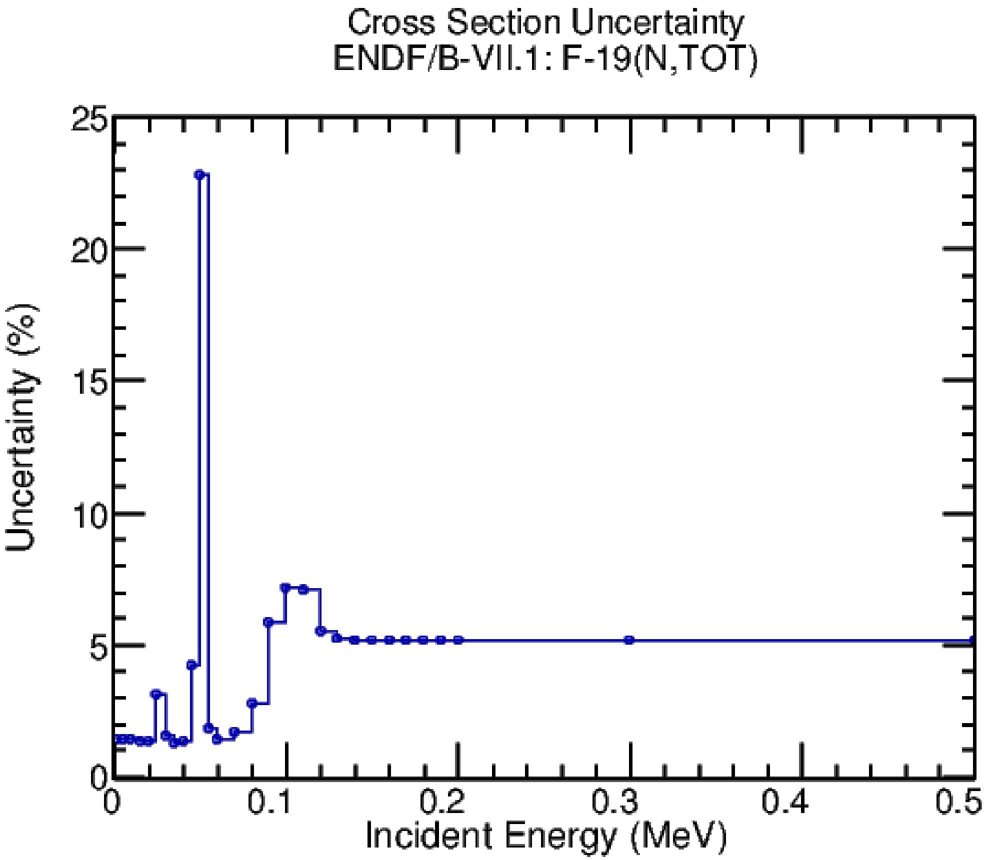
Simulations, backgrounds, and uncertainties in PICO-2L



THE UNIVERSITY OF CHICAGO

Alan Robinson
May 20, 2015
AARM, Rapid City South Dakota

Simulations in PICO-2L

- Background
  - Assays
  - α,n yields
  - Neutron propagation
- Calibration
  - AmBe
    - Rates
    - Reactions
  - Mono-E neutrons
    - Generation
    - Propagation

- Background estimates
  - Material assays
  - α,n yields and neutron generation
  - Neutron propagation
- Calibration
  - AmBe
    - Rates
    - Reactions
  - Monoenergetic neutrons
    - Generation
    - Propagation

Background Estimates

- Background
  - Assays
  - α,n yields
  - Neutron propagation
- Calibration
  - AmBe
    - Rates
    - Reactions
  - Mono-E neutrons
    - Generation
    - Propagation

Background neutrons produced primarily by (α,n) and spontaneous fission from nearby ^{238}U and ^{232}Th can produce both single and multiple bubble events. We perform a detailed Monte Carlo simulation of the detector to model the neutron backgrounds, predicting 0.9(1.6) single(multiple) bubble events in the entire data set, for an event rate of 0.004(0.006) cts/kg/day, with a total uncertainty of 50%. There were no multiple bubble events observed in the WIMP search data, providing a 90% C.L. upper limit of 0.008 cts/kg/day, consistent with the background model.

arXiv:1503:00008

Background Sources

- Background
  - Assays
  - α,n yields
  - Neutron propagation
- Calibration
  - AmBe
    - Rates
    - Reactions
  - Mono-E neutrons
    - Generation
    - Propagation

- Internal radioactivity – 55% of background
- External neutrons – 28%
- Radon inside the shield – 17%
- Gammas and exotic backgrounds
  - Negligible for PICO-2L at SNOLAB.

Internal Radioactivity

- Background
  - Assays
  - α,n yields
  - Neutron propagation
- Calibration
  - AmBe
    - Rates
    - Reactions
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    - Generation
    - Propagation

- Measured nearly every component.
  - OFHC Cu, synthetic silica, UPW assumed clean
  - Stainless steel bolts and screws negligible
  - LED cables installed before screening. 100 ppb U and Th assumed.
  - HDPE and PP shielding tanks assumed 1 ppb U/Th

Internal Radioactivity

- Background
  - Assays
  - α,n yields
  - Neutron propagation
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  - AmBe
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    - Reactions
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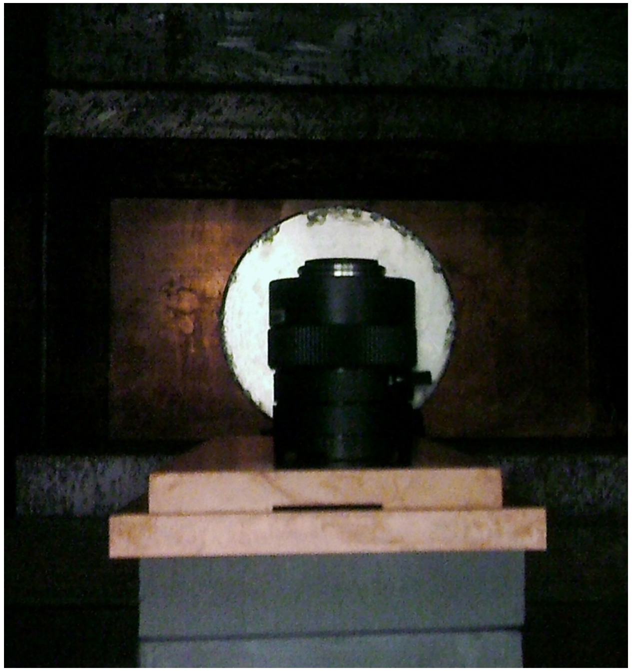
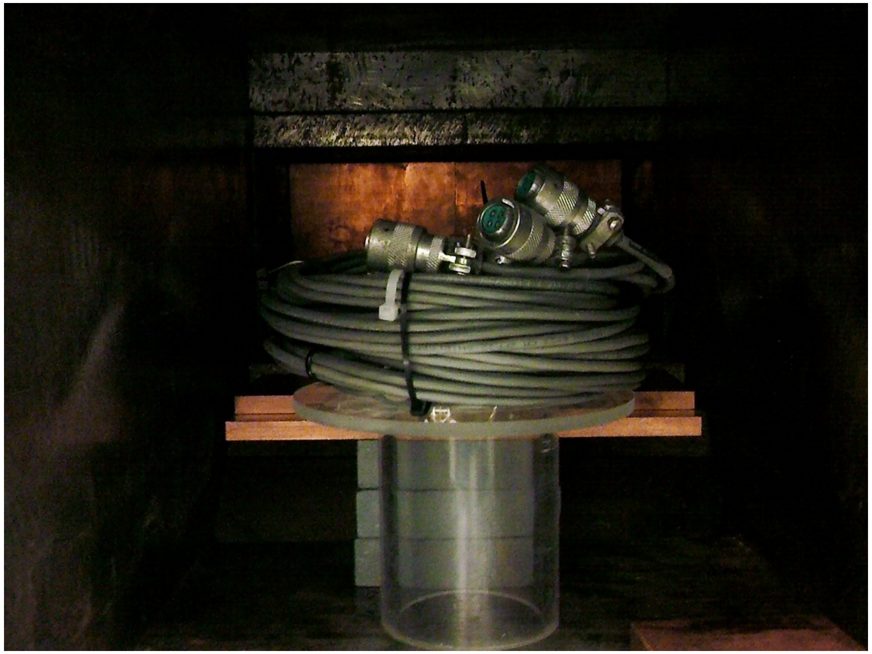
    - Generation
    - Propagation

- Most components measured by GES
  - University of Chicago HPGe
    - ORTEC GEM-10 in a pre-WWII steel/pb shield.





  - SNOLAB used for piezo components

University of Chicago Counter

- Background
  - Assays
  - α,n yields
  - Neutron propagation
- Calibration
  - AmBe
    - Rates
    - Reactions
  - Mono-E neutrons
    - Generation
    - Propagation

- Dead layer and DAQ deadtime measured using calibrated Ba-133 and Y-88 sources at various distances.
- 6' concrete overburden and μ veto on 5 sides.

