Neutron background measurements with a hybrid neutron detector at the Kuo-Sheng Reactor Neutrino Laboratory

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We report in situ neutron background measurements at the Kuo-Sheng Reactor Neutrino Laboratory (KSNL) by a hybrid neutron detector (HND) with a data size of 33.8 days under identical shielding configurations as during the neutrino physics data taking. The HND consists of BC-501A liquid and BC-702 phosphor powder scintillation neutron detectors, which is sensitive to both fast and thermal neutrons, respectively. Neutron-induced events for the two channels are identified and differentiated by pulse shape analysis, such that background of both are simultaneously measured. The fast neutron fluxes are derived by an iterative unfolding algorithm. Neutron induced background in the germanium detector under the same fluxes, both due to cosmic-rays and ambient radioactivity, are derived and compared with the measurements. The results are valuable to background understanding of the neutrino data at the KSNL. In particular, neutron-induced background events due to ambient radioactivity as well as from reactor operation are negligible compared to intrinsic cosmogenic activity and ambient γ-activity. The detector concept and analysis procedures are applicable to neutron background characterization in similar rare-event experiments.

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I. INTRODUCTION

The TEXONO Collaboration [1] is pursuing experimental investigation of neutrino physics [2–5], as well as weakly interacting massive particle (WIMP) dark matter [6], axions [7] and other physics searches beyond-standard-model (BSM) [8] at the Kuo-Sheng Reactor Neutrino Laboratory (KSNL). Quantitative understanding of neutron-induced background and nature of their sources is crucial to these studies.

We report in this article in situ measurement of thermal ($n_{\text{thermal}}$) and fast ($n_{\text{fast}}$) neutron background at KSNL under identical shielding configurations as during the various physics data taking. A custom-built hybrid neutron detector (HND), whose characteristics and performances were reported earlier in our previous publication [9], are used for these measurements.

The paper is structured as follows. Highlights of the laboratory KSNL are presented in Section II. The unique merits of the HND, its features and the associated pulse shape discrimination (PSD) techniques are summarized in Section III. Data taking at the KSNL is discussed in Section IV. Derivation of the internal contamination of HND are discussed in Section V. Results on the measured neutron-induced background in HND, the calculated neutron fluxes as well as the projected background to high-purity germanium detectors (HPGe) at the same location are presented in Section VI.

II. THE KUO-SHENG REACTOR NEUTRINO LABORATORY

The Reactor Neutrino Facility KSNL [1-3] is located at a distance of 28 m from the core #1 of the Kuo-Sheng Nuclear Power Station at the northern shore of Taiwan. The site is at the ground floor of the reactor building at a depth of 10 m below ground level, with an overburden of about 30 meter-water-equivalence (mwe). The nominal thermal power output is 2.9 GW supplying a $\bar{\nu}_e$-flux of about $6.4 \times 10^{12}$ cm$^{-2}$s$^{-1}$. A schematic view is depicted in Figure I.

A multi-purpose “inner target” detector volume of 100 cm$\times$80 cm$\times$75 cm is enclosed by 4π passive shielding materials which have a total weight of about 50 tons. The shielding provides attenuation to the ambient neutron and gamma background, and consists of, from inside out, 5 cm of OFHC copper, 25 cm of boron-loaded polyethylene, 5 cm of steel, 15 cm of lead, and cosmic-
FIG. 1: (a) Schematic side view, not drawn to scale, of the Kuo-Sheng Nuclear Power Station Reactor Building, indicating the experimental site. The reactor core-detector distance is about 28 m. (b) Schematic layout of the general purpose inner target volume, passive shielding and cosmic-ray veto scintillator panels. The schematic layout of the shielding structure is shown in Figure 1b. Different detectors are placed in the inner volume for the different scientific programs.

The primary cosmic-ray hadronic components are greatly attenuated by matter (nuclear interaction length of rock is about 38 cm). Their fluxes at a shallow depth of $\sim 30$ mwe are therefore negligible. The neutron background are mostly due to: (i) cosmic-ray muon-induced interactions \cite{10} and (ii) ambient radioactivity followed by $(\alpha, n)$ processes from the materials in the vicinity of the detectors. The neutron fluxes and their spectra, therefore, depend on the details of the experimental hardware and shielding configurations, in addition to the depth. Neutron background measurements at shallow depth sites have been made \cite{11}. The typical levels for neutrons fluxes above keV are $\mathcal{O}(10^{-4}, 10^{-3}, 10^{-5})$ cm$^{-2}$s$^{-1}$ for the unshielded, lead-shielded and moderator-shielded configurations, respectively.

