Monte Carlo Models of Neutron Detection with Organic Scintillators

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Outline

- Motivation
- Monte Carlo codes to describe neutron detection in organic scintillators
- Validation of Monte Carlo models by comparison of simulations with experimental data
- Conclusions and future work

Motivation

- Detection of diverted special nuclear material is of increasing concern to the United States and other nations
- Need for active and passive systems to detect threat objects

Motivation

Screening for HEU at Potential Points of Entry

Existing Systems

Research & Development Needs are Mission Driven

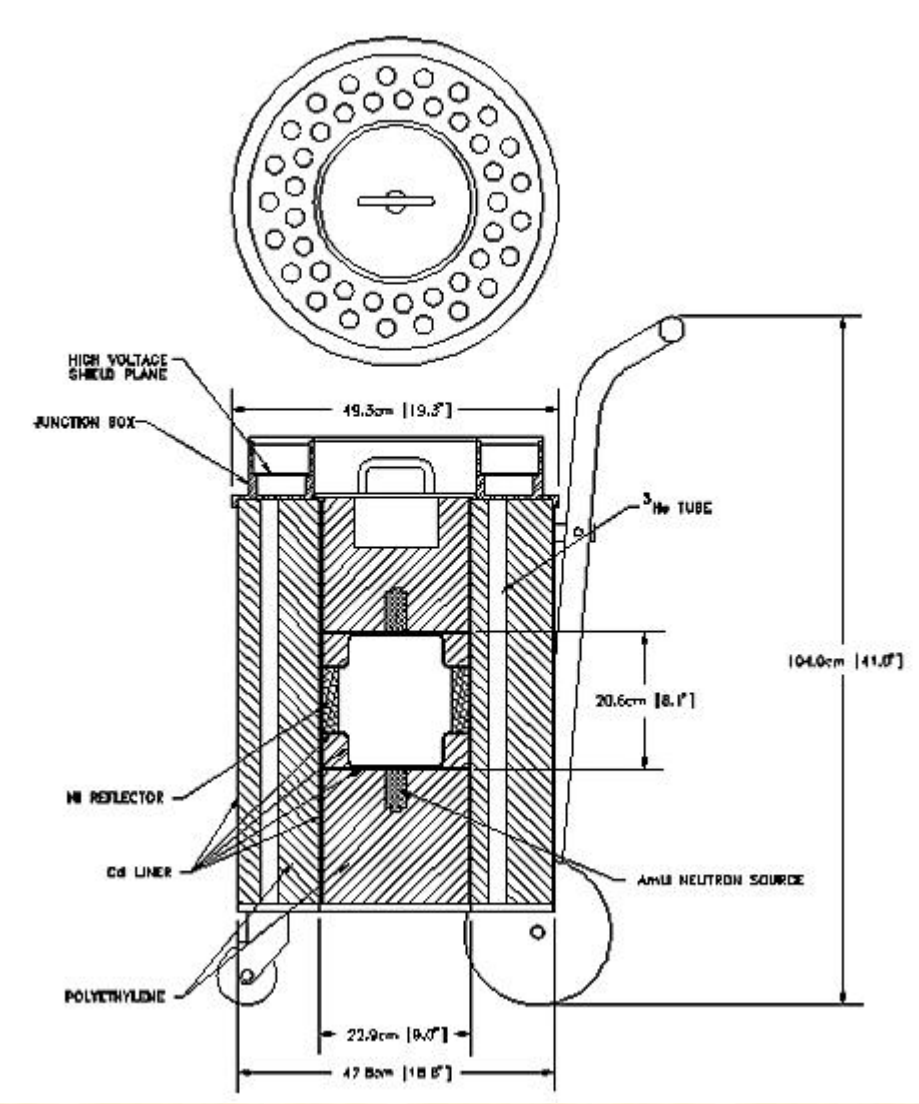
Fixed

Portable

Monte Carlo Modeling

- Used to evaluate new measurement techniques: provide useful insights on what works in different scenarios
  - Simulate the neutron and photon field in nuclear and non-nuclear materials
  - Simulate detector response
- Analyze data from existing measurement systems
- Develop novel measurement systems

Traditional Safeguards Instruments



Neutron moderation and He-3 detection

Advantages:

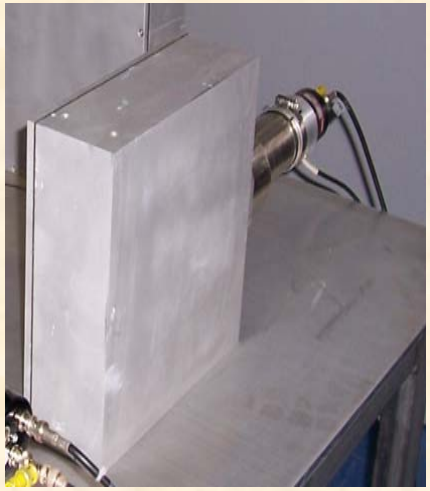
- Insensitive to gamma rays

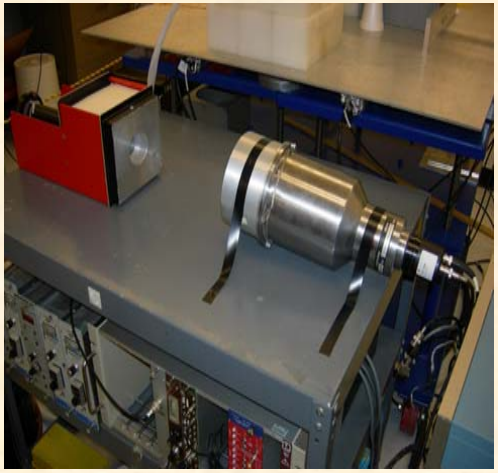
Disadvantages:

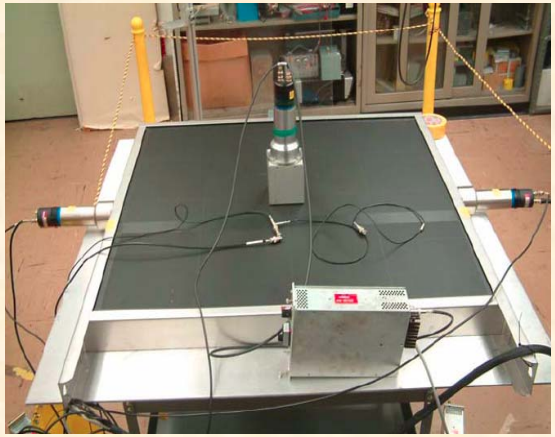
- Bulky
- No energy information

Organic Scintillators

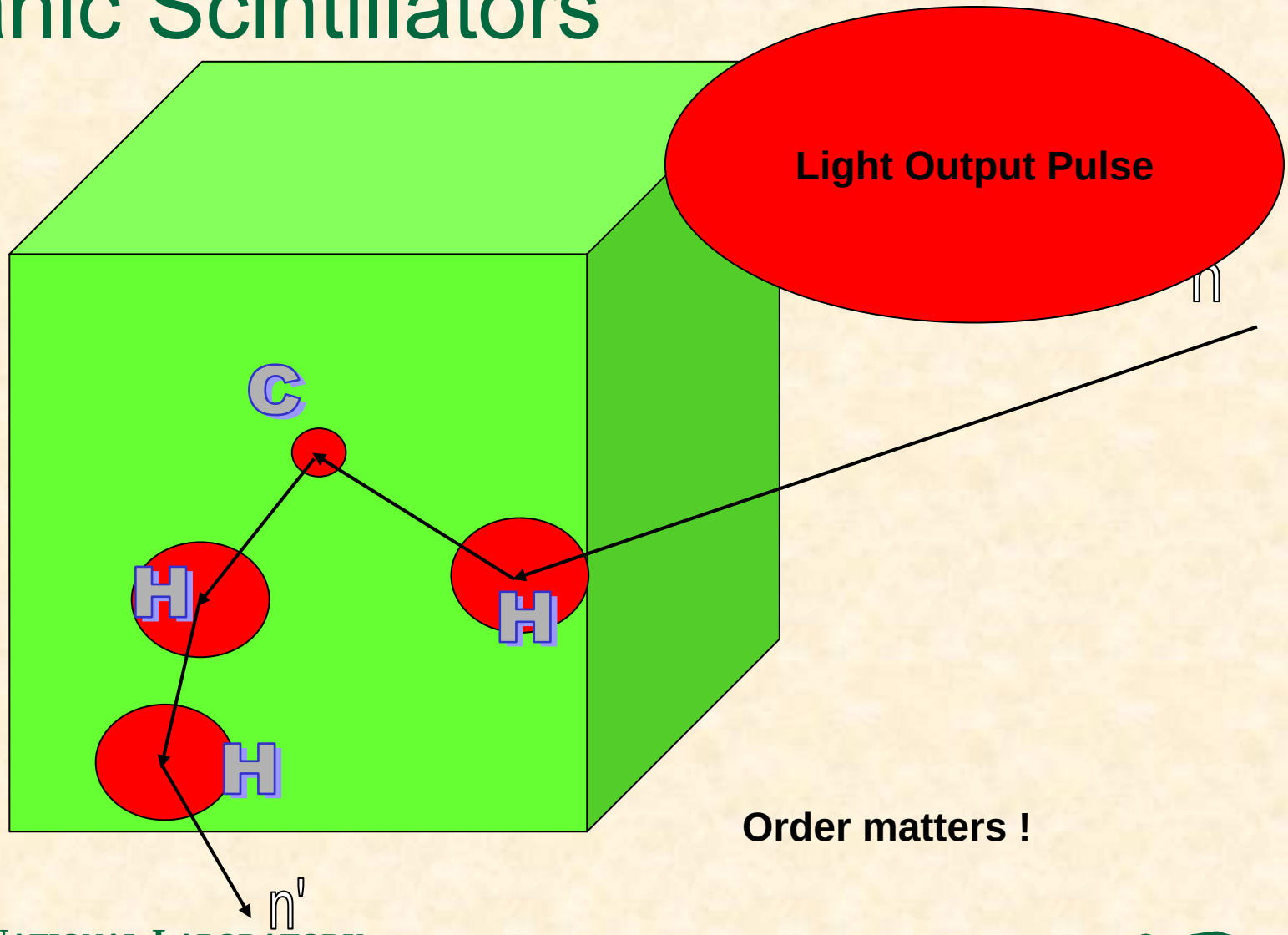
- Detection of fast neutrons and gamma rays from fission with organic scintillators is a promising technique





