Particle Transport Modeling

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Use of Particle Transport (PT)

1) Determination of source & detector response

$$R_{det} =< \psi_{par}\sigma_{det} >$$

Where ψ_{par} is obtained by

$$H\psi_{par} = S_{par}$$

2) Design of detector

3) Determination of background

4) Reduction of background,
   - identification of interfering noise and its removal
   - Shielding

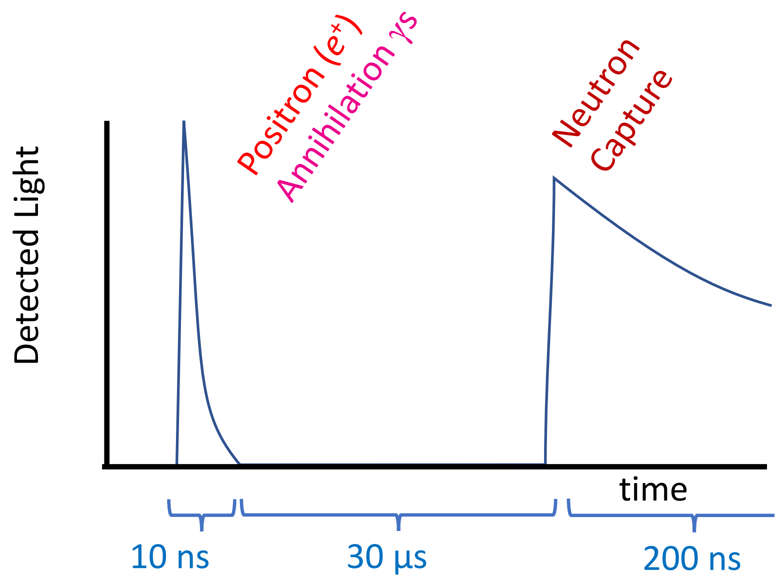
5) Source image reconstruction and inference of physical parameters

Antineutrino detection

- Inverse beta decay (IBD) interaction

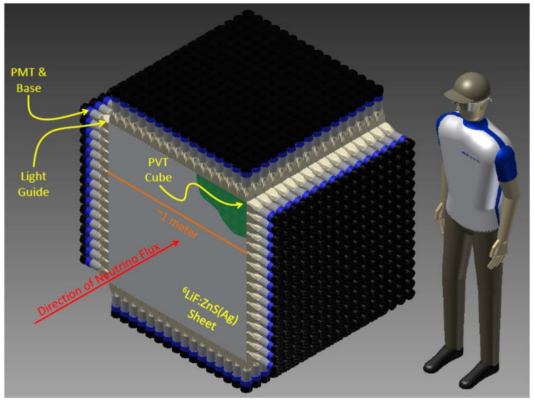
$$\bar{\upsilon}_e + p \rightarrow e^+ + n$$

  - Detection process by coincidence of two signals:
    1. light signal from scintillation materials caused by energy deposition due to **positron annihilation**
    2. Light signal from scintillation materials caused by energy deposition due to **neutron capture process** ${}_0^1n + {}_3^6Li \rightarrow {}_2^4He + {}_1^3T$

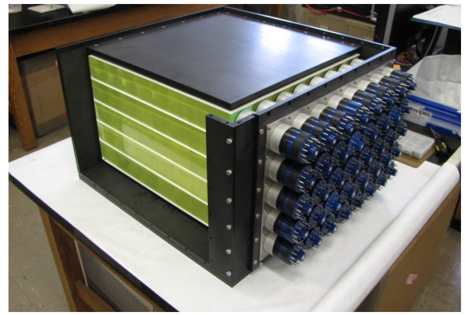


CHANDLER detection system

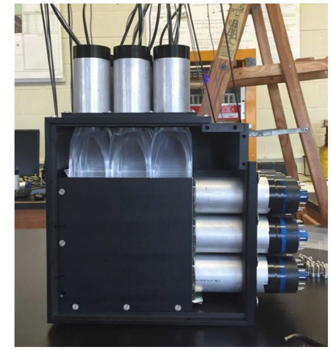
CHANDLER: 16x16x16 (to be built)

