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Simulations of Neutron Multiplicity Measurements of a Weapons-Grade Plutonium Sphere with MCNP-PoliMi

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Outline

- Objective
- Neutron Multiplicity Counting
- MCNP-PoliMi
- Benchmark Experiment
- Verification of Simulation Parameters
- ν-bar Analysis
- Conclusions and Future Work

Objective

- Demonstrate the ability of a Monte Carlo code to perform high-fidelity simulations of neutron multiplicity measurements
- The validated code can be used to model other experiments, design measurement systems, and benchmark other codes

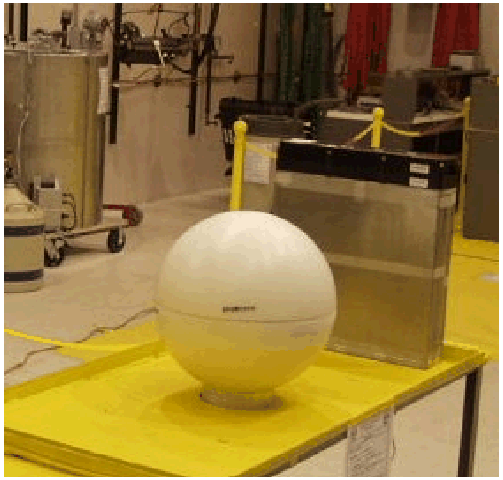
Neutron Multiplicity Counting

- Special Nuclear Material (SNM) is capable of fission and often has spontaneous fission events
- Fission events release neutrons that are correlated in time
- Neutron multiplicity counting is able to detect SNM by looking for correlated neutron events
- By detecting correlated neutrons it is possible to estimate the sample mass and multiplication

Benchmark Experiment

Overview

- 4.5-kg sphere of α-phase plutonium metal
  - 94% ^{239}Pu + 6% ^{240}Pu
- Sphere was reflected with up to 6 inches of high-density polyethylene
- Each experiment was repeated with a ^{252}Cf source in place of the plutonium
- Measurements taken using LANL NPOD detector
  - 15 ^{3}He tubes embedded in polyethylene
  - Entire detector is encased in a thin layer of cadmium to reduce background



Measurement Simulation

MCNPX-PoliMi

- MCNPX-PoliMi is a Monte Carlo code used for performing particle transport problems
- MCNPX-PoliMi is a modified version of the commonly used code MCNPX
- Developed to simulate correlation measurements with neutrons and gamma rays
- Corrected the order of the particle transport
  - Neutron and photon-induced fission multiplicity distributions have been implemented
  - Prompt neutrons and gamma rays associated with each event are modeled explicitly
- Each collision in a detector is treated individually

Measurement Simulation

NPOD Detector Module

- A FORTRAN post-processing code was developed to analyze the simulated data
- Searches the MCNP-PoliMi data file for neutron capture events on ^{3}He
- Sorts all capture events in time
- Apply a 4μs detector “dead-time” to each individual detector after collecting an event
- Determines the neutron multiplicity distributions

