Muon-induced neutrons at the
Boulby Underground Laboratory

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Outline

• Introduction: why do we need to know this background?

• Experiment
  – Set-up
  – Detection principle

• Calibrations.

• New measurement of muon flux.

• Measurement of neutrons from cosmic-ray muons
  – Energy spectrum of delayed pulses
  – Time delay distribution
  – Multiplicity distribution

• Simulations.

• Summary.
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Muon-induced neutrons

- Most data are for light targets.
- Data are controversial - no full MC for any data point at high energies.
- Models may not be very accurate - tests are needed.


GEANT4 v6.2: Araujo et al. NIMA 545 (2005), 398.
GEANT4 v8.2: Lindote et al., in preparation.

280 MeV muons

\[ C_nH_{2n} \]
Muon-induced neutrons


- Other data for lead (Bergamasco et al. Nuovo Cim. A, 13 (1973) 403; Gorshkov et al. Sov. J. Nucl. Phys., 18 (1974) 57) are old and controversial but also show significantly higher neutron production compared with simulations.

- Lead is important since it is used as a shield in underground experiments.
Measurements with ZEPLIN II veto

- 0.73 tonne of liquid scintillator + paraffin shielding interleaved with Gd impregnated resin + Gd painted on the inner surface of the veto vessel.
- Lead castle - about 50 tonnes - main target for neutron production.
- Detailed MC was carried out to take into account geometry and physics.
Detection principle

- Neutron detection principle: delay coincidences between muon signal and neutron capture:
  - Muon (or cascade) signal - large energy deposition (PMTs and DAQ are saturated);
  - Neutron capture signal - delayed by a few tens of microseconds, capture mainly on H.
- The detector is triggered by high-energy pulses: either high-energy gammas depositing energy close to PMTs (non-uniform light collection shifts the measured energy to higher values), or muons (cascades).
- Energy threshold: hardware - about 7 MeV, software - 20 MeV. Average energy deposition of muons - more than 50 MeV.
- Energy threshold for secondary (neutron) pulse analysis: about 0.15 MeV; increased to 0.55 MeV at the 2nd stage of analysis to avoid background etc.
- 3-fold coincidences between PMTs are required for trigger and secondary pulses.
- Total live time: 204.8 days (August 2006 - April 2007).
Gamma-ray and neutron calibrations

$^{60}$Co spectra collected in August 2006 and March 2007 (before and after the data run). Difference in pulse area-to-energy conversion factors is 6%.

Neutron calibration with Am-Be source; simulations using GEANT4. Exponential - neutrons, flat background - random coincidences.
Event display, muon selection

- Pulses with amplitude of about 0.6 V - logic pulses generated by 3-fold coincidences.
- Pulse at about 90 $\mu$s is the neutron-like pulse (delayed photon from neutron capture).
- Muon events: large amplitude, large area, saturation, large width.
Muon rate and flux

- 10832 muons during 204.8 days; rate $52.9 \pm 0.5$ muons/day.
- Comparing with Monte Carlo simulations gives the muon flux as $(3.79 \pm 0.04 \text{ (stat.)} \pm 0.11 \text{ (syst.)}) \times 10^{-8} \text{ cm}^{-2} \text{ s}^{-1}$.
- Systematic uncertainty is due to the uncertainty in the energy scale.
- The muon flux is defined as a flux through a spherical detector with unit cross-sectional area.
- The flux corresponds to the depth of $2850 \pm 20$ m w. e. in Boulby rock.
- The measured flux is slightly lower (by 8%) and the evaluated depth is slightly higher than previously reported (M. Robinson et al., NIMA 511 (2003) 347) mainly due to:
  - Different location of the new lab;
  - More accurate (3D instead of 1D) simulation of muon passing through and around the detector.
Energy spectrum of the secondary pulses

Spectrum of secondary pulses after muon trigger; an independent calibration using 2.22 MeV peak (plus Compton edge) - capture on H.

Simulated spectrum (GEANT4) was folded with the energy resolution function.

Uncertainty in the energy scale - 20%.
Time delay distributions

- 204.8 days of run time.
- Data run, muon trigger (E>20 MeV). The rate of secondary pulses: 0.096 ± 0.003 (stat) per muon above 0.55 MeV at 40-190 µs.
- Subtracting background rate 0.0164 ± 0.0009 (next slide) gives the neutron rate: 0.079 ± 0.003 (stat) per muon above 0.55 MeV at 40-190 µs.
- Simulations (same conditions): 0.143 ± 0.002 (stat.) ± 0.009 (syst.) n/µ.
- Systematic uncertainty is due to the uncertainty in the energy scale.

Red - sim roof on
Blue - sim roof off
Black - data
Simulations (plus flat background) are normalised to the data
Time delay distribution

Data run, gamma-ray trigger (7<E<15 MeV, high-energy detected due to non-uniform light collection).

Background rate:

0.0164 ± 0.0009 (stat) secondary pulses per event above 0.55 MeV at 40-190 µs.
Multiplicity distribution

Black solid histogram - neutrons, muon trigger (E>20 MeV);
Black dashed histogram - background, gamma-ray trigger (7<E<15 MeV).
Red dotted histogram - simulations for neutrons.
Conclusions

• Muon flux has been measured using ZEPLIN II liquid scintillator veto (0.73 tonnes) in the new lab (JIF area - Palmer Laboratory) at Boulby: 
  \[(3.79 \pm 0.04 \text{ (stat.)} \pm 0.11 \text{ (syst.)}) \times 10^{-8} \text{ cm}^{-2} \text{ s}^{-1}\] 
  (through a spherical detector with unit cross-sectional area). The flux corresponds to the depth of \(2850 \pm 20\) m w. e.

• Muon-induced neutron rate has been measured as \(0.079 \pm 0.003\) (stat.) n/µ above \(0.55\) MeV at \(40-190\) µs. Simulations give the rate of \(0.143 \pm 0.002\) (stat.) \(\pm 0.009\) (syst.) n/µ (with the same selection criteria), a factor of 1.8 higher than the measured value.

• As the vast majority of detected neutrons (90%) are produced in lead we evaluated from our measurements the total neutron yield in lead as \((1.31 \pm 0.06) \times 10^{-3}\) n/µ/(g/cm²) for mean muon energy of \(260\) GeV.

• Also: Neutron background from radioactivity in rock has been measured using small liquid scintillator cell: \((1.72 \pm 0.61\) (stat.) \(\pm 0.38\) (syst.)) \(\times 10^{-6}\) n/cm²/s (E>0.5 MeV) and found to be consistent with simulations based on the evaluated U/Th concentrations - \(1.20\times10^{-6}\) n/cm²/s (E. Tziaferi et al. Astroparticle Phys. 27 (2007) 326).