Chapter 68
P Type Point Contact Germanium Detector for Dark Matter Search

M.K. Singh and H.T. Wong

Abstract The p-type point-contact germanium detectors are novel techniques offering kg-scale radiation sensors with sub-keV sensitivities. They have been used for light dark matter WIMPs searches and may have potential applications in neutrino physics. The TEXONO collaboration reports limits on weakly interacting massive particle (WIMP)-nucleon spin-independent elastic interaction cross-section with 39.5 kg-days data at the Kuo-Sheng Reactor Neutrino Laboratory in Taiwan. Crucial to this study is the understanding of the selection procedures for the bulk and surface events differentiation at the sub-keV range. In this report we will describe the methods and results which is used to identify the bulk and surface events in analysis techniques, as well as the calibration schemes to evaluate the selection efficiency factors.

68.1 Introduction

About one-quarter of the energy density of the Universe can be attributed to cold dark matter [1] whose nature and properties are unknown. Weakly interacting massive particles (WIMPs denoted by χ) are its leading candidates. Germanium detectors with sub-keV sensitivities have been demonstrated as efficient means to probe WIMPs. This motivates development of p-type point-contact germanium detectors (pGe). The experimental signatures are the nuclear recoils, posing the challenging requirements of low background and low threshold to the detectors. The surface events in pGe exhibit anomalous behaviour [2–5]. It may limit the physics sensitivities, and can lead to false interpretation of the data. The analysis of these anomalous surface events is therefore an important experimental challenge. The physics origin, rise-

M.K. Singh (✉) · H.T. Wong
Institute of Physics, Academia Sinica, 11529 Taipei, Taiwan
e-mail: manoj@phys.sinica.edu.tw

H.T. Wong
e-mail: htwong@phys.sinica.edu.tw

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time measurements, separation of bulk from surface events as well as the derivations of efficiency factors and the associated uncertainties are fully discribed in TEXONO experimental reports [3, 4].

68.2 Experimental Overview

A research program on low energy neutrino and dark matter physics is pursued at the Kuo-Sheng Neutrino Laboratory (KSNL) by the TEXONO (Taiwan Experiment on Neutrino) Collaboration. The laboratory is located at a distance of 28 m from a 2.9 GW reactor core and has an overburden of about 30 mwe (meter-water-equivalent). Its facilities were described in [3–6]. The present goals are to develop advanced detectors with kg scale target mass, 100 eV threshold range and low-background specifications, for the searches of WIMPs, as well as to study neutrino-nucleus coherent scattering, and neutrino magnetic moments [3–6].

Signals from the point contact are supplied through a reset preamplifier. The output is distributed to a fast-timing amplifier which keeps the rise-time information, and to amplifiers at both 6 and 12 μs shaping time which provide energy information. Signals from the outer surface electrode are processed with a resistive feedback preamplifier and followed by amplifier at 4 μs shaping time. The fast-timing, slow-shaping, and AC-NaI(Tl) output were digitized by flash analog-to-digital converters at 200, 60, and 20 MHz, respectively. The discriminator and timing outputs of the CR panels were also recorded [3, 4].

68.3 Result and Discussion

There are three categories of selection criteria is adopted. Firstly we used physics versus noise events (PN) cuts to differentiate physics signals from spurious electronic noise. After that in Second step we apply AC and CR cuts, to identify events with activities only at the pGe target. Third and final step is the bulk versus surface events (BS) cut to selects events at the interior. In addition, the efficiencies and suppression factors (ε_X, λ_X) for every selection (X = PN, AC, CR, BS) are measured. They correspond to the probabilities of (signal, background) events being correctly identified. The physics events selected by the PN cuts are categorized by "$AC^{-(+)} \otimes CR^{-(+)} \otimes B(S)$" where $AC^{-(+)}$ and $CR^{-(+)}$ represent AC and CR signals in anticoincidence (coincidence), respectively, while B(S) denote the bulk (surface) samples.

The PN cuts are based on pulse shape characteristics and correlations among the fast and shaping signals. They suppress spurious triggers induced by microphonics effects or the tails of pedestal fluctuations. Background suppression with the PN, AC, and CR cuts and the evaluations of their respective (ε_X, λ_X) follow the well-studied procedures [3, 4]. The majority of the electronics-induced events above the noise edge are identified ($\lambda_{PN} \sim 1$) and the efficiencies for the AC and CR selections are ($\varepsilon_{AC} > 0.99$) and ($\varepsilon_{CR} = 0.93$). The BS selection, on the other hand, is a unique feature to pGe. The surface electrode is a lithium-diffused n^+ layer of mm-scale thickness. Partial charge collection in the surface layer gives rise to reduced measurable energy and slower rise time (τ) in its fast-timing output, as compared to those in the bulk region [3, 4]. The thickness of the S layer was derived to be (1.16 ± 0.09) mm, via the comparison of simulated and observed intensity ratios of γ peaks from a ^{133}Ba source.

