$$

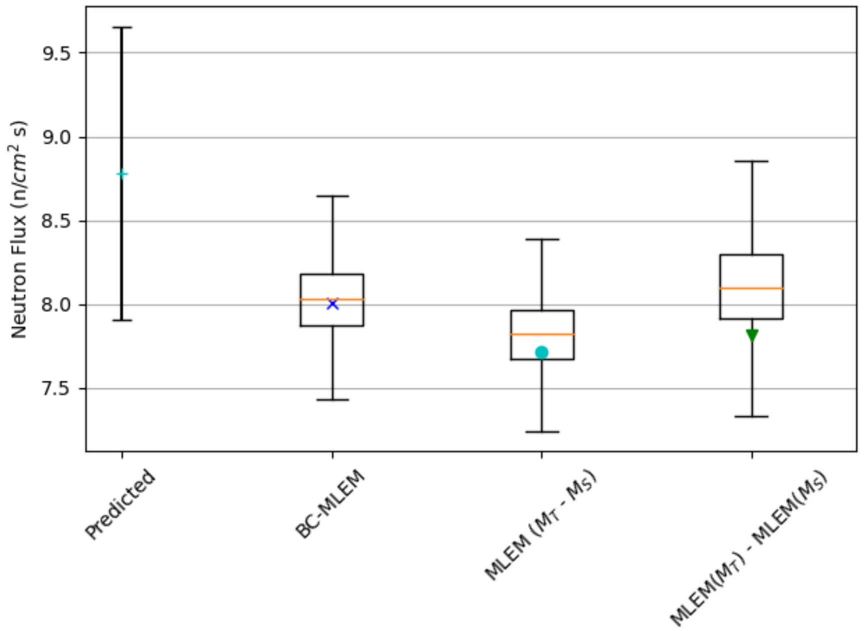
The background corrected MLEM algorithm used to provide a better unfolded estimate of the direct AmBe neutrons (unshadowed-shadowed)



The improved reconstructed direct spectrum, with ISO8529 AmBe source spectrum for reference. Shaded areas indicate 1σ uncertainties in reconstructed spectrum based on bootstrapped data.

Total Flux Estimates

- We assumed a Poisson distribution on the experimentally measured count data and resampled those counts to explore the variance in reconstruction from the measured data
  - Generated synthetic data to enable a bootstrap analysis of the variance in the spectra pictured previously
  - Non BC-MLEM methods demonstrated greater bias and variance than the BC-MLEM method
  - BC-MLEM estimated total flux was closest to the predicted flux value (from the manufacturer AmBe source certificate), $8.78 \pm 10\%\ n/cm^2s$ at the source to NNS distance

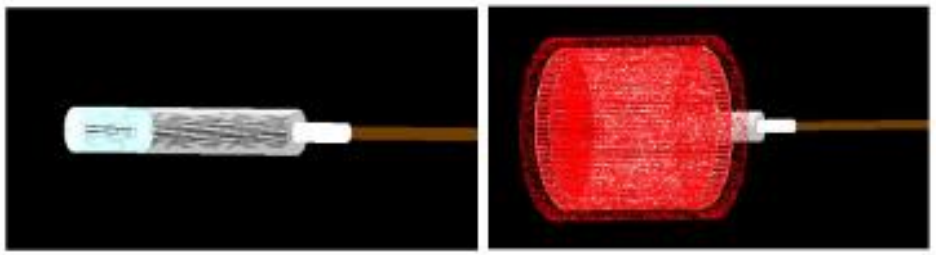


Differences in estimated total neutron flux using the different reconstruction methods.

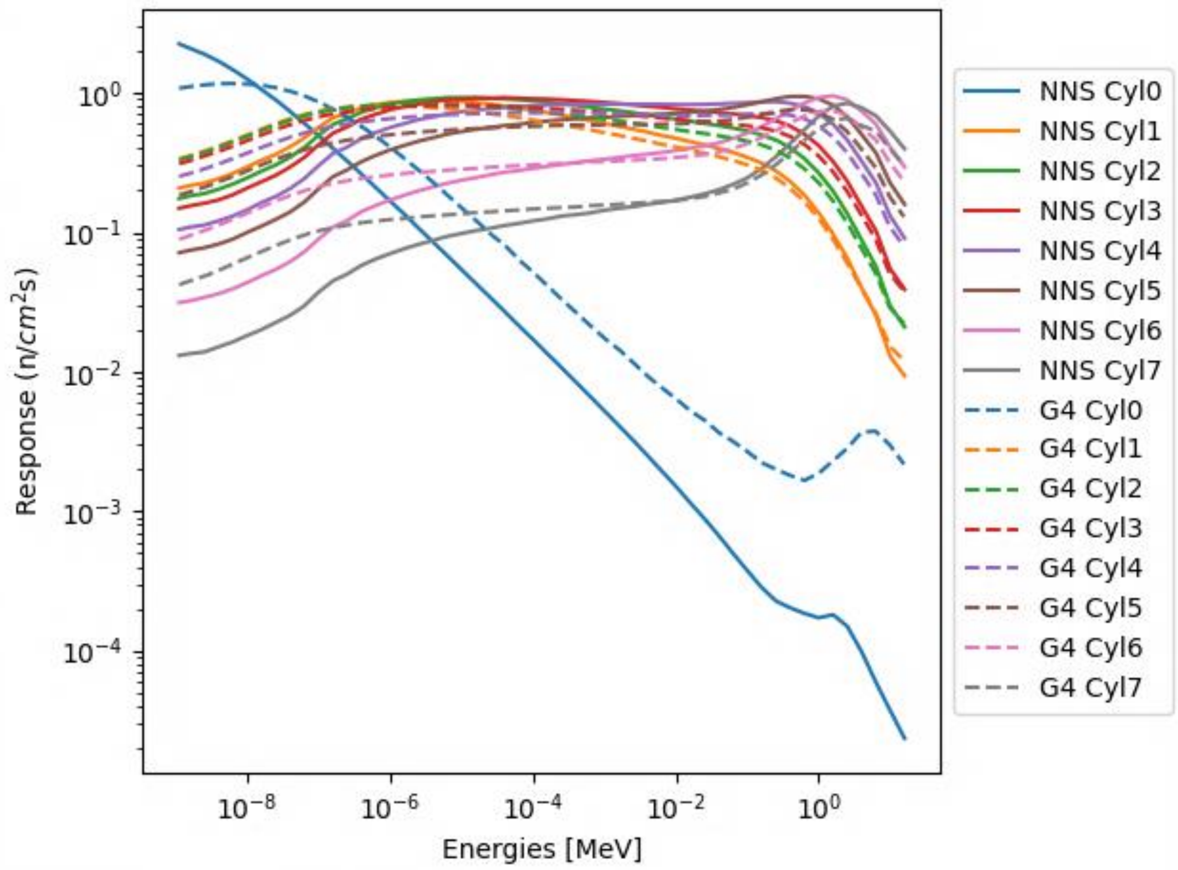
Method	BC-MLEM	BC-MLEM Bootstrapped	MLEM($M_T - M_S$)	MLEM($M_T - M_S$) Bootstrapped	MLEM(M_T) – MLEM(M_S)	MLEM(M_T) – MLEM(M_S) Bootstrapped
Flux (n/cm^2s)	8.04	$8.07 \pm 0.69\ (3\sigma)$	7.71	$8.14 \pm 0.91\ (3\sigma)$	7.88	$7.88 \pm 0.69\ (3\sigma)$