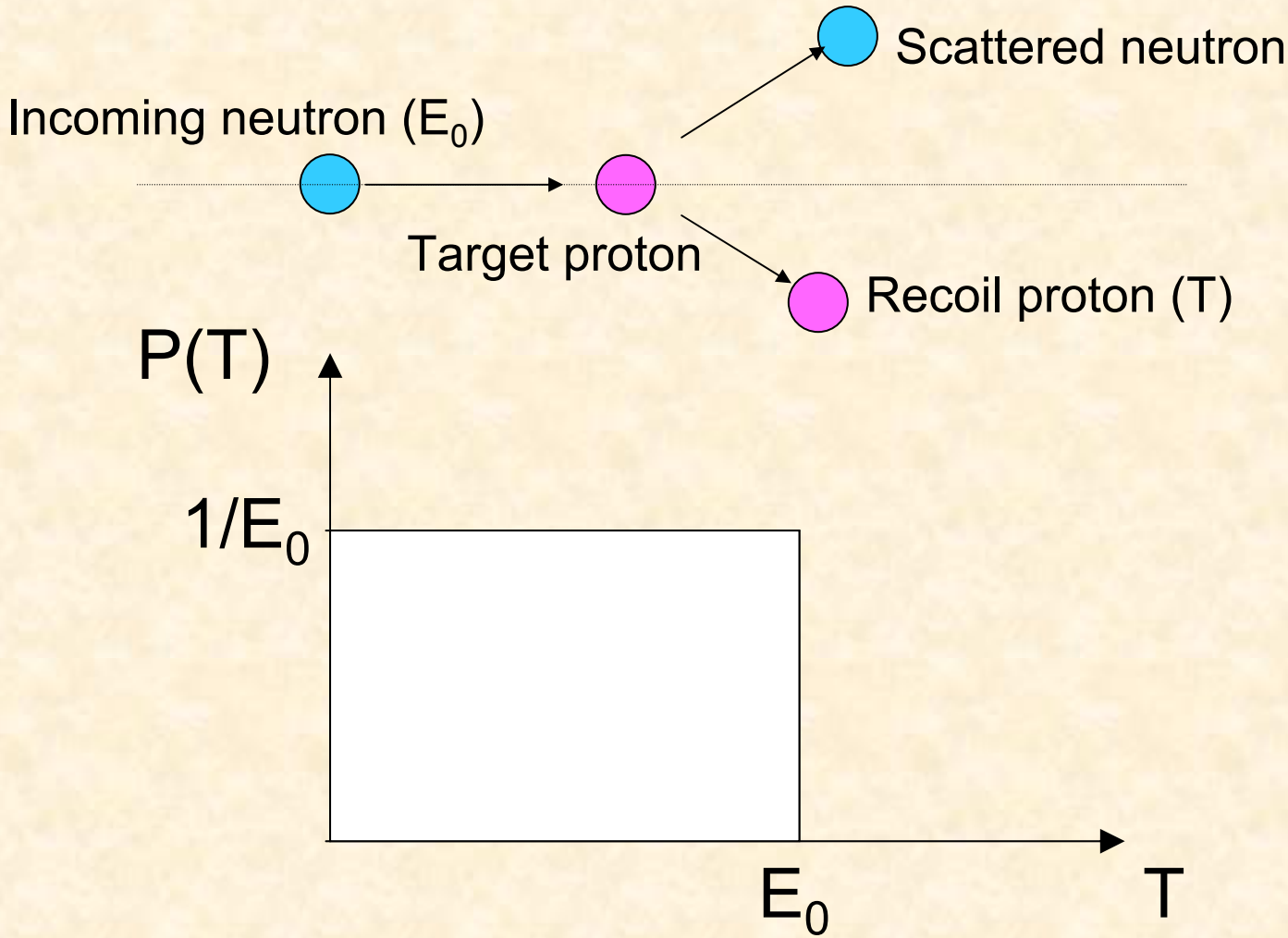


Mechanisms of Detection in Organic Scintillators

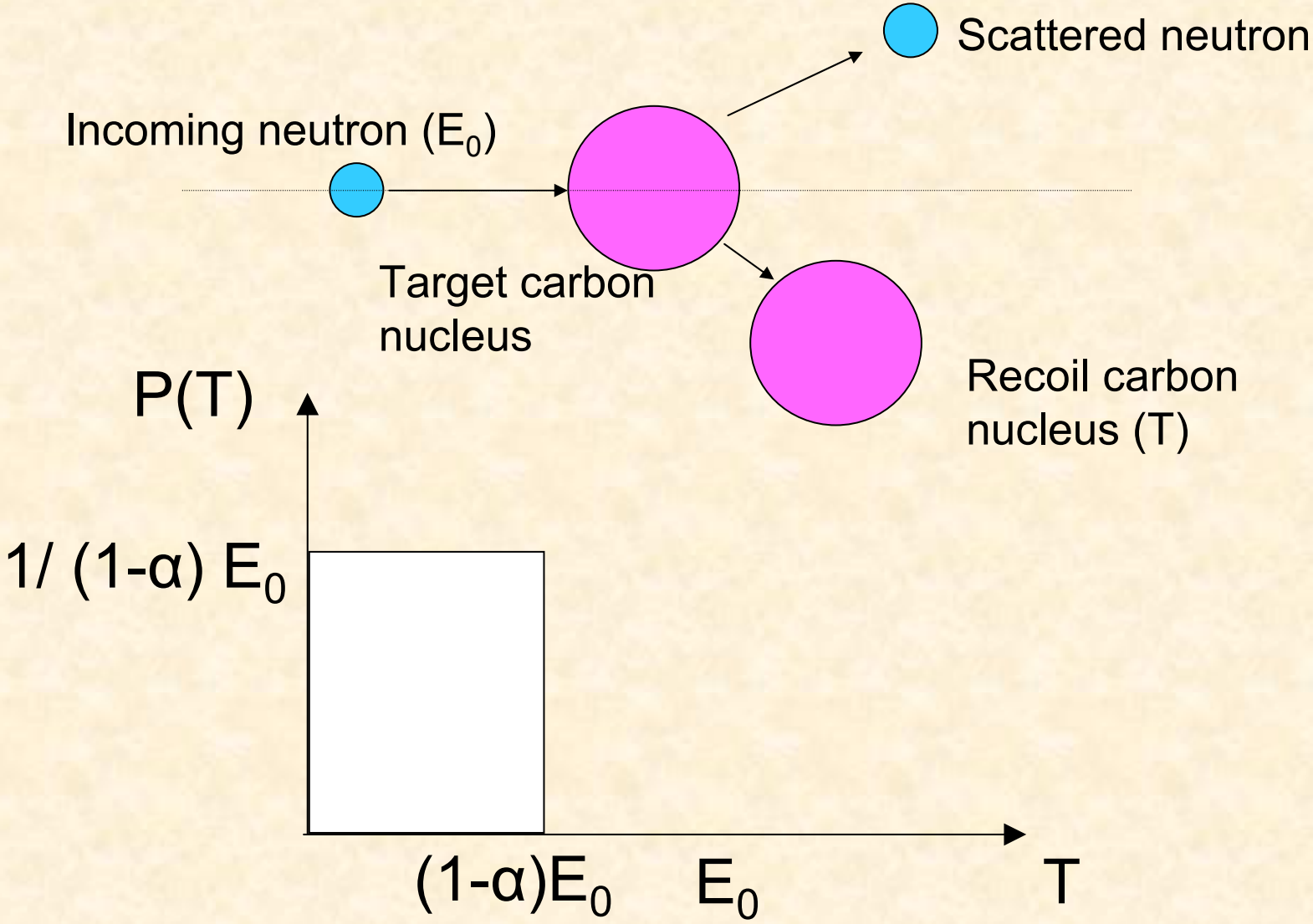


Order matters !