University of Chicago Counter

- Background
  - Assays
  - α,n yields
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    - Rates
    - Reactions
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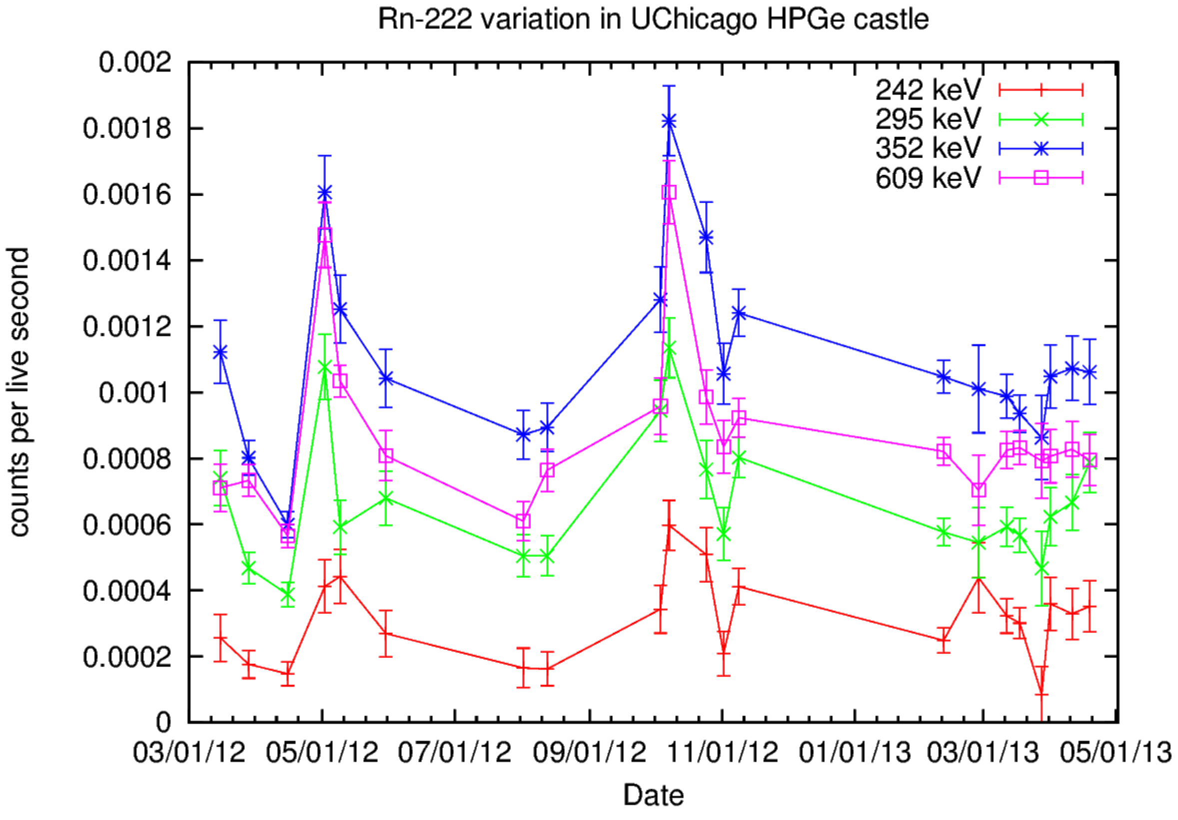
    - Generation
    - Propagation

- No radon purge. Radon variability requires background run immediately before every sample.



Internal Radioactivity

- Background
  - Assays
  - α,n yields
  - Neutron propagation
- Calibration
  - AmBe
    - Rates
    - Reactions
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    - Generation
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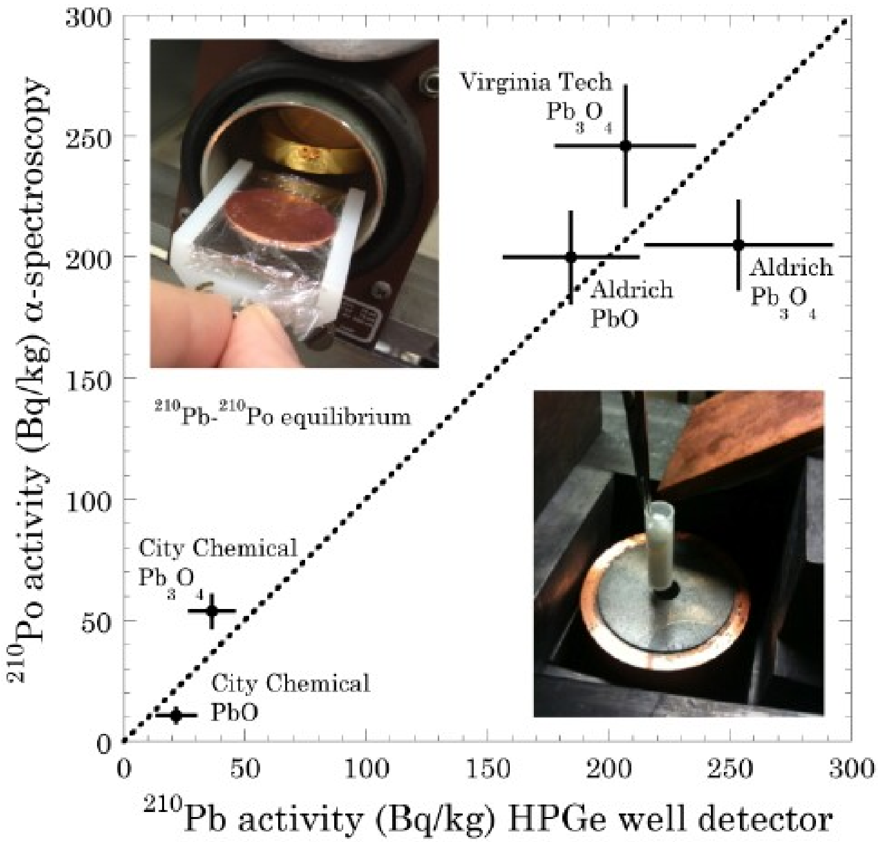
- ICP-MS for U and Th in pressure vessel
- Alpha counting and GES of Pb-210 in piezo salts.



D.A. Fustin
PhD thesis (2012)
Univ of Chicago

CAM 2013
Aug 16, 2013

Calibrations of Nuclear Recoils in C_3F_8

Internal Radioactivity

- Track results w/ Google Drive.

coupp4litemat

File Edit View Insert Format Data Tools Form Help All changes saved in Drive

PICO-lite materials counting

PICO-lite materials counting

Tracking number	Material	Required Sensitivity (ppb) U-238	Th-232	Sampled?	U-238 content (ppb)	uncertainty	Ref Source	Th-232 content (ppb)	uncertainty	Ref Source	Th-234 90% upper limit (ppb U-238)	Co-60 (mBq/kg)	K-40 (mBq/kg)	Passed?	ICP-MS required?	Notes
4	Split Flange	5.43	15.14	Original use	2.6	2	UChicago	1.4	1.4	UChicago	74	47	0	Passed	Yes	2615 line 22+/-7 ppb, hotter than other Tl-208 and Pb-212 lines
6	Plug Weldment	25,047.03	90,303.17	Original use	8	7	UChicago	0	11	UChicago	200	1.7	0	Passed x10		
7	Swagelok 6LVV-DPHFR	270.87	596.72	Original use	11	5	UChicago	0	7	UChicago	40	3	0	Passed x10		Simulated as a point source at the valve seat.
8	Fill Tube	15,040.98	46,314.34	Original use	340	120	UChicago	0	170	UChicago	770	50	0	Passed x10		
9	Hydraulic Fluid	0.13	0.65	No										In Queue		
11	1/4-28 hex jam nut	561.59	1,566.89	Original use	0	9	UChicago	0	20	UChicago	65	0	20	Passed x10		Measured with 25
12	Guiding Rod Extension	334.79	997.54	Original use	7	3	UChicago	0	4	UChicago	80	0	0	Passed x10		
13	Guiding Threaded Rod	133.24	371.74	Original use	7	3	UChicago	0	4	UChicago	80	0	0	Passed x10		
14	Guiding Rod	3,643.68	13,707.35	Original use	6	4	UChicago	2	6	UChicago		0	0	Passed x10		measured with 26
15	Guiding Rod Sleeve	2,169.58	4,032.53	Original use	410	60	UChicago	0	50	UChicago	330		0	Passed		may be out of equilibrium with lower U-238 content.
16	Guiding Base Flange	378.64	1,100.79	Original use	0	2.6	UChicago	6.3	3	UChicago	110	0.4	0	Passed x10		50 +/- 40 ppb U from Th-234
18	Large Bellows	30.88	87.19	Original use	7	3	UChicago	0	4	UChicago	80	0	0	Passed	Yes	
20	C-Ring 550	3,594.52	6,546.12	Original use	380	70	UChicago	230	100	UChicago	740			Passed		Counted w/ sample 28
21	1/4-28 hex nut	93.58	261.10	Original use	60	50	UChicago	20	40	UChicago	870			Passed	Yes	Counted w/ split flange (#4). Rate assumes all measured activity is in the nuts, none in split flange.
22	1/4-28 x 1-1/4 12-point	2,703.00	7,976.72	Original use	20	15	UChicago	7	19	UChicago	90			Passed x10		Counted w/ 29. Rate assumes all measured activity is in the nuts&bolts.
23	1/4-28 x 2-1/2 socket s	53.90	150.40	Original use	2.6	2	UChicago	1.4	1.4	UChicago	74	47	0	Passed x10	Yes	Counted while inserted into split flange (#4).
24	1/4-20 x 3/4 socket scr	13,200.59	36,240.40	Original use	6	4	UChicago	2	6	UChicago		0	0	Passed x10		measured with 26
25	1/4-28 x 7/8 socket scr	1,084,819	3,911,146.	Original use	0	9	UChicago	0	20	UChicago	65	0	20	Passed x10		measured with other hardware
26	2" Bellows	1,081.07	2,967.93	Original use	6	4	UChicago	2	6	UChicago		0	0	Passed x10		Counted with guide rods & screws
27	3M 3290 retroreflector	76.43	64.33	At UChicago	280	40	UChicago	1260	140	UChicago			36	Failed		
28	C-Ring 2393	27.60	61.51	Original use	26	6	UChicago	10	9	UChicago	80			Passed	Yes	Numbers for PTFE coated inconel used
29	Bellows Adapter Flange	399.39	1,178.63	Original use	4.5	3.1	UChicago	2	4	UChicago	70	62	0	Passed x10		Counted w/ hardware. If activity is in the hardware, it's 3-5 times weaker
30	Garlock Gasket	1,023.48	4,532.96	At FNAL	1530	210	UChicago	3200	400	UChicago			28000	Failed		
31	Jar	0.72	3.09	No										In Queue		
32	Retroreflector substrate	44.08	124.42	At UChicago	0	2.7	UChicago	6	6	UChicago	25	0	0	Passed x10		
40	Shielding base	40.87	125.63	No										In Queue		
41	Base Plate	269.89	972.47	No	0.62	0.01	PNNL ICP-MS	0.95	0.02	PNNL ICP-MS				Passed x10		
46	Bottom flange manifold	387.76	1,407.14	At UChicago	0	1.3	UChicago	0	2.6	UChicago	5	13	4	Passed x10		
47	1" Hyd pipe	1,000.00	3,628.93	No										In Queue		
48	1/2" NPT plug	4,075.17	8,977.61	No										In Queue		