Feynman Histogram

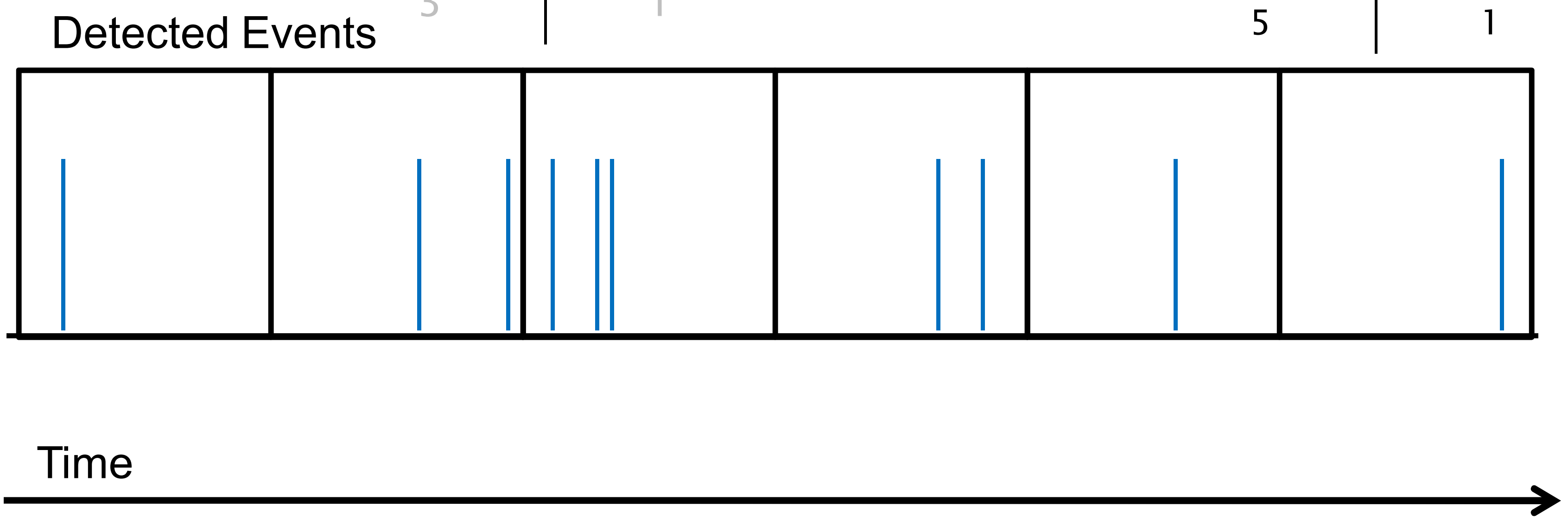
Calculation

Window = 16 μs

Multiplet	Count
0	0
1	3
2	2
3	1

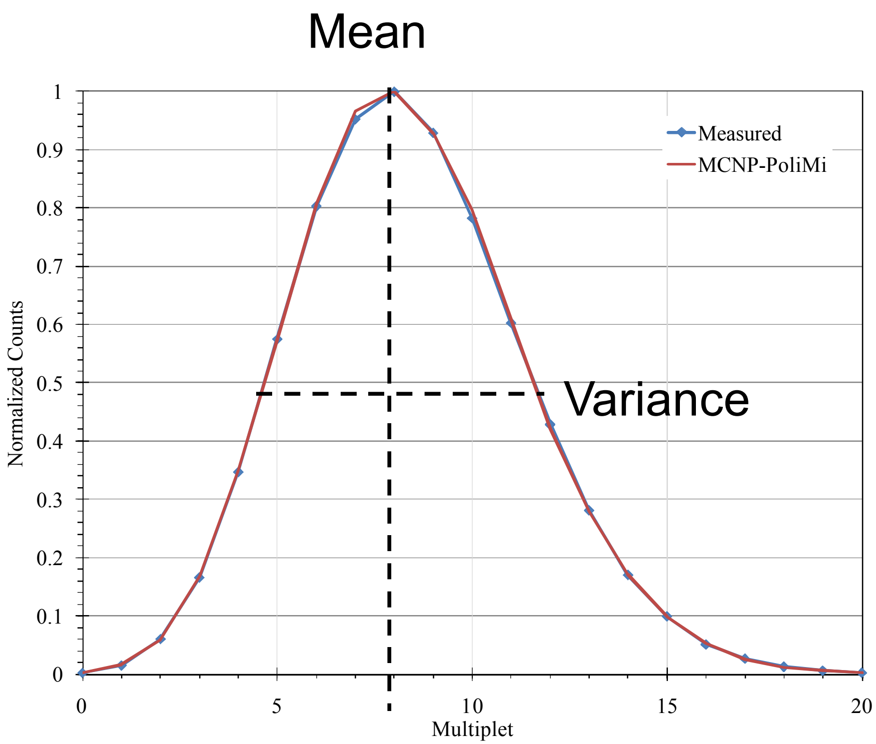
Window = 32 μs

Multiplet	Count
0	0
1	0
2	1
3	1
4	0
5	1

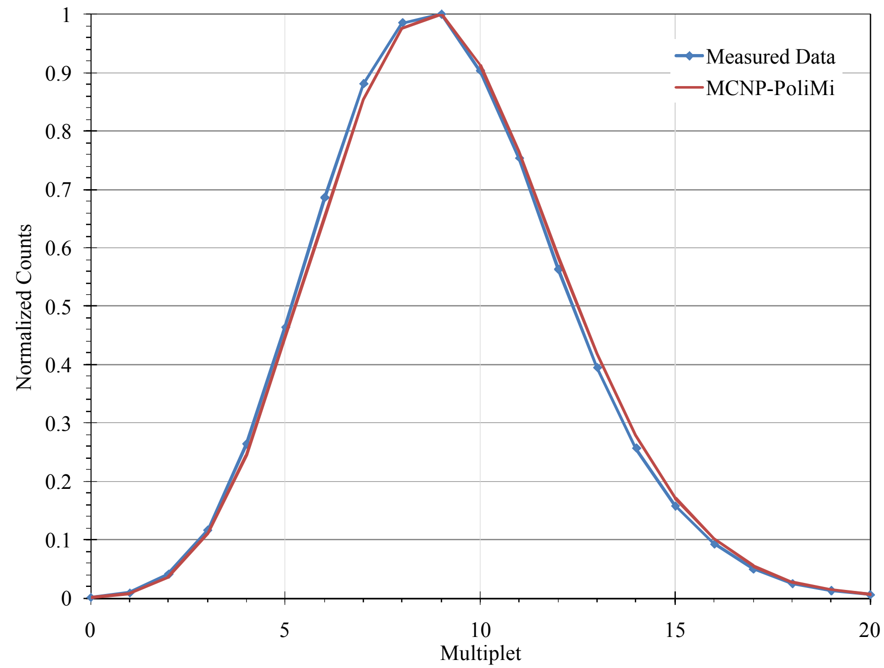


Feynman Histograms

^{252}Cf Source



Bare ^{252}Cf



^{252}Cf with 1 inch of polyethylene

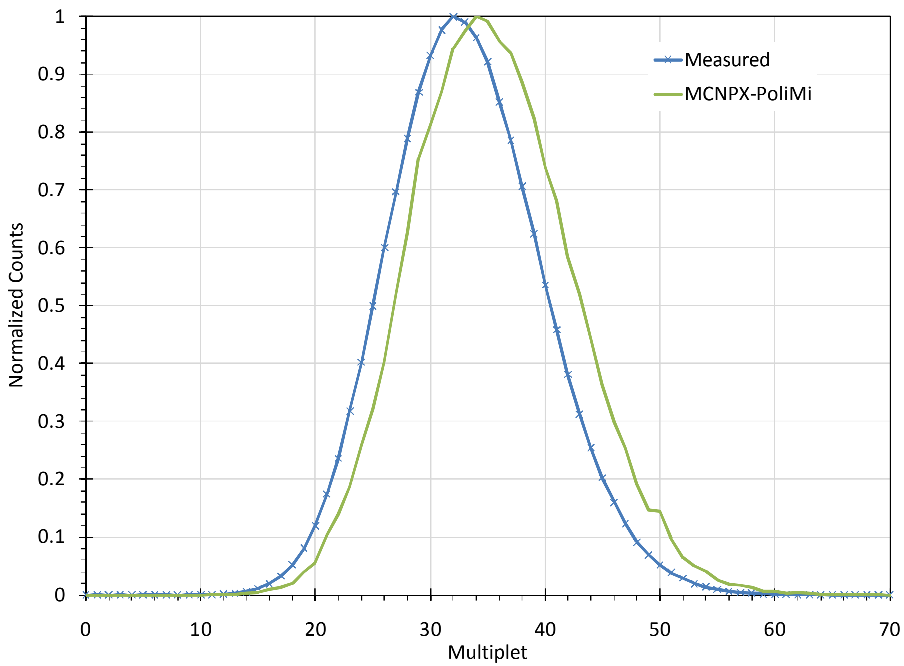
^{252}Cf Results

Summary

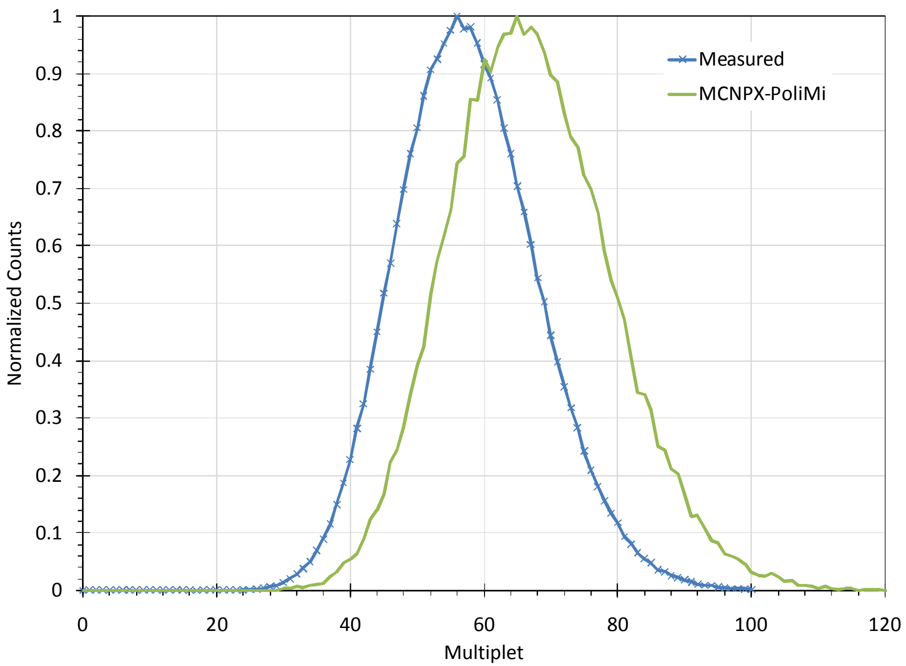
- The ^{252}Cf source results indicate that the experiment was correctly modeled in MCNP-PoliMi
- There is excellent agreement for the mean and variance
- All calculations are within 4% of the measured values

