Available online at www.sciencedirect.com

ScienceDirect

Nuclear and Particle Physics Proceedings 273–275 (2016) 2675–2677

www.elsevier.com/locate/nppp

Measurement of Cosmic-ray Muon-induced Spallation Neutrons in the Aberdeen Tunnel Underground Laboratory

S. C. Blyth[a], Y. L. Chan[b], X. C. Chen[b], M. C. Chu[b], K. X. Cui[c], R. L. Hahn[d], T. H. Ho[e], Y. B. Hsiung[e], B. Z. Hu[f], K. K. Kwan[b], M. W. Kwok[b], T. Kwok[c], Y. P. Lau[c], J. K. C. Leung[c], K. Y. Leung[c], G. L. Lin[f], Y. C. Lin[b], K. B. Luk[g], W. H. Luk[b], H. Y. Ngai[c,*], S. Y. Ngan[b], C. S. J. Pun[c], K. Shih[b], Y. H. Tam[b], R. H. M. Tsang[c], C. H. Wang[a], C. M. Wong[b], H. L. Wong[c], K. K. Wong[b], M. Yeh[d], B. J. Zhang[c]

[a] *Department of Electro-Optical Engineering, National United University, Miao-Li, Taiwan*
[b] *Department of Physics, Chinese University of Hong Kong, Hong Kong, China*
[c] *Department of Physics, University of Hong Kong, Hong Kong, China*
[d] *Chemistry Department, Brookhaven National Laboratory, Upton, NY 11973, USA*
[e] *Department of Physics, National Taiwan University, Taipei, Taiwan*
[f] *Institute of Physics, National Chiao-Tung University, Hsinchu, Taiwan*
[g] *Department of Physics, University of California at Berkeley, Berkeley, CA 94720, USA*

Abstract

Muon-induced neutrons are one of the major backgrounds to various underground experiments, such as dark matter searches, low-energy neutrino oscillation experiments and neutrino-less double beta-decay experiments. Previous experiments on the underground production rate of muon-induced neutrons were mostly carried out either at shallow sites or at very deep sites. The Aberdeen Tunnel experiment aims to measure the neutron production rate at a moderate depth of 611 meters water equivalent. Our apparatus comprises of six layers of plastic-scintillator hodoscopes for tracking the incident cosmic-ray muons, and 760 L of gadolinium-doped liquid-scintillator for both neutron production and detection targets. In this paper, we describe the design and the performance of the apparatus. The preliminary result on the measurement of neutron production rate is also presented.

Keywords: Cosmic-ray muon, Spallation neutron, Aberdeen Tunnel, Underground laboratory

---

1. Introduction

High-energy muons can penetrate into underground, and cause a source of background to some sensitive experiments, such as dark matter searches, low-energy neutrino oscillation experiments and neutrino-less double beta-decay experiments. Muons can be easily identified and vetoed. However, high-energy muons can induce spallation neutrons and radioisotopes. These neutrons can travel a long distance into the detector, and are difficult to be tagged. Therefore, understanding muon-induced neutrons is important to sensitive underground experiments. The goal of the Aberdeen Tunnel experiment was to determine the production rate of muon-induced neutrons in an organic liquid scintillator.

The Aberdeen Tunnel laboratory is located inside cross-tunnel No. 5 of the Aberdeen Tunnel, Hong Kong. The laboratory is 22 m above sea level, and has an overburden of approximately 235 m of rocks, which is equivalent to 611 meters water equivalent (m.w.e.). The rocks surrounding the laboratory are mostly granite. MUSIC [1] simulations predicted the average muon energy inside the laboratory to be 120 GeV, and the integrated muon flux to be approximately $1 \times 10^{-5}\text{cm}^{-2}\text{s}^{-1}$. The following sections briefly describe the experimental setup and its performance. A detailed description is given in Ref. [2].

---

[*] Corresponding author

Email address: `jimmyngai@graduate.hku.hk` (H. Y. Ngai)

http://dx.doi.org/10.1016/j.nuclphysbps.2015.10.027

2. Apparatus

The detection of muon-induced neutrons was done using a muon tracker (MT) and a neutron detector (ND). The MT gives the directions and positions of the incoming cosmic-ray muons. It consists of 60 plastic scintillator hodoscopes arranged in three layers. Each layer is made up of two planes of hodoscopes orthogonal to each other for determining the coordinates of a muon. The top and the middle layers are put above the neutron detector, and the bottom layer rests on the floor. The three layers of hodoscopes are aligned vertically.