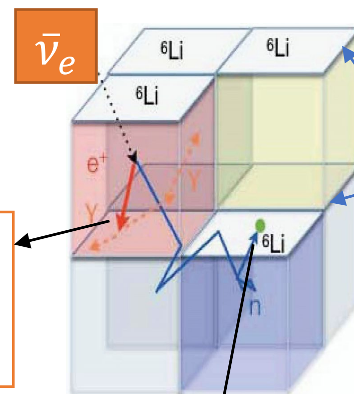


miniCHANDLER: 5x7x7 (tested at the North Anna Power station)



microCHANDLER: 3x3x3 (used for determination of proton quenching)





LiF-ZnS(Ag) sheets

$e^+ + e^-$ -> 2γ

Light is generated due to γ-ray interaction with scintillating cubes

$^6_3Li(n,\alpha)^3_1H$

Light is generated due to α-particle with scintillating sheet

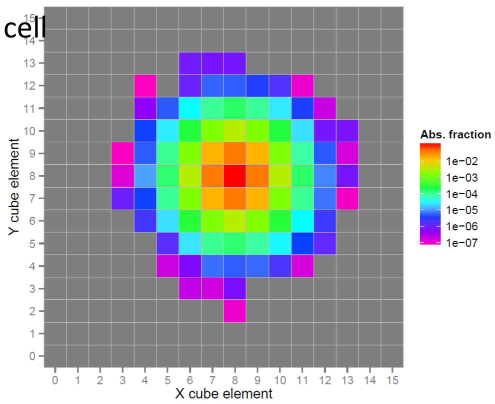
2) Detector Design : Size of cubes & thickness of Li sheets

- Performed MCNP Monte Carlo sensitivity analyses
- Efficiency of absorption in Li-6

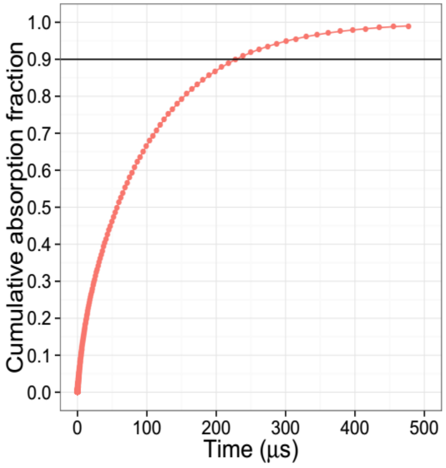
Loss Term	Fraction
Li-6 absorption (signal)	51.2 %
PVT absorption	33.0 %
Leakage	15.8 %
Other absorption	0.1 %

- Absorption from point of generation (distance & time)

85% of neutrons are absorbed within one cell from source cell



90% of neutrons are absorbed within 200 μs



3) Determination of background

Performed MCNP Monte Carlo simulation to determine cosmic ray neutrons at the sea level

Only 3.5 % of cosmic-ray fast neutrons create signals (proton + neutron) like IBD events:

Cosmic-ray: 112,000 counts/day

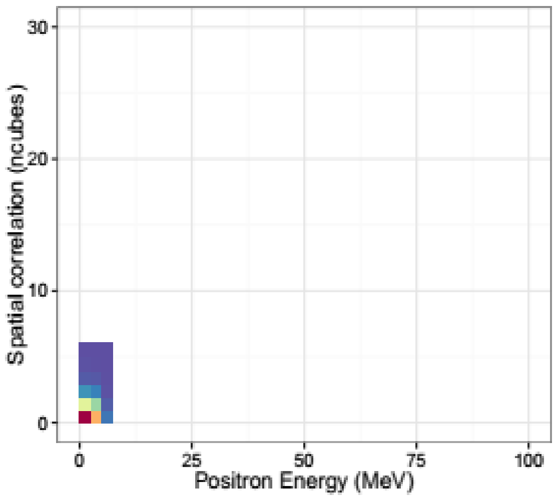
Antineutrino: 1000 counts/day

4a) Reduction of background
(interfering cosmic ray neutrons through proton recoil)

