Simulation of Muon-Induced Neutrons for the Neutron Multiplicity Meter

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"The coincidence counting rate of any particle telescope depends upon the effective dimensions and relative positions, i.e. the geometry, of the telescope sensors as well as the intensity of radiation in the surrounding space and the sensor efficiencies. The experimentalist's task is to compute the intensity of radiation given the coincidence counting rate and the parameters (e.g. sensor dimensions) of [the] telescope."

J.D. Sullivan. *Nuclear Instruments and Methods* **95** (1971) p. 5-11

Outline

- D.-M. Mei and A. Hime. *Physical Review D* **73** (2006) 053004
- Intensity vs. Flux
  - Determining flux from $\cos^\alpha(\theta)$ intensity
  - Measuring intensity in an experiment
  - Gathering power of detector/generating surface
- Generating $\cos^\alpha(\theta)$ intensity on a box
  - Generation parameters
- The neutron multiplicity meter
  - Detector description
  - Intensity measurement
- Summary
  - Put it all into LUXSim?

A Quick Note:

Geant4.9.4.p01

with

QGSP_BERT_HP neutron physics list

Introduction to D.-M. Mei and A. Hime

- FLUKA simulation of muons propagating through 20x20x20m rock thickness with 6x6x6m cavern
- Parameterized neutron energy passing through rock/cavern boundary

$$\frac{dN}{dE_n} = A_\mu \left(\frac{e^{a_0 E_n}}{E_n} + B_\mu(E_\mu) e^{a_1 E_n} \right) + a_2 E_n^{-a_3}$$
$$B_\mu(E_\mu) = 0.324 - 0.641 e^{-0.014 E_\mu}$$

- E_μ is the muon energy, units of GeV
- A_μ is in units of $\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{GeV}^{-1}$
- Only valid for $E_n > 10$ MeV
- Angular distribution in relation to muon angle, multiplicity distribution, lateral distribution, etc.

D.-M. Mei and A. Hime. *Physical Review D* **73** (2006) 053004
Y.F. Wang *et al.* *Physical Review D* **64** (2001) 013012

Muon Induced Neutron Flux in Units of 10^{-9} cm^{-2} s^{-1}

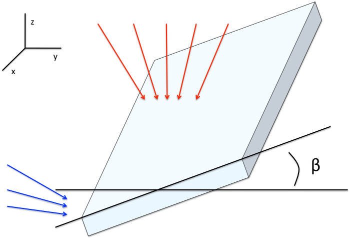
Site	Total	>1.0 MeV	>10 MeV	>100 MeV
WIPP	34.1	10.78	7.51	1.557
Soudan	16.9	5.84	4.73	1.073
Kamioka	12.3	3.82	3.24	0.813
Boulby	4.86	1.34	1.11	0.277
Gran Sasso	2.72	0.81	0.73	0.201
Sudbury	0.054	0.020	0.018	0.005

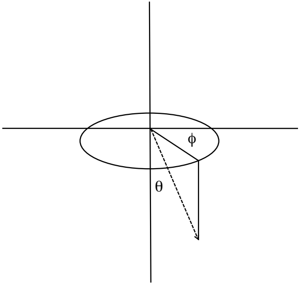
- In general, experiments measure a rate, quote flux or intensity
- "Gathering Power" needed to put rate in terms of flux/intensity (effective area, geometric factor, collection power, etc: all roughly the same quantity)
- Need to distinguish between flux and intensity: can't just generate randomly on all surfaces surrounding detector

D.-M. Mei and A. Hime. *Physical Review D* **73** (2006) 053004

Flux vs. Intensity for a Cosmic (only downward) Source

- Overall neutron intensity ($cm^{-2}s^{-1}sr^{-1}$) of the form: $\mathcal{I} = \mathcal{I}_0 cos^{\alpha}\theta$
  - Isotropic: $\alpha = 0$
  - Soudan muons: $\alpha \simeq 3$
- What is the flux ($cm^{-2}s^{-1}$) through a surface rotated by angle β?
- Particle direction is $\hat{n}_1$ and normal to surface is $\hat{n}_2$:
  - $\hat{n}_1 = \sin\theta\cos\phi\ \hat{x} + \sin\theta\sin\phi\ \hat{y} + \cos\theta\ \hat{z}$
  - $\hat{n}_2 = \sin\beta\ \hat{y} + \cos\beta\ \hat{z}$





Flux through Horizontal and Vertical Sheet

$$\mathcal{F} = \int_0^{2\pi} \int_0^{\frac{\pi}{2}-\beta} \mathcal{I}(\hat{n}_1 \cdot \hat{n}_2) d\Omega + \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} \int_{\frac{\pi}{2}-\beta}^{\frac{\pi}{2}} \mathcal{I}(\hat{n}_1 \cdot \hat{n}_2) d\Omega$$