The KSNL shielding structures as shown in Figure 1b can attenuate thermal and 1 MeV neutrons by factors of $\ll 10^{-6}$ and $\sim 10^{-2}$, respectively, according to the simulation studies. Therefore the ambient unshielded neutron fluxes are not of relevance to the physics background. Their direct measurements would be challenging due to the dominating $\gamma$-background. The background neutrons are cosmic-ray induced or originated from radioactivity of hardware components in vicinity of the detectors. Measurements of these are the themes of this work, and will be discussed in details in the subsequent Sections.

III. HYBRID NEUTRON DETECTOR

The design, characteristics and performance of the HND adopted in this measurement were described in detail in our previous publication \cite{9}. The HND is a novel detector concept initiated by this work and was custom-built for this particular purpose of in situ neutron background measurements at a localized volume at KSNL.

The HND has unique features not provided by conventional neutron detectors. It can perform simultaneous measurement of both thermal and fast neutron fluxes, in which the neutron induced events are identified by PSD, thereby greatly suppressing the much larger $\gamma$-rays background. The compact dimensions allows sampling of the fluxes in a relatively localized volume and under exact shielding configurations — matching well with the size ($\mathcal{O}(100)$ cm$^3$) of HPGe detectors. Commonly-used detectors like the Bonner multi-spheres array spectrometer \cite{12} would occupy too much volume to match the space constraints. Undoped liquid scintillators \cite{13} are sensitive to fast neutrons but not thermal ones. Doped liquid scintillators are sensitive to both thermal and fast neutrons. Those with signatures $^6\text{Li}(n, \alpha)^3\text{H}$ \cite{14} or $^{10}\text{B}(n, \alpha)^7\text{Li}$ \cite{15} can be made compact. However, the $\alpha$- and proton-recoils that characterize thermal and fast neutrons, respectively, are not distinguishable by PSD. The thermal neutron signatures as low-energy peaks can be easily contaminated by $\gamma$-background. Long-term stability on the performance of the doped scintillators may also pose technical problems. Stability has been achieved in Gd-doped liquid scintillators \cite{16}. The high-energy $(n, \gamma)$ signatures for thermal neutrons are distinctive. They have been used in low-level neutron background measurements at underground laboratories to sensitivities as low as $\mathcal{O}(10^{-9})$ cm$^{-2}$s$^{-1}$. However, capturing the $\gamma$-rays would require a detector volume much larger than that allowed by this application.

The HND is constructed with two different target materials— a Bicron BC-501A liquid scintillator with a 0.113 liter cell volume and a BC-702 scintillator of thickness 0.6 cm enriched with 95% $^6\text{Li}$ as fine ZnS(Ag) phosphor powder — to be read out by a 5.1 cm diameter photomultiplier (PMT) at the same time. A schematic drawing of HND is shown in Figure 2. As depicted in Figure 3 the HND was installed at the same location as the various HPGe inside the well of an NaI(Tl) anti-Compton
detector and kept under the same shielding configurations and data taking conditions. The measured ambient neutron flux is therefore the same as what the HPGe were exposed to in the physics data taking.

Different particles produce different pulse shapes with the HND [9]. The normalized reference pulses of $\alpha$, $n_{\text{fast}}$, $n_{\text{thermal}}$ and $\gamma$ are shown in Figure 4. In Ref. [9], two independent PSD techniques were developed, which are based on the parameter of $t_{\text{PSD}}$, derived from the ratio of partial ($Q_p$) to total ($Q_t$) integration of the pulses, and based on the $B/A$ ratio of individual pulses given as

$$L = A \times \left[ e^{-\theta(t-t_0)} / 226.6 - e^{-\lambda_s(t-t_0)/17.23} \right] + 0.115 \times \left[ e^{-\theta(t-t_0)} / 226.6 - 1 \right],$$

where $t$ is in nanosecond (ns), and $A$ is the only free normalization parameter that remains to be determined [9]. Individual pulses are fitted with the function given in Eq. 2 in order to identify $\gamma$ against neutron events.