The ND is a calorimeter. It employs a two-zone design. The outer zone contains 1900 L (1.63 ton) of mineral oil (MO) to attenuate gamma radiations from outside of the target volume and to suppress ambient slow-neutron backgrounds. The inner zone contains 760 L (0.65 ton) of 0.06% gadolinium-doped linear-alkylbenzene-based liquid scintillator (Gd-LS), which is the target for neutron production and detection. When the gadolinium captures a neutron, it produces a gamma cascade with a total energy of about 8 MeV. Scintillation photons created by the gamma-rays are detected with 16 Hamamatsu R1408 20-cm photomultiplier tubes (PMT). There are three calibration ports on the top of the ND for deploying calibration sources.

The data acquisition (DAQ) system consists of homemade front-end electronics (FEE) for the MT and CAEN remote-controllable VME electronics modules. The PMT signals from the MT are digitized by the FEE. A coincidence and pattern register module handles the signals from every MT FEE according to a multiplicity trigger condition. The output of the MT is a "hit pattern", showing which hodoscopes are hit in coincidence. For the ND, each PMT signal is duplicated into three copies by a linear fan-in/fan-out. One copy goes directly into a charge-to-digital converter (QDC) for charge measurement. The other two copies are used to form a multiplicity (N-HIT) trigger and an energy-sum (ESUM) trigger respectively. The logic signals of the N-HIT trigger, the ESUM trigger, and a LED trigger from the ND calibration device are passed to a Master Trigger Board (MTB) for the final trigger decision. The MTB records the trigger time and the corresponding event type (MT or ND) at 10 ns time resolution. Events can be correlated in off-line analyses to search for muon-induced neutrons.

3. Detector performance

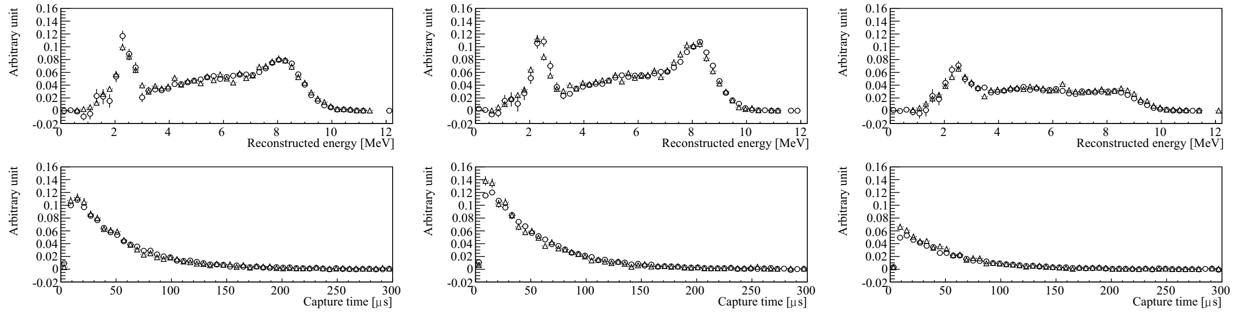
The MT was self-calibrated using the cosmic-ray muons passing through it. The efficiency along each hodoscope was uniform, with an average efficiency of above 95% for most of the hodoscopes. The ND was calibrated with gamma sources ^{137}Cs (0.66 MeV) and ^{60}Co (1.17, 1.33 MeV) as well as a neutron source ^{241}Am-Be. The neutron detection efficiency was broken down into different contributing components as shown in Table 1. The spilling fraction accounts for the gain or loss in neutron candidates that pass through the boundary of the target volume. Its value depends on the choice of neutron kinematic models which requires some further studies. The presented livetime corresponds to the case of single neutron production. It is required to extend the livetime calculation to the cases of different neutron multiplicity. The values for energy cut, time cut, Gd capture ratio and spilling were derived from GEANT4-based [3] simulations. The simulations had been cross-checked with calibration run data to determine the uncertainties. A comparison between the measured and the simulated neutron capture spectra is shown in Fig. 1.

	Efficiency	Uncertainty
Muon track length		1%
Energy cut	52%	2%
Time cut	87%	1%
Gd capture ratio	80%	1%
Spilling (preliminary)	90%	15%
Livetime (preliminary)	95%	1%
Overall (preliminary)	30%	5%

Table 1: Summary of efficiencies and systematic uncertainties in the measurement of muon-induced neutrons.

4. Result and conclusions

Muon-induced neutron candidates were selected using the delayed-coincidence method. A prompt muon signal was selected if the MT bottom layer was triggered and both the top and middle layers had a single hit point respectively. A delayed neutron capture signal was selected if the reconstructed energy was greater than 4.6 MeV and the event occurred within a time window of (10 - 210) μs after the preceding prompt signal. Background contribution was estimated within a time window of (800 - 1600) μs after the preceding prompt signal. The net number of muon-induced neutron candidates, divided by the neutron detection efficiency, the total muon track length and the target mass density, gave the total neutron yield N_n = (9.5±0.8(stat.)±1.6(syst.))× 10^{-5} n / (μ g cm^{-2}). The average energy of the muons that could be selected as the prompt signals was calculated to be 92 GeV. Our preliminary result was com-



North (+250 mm) Center (0 mm) South (-450 mm)

Calibration port

Figure 1: Comparison between the measured (circles) and the simulated (triangles) neutron capture spectra due to the ^{241}Am-Be.