The scatter plot for $\log_{10}[\tau]$ versus measured energy (T) is shown in Fig. 68.1. The observed and actual rates are denoted by (B', S') and (B, S), respectively. Events with (τ) less (larger) than (τ_0) are categorized as B'(S'). Typical B'(S') events at T $\sim$ 700 eVee are shown. At T $>$ 2.7 keVee where the (τ) resolution is better than the separation between the two bands, the assignments B = B' and S = S' are justified [3, 4]. At lower energy, (B', S') and (B, S) are related by the coupled equations:

$$B' = (\varepsilon_{BS})\text{B} + (1 - \lambda_{BS})\text{S, and } S' = (1 - \varepsilon_{BS})\text{B} + \lambda_{BS}\text{S}.$$

with an additional unitarity constrain B + S = $B' + S'$.

For the calibration of (ε_{BS}, λ_{BS}) three measurements of (B', S') where (B, S) are independently known were adopted well described in [3, 4], as shown in Fig. 68.2. The surface-rich γ events and the bulk-rich cosmic-ray induced neutron events play complementary roles in constraining λ_{BS} and ε_{BS}, respectively. The results are depicted in Fig. 68.3, with (ε_{PN}) overlaid. By comparing the measured in situ Ga-L

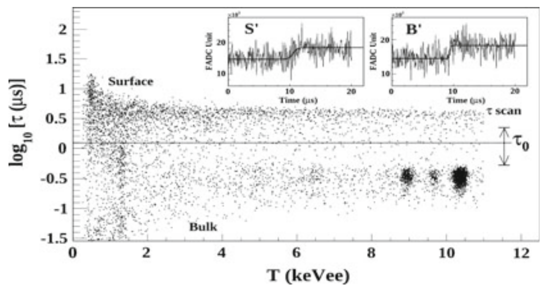

Fig. 68.1 Scatter plot of the pGe rise time ($\log_{10}[\tau]$) versus energy. The τ_0 line corresponds to the BS cut in this analysis, with τ scan indicating the range of cut-stability test. Typical B'(S') pulses at T $\sim$ 700 eVee are depicted in the *insets*

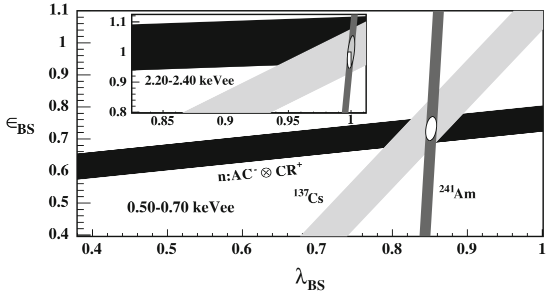

Fig. 68.2 Allowed bands at threshold and at a high energy band

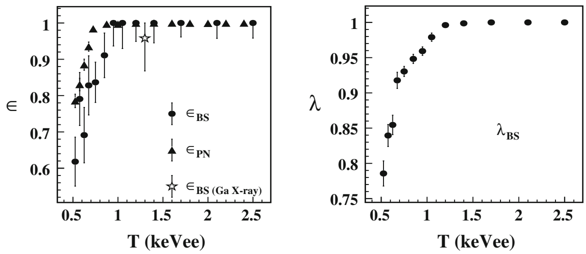

Fig. 68.3 The measured $(\varepsilon_{BS}, \lambda_{BS})$ and ε_{PN} as functions of energy. Independent measurement on ε_{BS} with Ga-L X rays is included

X-ray peak at 1.3 keVee after BS selection to that predicted by the corresponding K peak at 10.37 keVee, a consistent ε_{BS} is independently measured [3, 4].

