Nuclear Inst. and Methods in Physics Research, A 868 (2017) 109–118

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

Design and performance of a hybrid fast and thermal neutron detector

M.K. Singh [a,b,*], A. Sonay [a,c], M. Deniz [a,c,**], M. Ağartıoğlu [a,c], G. Asryan [a], G. Kiran Kumar [a], H.B. Li [a], J. Li [e], F.K. Lin [a], S.T. Lin [a,f], V. Sharma [a,b], L. Singh [a,b], V. Singh [b], V.S. Subrahmanyam [b], A.K. Soma [a,b], H.T. Wong [a,**], S.W. Yang [a], I.O. Yıldırım [a,d], Q. Yue [e], M. Zeyrek [d], The TEXONO Collaboration

[a] *Institute of Physics, Academia Sinica, Taipei 11529, Taiwan*
[b] *Department of Physics, Institute of Science, Banaras Hindu University, Varanasi 221005, India*
[c] *Department of Physics, Dokuz Eylül University, Buca, İzmir TR35160, Turkey*
[d] *Department of Physics, Middle East Technical University, Ankara TR06531, Turkey*
[e] *Department of Engineering Physics, Tsinghua University, Beijing 100084, China*
[f] *Department of Physics, Sichuan University, Chengdu 610065, China*

ABSTRACT

We report the characterization, calibration and performance of a custom-built hybrid detector consisting of BC501A liquid scintillator and BC702 scintillator for the detection of fast and thermal neutrons, respectively. Pulse Shape Discrimination techniques are developed to distinguish events due to γ-rays, fast and thermal neutrons. Software analysis packages are developed to derive raw neutron energy spectra from measured proton recoil spectra. The validity is demonstrated through the reconstruction of the $^{241}\mathrm{AmBe}(\alpha, \mathrm{n})$ neutron spectrum.

1. Introduction and physics motivations

Experiments in neutrino physics [1] and dark matter searches [2] often involve very small interaction rates, and therefore desire a good detection sensitivity with low count rates of background signals. The elimination of known background signals from the physical ones constitutes a major challenge to these experiments. A complete reduction of background signals, especially the neutron-induced events, is not possible even in very deep underground laboratories. Therefore, direct measurement and elimination of neutron background signals are very crucial for such experiments.

This work is pursued within the framework of the TEXONO research program [3]. The custom-built "Hybrid Neutron Detector" (HND) for this study consists of: (i) BC-501A [4] (equivalent to NE231 or EJ301) liquid scintillator sensitive to fast neutrons, and (ii) BC-702 [5] thermal neutron scintillating detector. However, BC-501A is also sensitive to γ rays as well. The n/γ discrimination can be performed effectively via Pulse Shape Discrimination (PSD) technique by the different behavior of decay time component of the pulse shape as well as the parametrization of the pulse shape with an exponential function. One of the objectives of this study is to develop PSD techniques providing a good and effective discrimination of neutron against γ rays background.

The structure of the paper is as follows: Design and Construction of the HND will be discussed in Section 2. Data taking and detector performance (the DAQ system, energy calibration, event identification and PSD techniques) will be discussed in Section 3. Reconstruction of the raw neutron spectra via Doroshenko and Gravel unfolding methods will be discussed in Section 4. Unless otherwise stated, light output from scintillators as well as detector response are expressed in "electron-equivalence" unit like $\mathrm{keV_{ee}}$, while the particle kinetic energy are in the standard keV units.

2. Design and construction

2.1. Detector structure

The neutron detector used in this study has a hybrid structure, bringing two different types of target materials to operate at the same time; Bicron BC-501A liquid scintillator having 0.113 liter cell volume and BC-702 type scintillator enriched to 95% ^{6}Li in a fine ZnS(Ag) phosphor powder. The scintillation light output is readout by Hamamatsu photomultiplier tube (PMT). The schematic diagram of the detector is shown in Fig. 1.