For this study, a reference pulse is constructed by the superposition of large number of $\gamma$-ray pulses collected from the $^{60}\text{Co}$ radioactive source. The parameters of decay constants $\theta$, $\lambda_s$, $\lambda_t$ and reference time $t_0$ are obtained from the fitting of the $\gamma$ reference pulse. The pulse shape is then parameterized as,

$$L = A \times \left[ e^{-\theta(t-t_0)/226.6} - e^{-\lambda_s(t-t_0)/17.23} \right] + 0.115 \times \left[ e^{-\theta(t-t_0)/226.6} - 1 \right],$$

where $t$ is in nanosecond (ns), and $A$ is the only free normalization parameter that remains to be determined [9]. Individual pulses are fitted with the function given in Eq. 2 in order to identify $\gamma$ against neutron events.

The $^{241}\text{AmBe}(\alpha,n)$ and $^{60}\text{Co}$ $\gamma-$sources are used as reference for the $t_{\text{PSD}}$ and $B/A$ PSD techniques, respectively. Adopting the PSD parameters given in Eq. 1 and Eq. 2, three spectral bands corresponding to $\gamma$, fast and slow neutron components of the events can be observed, as depicted in Figure 5.
FIG. 4: Reference pulse shapes for $\gamma$, $n_{\text{fast}}$, and $n_{\text{thermal}}$-induced events from the HND, from which PSD techniques are devised to differentiate them. Pulse shapes of fast neutrons and alpha-particles are very close and in practice not distinguishable.

IV. DATA TAKING AT KUO-SHENG NEUTRINO LABORATORY

Several HPGe-based measurements [2, 4–8] have been carried out at KSNL. The external dimensions of the HND were selected to resemble those of HPGe. Data were taken at KSNL with the HND placed at the same location as the HPGe [1] under identical active and passive shielding configurations, as depicted in Figure 3. The plastic scintillator panels function as cosmic-ray veto (CR) while the well-shaped NaI(Tl) serves as an anti-Compton (AC) veto detector, and in its cavity the HND (HPGe in early experiments) was placed. The HND+NaI(Tl) detectors were further shielded by oxygen-free high-conductivity (OFHC) copper and placed inside a sealed volume with nitrogen gas flow as a purge of the radioactive radon gas. The setup was installed inside a 50 ton shielding structure [1] consisting of, from inside out, OFHC copper, boron-loaded polyethylene, lead and CR panels, for suppression of ambient $\gamma$ and neutron background, and for tagging cosmic-ray induced events.

The schematic block diagram for the data acquisition (DAQ) system is given in Figure 6. The HND signals higher than the discriminator threshold provides the triggers. Signals from other detector components were recorded to be used for the suppression of AC and CR events in subsequent offline analysis. The HND signals were processed by two fast timing amplifiers [17] at different gains and recorded by 8-bit flash-analog-to-digital converters [18] at 1 GHz sampling rate. Data taking period lasted more than a month and a total of 33.8 live-time days of data were collected for subsequent analysis.

The goal of offline analysis is to categorize the events and determine their respective energy spectra. After standard filtering of events due to electronic noise and other spurious non-physical triggers, the physical events are identified as $\gamma$, $n_{\text{fast}}$, $n_{\text{thermal}}$ from the reference pulse shape information as in Figure 5. The origins of these events are derived from the AC and CR detectors according to four categories: $\text{CR}^+ \otimes \text{AC}^\pm$ where $\pm$ denotes coincidence (anti-coincidence) of the CR or AC with HND. In particular, the $\text{CR}^+ \otimes \text{AC}^-$ tag selects CR neutron-induced events, the $\text{CR}^- \otimes \text{AC}^+$ tag is rich in ambient $\gamma$-induced AC events, while $\text{CR}^- \otimes \text{AC}^-$ is the condition for selecting neutrino- or WIMP-induced candidate events uncorrelated with both CR and AC systems.
V. INTERNAL CONTAMINATION OF NEUTRON DETECTOR

The measurement of intrinsic radiopurity of the HND is essential for determining the ambient neutron background, especially those in CR− ⊗ AC−. Nuclear α-decays from the 238U and 232Th series can mimic neutron-induced nuclear recoil signatures, and hence their contributions must be determined.