Standalone NNS Geant4 Modelling

- Full NNS Geometry modelled in Geant4 v10.7
  - Polyethylene cylinders, He detector
- QGSP_BERT_HP base hadronic physics
  - Thermal neutrons
  - EM Standard Physics Option 4
  - Hadron Elastic Physics HP
- Noticeable difference between supplied NNS response and Geant4 based response



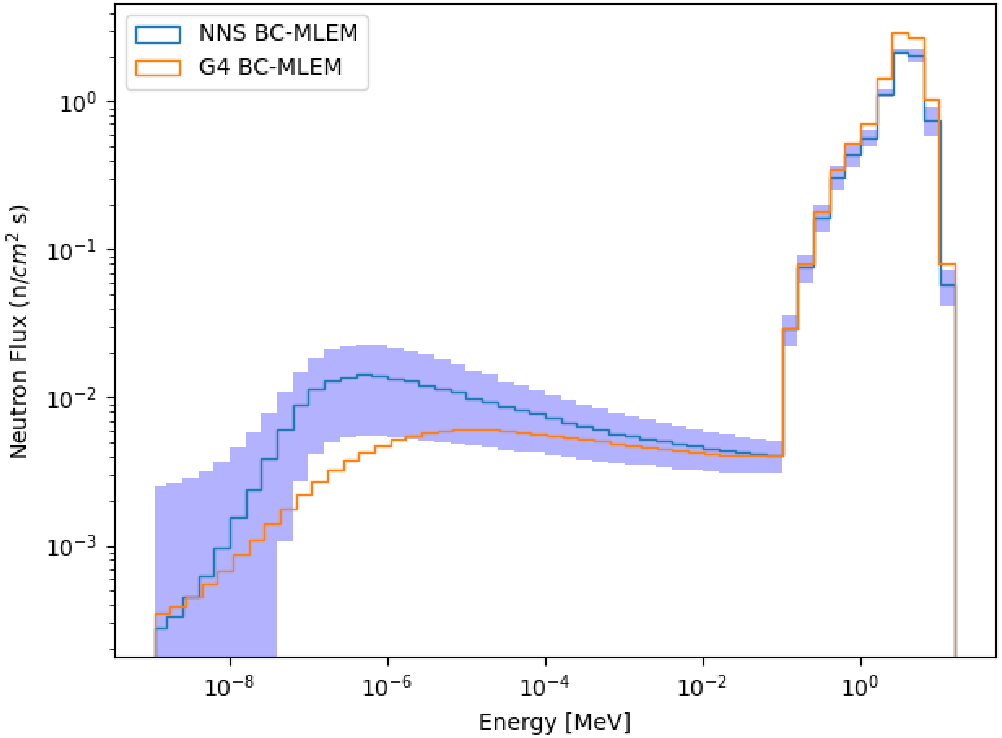
Geant4 based NNS Geometry with He sensitive detector and polyethylene nested cylinders



Comparison of the NNS supplied response functions and the scaled functions based on CDMPP simulations of the NNS

Response Function Sensitivity

- Improved suppression of thermal and epithermal neutrons
- Increase in total neutron flux when using Geant4 based response ($8.04\ n/cm^2s$ to $10.19\ n/cm^2s$)
  - Due to the calibration factors applied throughout data acquisition and analysis which are optimised for the manufacturer response functions



Comparison between reconstructed data using the manufacturer supplied NNS response functions and Geant4 (G4) response functions.

Conclusion & Next Steps

- Application of BC-MLEM and use of the shadow-cones suggests improved spectral reconstruction of direct neutron spectra in mixed neutron energy environments
- Geant4 modelling indicated differences between manufacturer supplied and modelled NNS response
- Further Geant4 based simulation of the experimental measurements is planned to validate the approach used
  - Based on replication via simulation, this approach may be used in other mixed neutron fields

Thanks for your attention

We would like to acknowledge the assistance of ARPANSA in loaning the shadow-cones for this experimental work