---

[*] Correspondence to: D.S. Kothari Fellow, Department of Physics, Institute of Science, Banaras Hindu University, Varanasi 221005, Uttar Pradesh, India.
[**] Corresponding authors.
E-mail addresses: manoj.hep.bhu@gmail.com (M.K. Singh), muhammed.deniz@deu.edu.tr (M. Deniz), htwong@phys.sinica.edu.tw (H.T. Wong).

http://dx.doi.org/10.1016/j.nima.2017.06.052
Received 1 December 2016; Received in revised form 7 March 2017; Accepted 28 June 2017

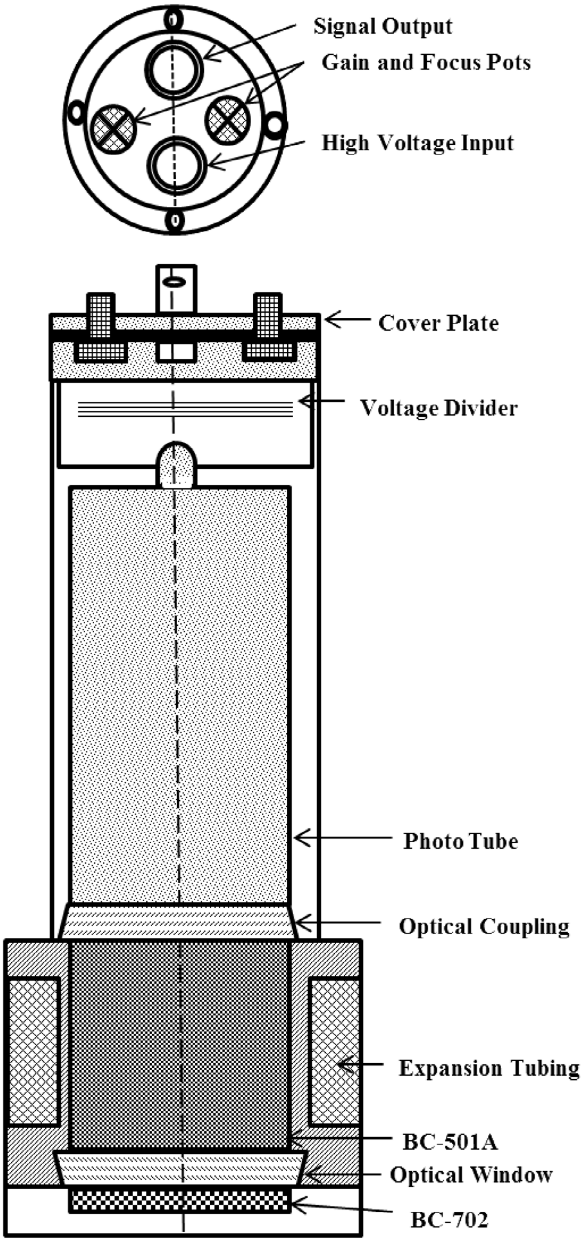

Fig. 1. Schematic diagram of the HND.

The selected detector dimension is similar to that of germanium detector cryostat used in experiments at the Kuo-Sheng Reactor Neutrino Laboratory (KSNL) [6] and China Jinping Underground Laboratory (CJPL) [7]. Therefore, HND can be installed, replacing the Ge-target, within the well of an NaI(Tl) Anti-Compton detectors under the same shielding configurations as those experiments to provide measurements of the ambient neutron background.

BC-501A is sensitive to fast neutrons detection while BC-702 has high efficiency of detection of thermal neutrons. Both scintillator detectors have, in addition to a good fast time response, a pulse shape discrimination property, which enables the isolation of γ ray events (due to different signal characteristics for proton and electron recoil events, enabling to distinguish neutron hit events from those of gamma ray). Therefore this HND provides good discrimination against γ ray background [8]. There is a large number of PSD studies for neutron detectors available in the literature [9].