The PSD characteristics of α-events as well as the unique time correlations of two decay sequences (DS) provide powerful means to measure contaminations of the 232Th and 238U series, from which the α-background can be evaluated, assuming secular equilibrium.

The related DS are [19]:

| Series | 232Th | 238U |
|---|---|---|
| Signatures | β-α | α-α |
| Decays | 212Bi → 212Po 222Rn → 218Po | 208Pb → 214Pb |
| χ²/n.d.f | 4.7/16 | 9.0/17 |
| Half-Life | Nominal 299 ns 3.10 min | Measured 302 ± 27 ns 3.14 ± 0.39 min |
| Counts | 366.20 ± 26.94 292.50 ± 15.43 |
| Radioactivity | (mBq/kg) 0.140 ± 0.010 0.110 ± 0.006 |
| Contaminations | ×10⁻¹¹ (g/g) 2.21 ± 0.16 0.89 ± 0.048 |

DS₁: Within the 232Th series, there is 64% branching ratio for 212Bi to decay via a β-α cascade –

\[
212\text{Bi} \rightarrow 212\text{Po} + \nu_e + e^- + \gamma '
\]

\[Q = 2.25\text{ MeV} ; \tau_{1/2} = 60.6 \text{ min}\]

\[212\text{Po} \rightarrow 208\text{Pb} + \alpha (Q = 8.95\text{ MeV} ; \tau_{1/2} = 0.30 \mu s)\]

DS₂: Within the 238U series, there is α-α cascade from 222Rn –

\[222\text{Rn} \rightarrow 218\text{Po} + \alpha (Q = 5.59\text{ MeV} ; \tau_{1/2} = 3.82 \text{ d})\]

\[218\text{Po} \rightarrow 214\text{Pb} + \alpha (Q = 6.12\text{ MeV} ; \tau_{1/2} = 3.10 \text{ min})\]

Typical example of a double pulse event is displayed in Figure 7, interpreted as a β − α cascade based on PSD. A collection of the delayed pulses in similar cascades provide the α reference pulse shape as shown in Figure 4. The \(n_{\text{fast}}/\gamma\) events are distinguishable while \(n_{\text{fast}}/\alpha\) events are not distinguishable in an event-by-event basis since the differences in their pulse shapes are smaller than electronic fluctuations. The α-events of DS₂ are mono-energetic and well-separated in time, and were used to confirm consistency with the resolution and quenching functions adopted in analysis.

The delay-time (\(\Delta t\)) distributions for the correlated-events from DS₁,₂ are shown in Figure 8(a) and Figure 8(b), respectively. Results of best-fit parameters to exponential decay functions are displayed in Table 1.

The measured event rate of the decay sequences of DS₁,₂ can be used for the estimation of contamination levels of their long-lived parent isotopes of 232Th and 238U in the detector. Simulated α energy spectra of 232Th and 238U series, convoluted with detector resolution and quenching effects are depicted in Figure 9.

| Series | 232Th | 238U |
|---|---|---|
| Signature | β-α | α-α |
| Decay | 212Bi → 212Po 222Rn → 218Po | 208Pb → 214Pb |
| χ²/n.d.f | 4.7/16 | 9.0/17 |
| Half-Life | Nominal 299 ns 3.10 min | Measured 302 ± 27 ns 3.14 ± 0.39 min |
| Counts | 366.20 ± 26.94 292.50 ± 15.43 |
| Radioactivity | (mBq/kg) 0.140 ± 0.010 0.110 ± 0.006 |
| Contaminations | ×10⁻¹¹ (g/g) 2.21 ± 0.16 0.89 ± 0.048 |
FIG. 8: Distribution for (a) β-α events from 212Bi→212Po→208Pb in DS1; (b) α-α events from 222Rn→218Po→214Pb in DS2.

The measured half-lives are consistent with nominal values. The measured event rates can be translated to the radioactivity and contamination levels of their long-lived parent isotopes of 232Th and 238U in the detector, assuming secular equilibrium. Simulated α energy spectra of 232Th and 238U parent isotopes convoluted with detector resolution and quenching effects are depicted in Figure 9.

