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Low energy neutron background in deep underground laboratories

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ABSTRACT

The natural neutron background influences the maximum achievable sensitivity in most deep underground nuclear, astroparticle and double-beta decay physics experiments. Reliable neutron flux numbers are an important ingredient in the design of the shielding of new large-scale experiments as well as in the analysis of experimental data. Using a portable setup of ^{3}He counters we measured the thermal neutron flux at the Kimballton Underground Research Facility, the Soudan Underground Laboratory, on the 4100 ft and the 4850 ft levels of the Sanford Underground Research Facility, at the Waste Isolation Pilot Plant and at the Gran Sasso National Laboratory. Absolute neutron fluxes at these laboratories are presented.

1. Introduction

The major challenge of many modern physics experiments is the measurement of very small event rates (down to a few events per year, e.g. [1]). Locating the equipment deep underground is a first step towards achieving this goal, since the rock overburden shields the experiment from cosmic rays. Generally the muon flux and the secondary gamma- and neutron fluxes are attenuated by a few orders of magnitude compared to the surface [2].

A wide range of deep underground experiments are sensitive to background neutrons: in underground nuclear astrophysics stellar neutron sources need to be measured down to very low cross-sections. Elastic scattering of neutrons can mimic signals expected from WIMP interactions. Neutrinoless $\beta\beta$ decay searches can be influenced by γ rays emitted after neutron inelastic scattering or capture and also by the decay of unstable nuclei produced through neutron capture. Therefore, the neutron background needs to be understood and sufficient shielding needs to be implemented to limit its impact on the experimental sensitivity.

The underground neutron flux is mostly due to spontaneous fission of ^{238}U in the cavity walls, (α,n) reactions induced by α-particles from the natural radioactivity of the underground environment and from the activity of the experimental setup itself [3–11]. The cosmic-ray induced neutron flux is two to three orders of magnitude lower than the radiogenic component [12]. Usually the laboratory neutron flux is simulated based on the composition of the rock and the concentration of radioactive isotopes [13,11]. However, these simulations carry a large degree of uncertainty and should be tested against measurements, if available.

Geological composition of the rock and the varying contents of uranium and thorium in the underground environment as well as differences in the water content of the surrounding rocks cause variations in the background between underground laboratories. In addition it has been found that even local differences in the composition of the rock can lead to background levels that vary by an order of magnitude between locations in the same laboratory (e.g., Halls A and C in Gran Sasso) [9].

Some data on measured neutron backgrounds are available, but a direct comparison is made difficult by the variety of detection setups used and differences in the covered neutron energy range. In this work we present measurements of the thermal neutron fluxes at various underground locations using a portable setup of ^{3}He detectors. Measurements were done at the Waste Isolation Pilot Plant (WIPP) near Carlsbad, New Mexico; the Soudan Underground Laboratory in Minnesota; the Kimballton Underground Research Facility (KURF) in West Virginia; the Sanford Underground Research Facility (SURF) located in the Black Hills in South Dakota and the Laboratori Nazionali del Gran Sasso (LNGS) in Italy.

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2. Site background parameters

The measurements presented here cover very different background environments: WIPP is located in a salt formation, Soudan is a former iron mine, KURF is situated in an active limestone mine, SURF is located in a retired gold mine; the Gran Sasso laboratory is in a limestone formation. The properties of each site relevant to the background conditions and measured values of the muon flux are listed in Table 1.

Although WIPP is at a relatively shallow depth, the radiogenic radioactivity is very low due to the low-activity salt environment. U and Th concentrations displayed in the table were measured by inductively coupled plasma mass spectrometry on salt samples. The low and high values from the range given in Table 1 were determined on a clear and a rocky sample showing a slight coloration, respectively.

The thermal neutron flux at WIPP has been reported previously as $(1.3\pm0.3)\cdot10^{-7}$ cm^{-2} s^{-1} [4]. At LNGS various measurements have been done; none of them agree with each other, possibly due to a variation in the background depending on the location in the laboratory or due to unknown systematic uncertainties. The reported values are: $(2.05\pm0.06)\cdot10^{-6}$ cm^{-2} s^{-1} [18], $(1.08\pm0.02)\cdot10^{-6}$ cm^{-2} s^{-1} [19], and $(5.4\pm1.3)\cdot10^{-7}$ cm^{-2} s^{-1} [20]. Only higher-energy neutron data are available at the other sites.