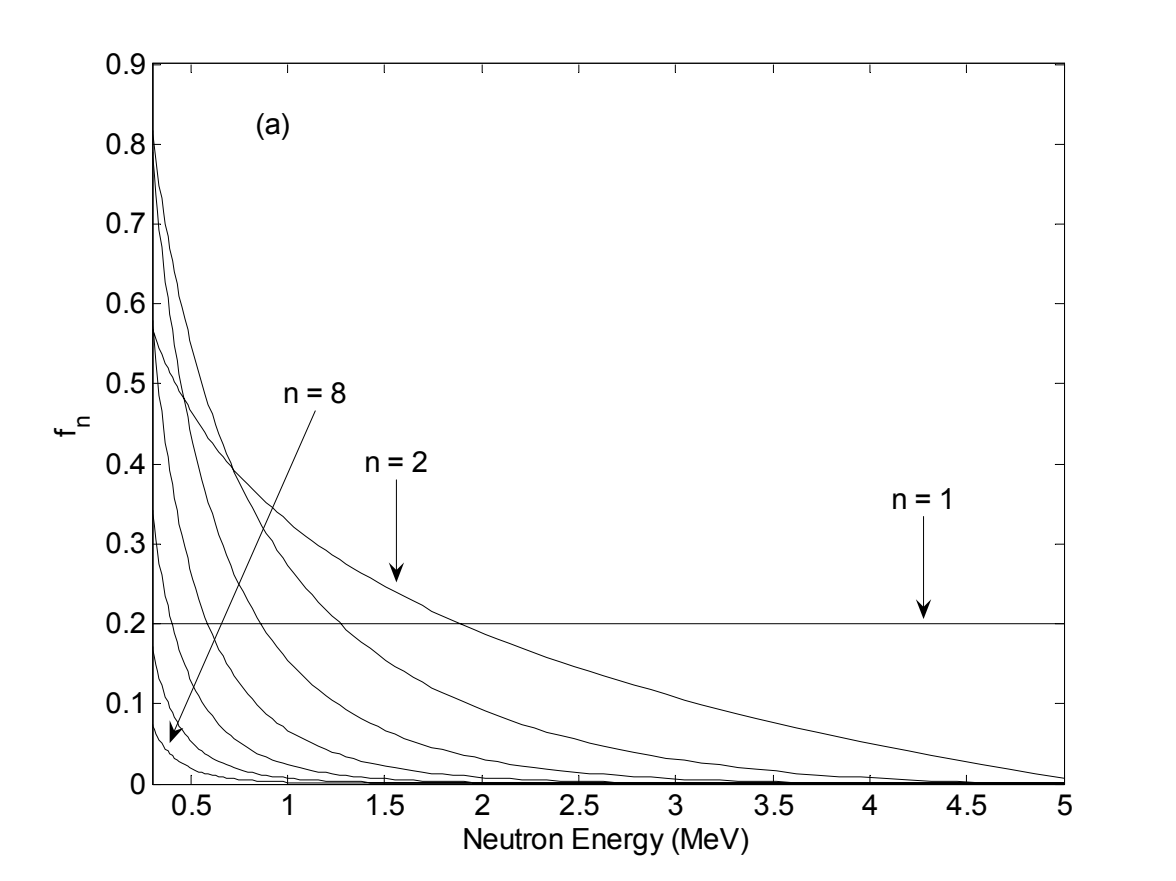
Neutron Scattering on Hydrogen



Neutron Scattering on Carbon



Energy Distributions following *n* Scatterings for 5-MeV Neutrons on H



$$f_0(E) = \delta(E - E_0)$$

$$f_1(E) = \frac{1}{E_0}$$

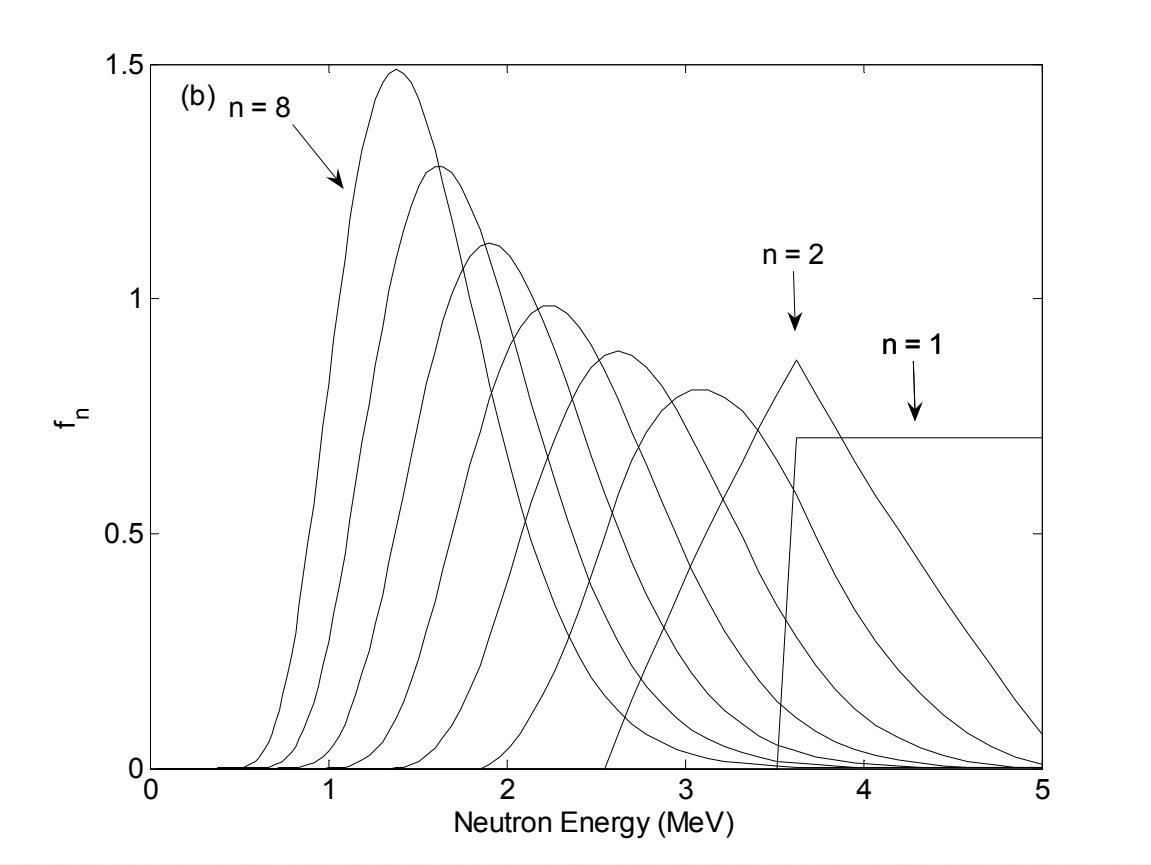
$$f_2(E) = \int_E^{E_0} \frac{f_1(E')dE'}{E'} = \frac{1}{E_0}\int_E^{E_0} \frac{dE'}{E'} = \frac{1}{E_0}\ln\left(\frac{E_0}{E}\right)$$

.

.

$$f_n(E) = \int_E^{E_0} \frac{f_{n-1}(E')dE'}{E'} = \frac{1}{E_0(n-1)!}\ln^{n-1}\left(\frac{E_0}{E}\right)$$

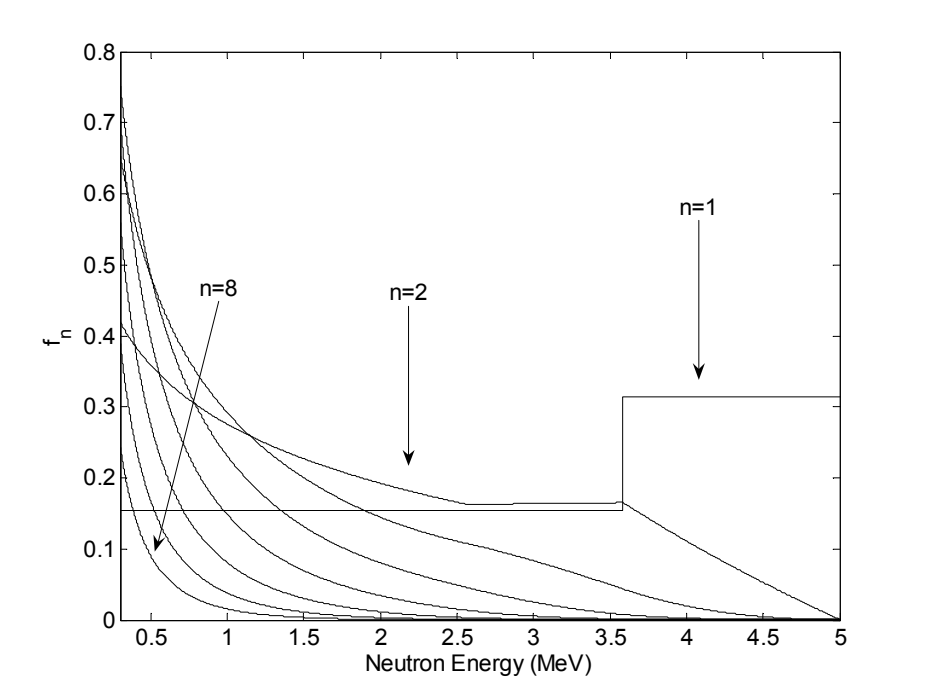
Energy Distributions following *n* Scatterings for 5-MeV Neutrons on C

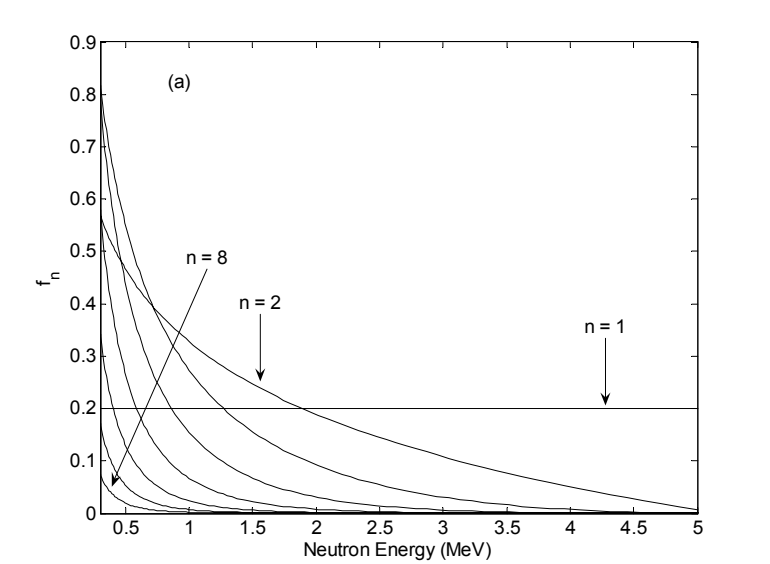


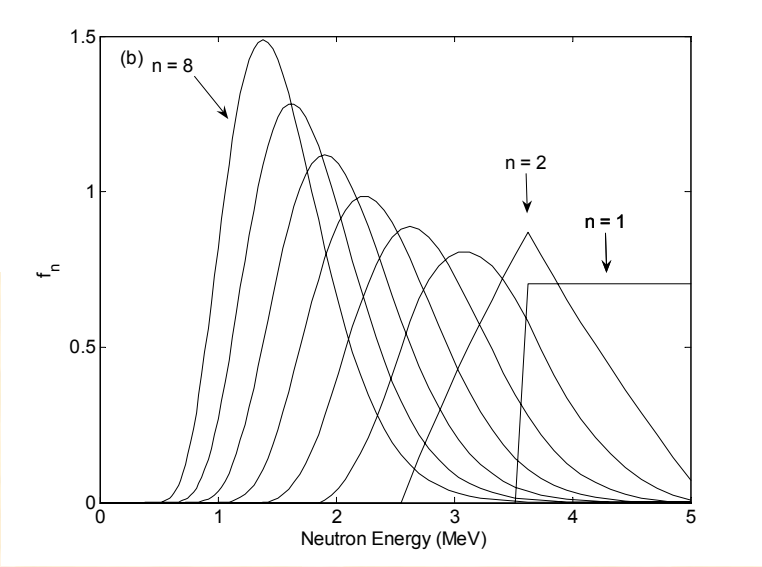
$$f_0(E) = \delta(E - E_0)$$

$$f_n(E) = \int_E^{E/\alpha} \frac{f_{n-1}(E')}{(1-\alpha)E'} dE'$$

Energy Distributions following *n* Scatterings for 5-MeV Neutrons on H and C







S. A. Pozzi and I. Pázsit, "Neutron Slowing Down in a Detector with Absorption," *Nuclear Science and Engineering*, vol. 154, p. 1-7, 2006.

S. A. Pozzi and I. Pázsit, "The Statistics of the Number of Neutron Collisions Prior to Absorption," *Nuclear Science and Engineering* vol. 153 p. 60-68, 2006.

