Neutron background in the Boulby Underground Laboratory

Vitaly A. Kudryavtsev for UKDMC, ZEPLIN-II and ILIAS
Department of Physics and Astronomy, University of Sheffield, Sheffield S3 7RH, UK
E-mail: v.kudryavtsev@sheffield.ac.uk

Abstract. The neutron background in the Boulby Underground Laboratory is reviewed. Measurements of the neutron flux from the rock have been carried out with a small liquid scintillator cell. The neutron flux from rock has been measured as $(1.72 \pm 0.61 \text{ (stat.)} \pm 0.38 \text{ (syst.)}) \times 10^{-6} \text{ cm}^{-2} \text{ s}^{-1}$ above 0.5 MeV. The simulations based on the measurements of the uranium and thorium concentrations in rock predict the flux of $1.21 \times 10^{-6} \text{ cm}^{-2} \text{ s}^{-1}$ above 0.5 MeV, in agreement with the measurements. Muon-induced neutron flux is measured with the large liquid scintillator, also served as an active veto system in the ZEPLIN-II experiment. The rate of gammas depositing more than $\approx 0.7 \text{ MeV}$, from neutron capture was found to be $0.096 \pm 0.003 \text{ (stat.) events/} \mu\text{m} \text{ in 20-190} \mu\text{s time window after the muon signal, about half of the rate predicted by GEANT4 models. This result is preliminary and more detailed simulations are in progress.}

1. Introduction
Neutron background can limit the detector sensitivity to rare event searches, such as dark matter WIMPs, double-beta decay, low and intermediate energy neutrinos (solar, reactors, geo-, atmospheric etc.) and proton decay. Neutrons from radioactivity are originated in spontaneous fission (of $^{238}\text{U}$ mainly) and $(\alpha,n)$ reactions on low and intermediate $Z$ isotopes ($Z<30$). Their energies are limited to about 10 MeV. Neutrons from cosmic-ray muons have spectra extended to GeV energies. Although the flux of muon-induced neutrons deep underground is far below that from radioactivity, they are more penetrating and can be responsible for a significant background component. They can travel far from the muon track or their point of origin, reaching detectors from large distances and reducing the efficiency of an anticoincidence system. Any high-$A$ material, usually used as a shielding against gammas, is also a good target for neutron production by muons or their secondaries.

In this paper we review the measurements and simulations of the neutron flux at the Boulby Underground Laboratory. The Laboratory is located in a salt and potash mine in North Yorkshire (UK) at a depth of 1070 metres. Several dark matter experiments have been and are carried out in the laboratory: NaI, NAIAD, ZEPLIN-I, ZEPLIN-II, ZEPLIN-III, DRIFT-I and DRIFT-II. To investigate the background due to the radioactivity and cosmic rays at Boulby and provide an input for the calculation of detector sensitivity to rare events, several measurements of background have been performed, partly supported by ILIAS (Integrated Large Infrastructures for Astroparticle Science) – an I3 European project, funded within FP6 programme.

One of the early works was the measurement of gamma-ray flux at Boulby using the high purity Ge detector exposed to the gamma radiation from rock (Smith et al., 2005). Measured
intensities of various gamma-ray lines were compared to the expectations based on the simulation of the gamma transport and detector efficiencies, and converted into concentrations of uranium, thorium and potassium in rock: U – 67 ± 6 ppb, Th – 127 ± 10 ppb, K – 1130 ± 200 ppm.

2. Neutron background from rock
Neutron background from salt rock in the Boulby was measured using small (6.5 litres) cylindrical liquid scintillator cell (Tziaferi et al, 2007). Liquid scintillator was loaded with Gd to enhance neutron capture. The detector was surrounded by lead and copper which acted as passive shielding against gammas from rock. The volume of the detector was viewed from both ends by the two photomultiplier tubes (PMTs) through quartz windows.

The data acquisition system has been triggered by the delayed coincidences between the two pulses within 195 µs. In case of a neutron event, the first pulse was expected to be from proton recoils whereas the delayed pulses was due to gamma-ray(s) from neutron capture on protons, Gd and other isotopes. The main background in the experiment was caused by random coincidences between two pulses from the gamma-ray background originated in detector components.

