Physics of the Dark Universe 13 (2016) 166–170

Contents lists available at ScienceDirect

Physics of the Dark Universe

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

Evaluation of neutron background in cryogenic Germanium target for WIMP direct detection when using reactor neutrino detector as neutron veto

Ye Xu [a,b,*], Jieqin Lan [b], Ying Bai [b], Weiwei Gao [b]

[a] School of Information Science and Engineering, Fujian University of Technology, Fuzhou 350118, China
[b] School of Mathematics and Physics, Fujian University of Technology, Fuzhou 350118, China

ARTICLE INFO

Article history:
Received 6 December 2015
Received in revised form
9 July 2016
Accepted 14 July 2016

Keywords:
Dark matter
Neutron background
Neutrino detector
High purity germanium

ABSTRACT

A direct WIMP (Weakly Interacting Massive Particle) detector with a neutron veto system is designed to better reject neutrons. An experimental configuration is studied in the present paper: 984 Ge modules are placed inside a reactor neutrino detector. In order to discriminate between nuclear and electron recoil, both ionization and heat signatures are measured using cryogenic germanium detectors in this detection. The neutrino detector is used as a neutron veto device. The neutron background for the experimental design has been estimated using the Geant4 simulation. The results show that the neutron background can decrease to O(0.01) events per year per tonne of high purity Germanium. We calculate the sensitivity to spin-independent WIMP–nucleon elastic scattering. An exposure of one tonne $\times$ year could reach a cross-section of about 2×10^{-11} pb.

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1. Introduction

In direct searches for WIMPs, there are three different methods used to detect the nuclear recoils, including collecting ionization, scintillation and heat signatures induced by them. The background of this detection is made up of electron recoils produced by γ and β scattering off electrons, and nuclear recoils produced by neutrons scattering elastically off target nuclei. Nuclear recoils can be efficiently discriminated from electron recoils with pulse shape discrimination, hybrid measurements and so on. The rejection powers of these techniques can even reach 10^6 [1,2]. For example, the CDMS-II [1] and EDELWEISS-II [3] experiments measure both ionization and heat signatures using cryogenic germanium detectors in order to discriminate between nuclear and electron recoils, and the XENON100 [4] and ZEPLIN-III [5] experiments measure both ionization and scintillation signatures using two-phase xenon detectors. However, it is very difficult to discriminate between nuclear recoils induced by WIMPs and by neutrons. This discrimination and reduction of neutron backgrounds are the most important tasks in direct dark matter searches.

The cross-sections of neutron–nuclei interactions are much larger than those of WIMP–nuclei, so the multi-interactions between neutrons and detector components are applied to tag neutrons and thus separate WIMPs from neutrons. In the ZEPLIN-III experiment, the 0.5% gadolinium (Gd) doped polypropylene is used as the neutron veto device, and its maximum tagging efficiency for neutrons reaches about 80% [6]. In Ref. [7], the 2% Gd-doped water is used as the neutron veto, and its neutron background can be reduced to 2.2 (1) events per year per tonne of liquid xenon (liquid argon). In our past work [8], the reactor neutrino detector with 1% Gd-doped liquid scintillator (Gd-LS) is used as the neutron veto system, and its neutron background can be reduced to about 0.3 per year per tonne of liquid xenon. These neutron background events are mainly from the spontaneous fission and (α, n) reactions due to ^{238}U and ^{232}Th in the photomultiplier tubes (PMTs) in the liquid xenon.

Because of its advantages of the low background rate, energy resolutions and low energy threshold, high purity Germanium (HPGe) is widely applied in dark matter and neutrino-less double beta decay experiments [1,3,9–11]. In our work, the cryogenic ^{73}Ge is used as a WIMP target material and WIMPs are detected by both ionization and heat channels (like the CDMS-II and EDELWEISS-II experiments). A detector configuration that can shield and tag neutrons will better reject neutron background in dark matter experiments. The feasibility of direct WIMPs detection with the

* Corresponding author at: School of Information Science and Engineering, Fujian University of Technology, Fuzhou 350118, China.
E-mail address: xuy@fjut.edu.cn (Y. Xu).