Polyethylene Thickness (in)		Measured	MCNP-PoliMi	Percent Difference
0.0	Mean	8.4170	8.4156	**-0.02**
	Variance	8.6461	8.6440	**-0.02**
0.5	Mean	8.9636	8.9964	**0.37**
	Variance	9.2365	9.2780	**0.45**
1.0	Mean	9.0498	9.1745	**1.38**
	Variance	9.3167	9.4479	**1.41**
1.5	Mean	8.5447	8.3399	**-2.40**
	Variance	8.8521	8.5801	**-3.07**
3.0	Mean	4.7867	4.7374	**-1.03**
	Variance	4.8732	4.8277	**-0.93**
6.0	Mean	1.1647	1.1441	**-1.77**
	Variance	1.1686	1.1525	**-1.37**

Feynman Histograms
Plutonium Sphere



Bare Sphere



With 1 inch of polyethylene

Plutonium Sphere Results

Summary

- The plutonium sphere results demonstrate a systematic bias in both the mean and the variance
- These errors are dramatically different than those observed with the ^{252}Cf model

Polyethylene Thickness (in)		Measured	MCNP-PoliMi	Percent Difference
0	Mean	33.9824	35.4599	4.35
	Variance	45.1047	48.1979	6.86
0.5	Mean	45.5861	49.8649	9.39
	Variance	70.5909	81.7837	15.86
1	Mean	59.1202	67.0009	13.33
	Variance	112.8321	145.8880	29.30
1.5	Mean	71.5946	81.0827	13.25
	Variance	173.4357	233.6593	34.72
3	Mean	60.1328	68.1398	13.32
	Variance	164.6912	235.1375	42.77
6	Mean	14.9306	16.1484	8.16
	Variance	21.8828	25.6663	17.29

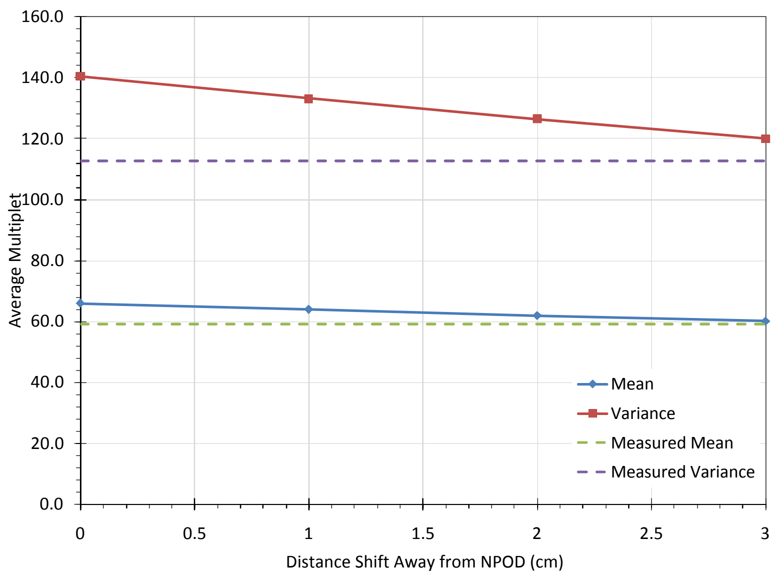
Model Verification
Potential Sources of Bias