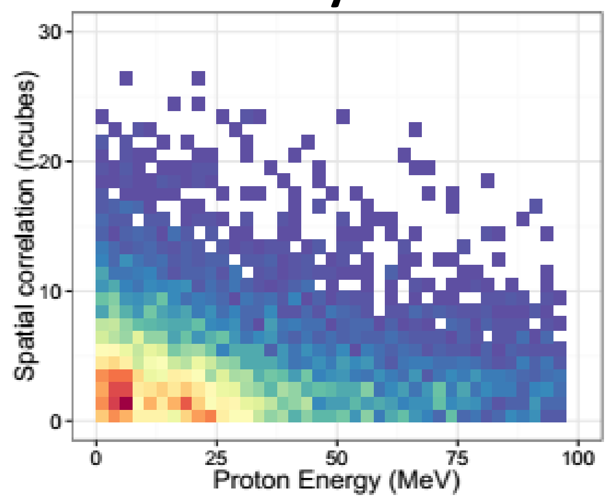
Performed MCNP Monte Carlo simulation to determine expected position and energy of positron (for IBD) and the competing effect , i.e., proton recoil due to cosmic ray neutrons

Space-energy correlation

IBD events



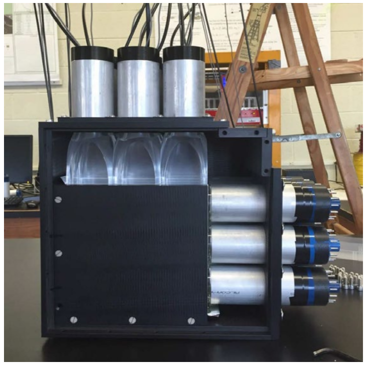
Cosmic ray events



- 5000 fast neutron counts/day
- 850 antineutrino counts/day
- SNR = ~0.2 SNR

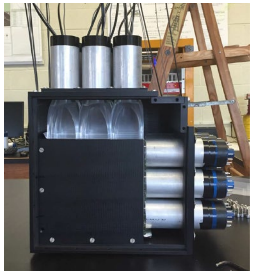
4a) Reduction of background
(determination of quenching factor due to fast neutron interactions in CHANDLER)

- Performed measurements at the Duke TUNL facility using the MicroCHANDLER which was exposed to beams of neutrons at different fast energies due D-D and D-T interactions



Neutron energy (MeV) D-D interaction	Neutron Energy (MeV) D-T Interaction
5.32	18.35
6.5	19.86
7.6	21.2
8.65	22.45
9.68	23.64
10.68	24.78
11.67	25.90
12.66	26.75

MCNP Monte Carlo Simulation for determination of energy deposition

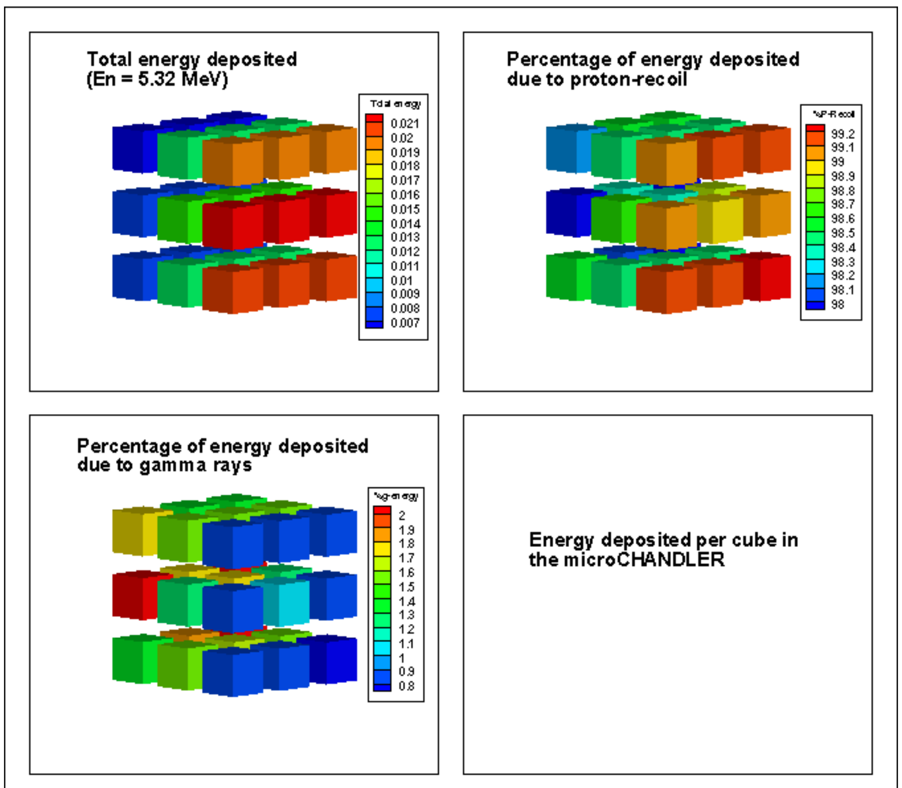


Fast neutron interactions with detector material:

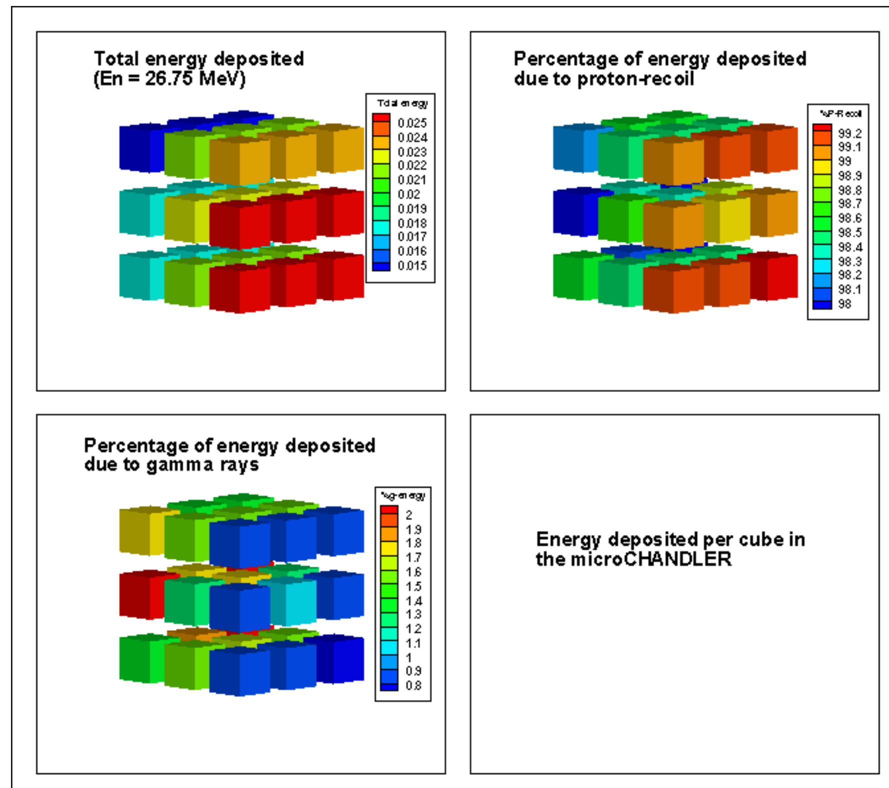
i) Proton recoil

ii) Gamma ray due non-elastic interactions, e.g., ^{12}C excitation

En = 5.32 MeV

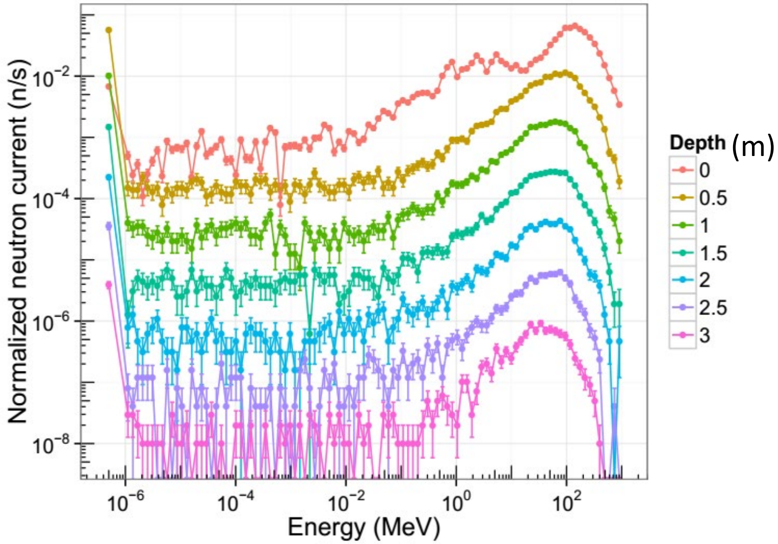


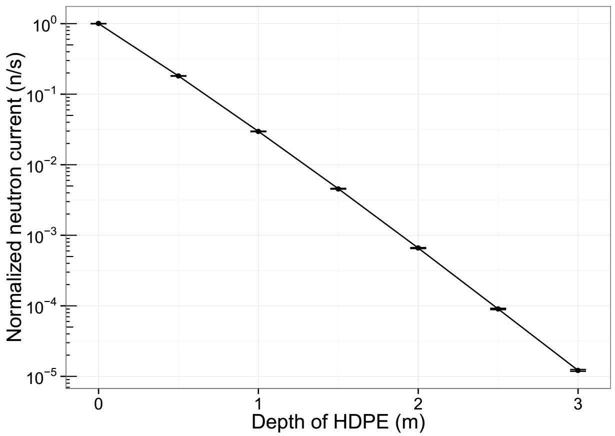
En = 26.75 MeV



4b) Reduction of background (Shielding)

Performed Monte Carlo simulation by placing a High Density Polyethylene (HDPE) shield in front of beam of cosmic ray neutrons