Detector was calibrated with a number of gamma-ray sources and 252Cf neutron source. The experiment was running for 4 months collecting about two hundred neutrons with a rate of about 1.5 neutrons per day (for a finite time window of 195 µs between the 1st and the 2nd pulses in an event). Neutrons were discriminated statistically from a much larger background of random coincidences between gamma-ray induced signals. Time delay distribution of two neutron-induced pulses in events (proton recoils and gammas from neutron capture) followed the exponential law whereas that of random coincidences was flat. Measured time delay distribution was a composition of the exponential and a flat background (Tziaferi et al, 2007).

Extensive simulations of neutrons produced in the 252Cf source and in rock, their transport and detection were carried out, allowing the conversion of the measured neutron rate in the laboratory: \((1.72 \pm 0.61 \text{(stat.)} \pm 0.38 \text{(syst.)}) \times 10^{-6} \text{ cm}^{-2} \text{ s}^{-1}\) above 0.5 MeV (Tziaferi et al, 2007). This agrees well with the predicted neutron flux of \(1.21 \times 10^{-6} \text{ cm}^{-2} \text{ s}^{-1}\) above 0.5 MeV based on the U/Th concentrations in rock estimated from the measurements of the gamma-ray intensities with Ge detector (Smith et al 2005).

3. Muon-induced neutrons
The measurements of muon-induced neutrons were carried out at the Boulby Underground Laboratory using the active veto system of the dark matter detector ZEPLIN-II. The veto is filled with about 0.73 tonnes of liquid scintillator and is viewed from above by ten 20 cm ETL hemispherical PMTs. The veto system (together with ZEPLIN-II) is surrounded by a ‘castle’ made of lead and designed to protect ZEPLIN-II from gamma-rays from rock. The total weight of lead is about 50 metric tonnes making it an excellent target for neutron production. Pure and Gd-impregnated wax and polypropylene were put on top of the veto detector under the castle roof. Part of the vessel of the veto detector was painted with Gd-loaded paint. All materials of and around the veto and their exact locations within the underground laboratory were put into the simulation code based on GEANT4 toolkit (Agostinelli et al, 2003). The principle of neutron detection was based on the delayed coincidences between the first, high-energy, pulse from a muon or muon-induced cascade and the delayed second, low-energy, pulse from neutron capture gamma(s). The electronics and data acquisition system were designed for this purpose.

Energy calibrations with 60Co gamma-ray source were performed at the beginning of the data run and at the end of the experiment. Neutron calibration with an Am-Be source of 0.1 GBq intensity has been carried out before the beginning of the data run. Figure 1 shows measured and simulated time delay distributions between the pulses in the events relative to the trigger pulse in the neutron calibration run. Simulation of this run was carried out using the GEANT4 toolkit taking into account the geometry of the setup, position of the source, neutron interactions and
capture. Two free parameters were used to tune the simulated distribution to match the data: (i) the normalisation constant; (ii) the flat component due to random coincidences between either proton recoil pulses from two neutrons or gamma-ray pulses from two neutron captures occurring because of the high event rate. The good agreement between measured and simulated time delay distributions proves the reliability of the GEANT4 toolkit in modeling neutron interactions and capture at MeV and sub-MeV energies. The data on muon-induced neutrons were collected from August 2006 until April 2007. The live time of the experiment was 204.8 days. 10832 muons depositing more than 25 MeV in the detector were selected for data analysis. The rate of muons was 52.9 ± 0.5 per day in agreement with previous measurements (Robinson et al 2003) giving the value of the total muon flux at Boulby as (3.92 ± 0.04 (stat.)±0.07 (syst.))×10^{-8} \text{ cm}^{-2} \text{ s}^{-1} through a sphere with unit cross-sectional area.

The time delay distribution of pulses in the events relative to trigger (muon) pulses is presented in Figure 2 together with the fit (solid curve) to a combination of an exponential and a flat background. The number of delayed pulses above ≈ 0.7 MeV in 20-190 µs time window after the muon signal was found to be 1239 ± 35 with an expected background, extrapolated from the rate of delayed events after gamma-induced triggers, of 201 ± 10. Background subtraction gives the rate of neutron events as as 0.096 ± 0.003 (stat.) neutrons/muon (for 20-190 µs neutron capture time window after the muon trigger). Preliminary results from GEANT4 simulations (Lindote et al 2007) show very similar time delay distribution of neutron capture events but predict the rate of 0.186 ± 0.003 (stat.)±0.020 (syst.) neutrons/muon in the time window of 20-190 µs after the muon signal, about twice the measured rate of muon-induced neutrons.

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