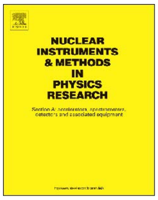
Nuclear Instruments and Methods in Physics Research A 836 (2016) 67–82

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

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



Characterization and performance of germanium detectors with sub-keV sensitivities for neutrino and dark matter experiments

A.K. Soma [a,b,1], M.K. Singh [a,b,*], L. Singh [a,b,*], G. Kiran Kumar [a,2], F.K. Lin [a], Q. Du [c], H. Jiang [d], S.K. Liu [c,d], J.L. Ma [d], V. Sharma [a,b], L. Wang [d], Y.C. Wu [d], L.T. Yang [d], W. Zhao [d], M. Agartioglu [a,e], G. Asryan [a], Y.Y. Chang [a], J.H. Chen [a], Y.C. Chuang [a], M. Deniz [a,e,f], C.L. Hsu [a], Y.H. Hsu [a], T.R. Huang [a], L.P. Jia [d], S. Kerman [a,e], H.B. Li [a], J. Li [d], F.T. Liao [a], H.Y. Liao [a], C.W. Lin [a], S.T. Lin [a,c], V. Marian [g], X.C. Ruan [h], B. Sevda [a,e], Y.T. Shen [a], M.K. Singh [a,b], V. Singh [b], A. Sonay [a,e], J. Su [d], V.S. Subrahmanyam [a,b], C.H. Tseng [a], J.J. Wang [a], H.T. Wong [a,**], Y. Xu [a,i], S.W. Yang [a], C.X. Yu [a,i], Q. Yue [d], M. Zeyrek [f]

[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, Sichuan University, Chengdu 610065, China*
[d] *Department of Engineering Physics, Tsinghua University, Beijing 100084, China*
[e] *Department of Physics, Dokuz Eylül University, Buca, İzmir35160, Turkey*
[f] *Department of Physics, Middle East Technical University, Ankara 06531, Turkey*
[g] *CANBERRA-Lingolsheim Facility, Lingolsheim 67380, France*
[h] *Department of Nuclear Physics, Institute of Atomic Energy, Beijing 102413, China*
[i] *Department of Physics, Nankai University, Tianjin 300071, China*

TEXONO Collaboration

ARTICLE INFO

Article history:
Received 29 January 2016
Received in revised form
8 August 2016
Accepted 22 August 2016
Available online 24 August 2016

Keywords:
Radiation detector
Germanium detector
Neutrino properties
Dark matter

ABSTRACT

Germanium ionization detectors with sensitivities as low as 100 eV$_{ee}$ (electron-equivalent energy) open new windows for studies on neutrino and dark matter physics. The relevant physics subjects are summarized. The detectors have to measure physics signals whose amplitude is comparable to that of pedestal electronic noise. To fully exploit this new detector technique, various experimental issues including quenching factors, energy reconstruction and calibration, signal triggering and selection as well as evaluation of their associated efficiencies have to be attended. The efforts and results of a research program to address these challenges are presented.

1. Introduction

Sensitivities on several important research programs in neutrino and dark matter physics can be significantly enhanced when the "physics threshold" can be lowered to extend the dynamic range of signal detection [1,2]. This motivates efforts to characterize detector behavior and to devise analysis methods in domains where the amplitude of physics signals is comparable to that caused by fluctuations of pedestal electronic noise.

In this article, we report on our research program and results on using advanced germanium (Ge) ionization detectors to address the above mentioned issues. Following a survey on physics topics relevant to low-background and low-threshold techniques, crucial aspects of detector operation and optimizations near electronic "noise-edge" are discussed. These include studies on energy estimators and calibration, trigger and data acquisition rates, signal event selections and evaluation of their efficiencies.

Data taken with point-contact Ge detectors with sub-keV

---

[*] Corresponding authors at: Institute of Physics, Academia Sinica, Taipei 11529, Taiwan

[**] Corresponding author.