Modeling the Physics of Detection

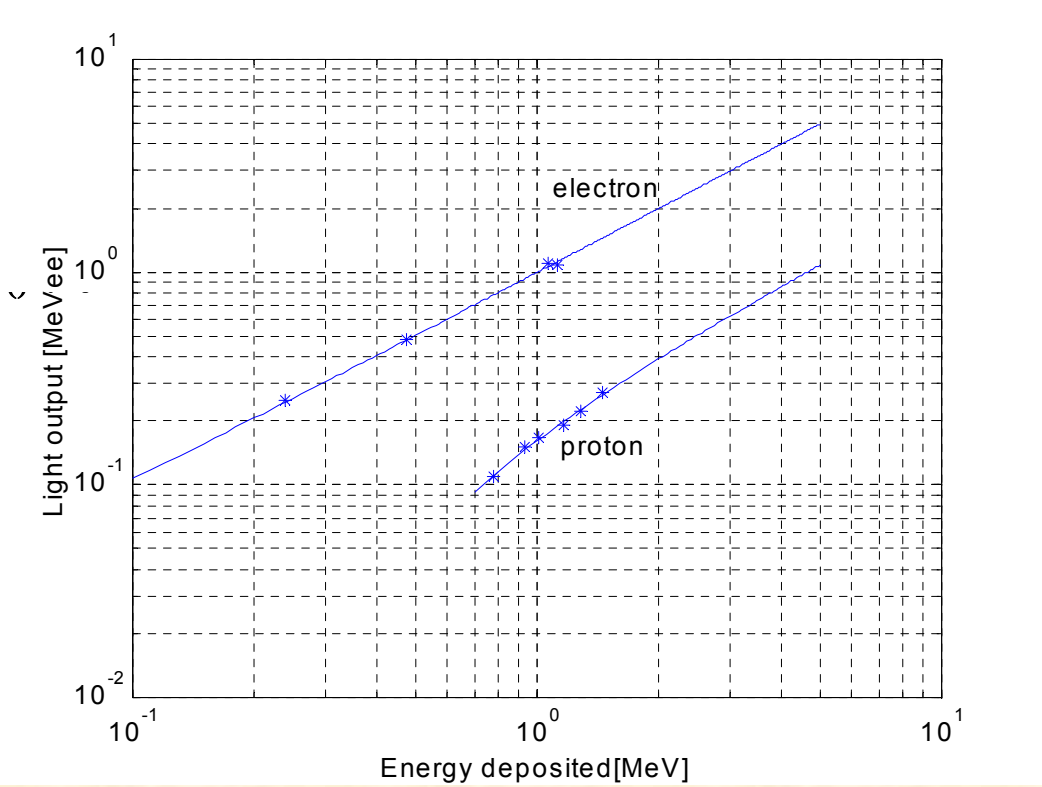
MCNP-PoliMi Collision Output File

History number	Particle number	Projectile type*	Interaction type$^{\Delta}$	Target nucleus•	Cell number of collision event	Energy deposited in collision (MeV)	Time (shakes)	Collision position (X)	(Y)	(Z)	Particle weight	Generation number	Number scatterings
...													
29	20	1	-99	1001	2		2.743	-25.64	14.37	8.7	1	2	2
29	20	1	-99	1001	2		2.846	-26.01	-14.8	9.48	1	2	3
29	20	1	-99	1001	2		3.045	-27.27	15.07	10.1	1	2	4
29	43	2	1	6	1		6.514	31.83	7.07	11.2	1	2	1
29	8	1	-99	1001	1		3.965	27.84	18.82	-0.6	1	0	1
...													

* 1 = neutron; 2 = photon
Δ -99 = elastic scattering; 1 = Compton scattering
• 1001 = hydrogen; 6 = carbon

Post-Processing Code for MCNP-PoliMi Collision Output File

Scintillation Detectors



Experimental calibration of scintillator to determine the light output for neutron interactions on H and the light output for γ interactions on e^-

$$L = aT^2 + bT \equiv L(T)$$

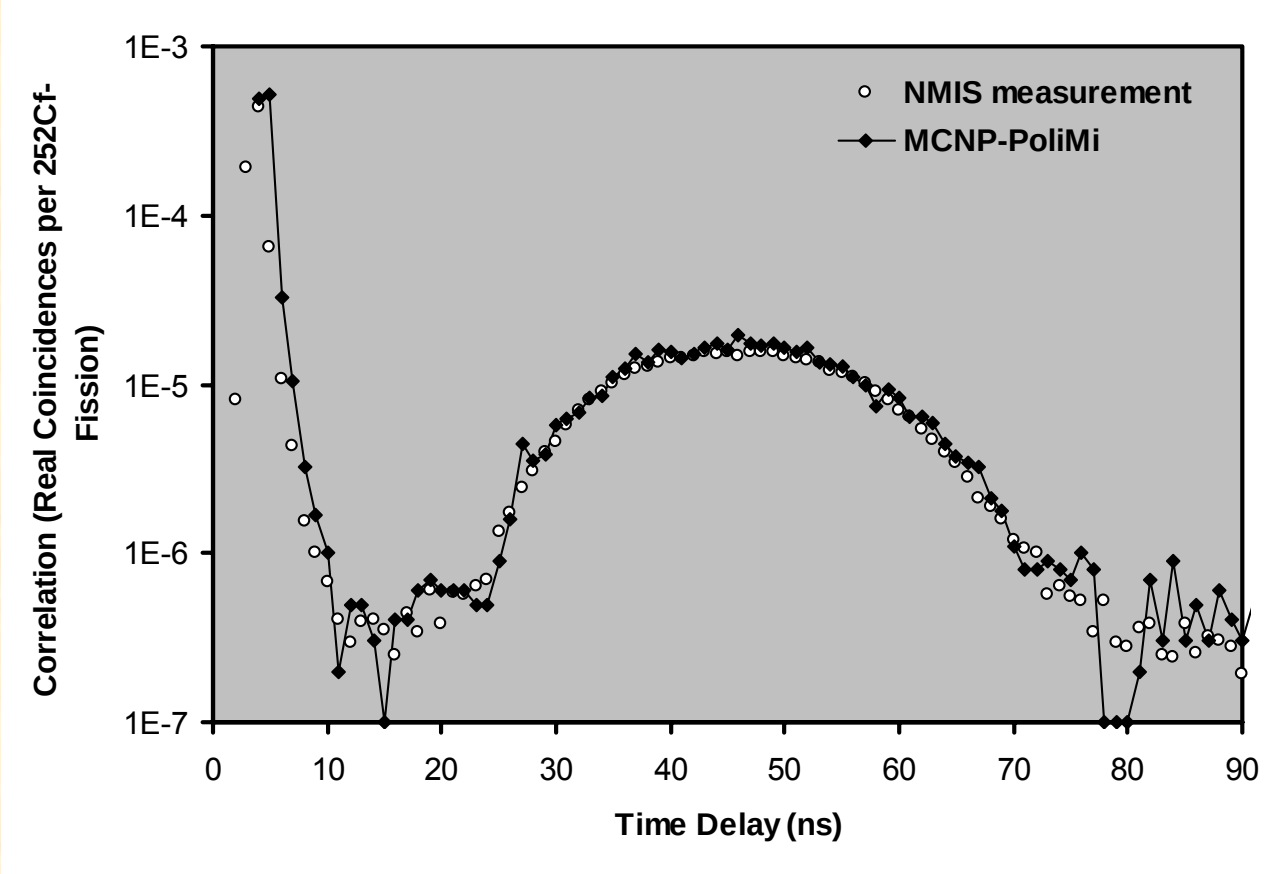
$$a = 0.035 \text{ MeVee/MeV}^2$$
$$b = 0.141 \text{ MeVee/MeV}$$

$$L(T) = cT$$

$$c = 0.02 \text{ MeVee/MeV}$$

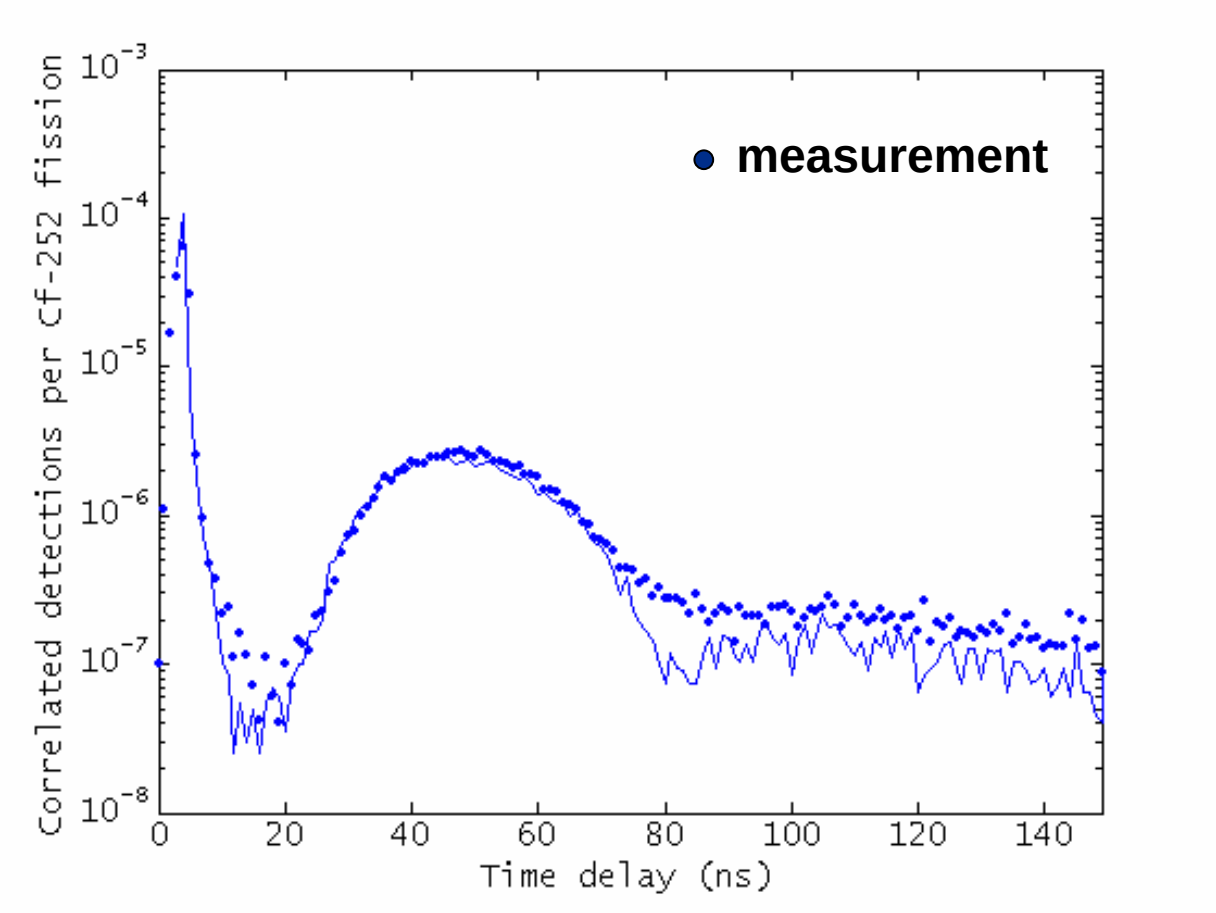
Comparison of Measurement and MCNP-PoliMi Simulation: Time-of-Flight in Air