VI. NEUTRON BACKGROUND

A. Thermal neutron background

Thermal neutrons are those with kinetic energy below 1 eV and in thermal equilibrium with the ambient surroundings. Their energy distribution is described by the Maxwell-Boltzmann distribution with a most probable energy of $E_{th} \sim 0.02$ eV, which corresponds to a velocity of $v_{th} \sim 2200$ ms$^{-1}$.

The scintillator BC-702 used for thermal neutron measurements does not provide energy information of the incident neutron. Calculation of the thermal neutron flux is performed assuming Maxwell-Boltzmann distributions.

For a neutron flux $\phi(E)$ with interaction cross-section $\sigma(E)$ in the detector, the count rate in the detector is given by:

$$ R_{th} = N \int \sigma(E) \phi_n(E) dE , $$

where $N$ is the total number of target nuclei in the detector. The thermal neutron captured by $^6$Li in HND

$$ n + ^6Li \rightarrow ^3H + \alpha $$

is inversely proportional to the neutron velocity $v(E)$, such that

$$ \sigma(E) = \sigma_{th} \frac{v_{th}}{v(E)} , $$

where $\sigma_{th} = 940$ b. An isotropic and homogeneous flux distribution can be described by

$$ \phi(E) = v(E) \rho_n(E) , $$

where $\rho_n(E)$ is the neutron number density at energy $E$ in the detector volume. The count rate can therefore be expressed as

$$ R_{th} = N \sigma_{th} v_{th} \langle \rho_n \rangle , $$
FIG. 10: Event selection criteria for (a) cosmic-ray CR⁺, and (b) anti-Compton AC⁻ events, showing most thermal neutrons are with CR⁻ ⊗ AC⁻ tag.

where \( \langle \rho_n \rangle \) is the energy-averaged thermal neutron number density. The average neutron velocity is given by

\[
\langle v \rangle = \frac{\int v(E) \rho_n(E) \, dE}{\int \rho_n(E) \, dE} = \frac{\Phi}{\langle \rho_n \rangle},
\]

where \( \Phi \) is the total flux. Accordingly, the rate becomes

\[
R_{th} = N \, \sigma_{th} \, v_{th} \, \langle v \rangle \, \Phi.
\]

Maxwell-Boltzmann distribution for thermal neutrons gives rise to the relation

\[
\frac{\langle v \rangle}{v_{th}} = \frac{2}{\sqrt{\pi}}.
\]

Accordingly, the total neutron flux is related to the measured count rate as

\[
\Phi_n = \frac{2R_{th}}{N\sigma_{th}\sqrt{\pi}}.
\]

The measured thermal neutron rate at KSNL with HND BC-702 is

\[
R_{th} = (4.15 \pm 0.12) \times 10^{-4} \text{ counts s}^{-1}.
\]

With a total number of \( N = 1.41 \times 10^{22} \) \(^6\)Li atoms in BC-702, the corresponding total thermal neutron flux is

\[
\Phi_n = (3.54 \pm 0.10) \times 10^{-5} \text{ cm}^{-2} \text{ s}^{-1}.
\]

The majority of the thermal neutron events are with CR⁻ ⊗ AC⁻ tag uncorrelated with the other detector systems, as depicted in Figure 10. The time difference between these events with the previous CR⁺ tag is displayed in Figure 11, in which accidental coincidence from random trigger events are superimposed. An excess is observed with a correlation time scale of about 200 \( \mu \)s, indicating that part (20\%) of thermal neutron capture events can be matched to the thermalization of specific cosmic-ray events. The time scale corresponds to that necessary for the cosmic-induced high-energy neutrons to lose their energy, get thermalized and diffuse into the localized BC-702 volume. Similar distribution profiles were measured and compared with simulations with gadolinium-loaded liquid scintillator at a shallow depth [22].
FIG. 12: The sample of CR$^+ \otimes AC^-$ – (a) HND nuclear recoil energy spectrum, (b) unfolded neutron flux with $\pm 1\sigma$ error as shadow area, (c) the comparison of HPGe data and predicted Ge-recoil spectrum from simulations with the measured neutron fluxes. Extrapolated spectra of (b) and (c) at low energy, as fixed by neutron flux models of Figure 17 derived from equilibrium yield of $^{70}$Ge$(n,\gamma)^{71}$Ge, are corrections to the effects due to finite HND threshold of 150 keV$_{ee}$.