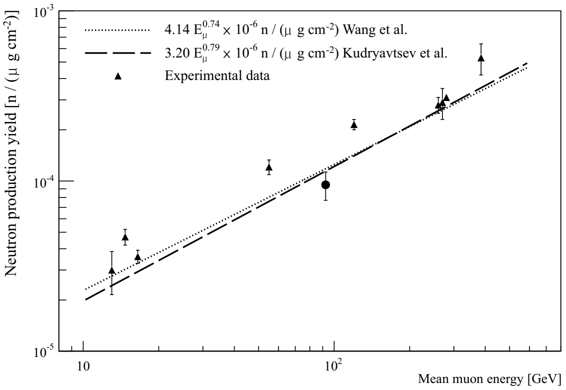


Figure 2: Total neutron production yield as a function of muon energy. The circle represents our preliminary result. The lines show the fitting result of simulation studies [4, 5]. The triangles, from left to right, are other experimental data from respectively, the Stanford Underground Facility [6], a gypsum mine [7], the Palo Verde experiment [8], a salt mine [7], the Artemovsk Scientific Station [9], the KamLAND experiment [10], the LVD in Gran Sasso [11], the Borexino experiment [12], and the LSD in Mont Blanc [13].

pared to previous simulation studies and measurement results in Fig. 2. It was 20% lower than the simulation predictions. Further studies on the neutron spilling effect and the detection livetime for different neutron multiplicity are required to confirm the observation.

5. Acknowledgments

This work is partially supported by grants from the Research Grant Council of Hong Kong Special Administrative Region, China, University Development Fund and Small Project Funding of The University of Hong Kong, and the Office of Nuclear Physics, Office of High Energy Physics, Office of Science, US Department of Energy, as well as the National Science Council in Taiwan and MOE program for Research of Excellence at National Taiwan University and National Chiao-Tung University.

References

[1] P. Antonioli, C. Ghetti, E. V. Korolkova, et al., A three-dimensional code for muon propagation through the rock: MUSIC, Astropart. Phys. 7 (4) (1997) 357 – 368.

[2] S. C. Blyth, et al., An apparatus for studying spallation neutrons in the Aberdeen Tunnel laboratory, Nucl. Instrum. Methods Phys. Res. Sect. A 723 (2013) 67 – 82.

[3] S. Agostinelli, et al., GEANT4–a simulation toolkit, Nucl. Instrum. Methods Phys. Res. Sect. A 506 (3) (2003) 250 – 303.

[4] Y.-F. Wang, V. Balic, G. Gratta, et al., Predicting neutron production from cosmic-ray muons, Phys. Rev. D 64 (1) (2001) 013012.

[5] V. A. Kudryavtsev, N. J. C. Spooner, J. E. McMillan, Simulations of muon-induced neutron flux at large depths underground, Nucl. Instrum. Methods Phys. Res. Sect. A 505 (3) (2003) 688 – 698.

[6] R. Hertenberger, M. Chen, B. L. Dougherty, Muon-induced neutron and pion production in an organic liquid scintillator at a shallow depth, Phys. Rev. C 52 (1995) 3449 – 3459.

[7] L. B. Bezrukov, V. I. Beresnev, O. G. Ryajskaya, et al., Investigation of depth-intensity curve of nuclear events induced by muons, Sov. J. Nucl. Phys. 17 (1973) 51 – 53.

[8] F. Boehm, et al., Neutron production by cosmic-ray muons at shallow depth, Phys. Rev. D62 (2000) 092005.

[9] R. I. Enikeev, G. T. Zatsepin, E. V. Korolkova, et al., Hadrons generated by cosmic-ray muons underground, Sov. J. Nucl. Phys. 46 (1987) 883 – 889.

[10] S. Abe, et al., Production of radioactive isotopes through cosmic muon spallation in KamLAND, Phys. Rev. C 81 (2010) 025807.

[11] R. Persiani, M. Garbini, G. Sartorelli, M. Selvi, Measurement of the muon-induced neutron yield in liquid scintillator and iron at LNGS with the LVD experiment, poster at the Workshop in Low Radioactivity Techniques 2013.

[12] G. Bellini, et al., Cosmogenic backgrounds in Borexino at 3800 m water-equivalent depth, J. Cosmol. Astropart. Phys. 08 (2013) 49.

[13] M. Aglietta, et al., Neutron flux generated by cosmic-ray mouns at 5200 hg/cm^2 s.r. underground. Depth-neutron intensity curve, Il Nuovo Cimento C 12 (1989) 467 – 477.