Bill of Materials | Piezo Materials | Tracking | Sensitivity | Counting | Background | Drop-down lists

Neutron Yields

- Background
  - Assays
  - α,n yields
  - Neutron propagation
- Calibration
  - AmBe
    - Rates
    - Reactions
  - Mono-E neutrons
    - Generation
    - Propagation

- α,n yields calculated using modified SOURCES-4C with self-made libraries.
  - Based on JENDL-AN/05 evaluation up to silicon.
  - Tomasello & Kudryavtsev libraries updated with experimental data where available: ^{46,48}Ti, ^{50,52}Cr, Mn, Fe.
- Rate and spectra simulated independently for each material.

Neutron Propagation

- Background
  - Assays
  - α,n yields
  - Neutron propagation
- Calibration
  - AmBe
    - Rates
    - Reactions
  - Mono-E neutrons
    - Generation
    - Propagation

- Using MCNP-Polimi.
- Estimates assume full efficiency above 3.0keV nuclear recoil threshold.
  - Background singles rate approx. independent of threshold.
- 16 geometry iterations
  - Not all simulations use the final geometry.
  - Additional geometry variations to check for uncertainties.

Simulation Geometries

- Background
  - Assays
  - α,n yields
  - Neutron propagation
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    - Reactions
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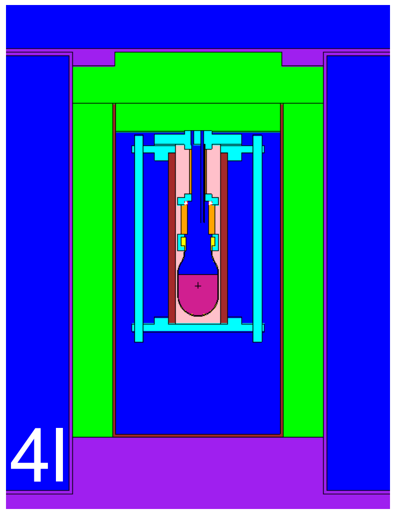
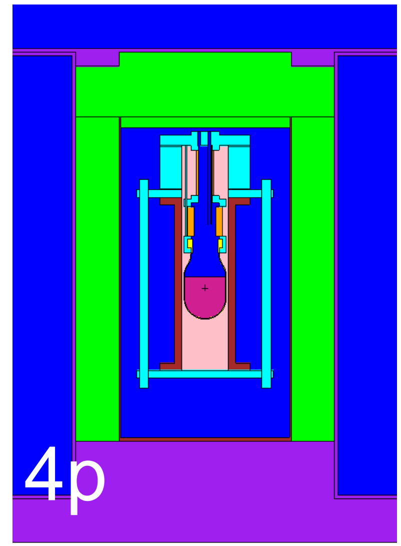
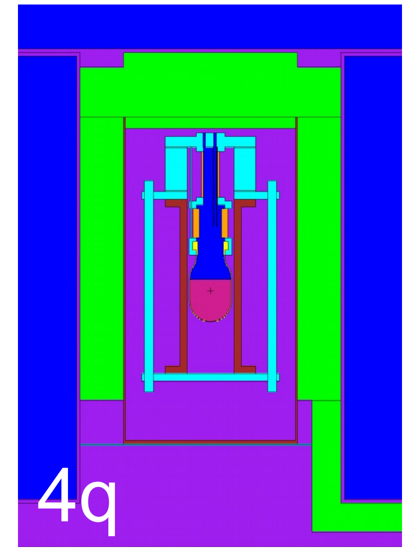
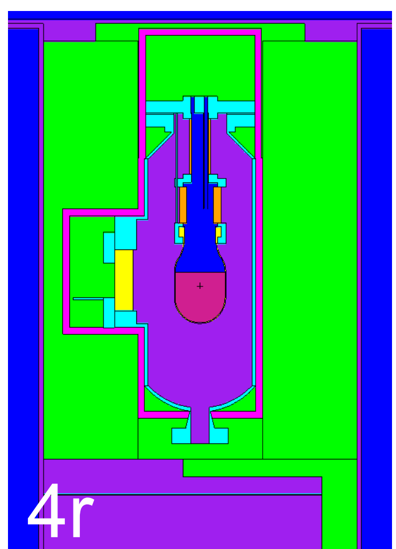
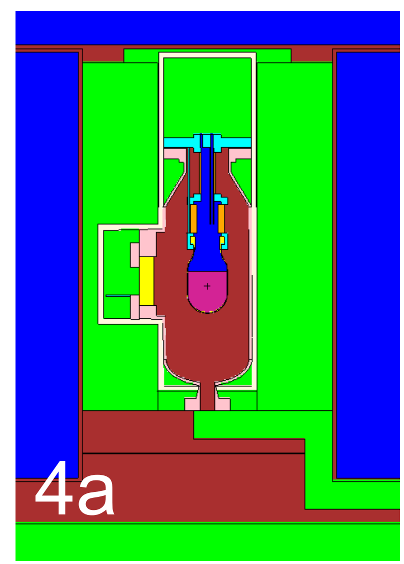
    - Propagation











As-built conditions

- Background
  - Assays
  - α,n yields
  - Neutron propagation
- Calibration
  - AmBe
    - Rates
    - Reactions
  - Mono-E neutrons
    - Generation
    - Propagation

- Coloured tags, bags, and spreadsheet tracking were attempted to verify that parts on site were screened
  - Only partially successful given lack of coordinated training.
- Final drawings used for simulations
  - Not always complete.
  - Did not accurately reflect as-built conditions.
  - Problems found by having lots of pictures.

Event Rate Uncertainties

- Background
  - Assays
  - α,n yields
  - Neutron propagation
- Calibration
  - AmBe
    - Rates
    - Reactions
  - Mono-E neutrons
    - Generation
    - Propagation

- Uncertainties from
  - Assay statistics and systematics (10%)
  - Simulation statistics and syst. (15%)
  - Alpha,n systematics (mat. dependent)
  - Material composition and mass
    - Asymmetric uncertainty where (alpha,n) yield varies amongst constituents.

Background Event Rate

- Background
  - Assays
  - α,n yields
  - Neutron propagation
- Calibration
  - AmBe
    - Rates
    - Reactions
  - Mono-E neutrons
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    - Propagation

- Totals per live-year:
  - Singles: 4.6 ±0.7 (stat.) +0.9/-2.1 (syst.)
  - All: 10.7 ±1.4 (stat.) +2.1/-5.0 (syst.)
- Largest contributors
  - Rock neutrons 1.3 singles ± 50%
  - Retroreflector 1.0 singles
  - Radon in air 0.78 singles
  - Computar lenses 0.62 singles
  - Pressure Vessel: 0.3 singles

Neutron Calibrations

- Background
  - Assays
  - α,n yields
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- Calibration
  - AmBe
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    - Reactions
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- Measure $$\frac{\text{Event Rate}}{\text{Simulated Rate}}$$ for multiple neutron energy spectra
- Requires absolute calibration of
  - Source rate
  - Geometry and fiducial volume
  - Neutron propagation
  - Recoil cross-section