FIG. 13: The sample of CR$^+ \otimes AC^+$ – (a) HND nuclear recoil energy spectrum, (b) unfolded neutron flux with $\pm 1\sigma$ error as shadow area, (c) the comparison of HPGe data and predicted Ge-recoil spectrum from simulations with the measured neutron fluxes. Extrapolated spectra of (b) and (c) at low energy, as fixed by neutron flux models of Figure 17 derived from equilibrium yield of $^{70}$Ge$(n,\gamma)^{71}$Ge, are corrections to the effects due to finite HND threshold of 150 keV$_{ee}$.
FIG. 14: The sample of CR$^{-} \otimes$ AC$^{+}$ – (a) HND nuclear recoil energy spectrum, (b) unfolded neutron flux with ±1σ error as shadow area, (c) the comparison of HPGe data and predicted Ge-recoil spectrum from simulations with the measured neutron fluxes.

FIG. 15: The sample of CR$^{-} \otimes$ AC$^{-}$ – (a) energy spectra for HND nuclear recoil-like events, together with the measured α− background from $^{232}$Th and $^{238}$U decay series and the 68% C.L. upper bound of neutron-induced nuclear recoils, from which the upper bounds of (b) unfolded neutron spectrum and (c) predicted Ge-recoil background in HPGe can be derived and compared with measured data.
B. Measured nuclear recoil spectra; Evaluated fast neutron flux; Projected HPGe background

Once the HND spectra are measured, unfolding algorithms as discussed in Ref. [9], followed by a Friedman smoothing algorithm [23], are applied to produce the corresponding fast neutron spectra. The expected nuclear recoil background in HPGe detectors at the same location and shielding configurations are then evaluated with full GEANT simulation [24] and compared with 173.5-kg-days of data taken under identical passive and active shielding configurations with an n-type point-contact germanium detector [25]. Standard quenching function of Ge [25] are used to convert nuclear recoil energy in keV$_{nr}$ into the observable energy in electron-equivalence unit keV$_{ee}$.

Results with CR$^+ \otimes$AC$^-$ samples are displayed in Figure 12, in which (a) is the recoil spectrum from the HND liquid scintillator, (b) is the evaluated neutron spectrum and (c) is the projected Ge recoil spectrum from the same neutron background. The fast neutron spectrum has a threshold at 700 keV$_{nr}$ due to HND response. The threshold effects give rise to a change of slope of the Ge-recoil spectrum at 4 keV$_{ee}$, below which the predicted spectrum is less than the measured one. This excess can be corrected for with an extrapolation to the neutron flux, the procedures and details of which are described in Section VI-C.

The same analysis procedures are applied to the CR$^+ \otimes$AC$^+$ samples, and the results presented in Figure 13 follow the same convention. There exists a finite residual spectrum after the Ge-recoils are accounted for, as depicted in Figure 13c. The residual events are due to Compton scattering of cosmic-ray induced high energy ambient $\gamma$-rays, characterized by a flat spectrum and consistent with simulations. The two peaks corresponds to copper $K_\alpha$ and $K_\beta$ X-ray emission lines produced by the interactions of cosmic-ray muons with the copper support materials in the vicinity of the active Ge crystal.

Similarly, the results of the cosmic-ray anti-coincidence samples with CR$^- \otimes$AC$^+$ and CR$^- \otimes$AC$^-$ tags are displayed in Figure 14 and Figure 15, respectively. It can be seen from Figure 14(c) and Figure 15(c), in both cases that neutron-induced Ge-recoil events, which are unrelated to cosmic-rays only constitute a minor component relative to that due to ambient $\gamma$-radioactivity. The CR$^- \otimes$AC$^-$ events are uncorrelated with CR and AC detectors and represent the physics candidate samples for the studies of neutrino and dark matter. The measured “recoil-like” spectrum can completely be explained by internal $\alpha$-contaminations as discussed in Section V such that only upper bounds for HND and HPGe as well as fast neutron spectra can be derived. The upper limits of these spectra at 68% C.L. are displayed in Figure 15. The peaks in both Figure 14(c) and Figure 15(c) are due to X-rays emissions following electron capture (EC) by the unstable isotopes, which are produced by cosmogenic activation of long-lived isotopes inside the HPGe target.