Plastic scintillator 10.1 × 10.1 × 10.1 cm^3



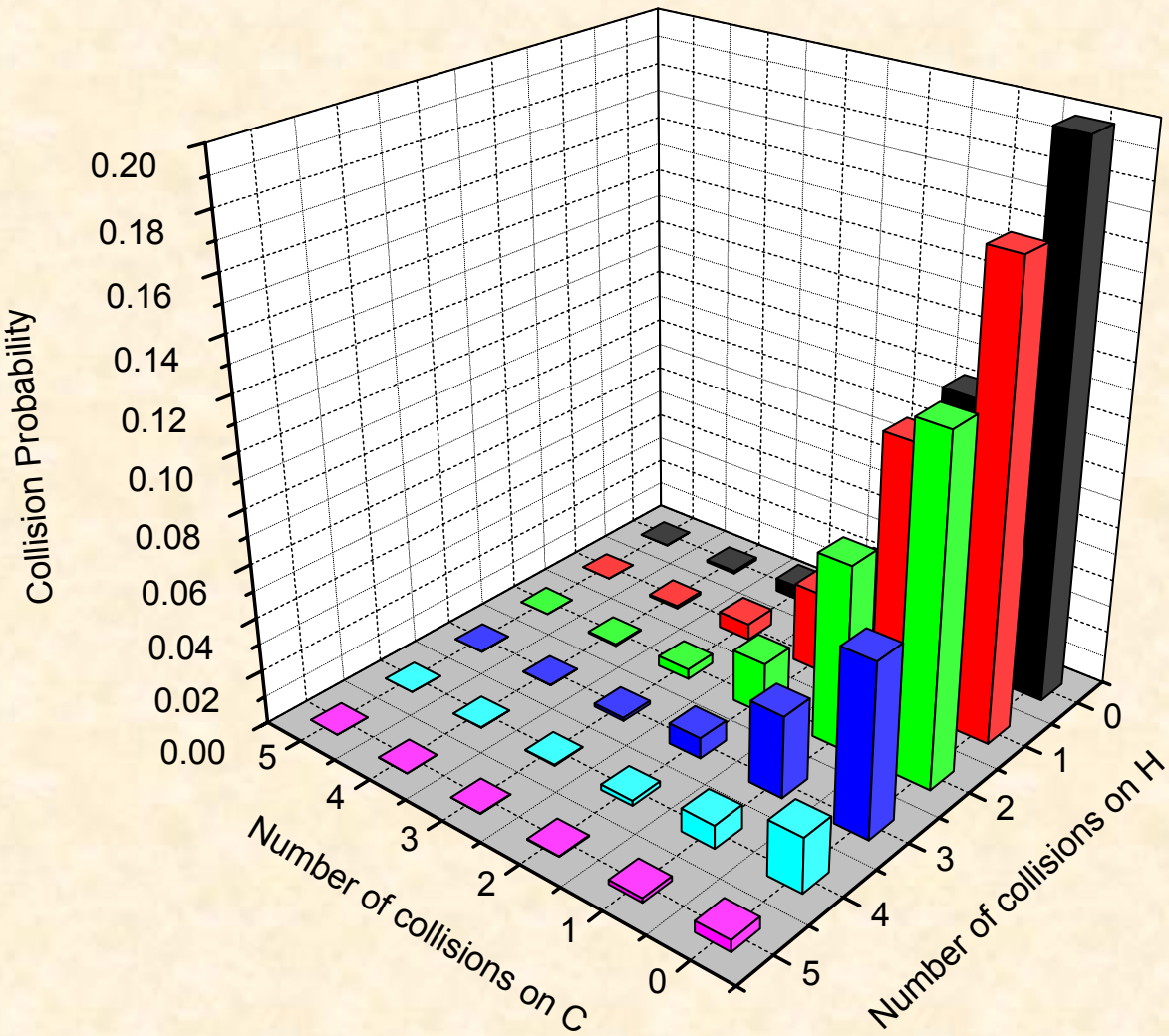
Comparison of Measurement and MCNP-PoliMi Simulation: Time-of-Flight in Air

Plastic scintillator 2.54 × 2.54 × 15.0 cm



Liquid Scintillator $10 \times 10 \times 10$ cm^3

E_0=1.0 MeV



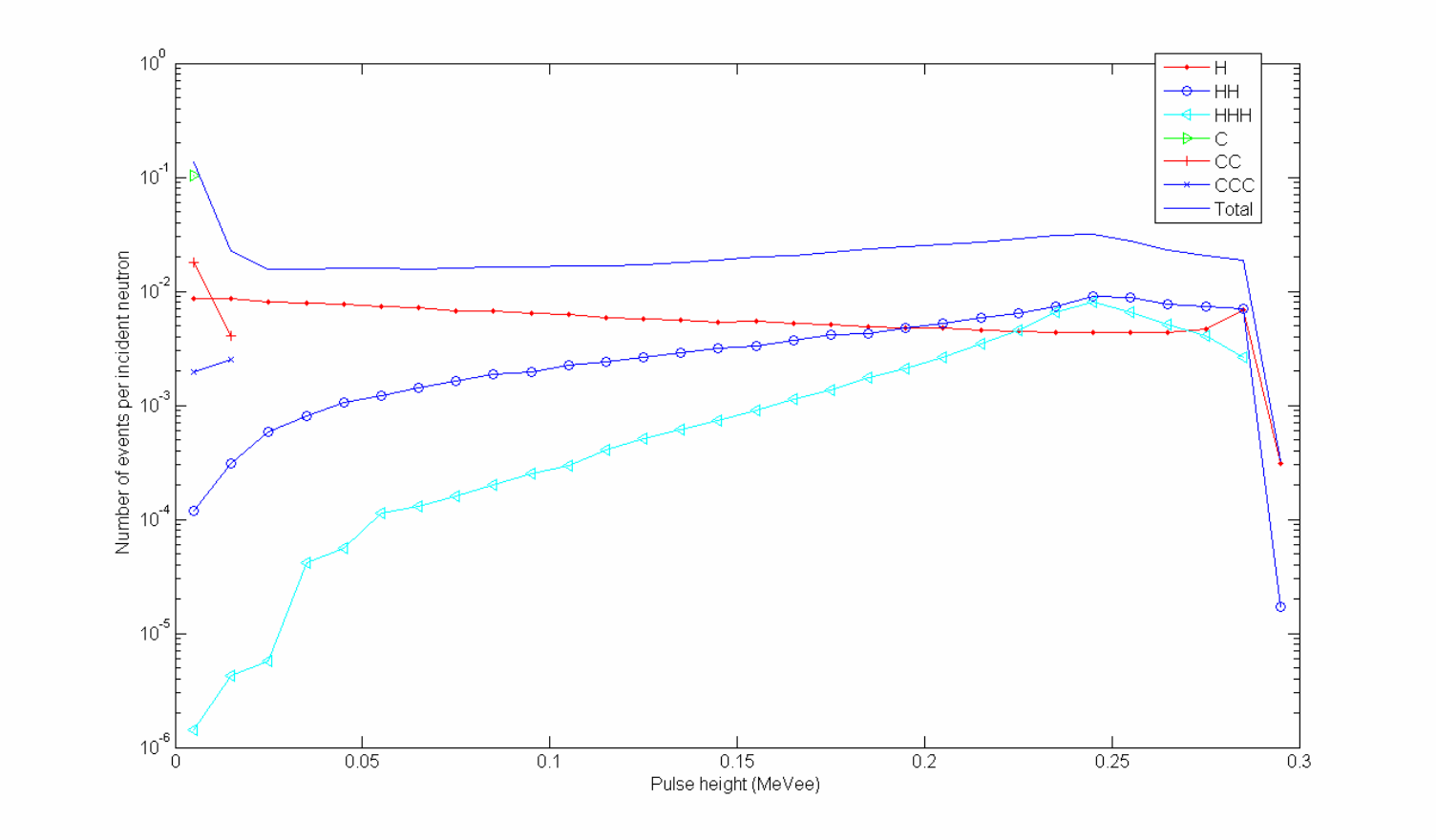
History types and relative probability

Liquid Scintillator 10 × 10 × 10 cm^3

History type	Relative probability E = 1 MeV	Relative probability E = 1.5 MeV	Relative probability E = 2 MeV
No collision	0.1985±0.0005	0.2580±0.0006	0.3079±0.0007
H	0.1705± 0.0005	0.1724±0.0005	0.1750±0.0005
HH	0.1265±0.0004	0.1093±0.0004	0.097447±0.0004
HHH	0.0639±0.0003	0.0543±0.0003	0.047741±0.0003
C	0.1025±0.0004	0.1043±0.0004	0.10411±0.0004
CC	0.0245±0.0002	0.02179±0.0002	0.018937±0.0002
CCC	0.00537±8.8e-005	0.004437±8e-005	0.0035057±7 e-005
HC	0.0483±0.0003	0.04532±0.0003	0.041987±0.0002
CH	0.05054±0.0003	0.04342±0.0002	0.037657±0.0002
HHC	0.01893±0.0002	0.01751±0.0002	0.016291±0.0002
CHH	0.02541±0.0002	0.02036±0.0002	0.01666±0.0002
HCH	0.02462±0.0002	0.02180±0.0002	0.019337±0.0002
CCH	0.01103±0.0001	0.008936±0.0001	0.0070771±0.0001
HCC	0.009783±0.0001	0.009151±0.0001	0.00841±0.0001
CHC	0.009393±0.0001	0.008157±0.0001	0.0070014±0.0001
Others	0.08395±0.0003	0.07669±0.0003	0.068684 ± 0.0003