Neutron Calibrations

- Background
  - ► Assays
  - ► α,n yields
  - ► Neutron propagation
- Calibration
  - ► AmBe
    - Rates
    - Reactions
  - ► Mono-E neutrons
    - Generation
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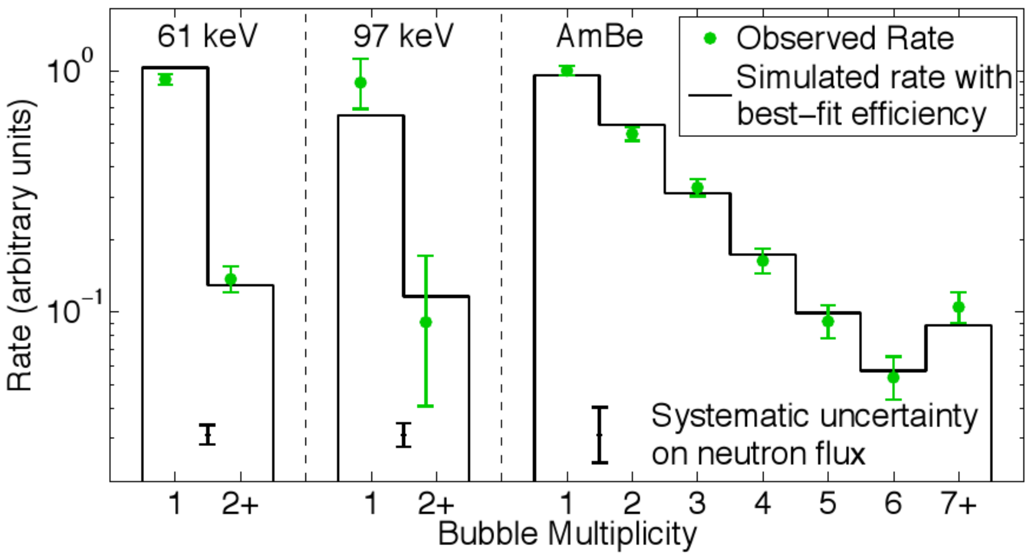
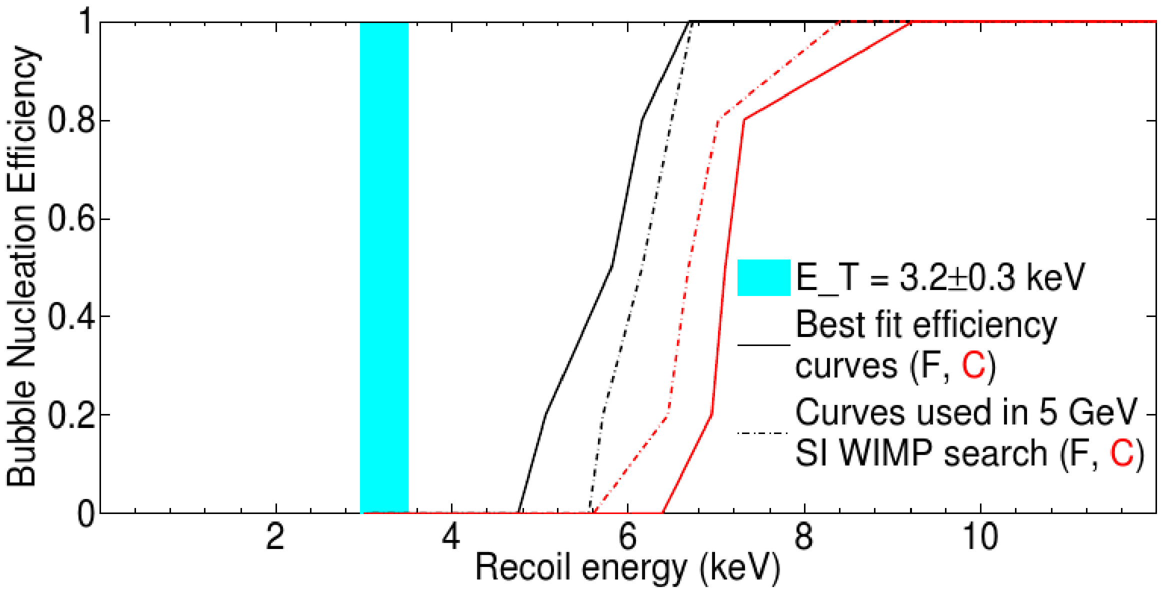
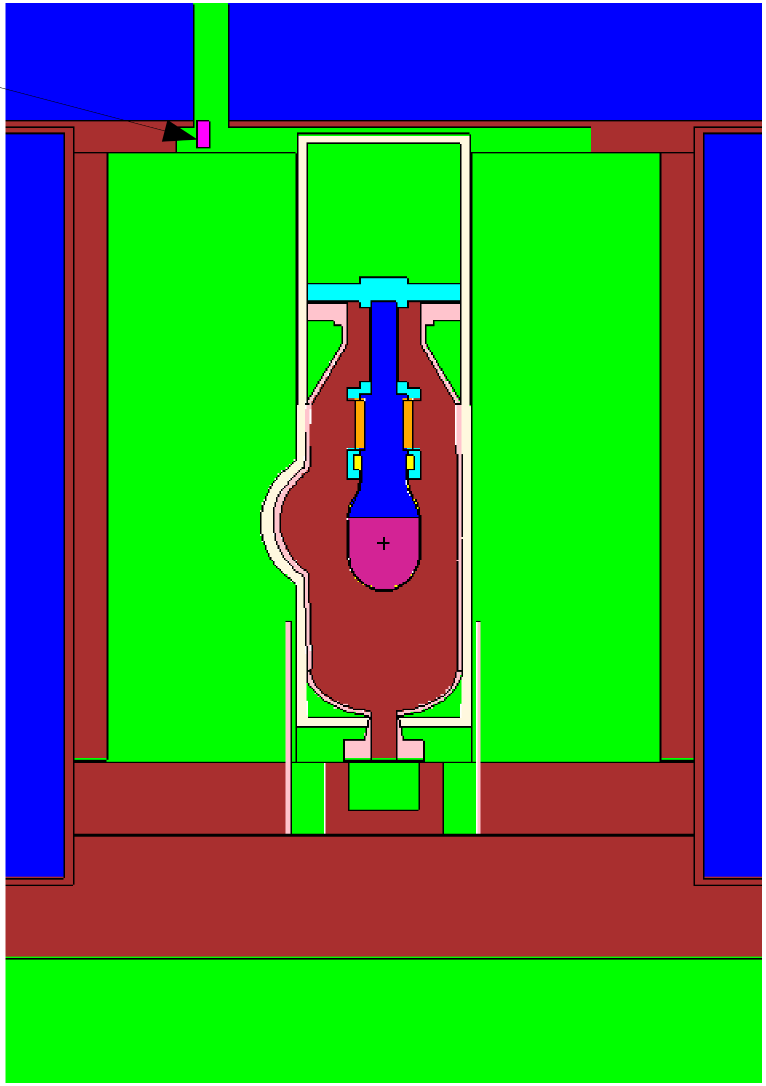




AmBe Calibrations

- Background
  - ► Assays
  - ► α,n yields
  - ► Neutron propagation
- Calibration
  - ► AmBe
    - Rates
    - Reactions
  - ► Mono-E neutrons
    - Generation
    - Propagation

- SNO calibrated source
- Far from active volume.
  - ► Needed reduced rate
  - ► Increases geometric uncertainties



AmBe Calibrations

- Background
  - Assays
  - α,n yields
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- Calibration
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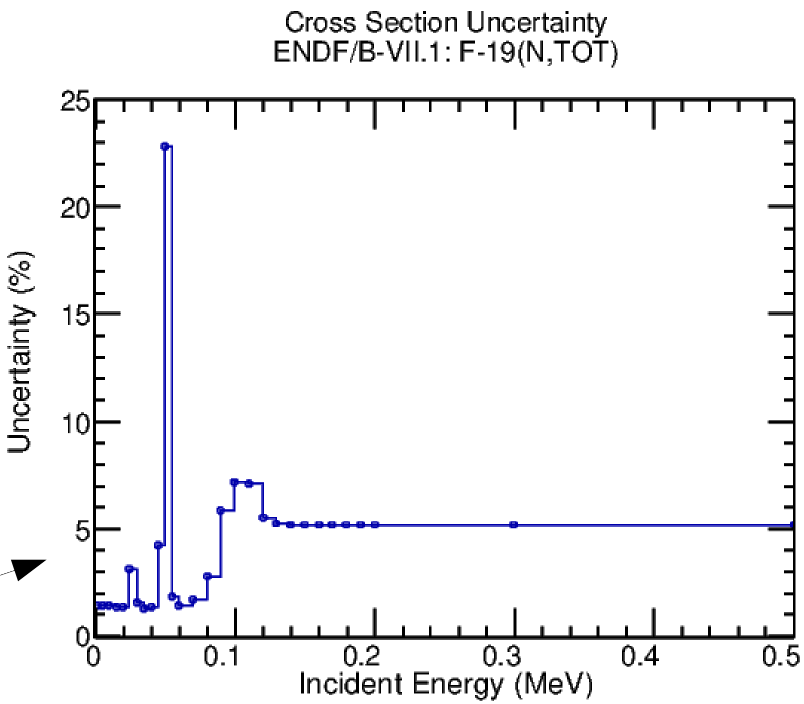
    - Rates
    - Reactions
  - Mono-E neutrons
    - Generation
    - Propagation

- Independent MCNP and Geant4 simulations
  - Cross-checked geometry
  - Rate difference between simulations
- Uncertainties
  - Hydrogen density of mineral oil
  - AmBe neutron energy spectrum
  - $^{19}F(n,el)$ cross-section