C. Complete Neutron Spectrum

Combining both the measured thermal and fast neutron fluxes and spectra, and adopting the neutron slowing-down theory [20], which is described by a $1/E$ behavior of the epithermal region in between, the complete neutron spectrum at KSNL can be modeled using information of the in situ measurements of neutron capture rates.

![Diagram](image)

**FIG. 16:** Time variation of characteristic K X-ray lines of (a) $^{71}$Ge and $^{68}$Ge, and (b) $^{68}$Ga. Exponential best-fits are superimposed.

Figure 16(a) and Figure 16(b) show the variations over the whole data taking period (347 days) of the X-ray peaks at 10.37 keV$_{ee}$ and 9.66 keV$_{ee}$, respectively, following EC of $^{71}$Ge+$^{68}$Ge and $^{68}$Ga. These isotopes are primarily produced by neutron capture channels $^{70}$Ge(n,\gamma)$^{71}$Ge followed by EC in $^{71}$Ge(e$^-$,\nu$e$)$^{71}$Ga and $^{70}$Ge(n,3n)$^{80}$Ge followed by $^{68}$Ge(e$^-$,\nu$e$)$^{68}$Ga and $^{68}$Ga(e$^-$,\nu$e$)$^{68}$Zn.
TABLE II: Summary of the in situ measured $^{71}\text{Ge}/^{68}\text{Ge}$ (10.37 keV$_{ee}$) and $^{68}\text{Ga}$ (9.66 keV$_{ee}$) characteristic K X-ray line rates at KSNL — for both transient and in equilibrium components. The measured $^{70}\text{Ge}(n,\gamma)^{71}\text{Ge}$ rates are in excellent agreement with simulation predictions using the neutron flux model of Figure 17 as input. The measured $^{70}\text{Ge}(n,3n)^{68}\text{Ge}$ rates are consistent with nominal values and the equilibrium levels hence the neutron fluxes. It can be seen from Figure 16 that the equilibrium yield of the 9.66 keV$_{ee}$ line and hence in situ production of $^{70}\text{Ge}(n,3n)^{68}\text{Ge}$ are consistent with zero. Accordingly, the equilibrium yield of the 10.37 keV$_{ee}$ line is due exclusively to in situ production of $^{70}\text{Ge}(n,\gamma)^{71}\text{Ge}$. This measured rate is used to fix the normalization of the epithermal neutron component.

| Channel (K X-ray Lines) | Half-Life ($\tau_1$) (day) | Rate (kg$^{-1}$ day$^{-1}$) |
|-------------------------|---------------------------|-----------------------------|
| $^{71}\text{Ge}$ from Transient 10.37 keV$_{ee}$ | 11.43 | 10.63 ± 1.08 | 2.70 ± 0.90 |
| $^{68}\text{Ge}$ from Transient 10.37 keV$_{ee}$ | 270.95 | 275.76 ± 9.01 | 23.9 ± 6.4 |
| $^{68}\text{Ge}$ from Transient 9.66 keV$_{ee}$ | 270.95 | 246.74 ± 46.16 | 2.2 ± 0.6 |
| Equilibrium 9.66 keV$_{ee}$ | | | 0.05 ± 0.29 |
| $=[^{70}\text{Ge}(n,3n)^{68}\text{Ge}]$ | | | < 0.34 (68% C.L.) |
| Equilibrium 10.37 keV$_{ee}$ | | | 12.40 ± 3.70 |
| $=[^{70}\text{Ge}(n,\gamma)^{71}\text{Ge}+^{70}\text{Ge}(n,3n)^{68}\text{Ge}]$ | | | |

Simulated Predictions (kg$^{-1}$ day$^{-1}$)

| $^{70}\text{Ge}(n,\gamma)^{71}\text{Ge}$ |
|-----------------------------|-----------------------------|
| $n_{thermal}$ | 8.05 ± 0.23 |
| $n_{epithermal}$ | 2.18 ± 0.67 |
| $n_{fast}$ | 3.67 ± 1.50 |
| Total | 13.90 ± 1.65 |

FIG. 17: Neutron spectrum model at the target region of KSNL. The total thermal and fast neutron components are based on measurements and analysis reported in this article. The epithermal component is from interpolation. The cut-off at ∼5 MeV is a consequence of the lack of event statistics below $O(10^{-2})$ kg$^{-1}$ keV$^{-1}$ day$^{-1}$ above a few MeV$_{ee}$.