(horizontal) (vertical)

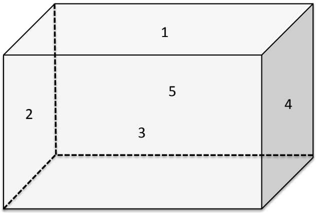
$$\hat{n}_1 \cdot \hat{n}_2 = \sin\theta\cos\phi\sin\beta + \sin\theta\cos\beta$$

The (α dependent) flux through a vertical and horizontal sheet is:

$$\beta = 0 \rightarrow \mathcal{F}_H = 2\pi\mathcal{I}_0 \int_0^{\frac{\pi}{2}} \cos^{\alpha+1}\theta\sin\theta d\theta = \frac{2\pi\mathcal{I}_0}{\alpha+2}$$

$$\beta = \frac{\pi}{2} \rightarrow \mathcal{F}_V = \mathcal{I}_0 \int_{\frac{\pi}{2}}^{-\frac{\pi}{2}} \cos^{\alpha}\theta\sin^2\theta d\theta = \mathcal{I}_0 \frac{\sqrt{\pi}\Gamma(\frac{\alpha}{2}+\frac{1}{2})}{2\Gamma(\frac{\alpha}{2}+2)}$$

Determining Gathering Power of Generating Box



- Particle source (i.e. from the cavern) crossing a cube on five sides
- Cube can be any size, encompassing detector
- Rate through cube, with intensity $\mathcal{I}_0$ is:

$$\mathcal{R} = \mathcal{F}_H A_1 + \mathcal{F}_V (A_2 + A_3 + A_4 + A_5)$$

$$\mathcal{R} = \mathcal{I}_0 \left(\frac{2\pi}{\alpha + 2} A_1 + \frac{\sqrt{\pi}\Gamma(\frac{\alpha}{2} + \frac{1}{2})}{2\Gamma(\frac{\alpha}{2} + 2)} (A_2 + A_3 + A_4 + A_5) \right) = \mathcal{G}_S \mathcal{I}_0$$

Determining Overall (detector+gen box) Gathering Power

- Simplest method is with simulation:

$$\mathcal{G} = \mathcal{G}_S \frac{N_{det}}{N_{gen}}$$

- The measured rate in detector for perfect detection/analysis cut efficiencies:

$$\mathcal{I}_0 = \frac{N_{det}}{t_r \mathcal{G}}$$

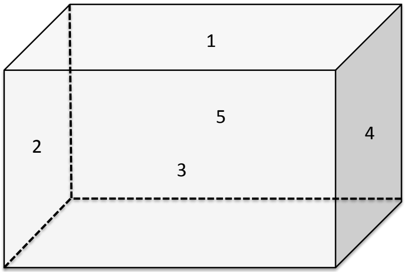
  - N_{det} is the total number of events detected
  - t_r is the runtime of the experiment
  - $\mathcal{G}$ is the overall gathering power, has units of cm^2 sr

- Can quote flux through horizontal (or vertical) sheet: $\mathcal{F}_H = \frac{2\pi\mathcal{I}_0}{\alpha+2}$

J.D. Sullivan. *Nuclear Instruments and Methods* **95** (1971) p. 5-11

Event Generation for $\cos^\alpha(\theta)$ Source

α	$\mathcal{F}_V/\mathcal{F}_H$
0	$1/2$
1	$1/\pi$
2	$1/4$
3	$2/3\pi$
4	$3/16$
5	$8/15\pi$
6	$5/32$



Surface	ϕ limits	$f(\theta)$	$f(\phi)$	Number of Events
1	$0 \to 2\pi$	$\cos^{\alpha+1}\theta\sin\theta$	Uniform	N_1
2	$-\frac{\pi}{2} \to \frac{\pi}{2}$	$\cos^{\alpha}\theta\sin^2\theta$	$\cos\phi$	$\frac{\mathcal{F}_V}{\mathcal{F}_H}\frac{A_2}{A_1}N_1$
3	$-\pi \to 0$	$\cos^{\alpha}\theta\sin^2\theta$	$-\sin\phi$	$\frac{\mathcal{F}_V}{\mathcal{F}_H}\frac{A_3}{A_1}N_1$
4	$\frac{\pi}{2} \to \frac{3\pi}{2}$	$\cos^{\alpha}\theta\sin^2\theta$	$-\cos\phi$	$\frac{\mathcal{F}_V}{\mathcal{F}_H}\frac{A_4}{A_1}N_1$
5	$0 \to \pi$	$\cos^{\alpha}\theta\sin^2\theta$	$\sin\phi$	$\frac{\mathcal{F}_V}{\mathcal{F}_H}\frac{A_5}{A_1}N_1$