- The plutonium source is incorrect
- Source/detector distance could have an effect on the distributions
  - Distance believed to be known within ~1cm
- Increasing the detector dead-time could result in a shift in the distribution
- Physics simulation in MCNPX-PoliMi could have errors
- The nuclear data libraries could have errors

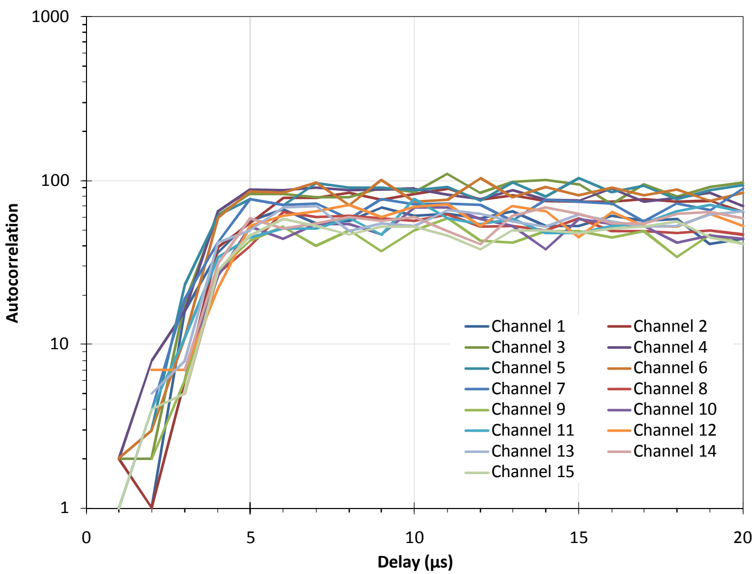
Model Verification

Simulation Parameters

- The k_{eff} of the plutonium source matched benchmark values
- Adjustments to the distribution using distance required ~3cm shifts, which is outside the accepted tolerance
- Dead-time effects were shown to be close to the 4μs that were used in the model



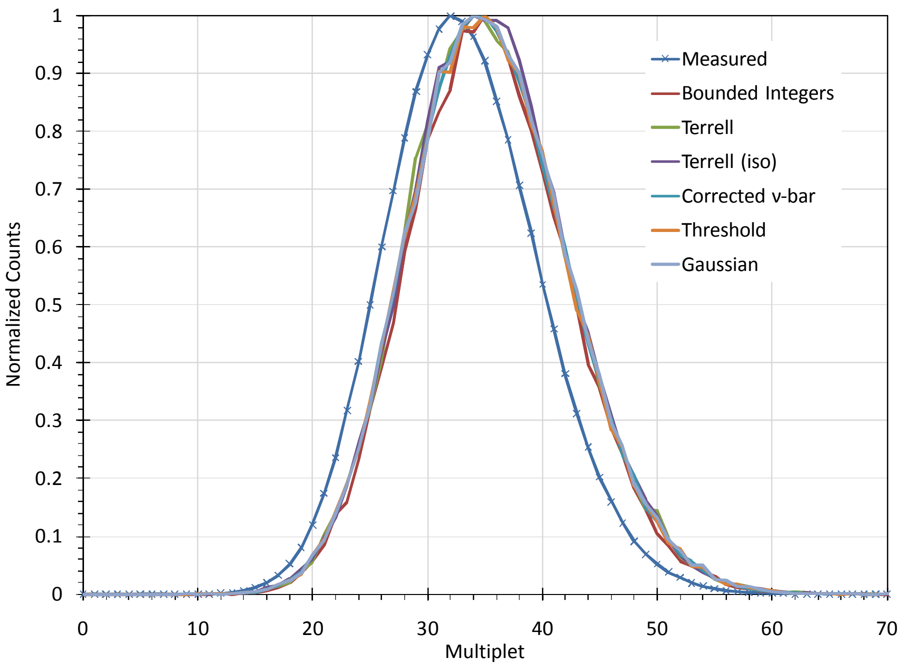
Effect of Distance on the 1-inch moderated sphere