E-mail addresses: manoj@gate.sinica.edu.tw (M.K. Singh), lakhwinder@gate.sinica.edu.tw (L. Singh), htwong@phys.sinica.edu.tw (H.T. Wong).

[1] Present Address: Department of Physics, University of South Dakota, Vermillion, SD 57069, USA.

[2] Present Address: Physics Department, KL University, Guntur 522502, India.

http://dx.doi.org/10.1016/j.nima.2016.08.044
0168-9002/

sensitivities were adopted to establish the results. However, the devised techniques would also be applicable to other detector systems, and at other energy ranges. Unless otherwise stated, electron-equivalent energy (eV_{ee}) is used throughout this article to denote detector response to a measurable energy T. The raw kinetic energy due to nuclear recoils is denoted by keV_{nr}.

Results on the characterization and performance of Ge detectors are original work. Surface background [3] and quenching factor [4] of Ge detectors have been discussed in the literature. They are summarized in Sections 4.3.2 and 3.4, respectively, for completeness and coherence.

2. Scientific motivations

The objective of our research program is to develop detectors with modular mass of $\mathcal{O}$(1 kg), physics threshold of $\mathcal{O}$ (100 eV_{ee}) and background level at threshold of $\mathcal{O}(1\ kg^{-1}\,keV_{ee}^{-1}\,day^{-1})$ [1]. Germanium semiconductors in ionization mode were selected as the detection technique. When these “benchmark” specifications are fulfilled, several important topics discussed in subsequent sections can be experimentally pursued.

2.1. Neutrino electromagnetic properties

Investigations of neutrino properties and interactions can reveal physics within and beyond the Standard Model (SM). An avenue is the study of possible neutrino electromagnetic interactions [5].

The neutrino magnetic moment (μ_ν) is an intrinsic neutrino property that describes possible neutrino-photon couplings via its spin [6,7]. The helicity is flipped in these μ_ν-induced interactions. Observations of μ_ν at levels relevant to present or future generations of experiments would strongly favor the case of Majorana neutrinos [8]. Most experimental searches of μ_ν make use of neutrino interactions with free electrons. The differential cross-section has an $(1/T)$-dependence, where the measurable T is due to recoil kinetic energy of electrons. The expected differential spectra for reactor neutrinos at a flux of $\phi(\bar{\nu}_e) = 10^{13}\ cm^{-2}\ s^{-1}$ are shown in Fig. 1a (details of reactor $\bar{\nu}_e$-spectra and their derivations are described in Refs. [7,9]). Contributions from μ_ν are enhanced as T decreases, with necessary modifications from the atomic binding energy effects [10,11].

In a similar spirit, studies on neutrino “milli-charge” probe possible helicity conserving QED-like interactions. It can be parametrized as $(\delta_Q \cdot e_0)$ where δ_Q is the charge fraction and e_0 is the standard electron charge. Finiteness of δ_Q would imply that neutrinos are Dirac particles. An enhancement in cross-sections induced by atomic effects, as depicted in Fig. 1a, has recently been identified [11,12]. The known ratios of peaks at discrete binding energies provide smoking-gun signatures for positive observations.

It follows from Fig. 1a that experimental studies on μ_ν and q_ν should focus on $T < 10\ keV_{ee}$. At benchmark experimental sensitivities and with comparable exposure as the GEMMA experiment [13], the potential reaches are $\mu_\nu \sim 2\times10^{-11}\mu_B$ and $\delta_Q \sim 6\times10^{-14}$, where μ_B is the Bohr magneton.

In addition, it was recognized [14] that the μ_ν-induced interaction with matter would have a pronounced enhancement in cross-section, manifesting as measurable peaks when the initial-state neutrinos are non-relativistic. The experimental signatures require good-resolution and low-threshold measurements for which Ge detectors would be optimal.