Procedure for Generating Generic Cosmic Source

- Given a value of α and some energy distribution
- Probability of neutron emerging from surface 1:

$$P_1 = \frac{N_1}{N_1 + N_1 \frac{\mathcal{F}_V}{\mathcal{F}_H A_1}(A_2 + A_3 + A_4 + A_5)}$$

- Surface 2,3,4,5:

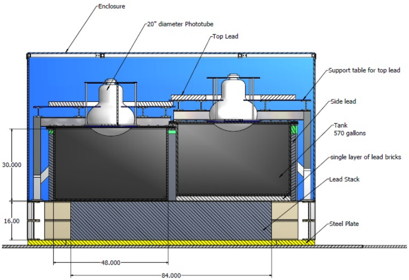
$$P_1 = \frac{N_1 \frac{\mathcal{F}_V A_{2,3,4,5}}{\mathcal{F}_H A_1}}{N_1 + N_1 \frac{\mathcal{F}_V}{\mathcal{F}_H A_1}(A_2 + A_3 + A_4 + A_5)}$$

- α determines the ratio $\frac{\mathcal{F}_V}{\mathcal{F}_H}$
- Choose cube that fully encompasses detector, i.e. determine A_1-A_5
- Use proper $f(\theta)$, $f(\phi)$, and ϕ limits
- One neutron at a time (cavern meters away, muon not going through detector)
- Simulated runtime is then $t_{r,sim} = \frac{N_{sim}}{\mathcal{I}_0 \mathcal{G}}$

The Neutron Multiplicity Meter at Soudan (2100 mwe)

Use lead target to convert high energy neutrons from rock to multiple neutrons that capture in gadolinium-doped water Cherenkov detector

- Two tanks: two tons of water, each tank with two KamLand PMTs
- 1 ppm Amino-G Salt waveshifter, halon coated walls
- North/South tank: 0.7%/0.3% $GdCl_3$
- 40 cm thick lead target

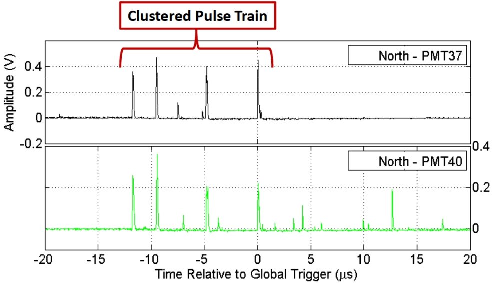


- First measurement of neutrons with energies >40MeV in anti-coincidence with muon
- Muon-induced high-energy neutron production processes at Soudan (and deeper) dominated by hadronic cascades

Picture by Susanne Kyre, UCSB HEP
Y.F. Wang *et al.* *Physical Review D* **64** (2001) 013012

Multiplicity Trigger

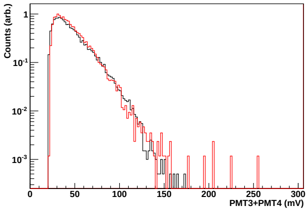
- North tank AND = PMT3 and PMT4 firing within 160 ns
- South tank AND = PMT1 and PMT2 firing within 160 ns
- Multiplicity = number of ORs of the North and South tank ANDs
- Trigger on multiplicity
- Acquire 100 μs pre- and post- trigger window



