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Measurement of the fast neutron background at the China Jinping Underground Laboratory

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A R T I C L E I N F O

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A B S T R A C T

We report on the measurements of the fluxes and spectra of the environmental fast neutron background at the China Jinping Underground Laboratory (CJPL) with a rock overburden of about 6700 meters water equivalent, using a liquid scintillator detector doped with 0.5% gadolinium. The signature of a prompt nuclear recoil followed by a delayed high energy γ-ray cascade is used to identify neutron events. The large energy deposition of the delayed γ-rays from the (n,γ) reaction on gadolinium, together with the excellent n-γ discrimination capability provides a powerful background suppression which allows the measurement of a low intensity neutron flux. The neutron flux of $(1.51 \pm 0.03\,(stat.) \pm 0.10\,(syst.)) \times 10^{-7}$ cm^{-2} s^{-1} in the energy range of 1–10 MeV in the Hall A of CJPL was measured based on 356 days of data. In the same energy region, measurement with the same detector placed in a room surrounding with one meter thick polyethylene shielding gives a significantly lower flux of $(4.9 \pm 0.9\,(stat.) \pm 0.5\,(syst.)) \times 10^{-9}$ cm^{-2} s^{-1} with 174 days of data. This represents a measurement of the lowest environmental fast neutron background among the underground laboratories in the world, prior to additional experiment-specific attenuation. Additionally, the fast neutron spectra both in the Hall A and the polyethylene room were reconstructed with the help of GEANT4 simulations.

1. Introduction

Deep underground sites provide a unique opportunity to explore rare-event phenomena including the direct searches for dark matter [1], proton decay [2], neutrinoless double beta decay ($0\nu\beta\beta$) [3], neutrino oscillation experiments [4], and so on. A comprehensive range of underground experiments are sensitive to neutrons and their induced background.

In addition to the highly suppressed cosmic-ray induced neutrons, the majority of neutrons at the deep underground site is produced in the rock through the spontaneous fission of ^{238}U and the (α, n) reactions of light nuclei bombarded by the α-particles emitted in the U/Th decay chains. An additional neutron background is brought by the infrastructure and the experimental setup of laboratories. Nuclear recoils and other interactions due to the environmental neutron background can restrict experimental sensitivities or bring about false signals in the studies of rare phenomena. Therefore, the understanding of the neutron spectrum and identifying neutron sources are substantial issues for background reduction and guide the design of shielding systems for the next generation of large-scale experiments.

The China Jinping Underground Laboratory (CJPL) [5] with about 2400 m rock overburden (6700 m water equivalent) is the deepest operating underground laboratory, located in Sichuan, China. The cosmic-ray flux at CJPL is measured to be $(2.0 \pm 0.4) \times 10^{-10}$ cm^{-2} s^{-1} [6]. Low background counting facilities are installed and implemented. The environmental gamma radioactivity at CJPL has been studied [7] and the contamination levels of U/Th in the rock at CJPL are demonstrated to be one order of magnitude lower than those at surface due to the carbonate components (96% calcite and <4% micritic limestone). The science program of dark matter experiments at CJPL, in the first phase, includes CDEX (the China Dark matter EXperiment) [8] carried out in a room surrounding with one meter thick polyethylene (PE) shielding, and PandaX (the Particle and Astrophysical Xenon Detector) [9] conducted

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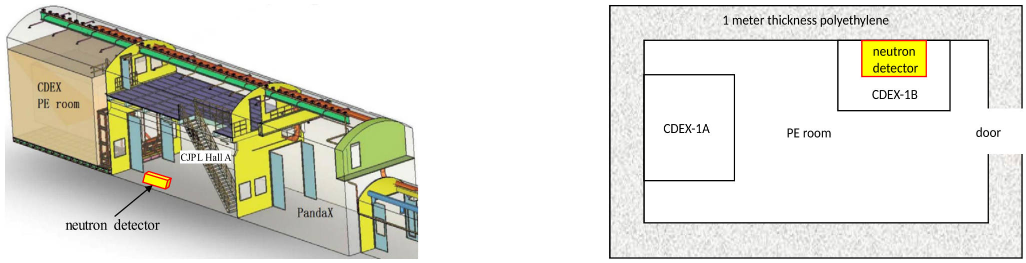

(a) (b)

Fig. 1. (Color online) The structure of the China Jinping Underground Laboratory and the location of the neutron detector. (a) The position of the Hall A and the polyethylene (PE) room; (b) The structure of the PE room.

in the hall. The layout of CJPL with the operated experiments is depicted in Fig. 1.

The thermal neutron flux was measured with a gaseous ^{3}He proportional ionization chamber in the Hall A of CJPL, giving a flux of $(4.00 \pm 0.08) \times 10^{-6}$ cm^{-2} s^{-1} [10]. The same measurement was performed inside the PE room. A preliminary thermal neutron flux of $(3.18 \pm 0.97) \times 10^{-8}$ cm^{-2} s^{-1} was derived [11]. A Bonner multi-sphere neutron spectrometer has been used to investigate the neutron background below 20 MeV in the Hall A and gives a fast neutron flux of $(3.63 \pm 2.77) \times 10^{-6}$ cm^{-2} s^{-1} [12]. Due to the limited detector sensitivity and resolution, the fast neutron background inside the PE room has not been reported.