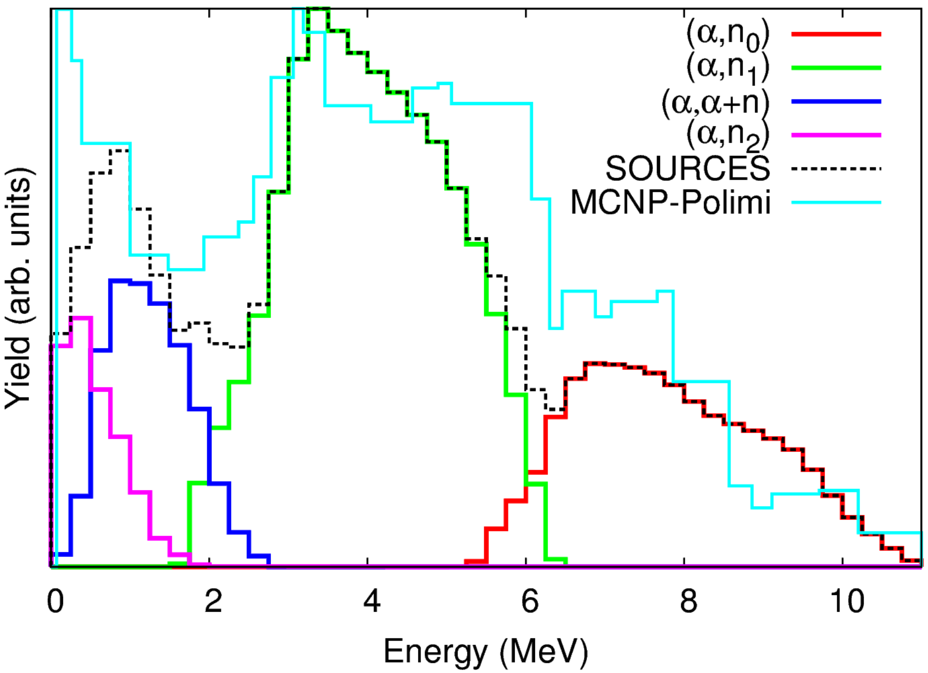


AmBe Spectrum

- Background
  - Assays
  - α,n yields
  - Neutron propagation
- Calibration
  - AmBe
    - Rates
    - Reactions
  - Mono-E neutrons
    - Generation
    - Propagation

- 4 neutron production channels
  - ^{9}Be (α,n_0) ^{12}C (Q = 5.702 MeV)
  - ^{9}Be (α,n_1) ^{12}C (Q = 1.263 MeV)
  - ^{9}Be (α,α+n) ^{8}Be (Q = -1.664 MeV)
  - ^{9}Be (α,n_2) ^{12}C (Q = -1.952 MeV)

Modified SOUCES calculation



AmBe Calibrations

- Background
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  - α,n yields
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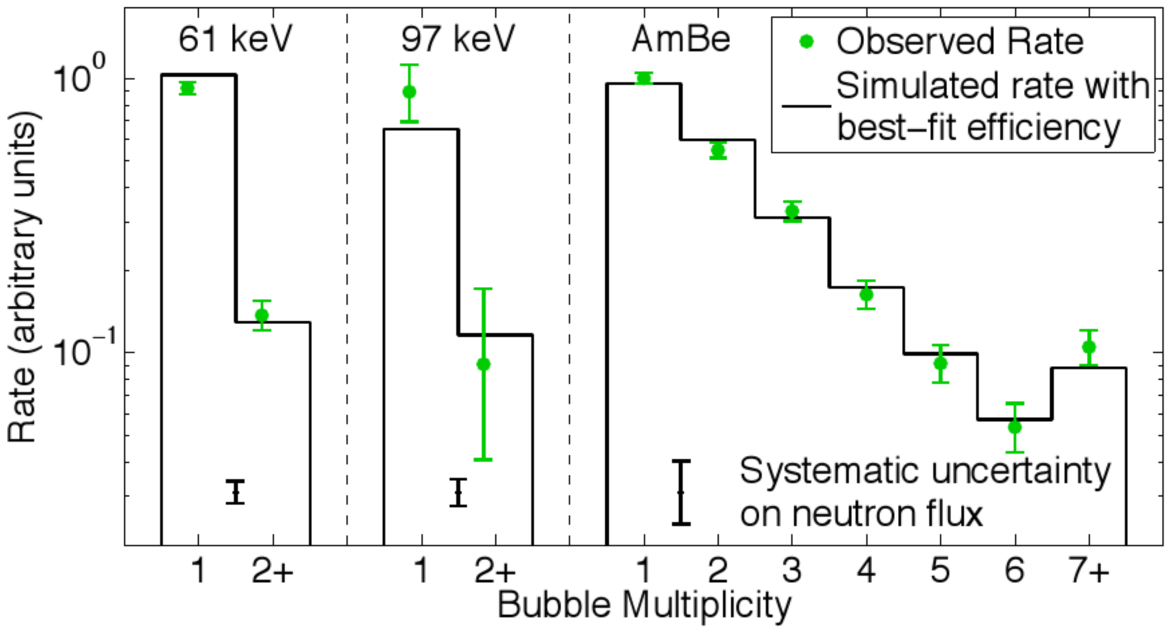
- Uncertainties
  - ~30% on recoil rate from MCNP/Geant4 difference.
  - 3% per step in multiplicity ratio due to $^{19}F(n,el)$ cross-section.



AmBe Reactions

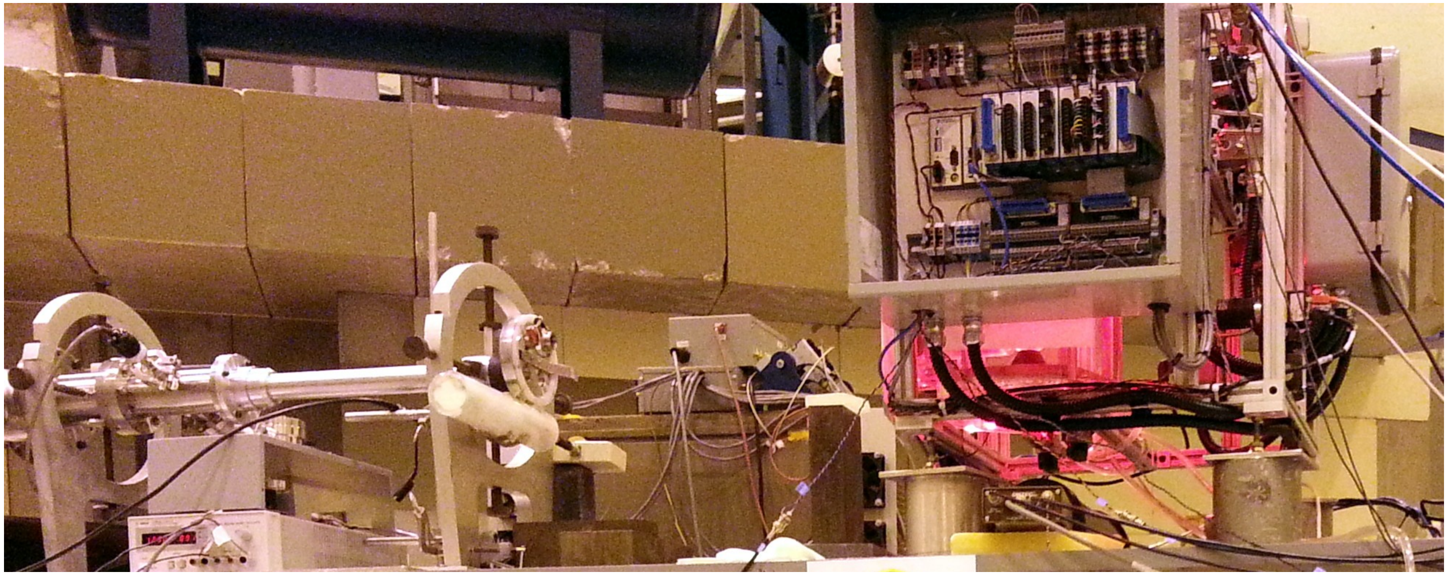
- Background
  - Assays
  - α,n yields
  - Neutron propagation
- Calibration
  - AmBe
    - Rates
    - Reactions
  - Mono-E neutrons
    - Generation
    - Propagation

- MCNP-Polimi does not handle 3-body reaction energetics.
  - Used ptrac output to tag (n,n+α) and charged particle reactions. Nominally cut via acoustics.
  - 2% correction to the simulated rate.
  - Bug reported and fixed in next version.

Monoenergetic neutron calibrations

- Background
  - Assays
  - α,n yields
  - Neutron propagation
- Calibration
  - AmBe
    - Rates
    - Reactions
  - Mono-E neutrons
    - Generation
    - Propagation

- Monoenergetic 61 & 97 keV neutrons at the University of Montreal
  - $^{51}V(p,n)$ reaction
  - Neutron flux measured with He-3 detectors.