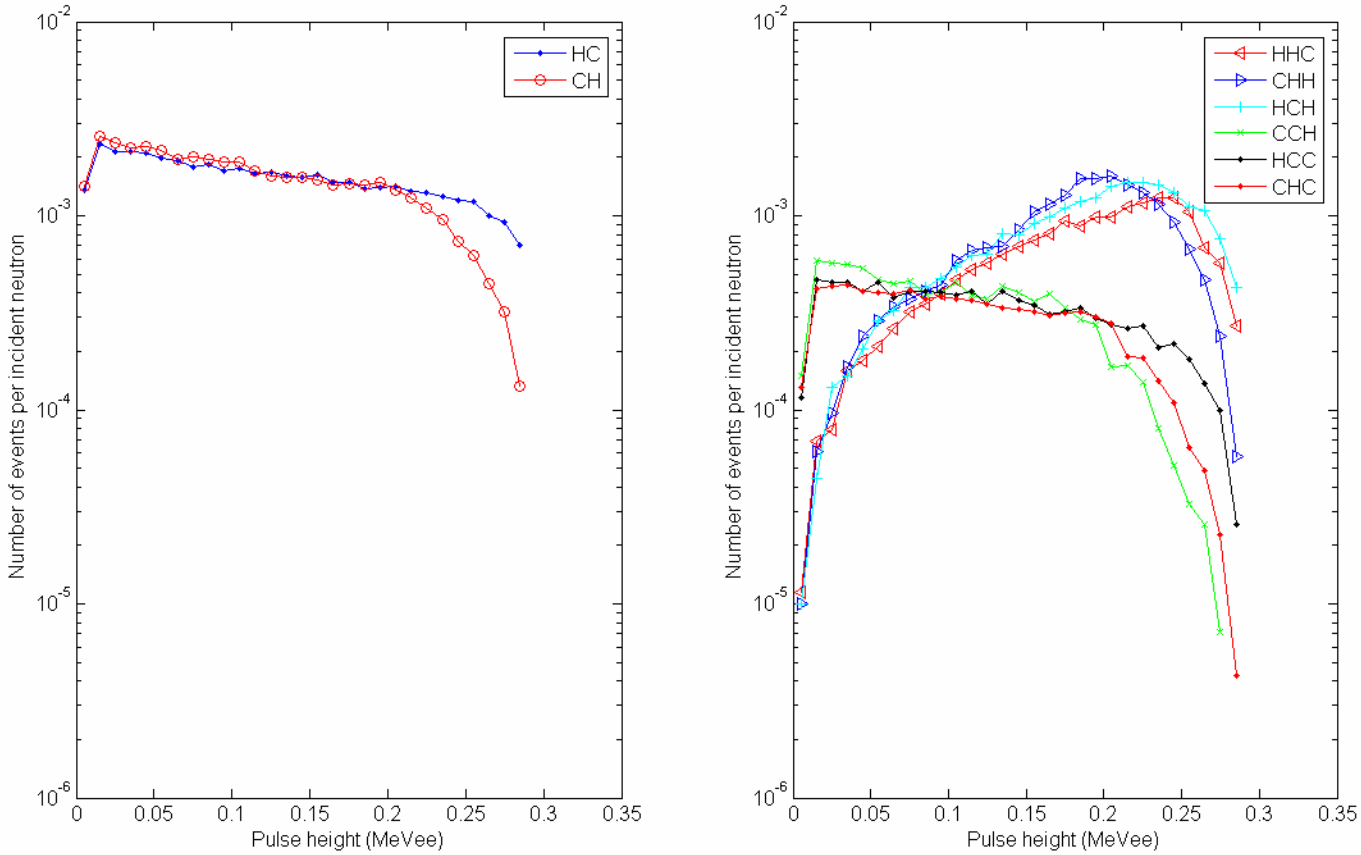
Pulse-Height Distributions: Scattering on C only or H only

Liquid Scintillator 10 × 10 × 10 cm^3; E_0=1.5 MeV

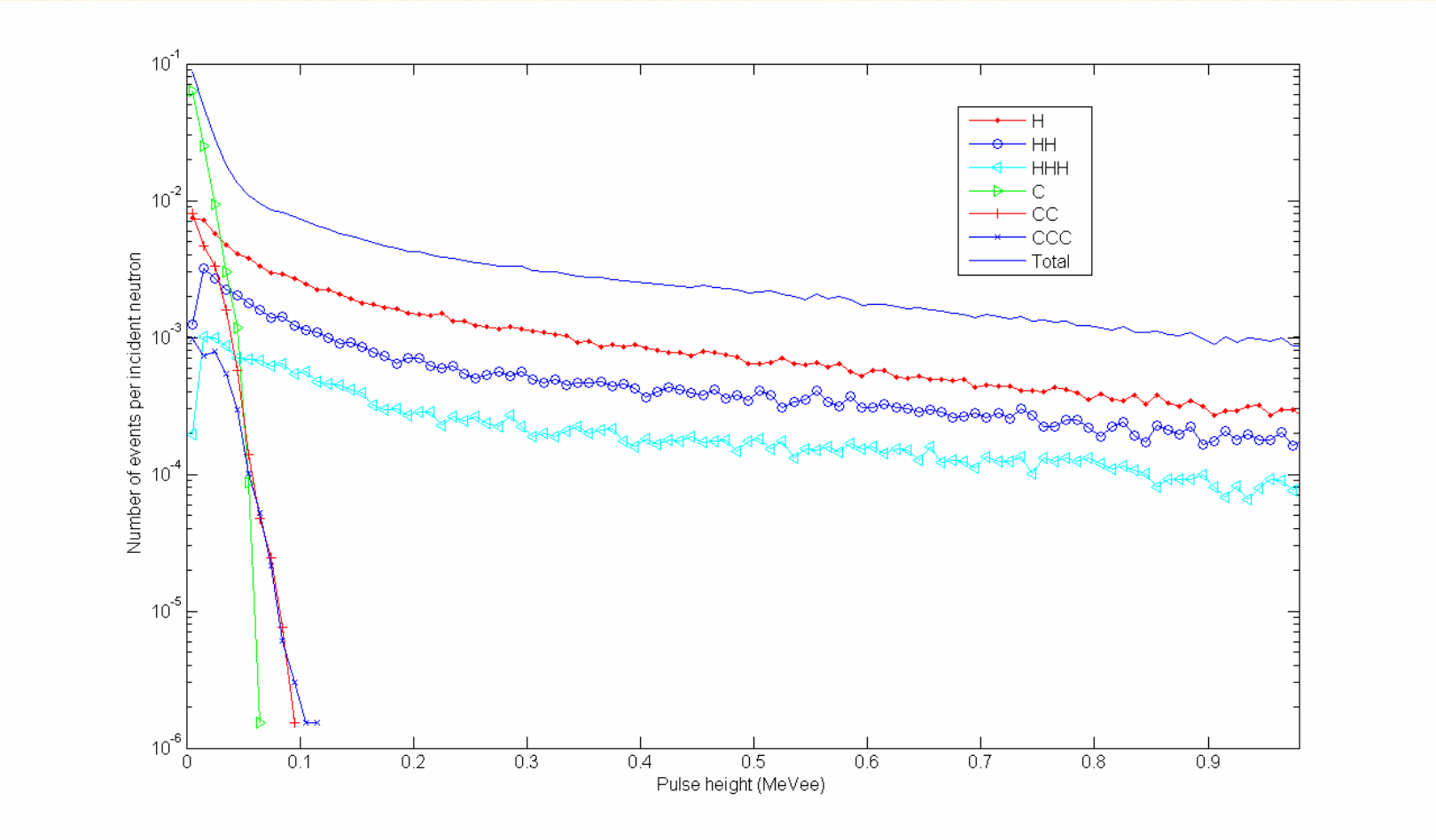


Pulse-Height Distributions: Scattering on C and H

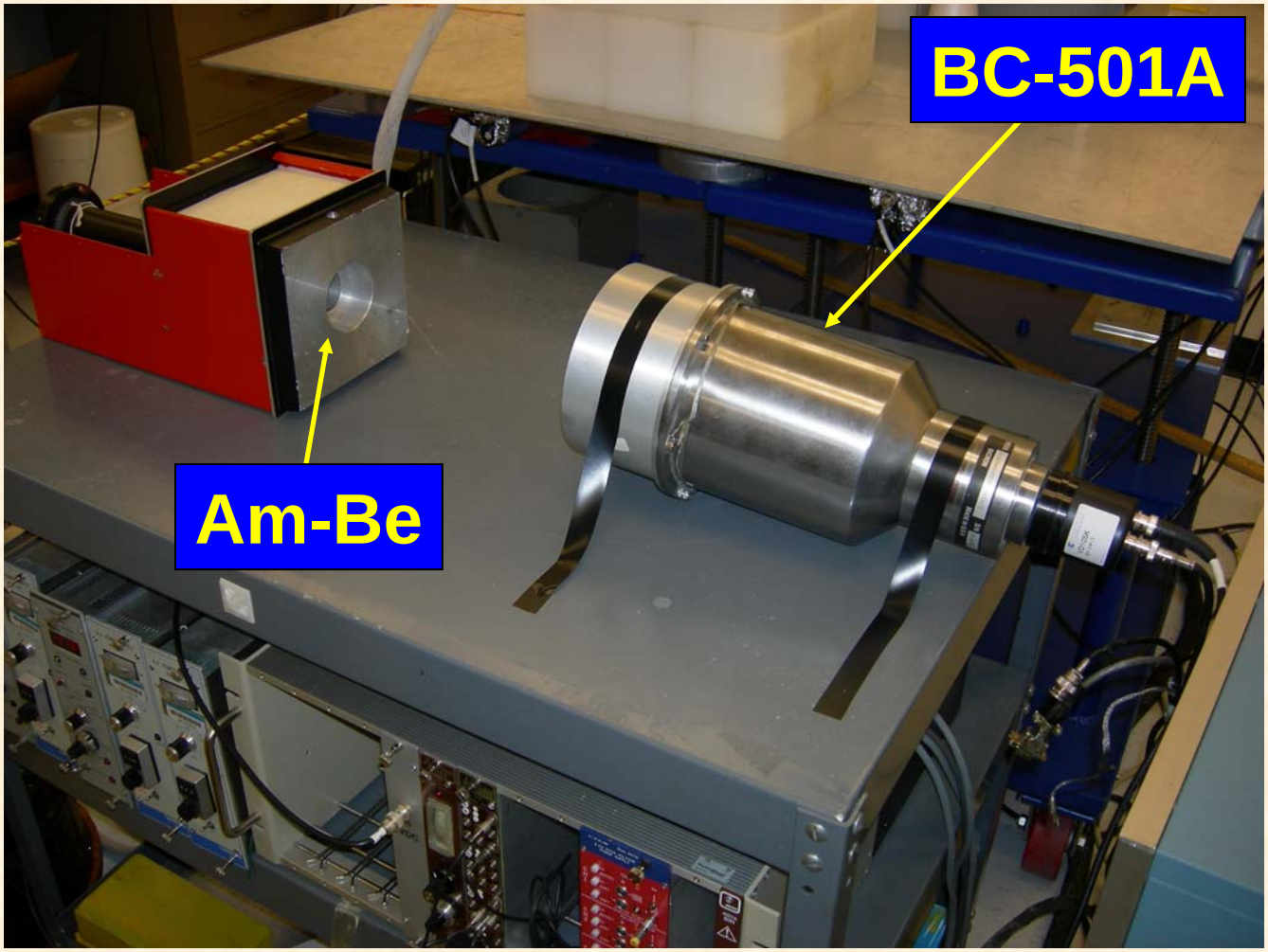
Liquid Scintillator 10 × 10 × 10 cm^3; E_0=1.5 MeV



Pulse-Height Distributions–Am-Be



Validation Experiments



Neutron sources:
Cf-252 (~60e3 n/s)
Am-Be (~10e5 n/s)
Am-Li (~10e5 n/s)