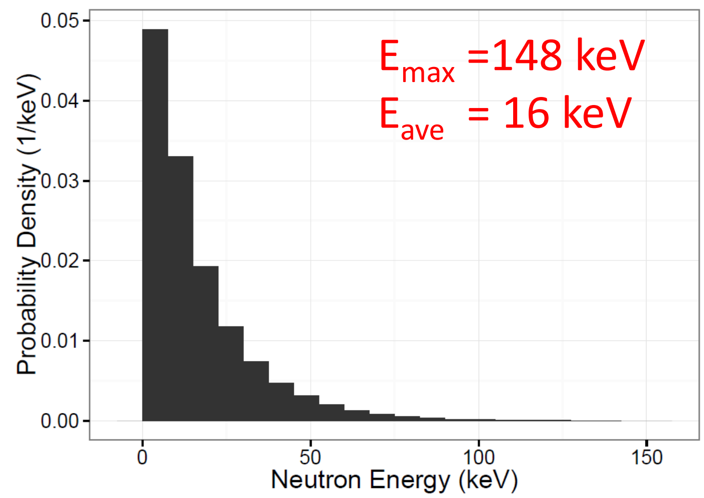


- With 1m of shielding:
- 60 fast neutron counts/day
- 850 antineutrino counts/day
- SNR = ~14

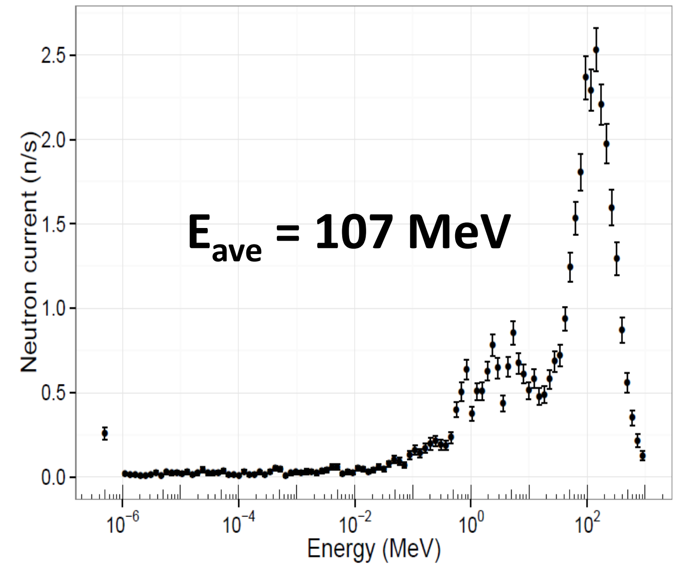
Nuclear data needs

- Common elements used in antineutrino detection system
- scintillators
  - C, H, O, F, N, S, Zn
- Absorbers
  - Li, B, Gd, Cd

