The UMD/NIST Fast Neutron Spectrometer at KURF

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Outline

• Fast Neutrons as backgrounds
• FN Detection Techniques
  • Capture-gated spectroscopy
  • $^3$He rise-time discrimination
• FaNS-1 at the surface and KURF
• FaNS-2: Design and Testing
Fast Neutron Backgrounds for Underground Science

- Fast neutrons play a particularly problematic role in low background experiments
  - Deeply penetrating
  - Create long lived isotopes (Co60, Xe137,...)
  - FNs are indistinguishable from WIMP dark matter interactions
- Important to know the surface fast neutron spectrum for shielding and transport of materials
LUX Dark Matter Search

10 MeV n
LUX Dark Matter Search
Finally, it is apparent that the experimental points lie far above the MC data. If the disagreement for the light materials is already unreasonable, the case of lead cannot be easily explained. In fact, even if a much lower neutron threshold of 1 MeV is considered, both MC models would still predict a lower cross-section than those reported in Ref. [18].

The production of lower energy neutrons by deep inelastic scattering (DIS) of 470 GeV muons in lead was studied by the E665 Collaboration, who found average neutron multiplicities per DIS event of $5$ for neutron energies under 10 MeV [19]. A value of $3.7$ is obtained for the GEANT4 simulation of the $\mu$–$N$ process at this muon energy, in reasonable agreement with the experimental result. The simulated neutron spectrum (per unit energy) exhibits a double-exponential behaviour below 10 MeV—also in agreement with the experimental findings. The two decay constants, due to neutron evaporation from the thermalised nucleus and from pre-equilibrium emission, are characterised by nuclear temperatures of $0.93$ and $3.7$ MeV, compared to $0.7$ and $5.0$ MeV obtained in E665. In conclusion, the spallation of neutrons under 10 MeV as predicted by GEANT4 for lead does not conflict with these experimental data.

The role of the minimum energy transfer in the muon photonuclear models in neutron production was pointed out in Paper 2. This threshold comes about because the virtuality of the photon can no longer be neglected when it becomes comparable to its energy. Recently, the total $\mu$–$N$ cross-section was reported to increase by 2–3 times if the minimum energy transfer is decreased from 140 to 10 MeV, based on the parameterisation used in FLUKA [20]. We have confirmed that this difference is only 10–15% greater for the 200 MeV threshold in GEANT4. The aforementioned study also found that the parameterisation used to describe the $g$–$N$ cross-section in FLUKA [16] (similar to that from Ref. [17] used in GEANT4) overestimates more rigorous theoretical calculations when extrapolated to low energy gammas. Consequently, the increase in the muon cross-section with decreasing threshold is not expected to be as large as mentioned above. In any case, as pointed out in Paper 2, we expect many more neutrons to be produced by bremsstrahlung (real) photons with low energies in electromagnetic cascades than by virtual ones in muon interactions with small energy transfers.

3. Underground neutron fluxes: a case study

The UK Dark Matter Collaboration (UKDMC) has been assessing the feasibility of a xenon-based tonne-scale dark matter experiment to be installed at the Boulby Underground Laboratory. In this context, initial calculations using FLUKA, reported in Paper 3, have so far been performed of the muon-induced background in a 250 kg xenon target. Building on that work we present here a case-study comparison between FLUKA and GEANT4. The calculated neutron fluxes and spectra at the rock/cavern boundary and after various shields are also relevant to other underground experiments in different laboratories.

Fig. 7. Differential cross-section of neutron production by 190 GeV muons for a 10 MeV threshold in neutron energy. The data points represent the results of the NA55 experiment. The thin-line histogram shows the GEANT4 simulation considering muon–nucleus interaction only; the thick histogram includes all physics processes. The dashed line represents the FLUKA results for the latter case. Araújo, et. al. NIM A, 2005
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Surface Fast Neutron Spectrum

Fig. 8. Differential flux, $d\phi/dE$, ($\text{cm}^{-2} \text{s}^{-1} \text{MeV}^{-1}$) of cosmic-ray induced neutrons as a function of neutron energy. The data points are our reference spectrum from the measurements, the solid curve is our analytic model, and the dashed curve is the JEDEC model [38].

Array of 14 Bonner spheres, count rates are unfolded to make a spectrum

The UMD/NIST
Fast Neutron Spectrometers
The FaNS Detectors

- Arrays of plastic scintillator segments and helium-3 proportional counters
  - Segmentation improved energy reconstruction
  - *Use Capture-gated Spectroscopy for particle identification and energy information*
- Calibrated at NIST with Cf-252, DD, and DT neutrons
- Measure the surface and underground neutron spectra
  - FaNS-1: operated at Kimballton Underground Research Facility
  - FaNS-2: to be operated at shallow location at NIST
FaNS-I

BC400 Plastic Scintillator

He3 Proportional Counters
FaNS-1
FaNS- I

n
Capture Gated Spectroscopy

Main features of CGS:
1. Particle identification
2. Full energy deposition
3. Simply background subtraction

Neutron Scatters

Neutron Capture

\[ \Delta t \]
Timing Spectrum

- Counts/bin
- Time Separation (us)

Real Coincidences

Random Coincidences
Risetime of Helium Signals

1. Use preamp signals directly
2. Digitize signals
3. Risetime = 50% - 10%

Allows for suppression of alpha, gamma, and microdischarge noise signals

Calibrations as NIST

- Used two mono-energetic neutron generators to measure FaNS-I energy reconstruction
- Both show good agreement with MCNP
- *Shows that we have full energy deposition*
• Operated FaNS-1 for $1.6 \times 10^5$ seconds
• Recorded $1.3 \times 10^5$ events (0.8 Hz)
• After cuts, ~6000 neutron events (0.04Hz)
• Recorded neutron energies up to 300 MeV
FaNS-I at KURF