This work presents the background measurement of fast neutron fluxes and spectra both in the Hall A and inside the PE room at CJPL, using a 28 l liquid scintillator detector doped with 0.5% gadolinium. The location of the neutron detector at CJPL is also shown in Fig. 1. The combination of prompt and delayed signatures offers a powerful background suppression against the alpha-contamination from the liquid scintillator. The detector configuration and the data acquisition system is described in Section 2. The energy calibration, the energy resolution of the detector and the efficiency of signal selection are derived by comparison with simulations and are presented in Section 3. Following the data analysis in Section 4, the results and the conclusions are reported in the last two sections.

2. Experimental setup

The (n, γ) reaction on gadolinium in the liquid scintillator allows the discrimination of neutron events from the background with the prompt-delayed time coincidence method. This method is based on the time delay between the prompt nuclear recoil signal and the γ-signal produced by the capture of thermalized neutrons. Nuclear recoils due to the multiple elastic scatterings of fast neutrons constitute the prompt signals. After thermalization, the neutron diffuses in the detector for a few microseconds (~7 μs) before it is captured on the gadolinium and soon after, emits γ-rays giving rise to the delayed signal. This delayed coincident signature is different from the decay sequences of the β-α or the α-α cascade decays from U and Th series. Therefore, the gadolinium doped liquid scintillator (Gd-LS) neutron detector is insensitive to its intrinsic U/Th contaminants; their signals can be filtered out by using pulse shape discrimination (PSD) method.

The Gd-LS detector has been used for many years by several experimental groups for measurements of the neutron background at underground laboratories, such as Boulby [13] and Aberdeen Tunnel [14], or for neutrino experiments, such as Double Chooz [15], RENO [16] and Daya Bay [17] measuring the neutrino mixing angle θ_{13}. The employed Gd-LS in this work is of the type EJ-335 produced by Eljen Technology Company and is an organic scintillator loaded with 0.5% gadolinium by weight [18].

The Gd-LS is filled in a cylindrical container with 30 cm diameter and 40 cm length made of quartz glass that is wrapped with PTFE sheet

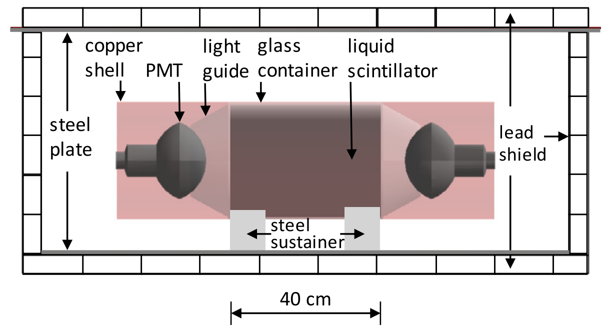

Fig. 2. (Color online) The schematic diagram of the liquid scintillator detector. The liquid scintillator is EJ-335. The container for EJ-335 is a quartz glass cylinder with 30 cm diameter and 40 cm length. The copper shell is used for supporting and shielding. The detector is located in a lead castle with 5 cm thick walls. The top steel plate is used to hold the roof of the lead castle. The bottom one is used to support the detector with two steel sustainers.

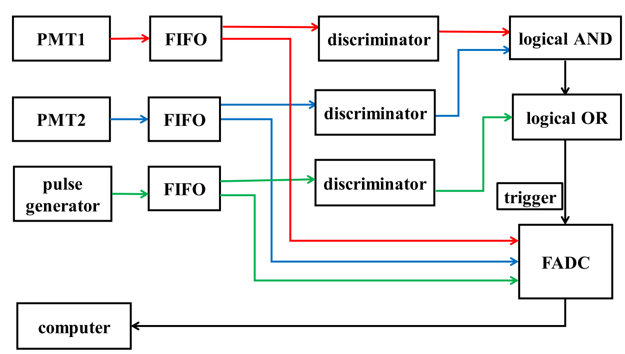

Fig. 3. The flow scheme of the data acquisition (DAQ) system. The duplicate signals are generated by linear fan-in/fan-out (FIFO) modules from the two PMTs, as well as the periodic pulse generator. One is fed into the discriminator, and the other is read out by a flash analog-to-digital converter (FADC). The DAQ triggers are provided by the coincident signals of the two PMTs and by the periodic signals from the pulse generator.

for high diffuse reflection. The two flat surfaces of the glass vessel are optically connected by light guides to two 8 in. photomultiplier tubes (PMTs) from Hamamatsu (type R5912-02). The container is supported by a cylindrical oxygen-free copper shell with 3 mm thickness, placed in a lead castle with the dimensions of $150 \times 60 \times 70$ cm^3 and the thickness of 5 cm depicted in Fig. 2. A hole was made available to insert radioactive sources into the lead castle to perform calibrations.

The flow scheme for data acquisition (DAQ) system is illustrated in Fig. 3. The signals are duplicated by linear fan-in/fan-out (FIFO) modules from the two PMTs, as well as from a periodic pulse generator with high accuracy which allows the measurement of live time and