http://dx.doi.org/10.1016/j.dark.2016.07.003
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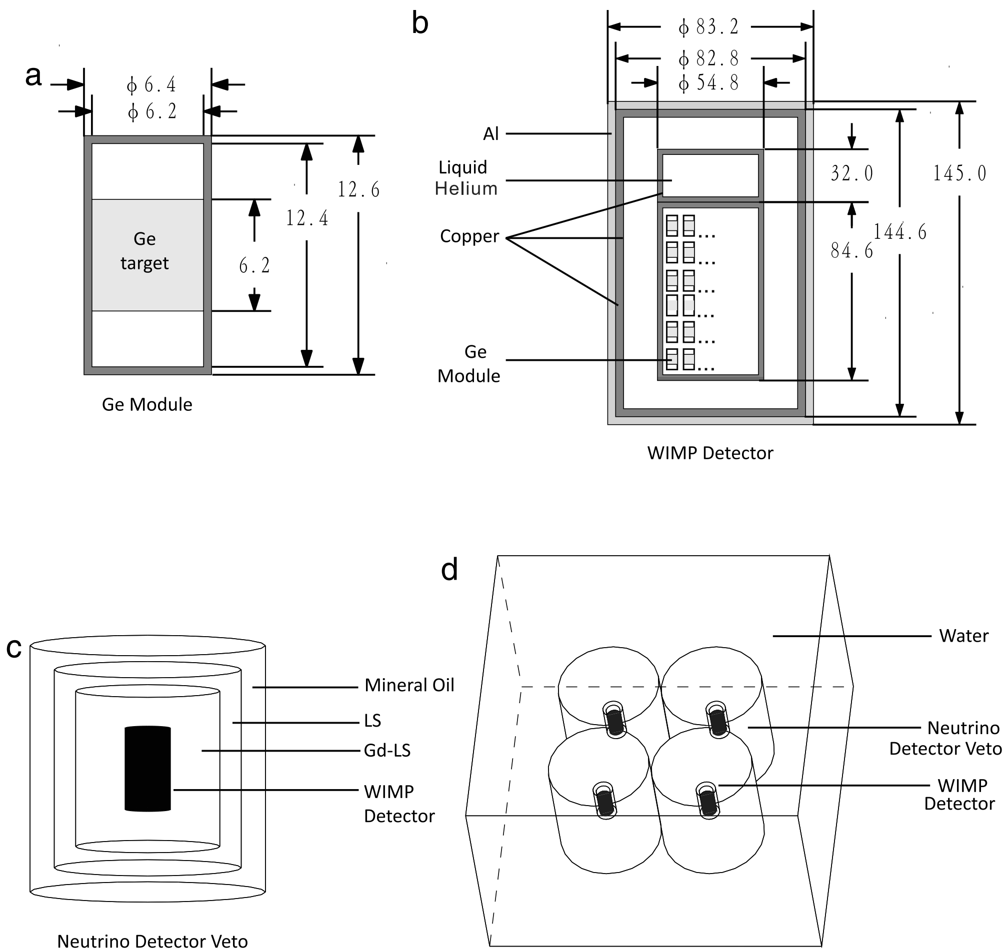

Fig. 1. (a): Ge Module with HPGe material (length unit, cm), (b): WIMP detector with 246 Ge Modules (length unit, cm), (c): a neutrino detector where a WIMP detector is placed, (d): four WIMP detectors individually placed inside four neutrino detectors in a water shield.

neutron veto based on the neutrino detector had been validated in our past work [8]. So, in the present paper, a neutrino detector with Gd-LS (1% Gd-doped) is still used as a neutron-tagged device and WIMP detectors with HPGe targets (called Ge modules) are placed inside the Gd-LS. Here we designed an experimental configuration: 984 Ge modules are individually placed inside four reactor neutrino detector modules which are used as a neutron veto system. The experimental hall of the configuration is assumed to be located in an underground laboratory with a depth of 910 meter water equivalent (m.w.e.), which is similar to the far hall in the Daya Bay reactor neutrino experiment [12]. The neutron background for this design are estimated using the Geant4 [13] simulation.

The basic detector layout will be described in the Section 2. Some features of the simulation in our work will be described in the Section 3. The neutron background of the experimental configuration will be estimated in the Section 4. The other background will be roughly estimated in the Section 5. We give a conclusion in the Section 6.

2. Detector description

Four identical WIMP detectors with HPGe targets are individually placed inside four identical neutrino detector modules. The experimental hall of this experimental configuration is assumed to be located in an underground laboratory with a depth of 910 m.w.e., which is similar to the far hall in the Daya Bay reactor neutrino experiment. The detector is located in a cavern of $20 \times 20 \times 20$ m^3. The four identical cylindrical neutrino modules (each 413.6 cm high and 393.6 cm in diameter) are immersed into a $13 \times 13 \times 8$ m^3 water pool at a depth of 2.5 m from the top of the pool and at a distance of 2.5 m from each vertical surface of the pool. The detector configuration is shown in Fig. 1.

Each neutrino module is partitioned into three enclosed zones. The innermost zone is filled with the 1% Gd doped liquid scintillator [8] (2.6 m height, 2.4 m in diameter), which is surrounded by a zone filled with unloaded liquid scintillator (LS) (35 cm thickness). The outermost zone is filled with transparent mineral oil (40 cm thickness) [15]. 366 8-inch PMTs are mounted in the mineral oil. These PMTs are arranged in 8 rings of 30 PMTs on the lateral surface of the oil region, and 5 rings of 24, 18, 12, 6, 3 on the top and bottom caps.

Each WIMP detector consists of a outer copper vessel (144.6 cm height, 82.8 cm in diameter and 0.8 cm thickness) which is surrounded a Aluminum (Al) reflector (0.2 cm thickness) and inner copper vessel (116.6 cm height, 54.8 cm in diameter and 0.5 cm thickness). There is a vacuum zone between the outer and inner copper vessels (about 13 cm thickness). The part inside the inner copper vessel is made up of two components: the upper component is a cooling system with liquid Helium of very high purity (32 cm height, 54.8 cm in diameter) and the lower one is an active target of 246 Ge modules arranged in 6 columns (each column includes 4 rings of 20, 14, 6, 1). Each Ge module is made up of a copper vessel and a HPGe target: there is a HPGe target (6.2 cm height, 6.2 cm in diameter, ~1 kg) in a 0.1 cm thick copper vessel (12.6 cm height, 6.4 cm in diameter).

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