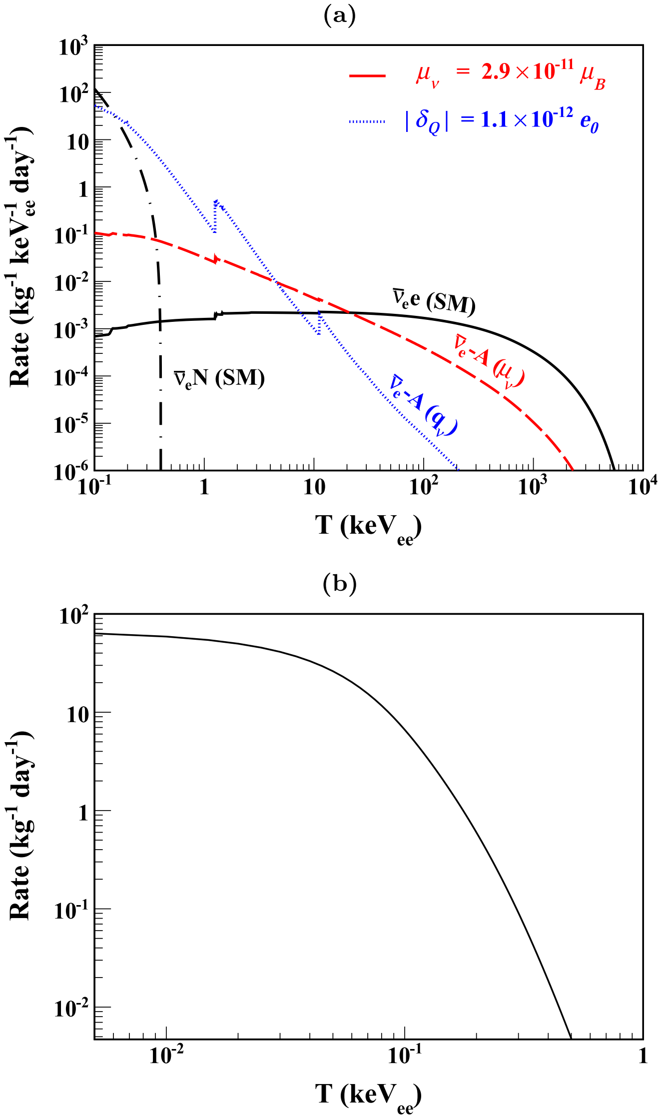


Fig. 1. (a) Observable spectra due to reactor-$\bar{\nu}_e$ interactions on Ge target with $\phi(\bar{\nu}_e) = 10^{13}\ cm^{-2}\ s^{-1}$, neutrino magnetic moment and neutrino milli-charge fraction at the current bounds from direct experimental searches: $\mu_\nu = 2.9\times10^{-11}\mu_B$ and $|\delta_Q| = 1.1\times10^{-12}$, respectively. Superimposed are SM $\bar{\nu}_e$-e and coherent scattering $\bar{\nu}_e$-N. Quenching effects of nuclear recoils are taken into account. (b) Expected integral $\bar{\nu}_e$-N coherent scattering rates due to SM contributions at the same flux, as a function of physics threshold, assuming realistic detector resolution.

2.2. Neutrino nucleus coherent scattering

The elastic scattering between a neutrino and a nucleus (νN) [1,15]

$$\nu + N \to \nu + N \tag{1}$$

is a fundamental SM interaction that has never been observed [16]. It probes coherence effects in electroweak interactions [17], and provides a sensitive test for physics beyond SM. The coherent interaction plays an important role in astrophysical processes and constitutes the irreducible background to the forthcoming generation of dark matter experiments. Coherent neutrino scattering may provide new approaches to the detection of supernova neutrinos and offer a promising avenue towards a compact and transportable neutrino detector capable of real-time monitoring of nuclear reactors.

The maximum nuclear recoil energy for a Ge target (A=72.6) due to reactor $\bar{\nu}_e$ is about 2 keV_{nr}. The quenching factor (QF;