The raw spectrum and those of $AC^- \otimes CR^- \otimes B^{'}$ are depicted in Fig. 68.4. The peaks correspond to known K-shell x rays from the cosmogenically activated isotopes. The $(\varepsilon_{BS}\ , \lambda_{BS})$-corrected spectrum of $AC^- \otimes CR^- \otimes B^{'}$ is shown in the large inset, while the small inset showing the residual backgrounds. The analysis threshold is placed at 500 eVee, where $(\varepsilon_{BS}, \lambda_{BS}) \sim 0.5$ and the BS selection is no longer valid [3, 4]. The stability of $(\varepsilon_{BS}, \lambda_{BS}, B^{'}, S^{'}, \mathrm{B})$ is studied over changes of (τ_0) within the (τ)-scan range of Fig. 68.1. Measurements of B are stable and independent of (τ_0), as indicated by the small variations relative to the uncertainties, while $(\varepsilon_{BS}\ , \lambda_{BS})$ exhibit significant shifts in the expected directions, which show that the BS calibration procedures are valid [3, 4]. An exclusion plot of $\sigma_{\chi N}^{SI}$ versus m_χ at 90 % confidence level is displayed in Fig. 68.5, and bounds from other benchmark experiments are superimposed [4, 5].

Despite advances in the BS-selection and efficiency factors measurements discussed in this report, there are still fundamental challenges to further boost the sensitivities on the studies of sub-keV events with pGe. In addition, B depends on

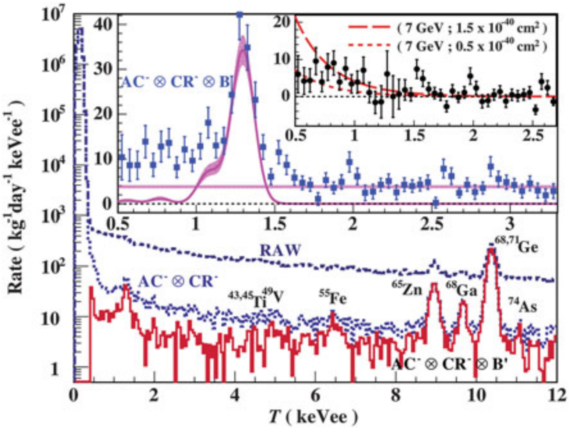

Fig. 68.4 Measured energy spectra showing the raw data and those with $AC^- \otimes CR^-(\otimes B^{'})$ selections. The large *inset* shows the $(\varepsilon_{BS}, \lambda_{BS})$-corrected $AC^- \otimes CR^- \otimes B$ spectrum, with a flat background and L-shell X-ray peaks overlaid. The small *inset* depicts the residual spectrum

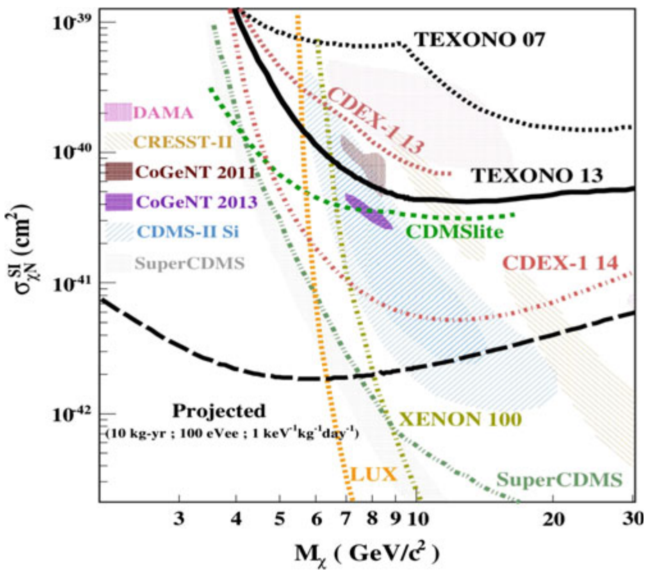

Fig. 68.5 Exclusion plot of spin-independent χN coupling at 90 % confidence level, superimposed with the results from other benchmark experiments

measurements of all of the input parameters (ε_{BS}, λ_{BS}, $B^{'}$, $S^{'}$). This calls for caution in the investigations of time variation and modulation effects on B , in which the time stabilities of these input have to be independently monitored. To overcome these difficulties, the elimination of the anomalous surface effects at the hardware raw signal level in pGe detectors is much more desirable. To these ends, the merits and operation of nGe are being studied. This detector has already proved crucial to provide calibration data to the pGe. A by-product of this investigation is that the pGe τ distributions are different for different sources, as depicted [3]. Therefore, the studies of signal rise-time may shed light on the nature of the background. Further systematic and quantitative studies are under way. Studies continue on pGe and nGe at KSNL. Projects on improvement of electronics and sub-noise-edge analysis are being pursued. The dedicated dark matter experiment CDEX with sub-keV germanium detectors is taking data at the new China Jinping Underground Laboratory [5].

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