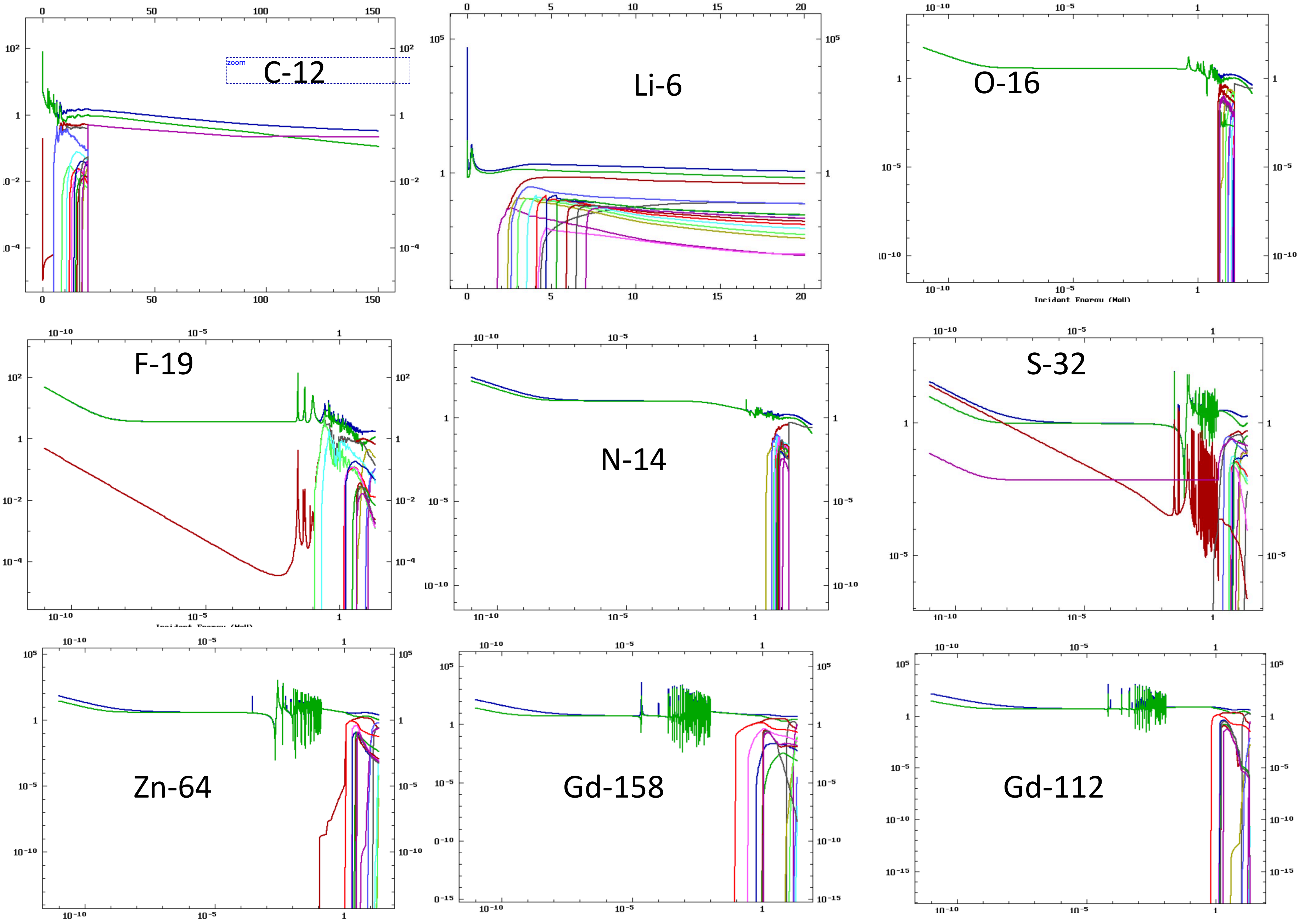
IBD Neutron Spectrum



Cosmic-ray neutron spectrum



Neutron cross sections (ENDF/B-VIII.0) for scintillators and absorbers



Nuclear data needs

- Particle transport performed
  - For **IBD neutron** simulation for optimization of detection system; data available for all the elements
  - For **cosmic-ray neutron** simulation (with average energy of 107 MeV) for determination and removal of interference (noise) and shielding; there is **a need for data and further evaluation of the available data**
- Additionally, for NASA's space activities
  - **data is needed** for both fast neutrons and charged particles