3. Experimental setup

3.1. Neutron detection with ^{3}He proportional counters

The ^{3}He detectors used in our experiments consist of an Al tube that is filled with ^{3}He (and a small amount of CO_2 as quench gas) under a pressure of 10 bar. A wire at a +1400 V potential runs through the center of the Al cylinder. ^{3}He has a very high cross-section for capturing thermal neutrons through the reaction ^{3}He(n,p)^{3}H (σ=5330 barn, Q=764 keV [21]). After a neutron has been captured the proton (p) and the triton (T) deposit their kinetic energy ($E_p = 573$ keV, $E_T = 191$ keV) in the ^{3}He gas. In case both reaction products are fully stopped in the sensitive volume a pulse with a height proportional to 764 keV is generated. Due to the finite volume of the detectors there is a chance that one or both nuclei hit the Al cylinder and only deposit a fraction of their energy in the detector (wall effect). This gives lead to the characteristic pulse height spectrum of a ^{3}He proportional counter. Fig. 1 shows a typical spectrum taken with one of the ^{3}He counters used in this work, with the two wall-effect peaks around channels 200 and 550. γ-Rays and electronic noise generate counts below channel 180 and can be clearly distinguished from the neutron signals. The displayed spectrum was acquired in the Nuclear Science Laboratory of the University of Notre Dame and shows the typical response of the counters to a reasonably high flux of thermal neutrons.

3.2. Intrinsic background

The counts visible at energies above the neutron peak are due to the internal radioactivity of the counters themselves. α-Particles from the decay of the uranium and thorium present in the detector walls generate background signals covering the area of the thermal neutron peak (at 764 keV and below) and extending up to 9 MeV [5]. An additional background component is due to microdischarges near the central wire of the detectors [22]. The count rate in this range corresponds to the sensitivity limit for low-level neutron detection. The combined effect can be seen in Fig. 2, where the amplification of the detector signal has been lowered to cover a wider energy range. The thermal neutron full-energy peak lies at channel 200 with the internal detector background extending beyond it. This background is usually not of concern on the earth's surface but at the very low neutron background conditions in an underground environment it becomes a major background component that can be stronger than the actual neutron signals. The average background rate integrated over the region of the neutron peak is about 10^{-3} s^{-1} for the counters used here. Using the ratio of alphas in the neutron signal range to total alpha particles from the simulation (see below) and the area of the counter one obtains a total alpha activity of the counters of about $6\cdot10^{-5}$ cm^{-2} s^{-1}. This value is in very good agreement with measurements of similar ^{3}He counters and an assay of commercially available aluminum [22].

To model the α-induced background Geant4 simulations [23] were performed with α-particles being emitted from inside the aluminum container of the ^{3}He counter. Contributions from decays in the anode material are negligible due to its much smaller surface area. Secular equilibrium in both the thorium and uranium chains was assumed and the particle energies were randomly chosen from the transition energies in the chains. The ^{3}He counters are at least 25 years old, justifying the assumption of

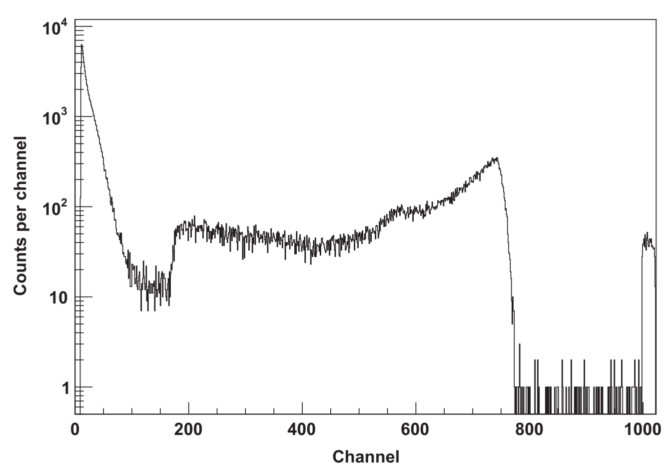

Fig. 1. Typical spectrum from a ^{3}He counter (1 channel ≈ 1 keV). A neutron generates a signal between channels ~200 and 800. Signals above and below this region are due to alpha particles and electronic noise, respectively. Counts above channel 1000 are from ADC overflow.

Table 1
Properties of the visited underground sites. SURF values are stated for the 4850 ft level. See text for details on the WIPP U and Th concentrations.

Location	WIPP [14]	Soudan [12,15]	KURF [16]	SURF [11,12]	LNGS [9,17]
Environment	Salt	“Ely Greenstone”	Limestone	Poorman foundation	Limestone
Depth (m)	655	780	500	1500	1400
Equivalent depth (m.w.e.)	2000	2090	1450	4300	3800
Muon flux (10^{-7} s^{-1} cm^{-2})	4.77 ± 0.09	2.0 ± 0.2	≈20	0.044 ± 0.001	0.32 ± 0.01
^{238}U (ppm)	$(0.5-1.5)\cdot10^{-3}$	0.2		3.4	6.8 (Hall A)
^{232}Th (ppm)	$(1.0-1.9)\cdot10^{-3}$	0.9		7.1	2.2 (Hall A)