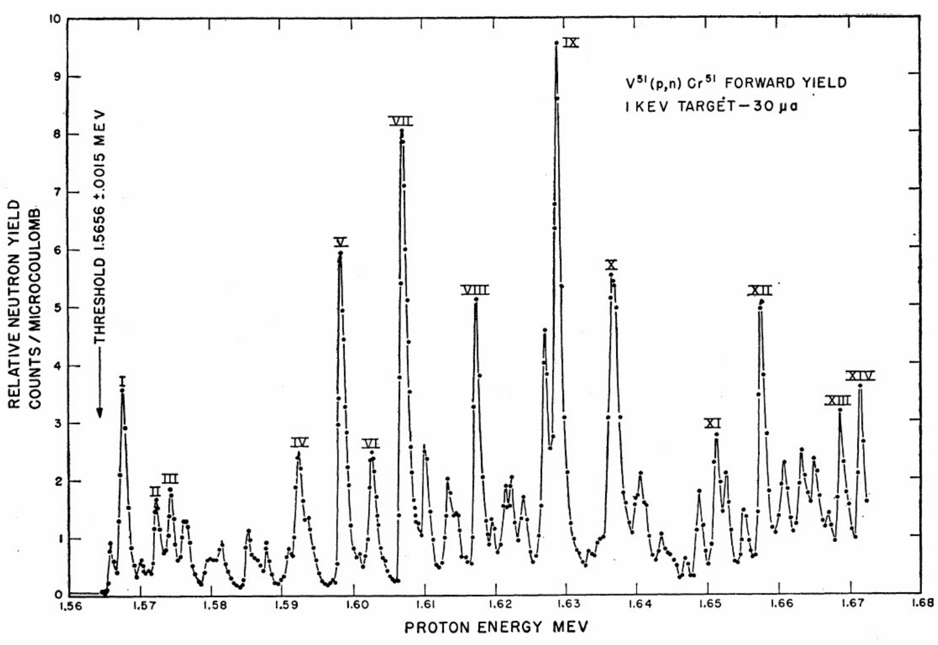
^{51}V(p,n) reaction

- Background
  - Assays
  - α,n yields
  - Neutron propagation
- Calibration
  - AmBe
    - Rates
    - Reactions
  - Mono-E neutrons
    - Generation
    - Propagation

- Narrow resonances
- Uncertain angular distribution

TABLE I. $V^{51}(p,n)Cr^{51}$ neutrons: Selected peaks. The figures in the last column represent the coefficient A, of the angular distribution $W(\phi) \sim 1 + AP_2(\cos\phi)$.

Peak	E_p(Mev)	0°E_n(kev)	A
I	1.568	4.8	0±0.13
II	1.573	11.3	0±0.13
III	1.575	13.6	···
IV	1.592	34	−0.21±0.07
V	1.598	40	−0.30±0.05
VI	1.603	45	0±0.13
VII	1.607	50	0±0.13
VIII	1.617	61	0±0.13
IX	1.629	74	0±0.13
X	1.637	82	0±0.13
XI	1.651	97	···
XII	1.658	104	0±0.13
XIII	1.669	116	−0.11±0.13
XIV	1.672	119	···



^{51}V (p,n)
Cross-section

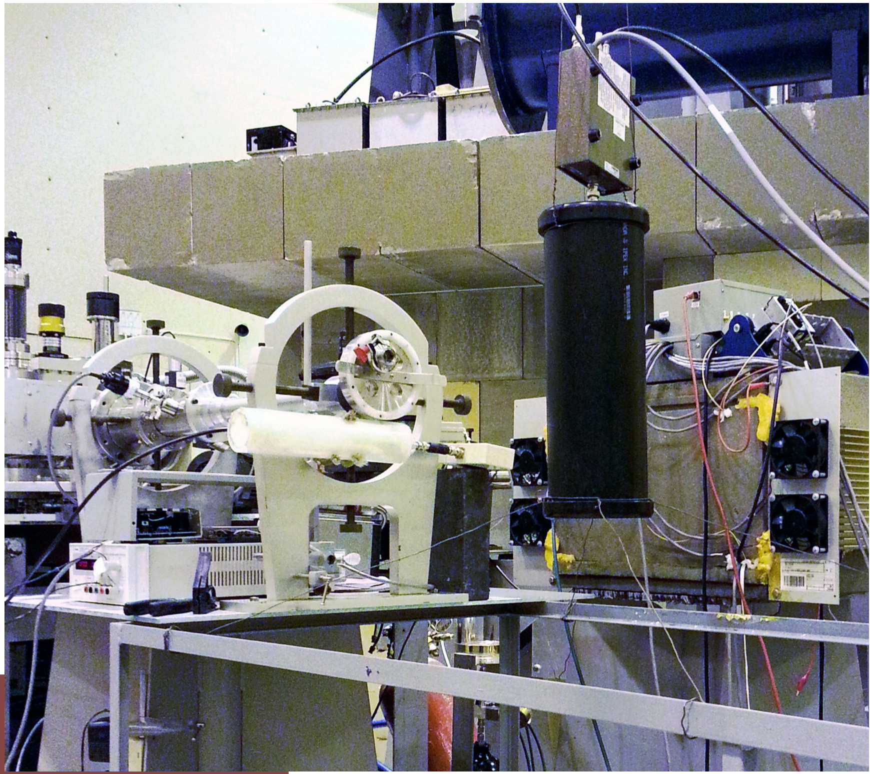
PR **100** 167

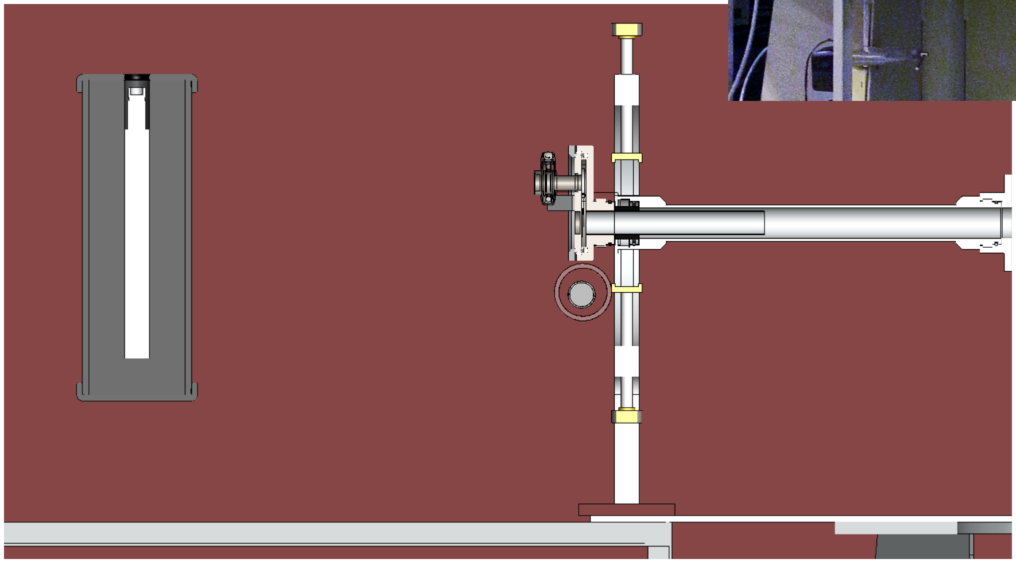
AARM 2015
May 21, 2015

He-3 Measurements

- Background
  - ► Assays
  - ► α,n yields
  - ► Neutron propagation
- Calibration
  - ► AmBe
    - Rates
    - Reactions
  - ► Mono-E neutrons
    - Generation
    - Propagation

- Intercalibration at 0° and 90°
  - ► Precise masses, dimensions, materials.
  - ► Matches MCNP.





Neutron propagation

- Background
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    - Propagation

- High sensitivity to neutron cross-section uncertainties.
  - Monoenergic neutrons
  - Cannot reconstruct full kinematics in a bubble chamber.
    - Exception of CIRTE π-beam experiment