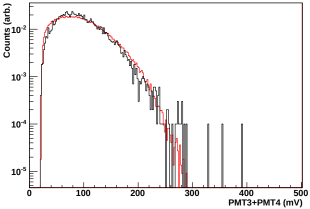
Picture by Ray Bunker, UCSB HEP

Energy Calibration: Experimental Data vs. Simulated Data

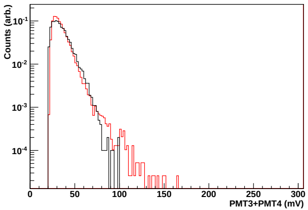
U/Th Gammas



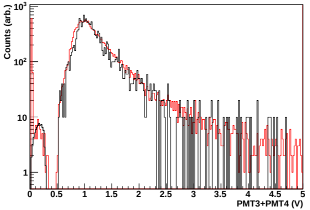
^{252}Cf neutrons



^{60}Co Gammas

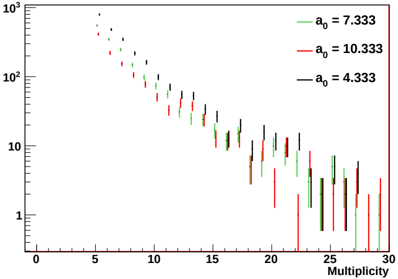


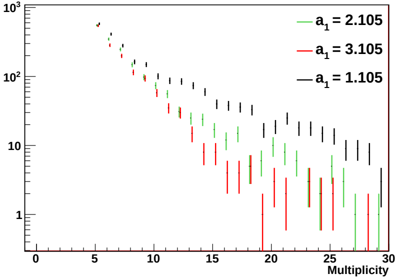
muons and Michele electrons



Toying with Mei and Hime Parameters in Simulations

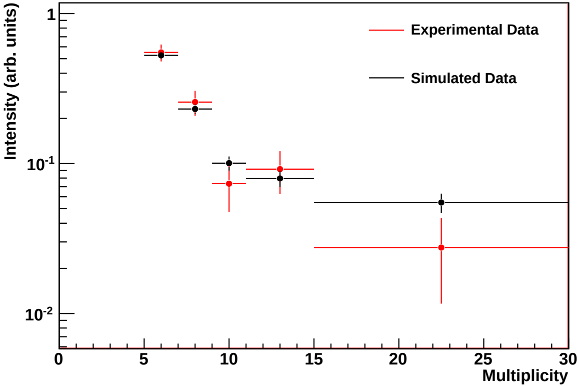
At Soudan, Mei and Hime have $a_0 = 7.333, a_1 = 2.105$





$$\frac{dN}{dE_n} = A_\mu \left(\frac{e^{a_0 E_n}}{E_n} + B_\mu(E_\mu) e^{a_1 E_n} \right) + a_2 E_n^{-a_3}$$

Sensitivity to Fast Neutron Intensity, Energy Spectrum



$$\mathcal{I}_0 = \frac{\sum_{m=5}^{M} N(m)/(\epsilon_L(m)\epsilon_\mu(m)\epsilon_{ts}(m))}{\epsilon_t t_r \mathcal{G}}$$

Summary

- Established a generic framework for generating cosmic sources with $\mathcal{I} = \mathcal{I}_0 cos^\alpha \theta$
- Neutron energy spectrum and angular spectrum is modeled by isotropic neutrons ($\alpha = 0$) with energies from D.-M. Mei and A. Hime
  - Can also input energy spectrum from Geant4 or MUSIC/MUSUN for muons
  - Angular spectrum of neutrons must be convoluted with muon angular spectrum
- Different depths effect energy spectrum, and to lesser degree angular spectrum
- Neutron Multiplicity Meter at Soudan is sensitive to overall fast neutron flux, some energy parameters from D.-M. Mei and A. Hime
- Need to implement this into LUXSim for community to use?

V. A. Kudryavtsev, *Computer Physics Communications* **180** (2009) p. 339-346

Thank You!

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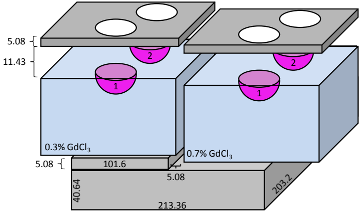
Mani Tripathi, UC Davis
Dean White, UCSB HEP

Geant4 Detector Model - Energy Calibration

- wall reflectivity to reproduce pulse asymmetry: 95% total, 5% specular
- photoelectrons converted to pulses with overall mV/PE conversion: 2.5 mV/PE
- individual PMT threshold applied: 20 mV
- variable-width Gaussian convolution to reproduce low-energy response: $0.9\sqrt{\text{pulse height}}$

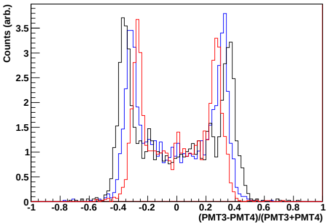


Tested with five different sources:

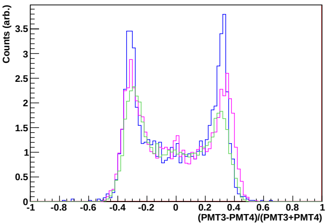
- Muons and Michel electrons
- Gammas from ^{60}Co and rock (U/Th) radiation
- Neutrons from ^{252}Cf

Tuning Wall Reflectivity - Pulse Asymmetry

$$Asymmetry = \frac{\mathrm{PMT_E} - \mathrm{PMT_W}}{\mathrm{PMT_E} + \mathrm{PMT_W}}$$



92%, 94%, and 96% reflectivity



simulated 94% compared to two different muon experimental data runs (pink and green)