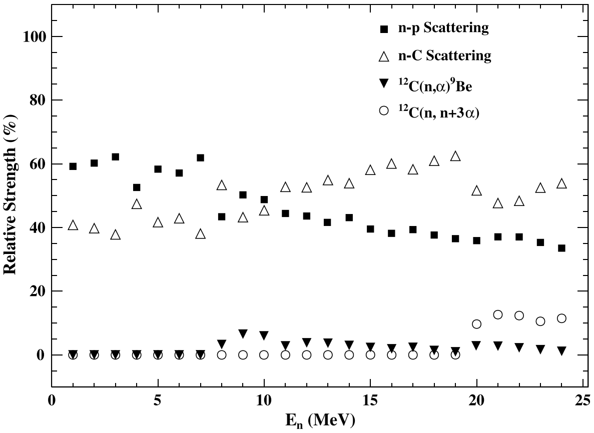

Fig. 2. GEANT-4 simulation for the proportions of the reactions occurred in the BC-501A neutron detector.

2.2. Physical interactions

BC-501A liquid scintillator detector is designed to yield good PSD between γ ray and neutron incident particles. BC-501A is an liquid scintillator containing 4.82×10^{22} and 3.98×10^{22} atoms of hydrogen and carbon per cm^3, respectively. The high density of hydrogen and carbon atoms present in its compound makes it a good target material for the detection of fast neutrons in the MeV range via the reactions of,

$$\begin{aligned}
&\mathrm{p(n,n)p},\\
&{}^{12}\mathrm{C(n,n)}{}^{12}\mathrm{C},\\
&{}^{12}\mathrm{C(n,n+3}\alpha), \quad \text{and}\\
&{}^{12}\mathrm{C(n,}\alpha)^{9}\mathrm{Be}.
\end{aligned} \tag{1}$$

A GEANT-4 Monte Carlo Simulation for the proportions of the reactions listed in Eq. (1) is illustrated in Fig. 2. As it can be seen, the most dominant interactions are $\mathrm{p(n,n)p}$ and $^{12}\mathrm{C(n,n)}^{12}\mathrm{C}$. But as the incident neutron energy increases the proportion of the $^{12}\mathrm{C(n,n)}^{12}\mathrm{C}$ interaction increases and becomes dominant over p(n,n)p above around 10 MeV. However, the regular neutron energy range in underground labs is usually below 10 MeV [10]. Therefore, $\mathrm{p(n,n)p}$ interaction is still the most probable and dominant interaction among the neutron detection channels for underground experiments.

BC-702 detector is designed as a 6.35 mm thick and 50.8 mm diameter disk. BC-702 is sensitive to the detection of slow/thermal neutrons, which are present in the background environment mostly as a result of moderation of fast neutrons via elastic scattering in the shielding and other materials. BC-702 is highly efficient to detect neutrons of kinetic energy around 0.01 eV with a detection efficiency above 50% but is slightly efficient for neutrons of kinetic energy above 0.1 eV for which the detection efficiency rapidly decreases. BC-702 scintillator is composed of 11 mg of ^{6}Li per cm^3 with 95% purity which is dispersed in ZnS(Ag) phosphor powder. The detector provides a good capture efficiency for thermal neutrons due to the large neutron capture cross-section of Li through the reaction,

$$^{6}\mathrm{Li} + \mathrm{n} \rightarrow \mathrm{t}\ (2.05\ \mathrm{MeV}) + \alpha\ (2.73\ \mathrm{MeV}). \tag{2}$$

The detection mechanism of neutron absorption by ^{6}Li is given in Eq. (2) where the resulting α particle and triton with recoil kinetic energy induce scintillation light upon their interaction with ZnS(Ag). BC-702 detector provides a very good discrimination of thermal neutrons against both γ ray and fast neutron background.

The simulated efficiencies of the detector for γ ray, fast and slow neutrons are illustrated in Fig. 3.