Development of physics-based machine-learning (ML) System (For reactor monitoring, safety and safeguards applications) (1)

- Machine Learning (ML) system requires the availability of both **measured and computed data in real time**

- The standard Monte Carlo or deterministic methods are not practical for real-time computation

- **We have developed the RAPID (**Real-time Analysis for Particle Transport and In-situ Detection) code system that solves particle transport problems by a **hybrid deterministic and Monte Carlo technique:**

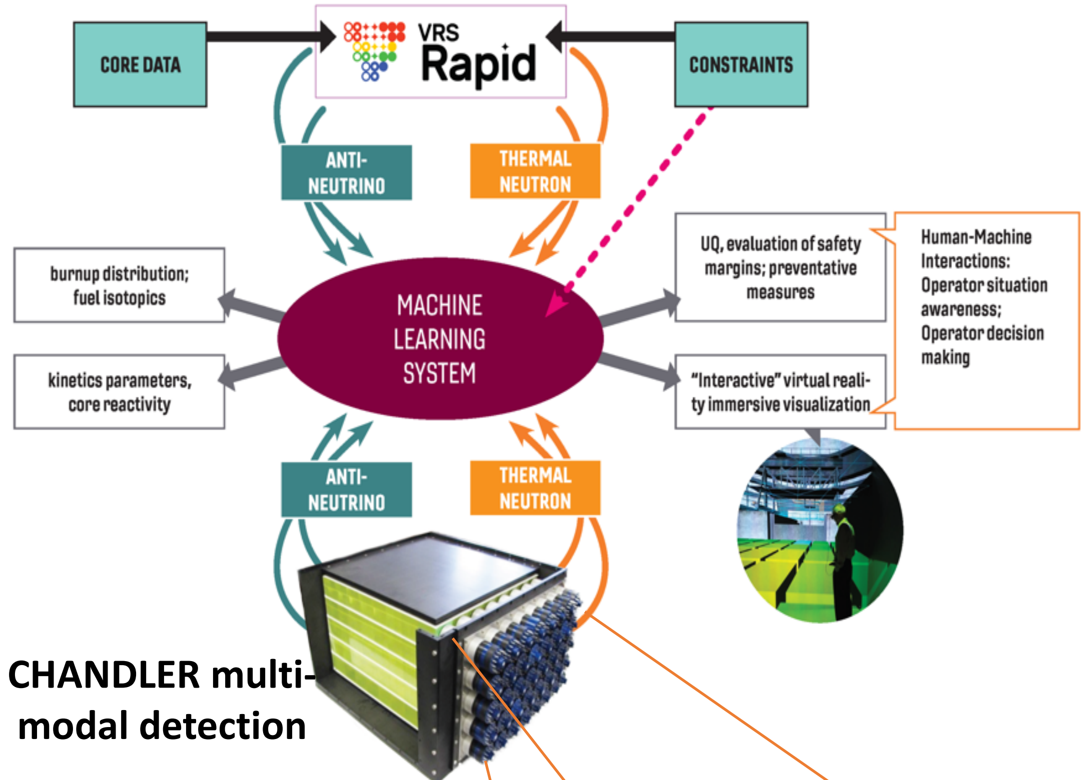
(fission density) $$\boldsymbol{F_i = \frac{1}{k}\sum_j a_{i,j}F_j}$$

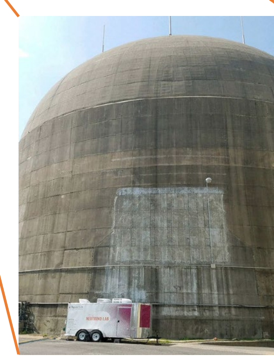
(detector response) $$\boldsymbol{R_i = \sum_j \beta_{i,j}F_j}$$

$where,\ a_{i,j}$ and $\beta_{i,j}$ are pre-calculated using the Monte Carlo method as a function of different parameters

Development of physics-based machine-learning system For reactor monitoring, safety and safeguards applications (2)

Using ML learning algorithms, e.g., Least squares Minimization (LSM), or Maximum Likelihood Estimation Maximization (MLEM), which compare CHANDLER (in multi-modal mode) and RAPID data to determine various parameters





Nuclear reactor

Thanks

Questions?