- Multiple upgrades to electrons to reduce backgrounds and noise
- Measured efficiency with Cf-252 source $(1.3\pm0.1)\%$
- Final dataset included 100 days of operation
• 62 day dataset
• $1.67 \times 10^5$ events
• 250 counts pass all cuts
• 92 remain after BG sub.
(alpha,n) vs Fission Spectrum

- The measured spectrum at KURF is more (alpha,n)-like
- We are working on simulating the expected spectrum based on BG measurements of U, Th

**Mei Hime 2005**

FIG. 26: The neutron energy spectrum arising from (alpha,n) reactions due to radioactivity in the rock. We predict a harder energy spectrum in Gran Sasso rock relative to standard rock owing to the presence of carbon and magnesium.
FaNS-2

He3 Neutron Detectors

Plastic Scintillator
Data Acquisition System

7 CAEN V1720 Digitizers
FaNS-2 Operation at NIST

- NIST provides an array of neutron sources for calibrations
  - Californium-252 (known activity at 1%)
  - DD and DT mono-energetic generators
  - AmBe
- FaNS-2 is operating in a low scatter room measuring source and ambient neutrons
  - Low number of backscattering neutrons
  - Effectively no shielding of ambient neutrons from cosmic rays
- FaNS-2 will move to a 20mwe lab at NIST soon
Timing Spectrum

![Graph showing the timing spectrum with 'Real + Random' and 'Random Only' regions]

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Neutron Source Calibration

Have measured the absolute efficiency with calibrated Cf source, ~9% above 1MeV
Cosmogenic Neutrons at NIST

Counts /MeV/s

Real + Random

Random Only

Energy (MeV)
Cosmogenic Neutrons at NIST

Counts /MeV/s

Energy (MeV)

Background Subtracted
MCNP Simulation
Conclusions

• We have shown that FaNS-1 has sensitivity up to 300 MeV
• FaNS-1 has been calibrated with Cf, DD, and DT neutron sources
• MCNP simulations have been done that match the response of the detector
• A measurement of the neutron spectrum at KURF has been made
• FaNS-2 is now operating, and moving underground soon
Backup Slides
FaNS-2

9cm X 9cm X 56cm Plastic Scintillator Bars
FaNS-2

He3 Neutron Detectors

9cm X 9cm X 56cm Plastic Scintillator Bars
Data Acquisition Requirements

• *Synchronous sampling and triggering of 56 channels*

• Operate in three trigger modes:
  • Gamma calibration: Any PMT triggers all PMTs
  • Muon calibration: Trigger on high multiplicity PMT events
  • Neutron data: Any helium signal triggers all channels
    • ~1ms long traces with ZLE to reduce data size
    • Large dynamic range (30 keV:200 MeV per channel)

• Need to automatically switch between different modes
Neutron Trigger

Synchronous Sampling

PMT Optical Branch

To A3818 Optical controller in Ubuntu PC

He3 Optical Branch

PMTs

He3

Trigger

Sync Start

Sync Start zeros time stamps and begins acquisition on all boards

Buffer Status

Veto

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DD Neutron generator

- No Cuts
- Real + Random
- Random Only

Energy (MeV)

Counts

Energy (MeV)
PMT Signal Conditioning

- Custom circuit board
- 8ch, NIM form factor
- *Factor of 10 increase in dynamic range*
- Increase of signal width from 10ns to 50ns
  - Reduces digitization error

Graph showing time (ns) on the x-axis and channel on the y-axis.
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**PMT Signal Conditioning**

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- Homebuilt code with C++
- GUI uses QT for cross platform
- Controls an arbitrary number of cards, set at compile time
- Each card can operate separately or any combination can be coordinated
- Settings can be loaded from a file
- Controlled by an external Python function over TCP/IP
- Homebuilt code with C++
- GUI uses QT for cross platform
- Controls an arbitrary number of cards, set at compile time
- Each card can operate separately or any combination can be coordinated
- Settings can be loaded from a file
- **Controlled by an external Python function over TCP/IP**
Python Control Program

- Platform independent development
- Simple to program, easy to debug!
- Commands sent over TCP/IP to DAQ program
- Script controls card settings, start, stop, saving data, writing MCAs, etc.
- Can be controlled locally or remotely
- Easy interoperation with HV control, logging, email notifications, environmental monitoring, and data transfer
Gamma/Muon Trigger

2.3. Front Panel

SCALER
8 CH 12 BIT
250 MS/S
DIGITIZER

Mod. V560E
Mod. V1720

ANALOG INPUT
DIGITAL I/O's
ANALOG MONITOR OUTPUT
LOCAL TRIGGER OUT
EXTERNAL TRIGGER IN
SYNC/SAMPLE START
EXTERNAL CLOCK IN
INTERNAL CLOCK OUT

Fig. 2.1: Mod. V1720 front panel
DAQ at Work!
NIST nTOF Apparatus

Graph showing amplitude (ch) vs samples for Plastic Scintillator and NaI Crystal.
Time of Flight

Deposited Energy (MeVee)

neutrons

gammas

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MeV vs MeVee
MeV vs MeVee
MeV vs MeVee
Measured Light Response

Energy (MeV)

Energy (MeVee)

kB = .0095, c = 10e-6

tofE
New Light Recon
FaNS-2 Outlook

- Efficiency calibration up to 10 MeV with Cf neutron sources
- Measure response to 14 MeV neutrons with DT generator
- Continue collecting ambient neutron data at the surface, measure from 500 keV to >1 GeV
- Install in a shallow underground facility at NIST to measure the muon induced neutron spectrum
- Simulate the spectrum with Geant4/Fluka/MCNP to compare with data