PICO-0.1 detector

- Background
  - ► Assays
  - ► α,n yields
  - ► Neutron propagation
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  - ► AmBe
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  - ► Mono-E neutrons
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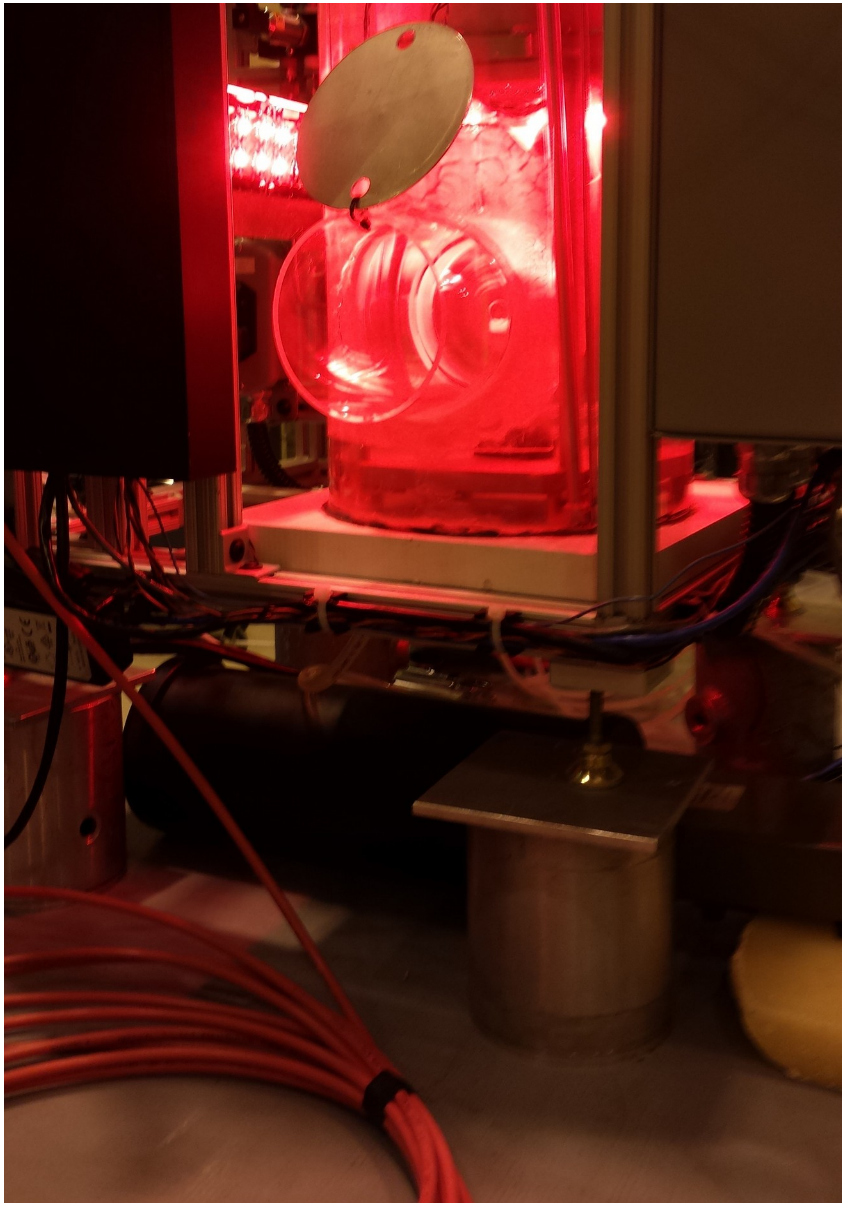
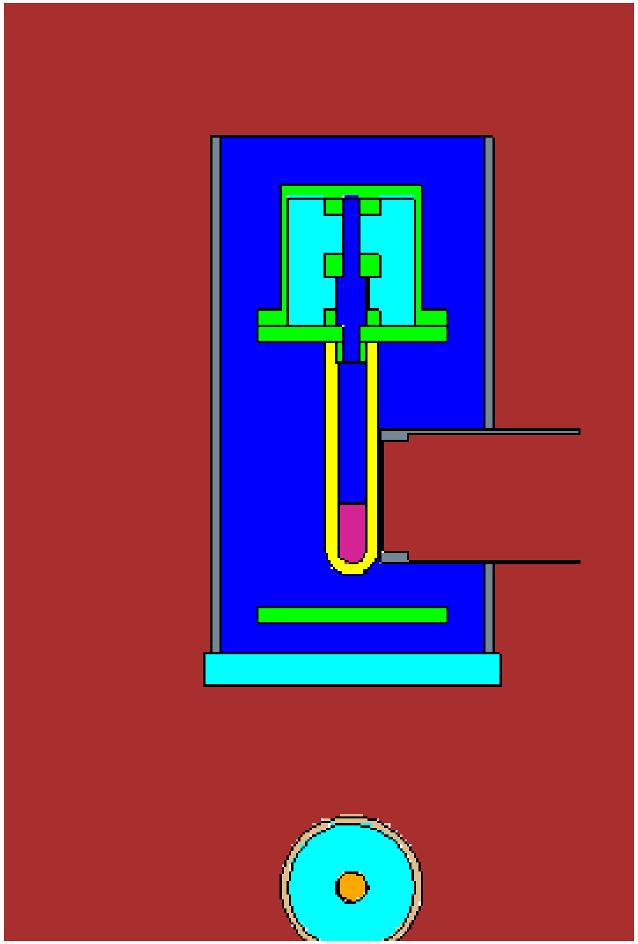
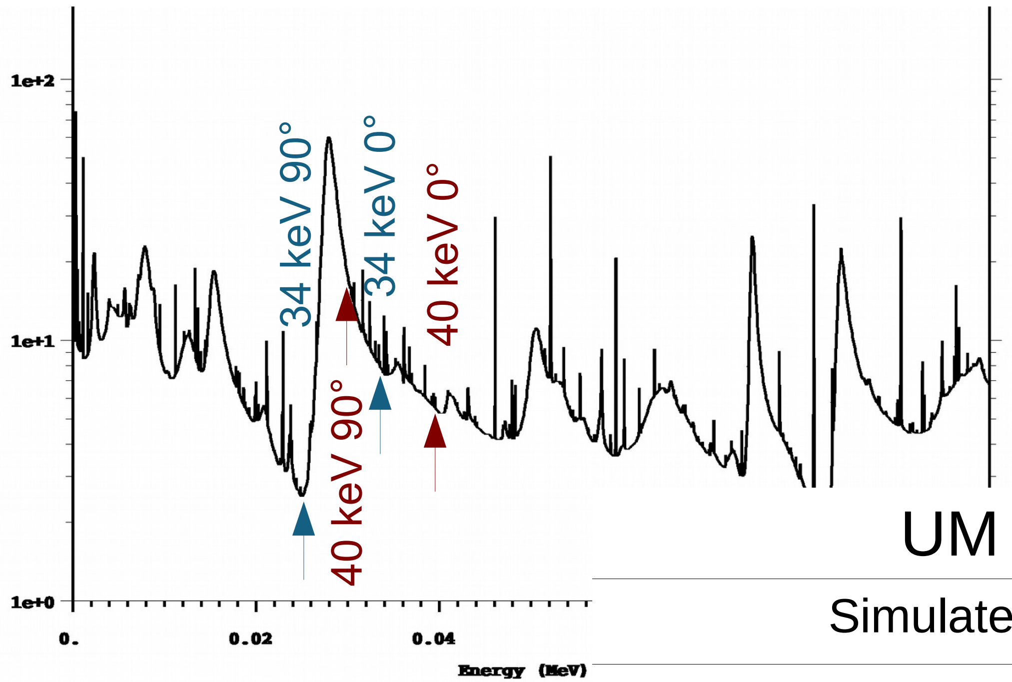




40 keV data

- Intercalibration at 0° and 90°
  - Matches MCNP except at 40 keV.

(n,el) cross-section in 304SS



UM counts / UC counts

	Simulated	Measured	Meas / Sim
40 keV	2.55	3.34 ± 0.21	1.31
61 keV	2.26	2.02 ± 0.07	0.89
97 keV	2.21	2.07 ± 0.10	0.93

- Background
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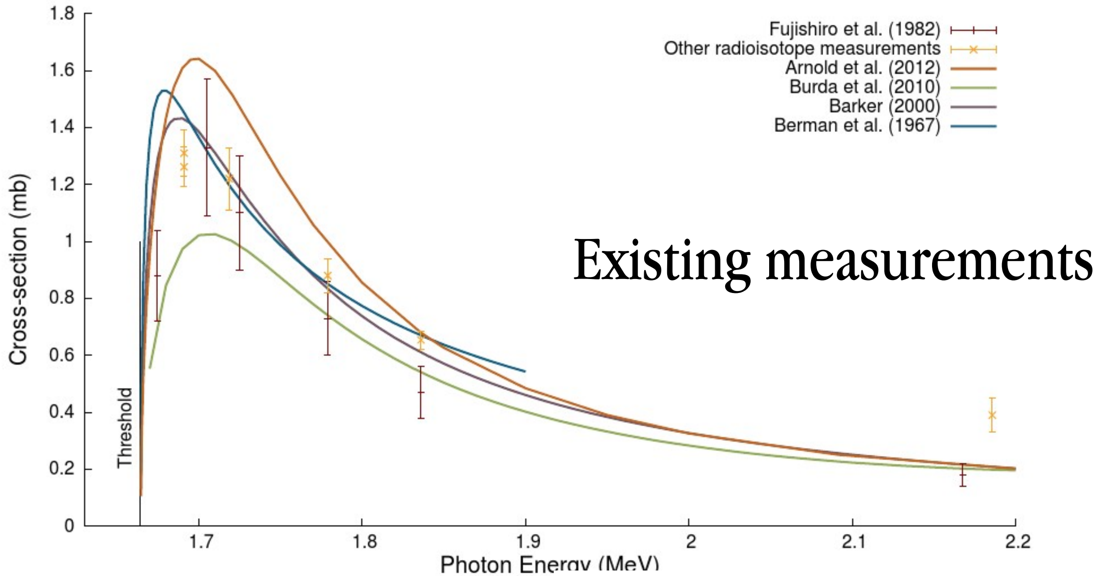
- Calibration
  - AmBe
    - Rates
    - Reactions
  - Mono-E neutrons
    - Generation
    - Propagation