Autocorrelation data for the plutonium sphere

Model Verification

Physics Options and Cross-Section Libraries



Physics Options with the Bare Sphere

Case (in)		ENDF VII	Jeff 3.1	JENDL 3.3
0.0	Mean	4.35	3.41	2.86
	Variance	6.86	6.09	4.56
1.0	Mean	13.33	11.53	11.14
	Variance	29.30	24.39	25.31

Percent Difference using Different Libraries

- Evaluation of the physics options indicate that they have no significant bearing on the results
- A comparison of three major libraries achieved only minor changes to the distributions

^{239}Pu Induced Fission

- With the other sources of systematic bias ruled out, the nuclear data become suspect
- ν-bar is the average number of neutrons that are released in a fission event
- In the nuclear data libraries, the ν-bar for ^{239}Pu was artificially raised (by the library publishers) to match certain criticality experiments
- To examine the impact of this bias, the ν-bar was lowered until it matched our experiments

Results with Adjusted ν-bar

- The optimum change in the value of v-bar was determined to be -1.14%
- With this change, a dramatic improvement over all cases was observed
- With a max deviation of 12% compared to the 43% observed earlier

Polyethylene Thickness (cm)	Percent Difference in Mean	Percent Difference in Variance
0	0.31	-0.08
0.5	3.36	4.35
1	4.44	9.39
1.5	1.27	3.79
3	-5.37	-5.74
6	-10.36	-11.57

Results with optimal ν-bar

Summary

- The ^{252}Cf results demonstrate that the MCNP geometry, materials and post-processing algorithms are capable of reproducing measured results accurately
- Several sources of error were investigated
- This systematic analysis of the various sources of error eliminated the possibility that any other single effect was responsible for the deviation, except changes in ν-bar in the nuclear data library
- The optimal ν-bar was found to be -1.14% of the currently accepted value
- Using the optimal fit for the value of ν-bar, dramatic improvement was observed

Future Work

- Investigate the effect of varying distance with the optimal ν-bar value in place
- Some of the observed optimal ν-bar values for individual cases did not correct both the mean and the variance
  - It is possible that this indicates another parameter has been mis-stated (e.g., distance)
- Investigate the effect of an energy-dependent adjustment to ν-bar

Acknowledgements

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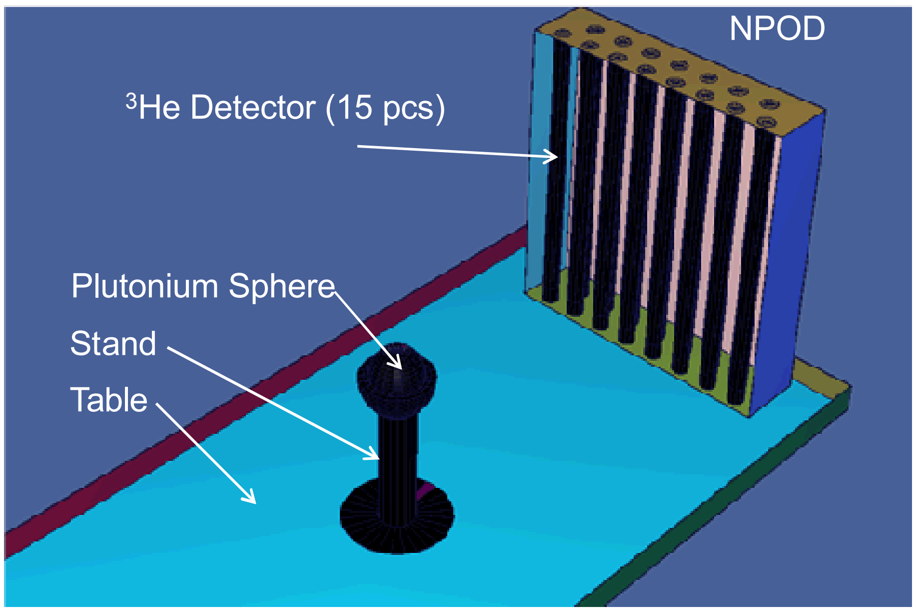
Benchmark Experiment

Geometry and Model



MCNPX-PoliMi Model

Top View