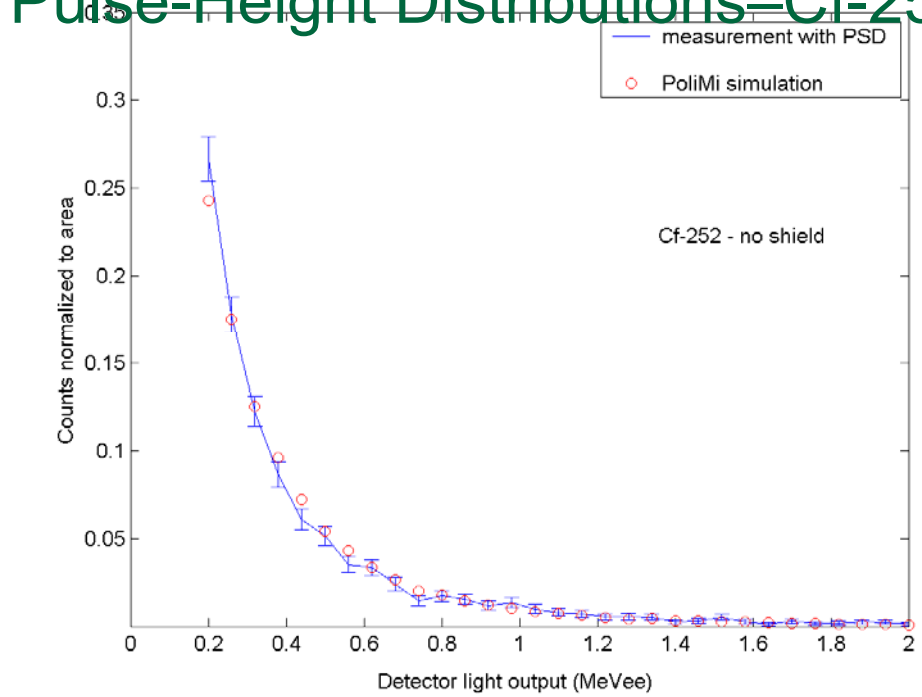
Shielding:
Pb blocks (up to 3 in.)
PE blocks (up to 3 in.)

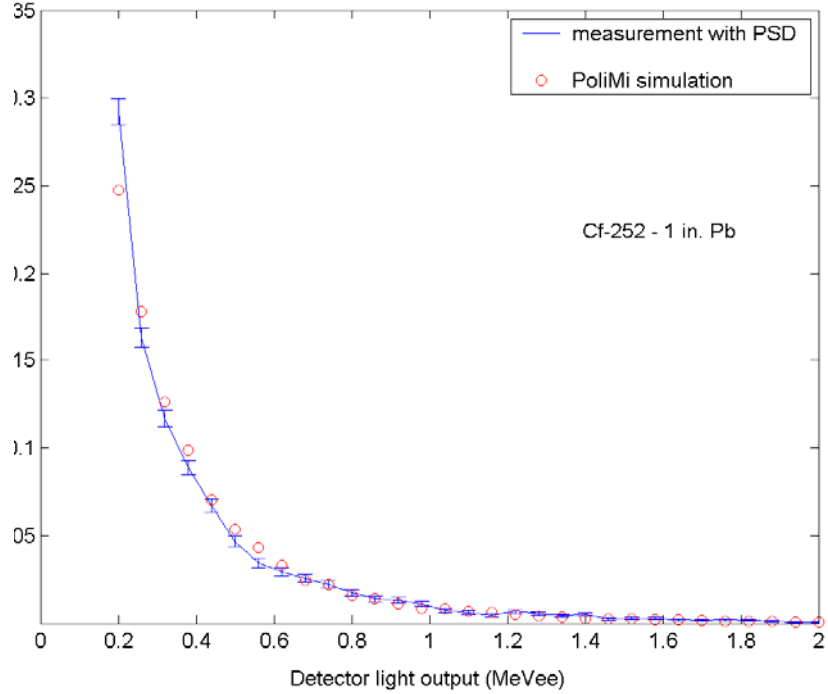
Source Distance:
Up to 50 cm

Data structure:
200 ns/pulse
~27000 pulses/case

Comparison of Measurement and MCNP-PoliMi Simulation

Pulse-Height Distributions–Cf-252

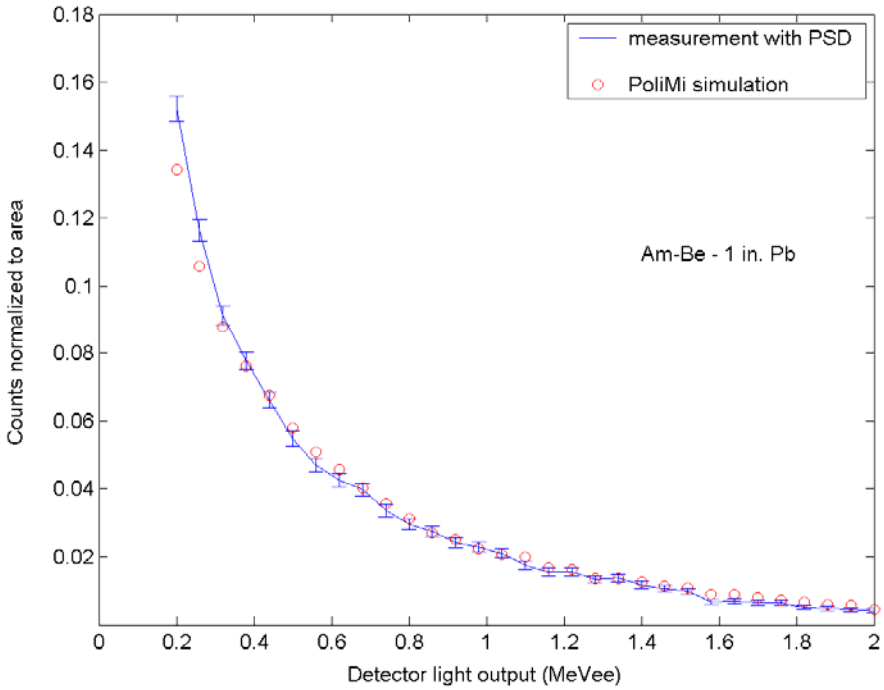


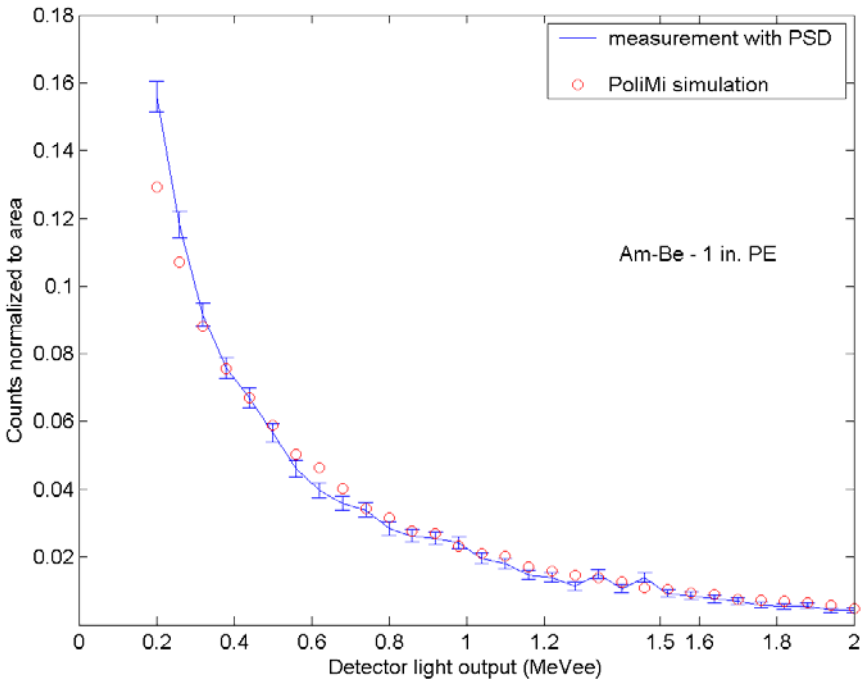


- Very good agreement between the measurement and MCNP-PoliMi
- Pb shielding results in more neutron pulses per acquisition, which improves statistics of neutron data
- Detection threshold of 0.094 MeVee

Comparison of Measurement and MCNP-PoliMi Simulation

Pulse-Height Distributions–Am-Be





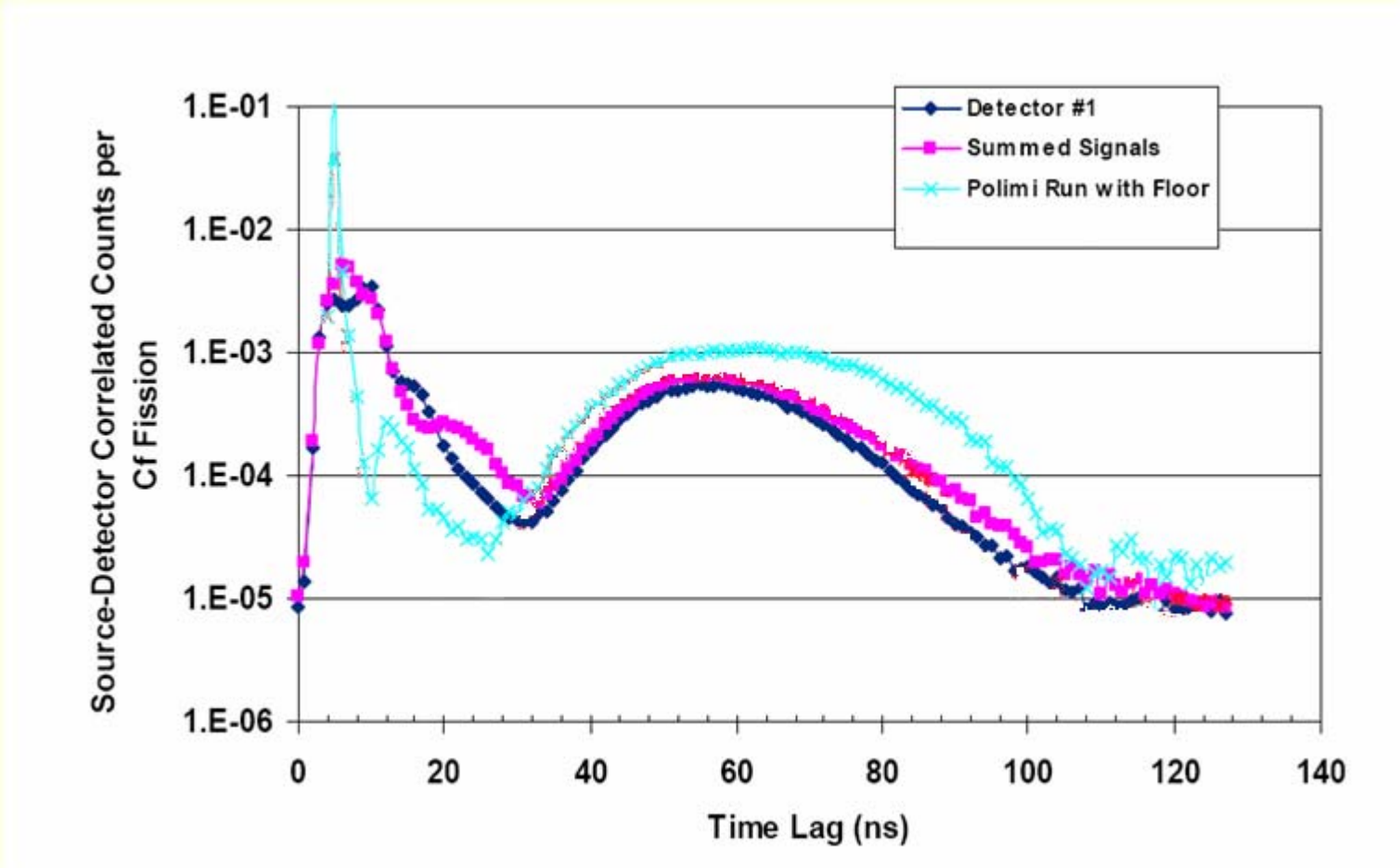
- Very good agreement between the simulated and measured pulse-height distributions.