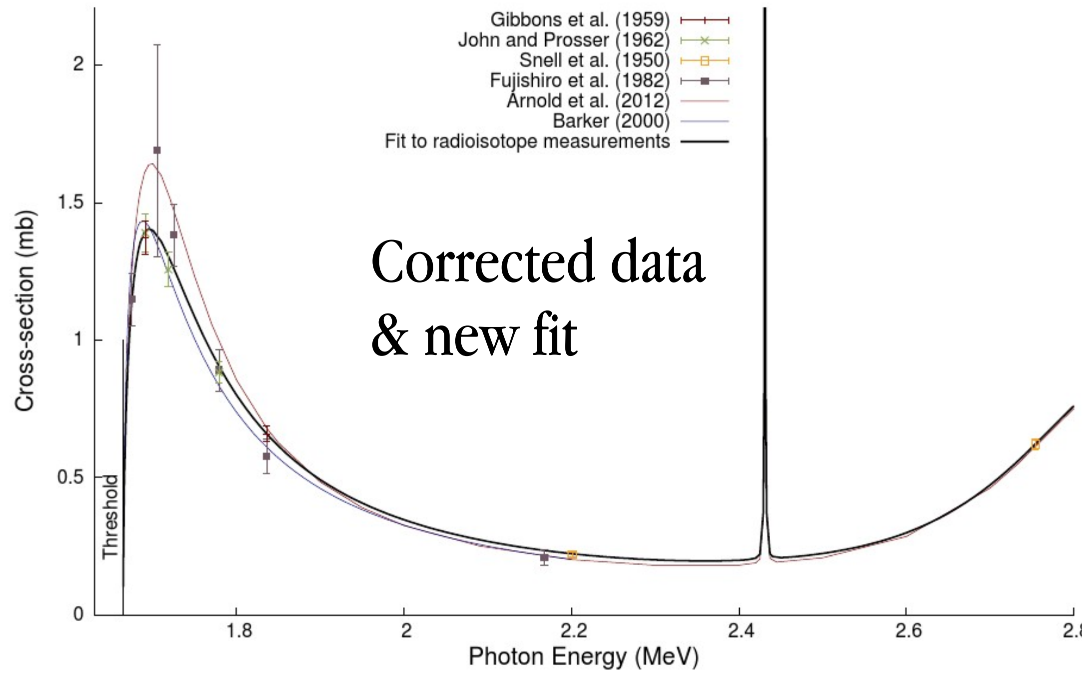
4

$^9Be(\gamma,n)$ Sources

- Background
  - ► Assays
  - ► α,n yields
  - ► Neutron propagation
- Calibration
  - ► AmBe
    - Rates
    - Reactions
  - ► Mono-E neutrons
    - Generation
    - Propagation

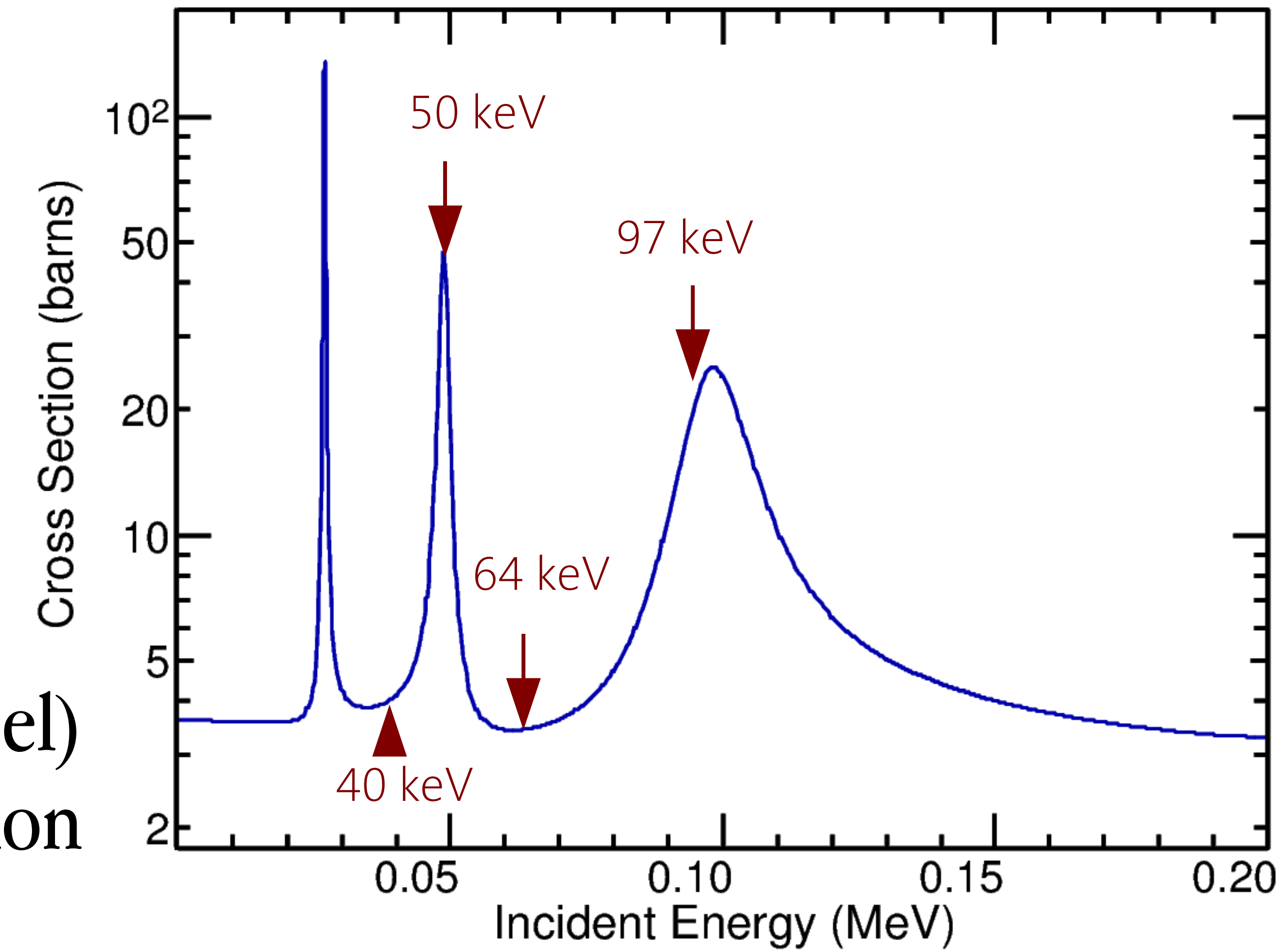


New $^9Be(\gamma,n)$ cross-section fit for determining source yields



Cross-sections

- Uncertainty in ^{19}F resonance strength.
  - 97 keV ± 7%   61 keV ± 1.5%



^{19}F (n,el) Cross-section

- Background
  - Assays
  - α,n yields
  - Neutron propagation
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  - AmBe
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    - Reactions
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Cross-sections

- Background
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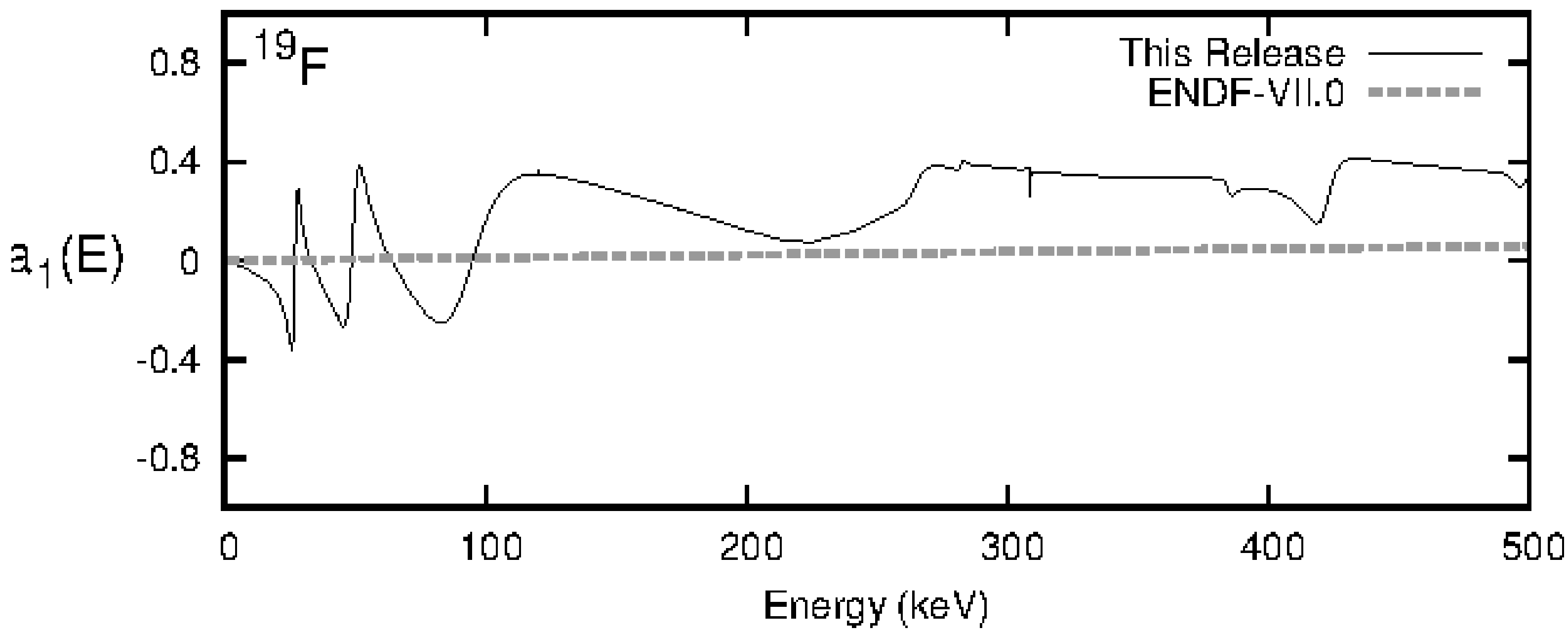
- New libraries for MCNP and Geant4 created with R-matrix calculated angular scattering distributions in the Resolved Resonance Region
  - PRC **89**, 032801 (2014)

Dipole Term of Angular Scattering Distribution

Fluorine-19



Lessons

- Develop a radiopurity tracking and change control system.
  - Train engineers, technicians, and detector operators.
- Independently check all critical simulations, and reconcile differences. Typographical errors are common.
- Know where your data is coming from, reverify all calibrations, and use experimental checks where possible.