The decreasing intensities with time are consequences of less in situ cosmogenic activation compared to the pre-installation activities. The measured lifetimes are consistent with nominal values and the equilibrium levels displayed in Table III on the other hand, provide information on the in situ neutron capture rates of $^{70}\text{Ge}$, and hence the neutron fluxes. It can be seen from Figure 16 that the equilibrium yield of the 9.66 keV$_{ee}$ line and hence in situ production of $^{70}\text{Ge}(n,3n)^{68}\text{Ge}$ are consistent with zero. Accordingly, the equilibrium yield of the 10.37 keV$_{ee}$ line is due exclusively to in situ production of $^{70}\text{Ge}(n,\gamma)^{71}\text{Ge}$. This measured rate is used to fix the normalization of the epithermal neutron component.

The complete neutron background spectrum at KSNL is displayed in Figure 17. The capture rates of $^{70}\text{Ge}(n,3n)^{68}\text{Ge}$ and $^{70}\text{Ge}(n,\gamma)^{71}\text{Ge}$ due to the thermal, epithermal and fast neutron components evaluated by full GEANT simulations [24] are listed in Table II, the sum of which is in excellent agreement with the measured rates. The consistency is illustrated in the measured CR$^+ \odot$ AC$^-$ HPGe spectra of Figure 18 in which the different components of the Ge K X-ray lines are shown. Their total fluxes under different tags are given in Table III. The high-energy cut-off at ∼5 MeV in Figure 17 is a consequence of the lack of event statistics below $O(10^{-2})$ kg$^{-1}$ keV$^{-1}$ day$^{-1}$ for proton recoils at energy above few MeV$_{ee}$. This, however, would not affect background studies and understanding of the HPGe experiments at KSNL, since the background is dominated by the lower energy background neutron which has much higher intensity.

Once the complete neutron background is modeled, the cut-off effects of the fast neutron spectra around 700 keV in Figure 12(b) and Figure 13(b) due to the HND thresh-
The expected exponential decrease with energy. Once accounted for, the residual cosmic-induced \( \gamma \)-background is flat down to sub-keV, also expected from Compton scattering of high energy \( \gamma \)-rays. The consistencies of these independent measurements serve as non-trivial cross-checks on the validity of neutron flux measurements as well as the experimental approaches and analysis procedures reported in this work.

VII. SUMMARY AND PROSPECTS

We report in this article in situ measurements of neutron-induced background at KSNL with a HND under identical active and passive shielding configurations during the neutrino physics measurements. The different components of neutron fluxes thus derived are summarized in Table III and the neutron spectrum is depicted in Figure [17]. The derived neutron spectrum provides excellent agreement with the cosmic-ray neutron-induced Ge-recoil spectra as shown in Figure [12](c) and Figure [13](c), thereby providing strong support to the validity of the results as well as the experimental approaches and analysis procedures.

It was demonstrated that elastic nuclear recoil events due to cosmic-ray induced high energy neutrons contribute almost exclusively to the CR\(^+\) \( \otimes \) AC\(^-\) channel below 12 keV\(_{ee}\), and are major components of the CR\(^+\) \( \otimes \) AC\(^+\) channel, dominating over \( \gamma \)-induced background below 4 keV\(_{ee}\). On the other hand, contributions of cosmic-uncorrelated neutrons to the background are minor in CR\(^-\) \( \otimes \) AC\(^+\) and unobservable in CR\(^-\) \( \otimes \) AC\(^-\). In particular, the dominant background to the studies of neutrinos, WIMP dark matter and axions with CR\(^-\) \( \otimes \) AC\(^-\) selection at KSNL are ambient \( \gamma \)-radioactivity and intrinsic cosmogenic activation. Contributions of neutrons from ambient radioactivity and reactor operation are negligible, a feature consistent with expectations from full GEANT simulations. The HND detector concept and analysis procedures can be applicable to characterize neutron background in other rare-event experiments, in both surface and underground laboratories. In particular, the equilibrium levels of the X-ray peaks in HPGe detectors can be used to measure in situ background neutron fluxes. This technique can be extended to other Ge-based underground WIMP-search experiments[27,29].

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