Conclusions

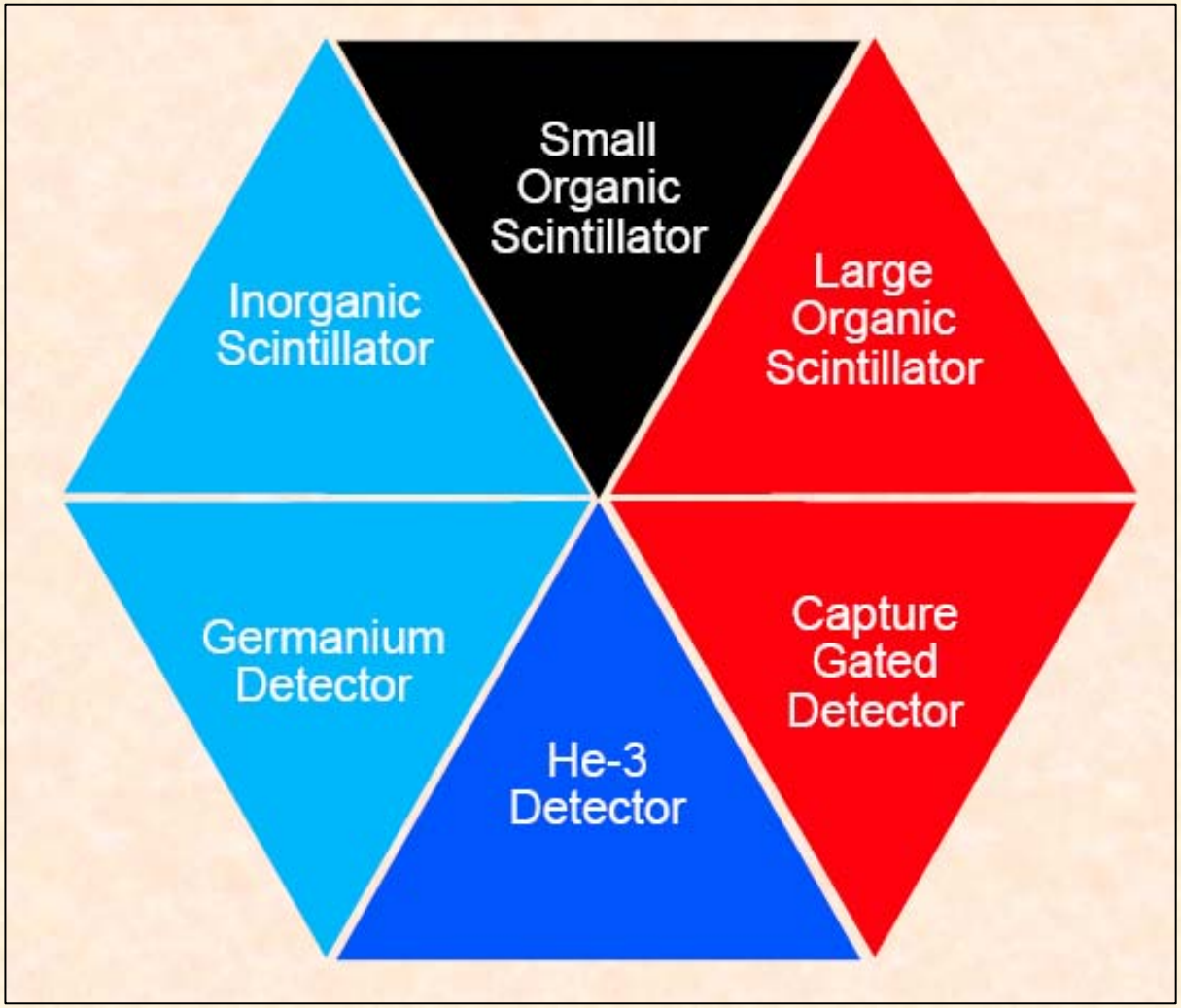
- MCNP-PoliMi and its post-processing code can be used to accurately simulate the detector response of organic scintillators
- A detailed, event-by-event simulation is possible for the entire system geometry
- Very good agreement between measurements and simulations was obtained for several source-shielding configurations, and several detector sizes

Large Plastic Scintillators for Homeland Security Systems ($100 \times 100 \times 8$ cm^3)

Existing Models Applied to Large Plastic Scintillators: Serious Disagreement !



Future Work: Detector Simulation Tool



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Average Energy after *n* Collisions

The average energy after *n* collisions, $\langle E_n \rangle$, can be calculated from the energy distributions

$$f_n(E) = \frac{1}{E_0(n-1)!} \ln^{n-1}\left(\frac{E_0}{E}\right)$$

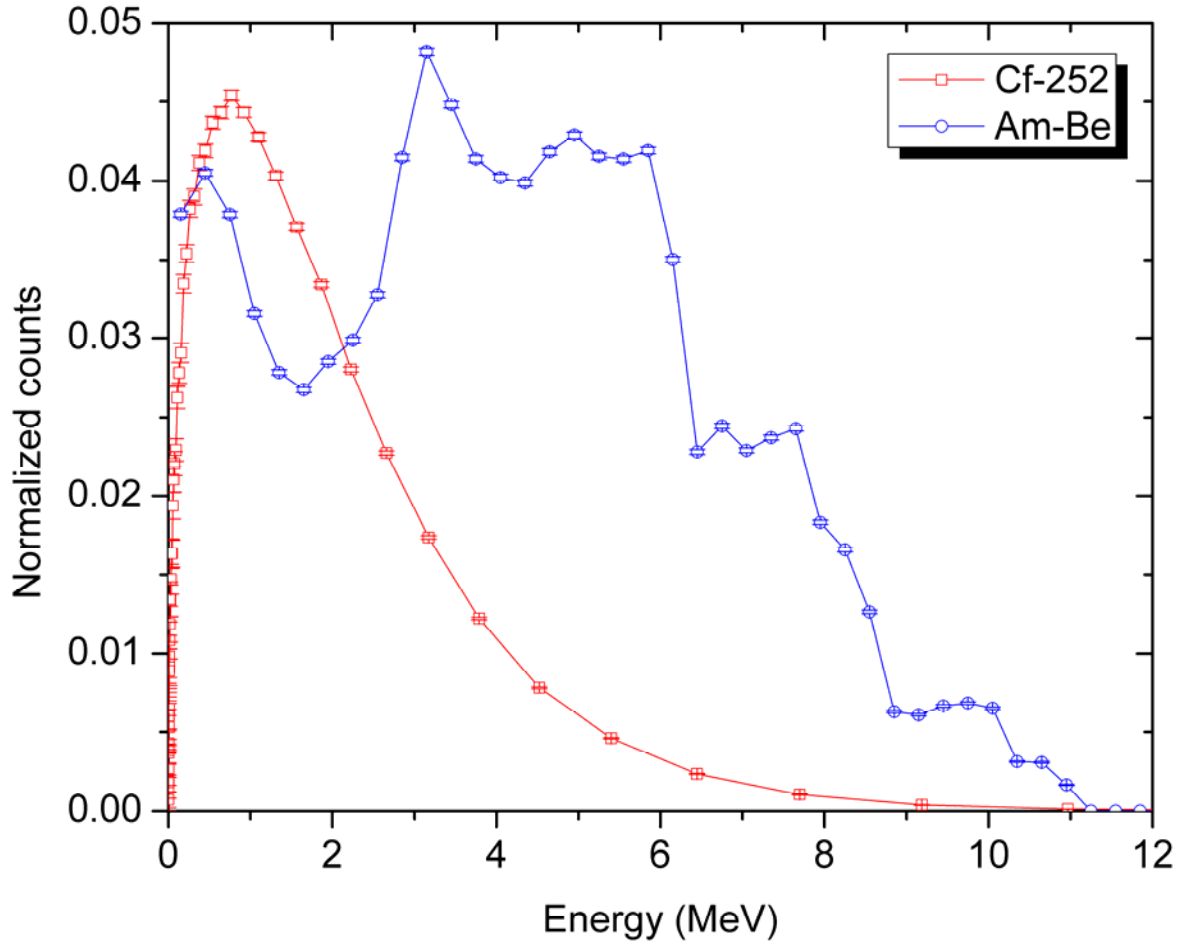
$$\langle E_n \rangle = \int_0^{E_0} E\, f_n(E)\, dE = \frac{E_0}{2^n}$$

Average Number of Collisions

Average number of collisions needed to downscatter to energy E

$$\langle n(E)\rangle = \frac{\sum_{n=1}^{\infty} n f_n(E)}{\sum_{n=1}^{\infty} f_n(E)} = \frac{\sum_{n=1}^{\infty}(n-1) f_n(E) + \sum_{n=1}^{\infty} f_n(E)}{\sum_{n=1}^{\infty} f_n(E)} =$$

$$\frac{\sum_{n=1}^{\infty}(n-1) f_n(E)}{\sum_{n=1}^{\infty} f_n(E)} + 1; \quad but \;\; (n-1) f_n(E) = \ln\left(\frac{E_0}{E}\right) f_{n-1}(E)$$

$$\Rightarrow \langle n(E)\rangle = \ln\left(\frac{E_0}{E}\right) + 1 = u + 1$$

Energy Spectra