Neutrino and dark matter physics with sub-KeV
Germanium detectors

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Abstract. Germanium detectors with sub-keV sensitivities [1, 2, 3] offer a unique opportunity to study neutrino interactions and properties [4] as well as to search for light WIMP Dark Matter [5, 6]. The TEXONO and CDEX Collaborations have been pursuing this research program at the Kuo-Sheng Neutrino Laboratory in Taiwan and in the China Jinping Underground Laboratory in China. We will present highlights of the detector R&D program which allow us to experimental probe this new energy window. The results, status and plans of our neutrino physics program will be discussed, with focus on the quest on neutrino-nucleus coherent scattering.

1. Introduction
Germanium detectors with sub-keV sensitivities have been demonstrated as efficient means to probe Weakly Interacting Massive Particles(WIMP) [1, 7, 3]. This detector technique offer a unique opportunity to study neutrino interactions and properties [4] as well as studies of neutrino-nucleus coherent scattering with reactor neutrinos. This motivates development of point-contact germanium detectors. The experimental signatures of WIMP and neutrino-nucleus coherent scattering are the nuclear recoils, posing the challenging requirements of low background and low threshold to the detectors. The Collaborations have developed and used several Germanium detectors, both p-type (pGe) and n-type (nGe). The generic benchmark goals in terms of detector performance are: (1) modular target mass of order of 1 kg; (2) detector sensitivities reaching the range of 100 eV; (3) background at the range of 1 kg⁻¹ keV⁻¹ day⁻¹ (cpskd).

The setup of pGe detectors at the Kuo-Sheng Neutrino Laboratory(KSNL) in Taiwan and in the China Jinping Underground Laboratory(CJPL) in China were described in Rf. [1, 6].

2. Light WIMP Searches
About one-quarter of the energy density of the Universe can be attributed to cold dark matter [9] whose nature and properties are unknown. Weakly interacting massive particles (WIMPs denoted by $\chi$) are its leading candidates. The WIMPs interact with matter pre-dominantly via the same coherent scattering mechanism like the neutrinos: $\chi + N \rightarrow \chi + N$. There may be both spin-independent and spin-dependent interactions between WIMP and matter. Most experimental programs optimize their design in the high-mass region and exhibit diminishing sensitivities for $m_\chi < 10$ GeV. To probe the low-mass region, detector with sub-keV threshold
is necessary. Such threshold presents a formidable challenge to detector technology and to background control. Based on data taken with p-type point contact germanium detector with the TEXONO experiment at KSNL [5] and the CDEX experiment at CJPL [6] competitive limits are derived.

The p-type point contact Germanium detectors were adopted at both sites for light WIMP searches. Three categories of selection criteria is adopted. Firstly we used physics versus noise events (PN) cuts to differentiate physics signals from spurious electronic noise. In second step we apply anti-Compton (AC) and cosmic (CR) cuts (cosmic cuts relevant to KSNL site only), to identify events with activities only at the Germanium 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 ($\epsilon_X, \lambda_X$) for every selection ($X =$ PN, AC, CR, BS) are measured. They correspond to the probabilities of (signal,background) events being correctly identified [3].

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 ($\epsilon_X, \lambda_X$) follow the well-studied procedures. 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 ($\epsilon_{AC} \geq 0.99$) and ($\epsilon_{CR} = 0.93$).

The outer surface electrode of the p-type point contact Germanium detector (pGe) are fabricated by lithium diffusion, giving a finite thickness. Electron-hole pairs produced by radiations at the surface (S) layer are subjected to a weaker drift field than those at the crystal bulk region (B). The S-events have only partial charge collection and slower rise-time [2, 3, 5]. 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 $\gamma$ peaks from a $^{133}$Ba source [10].

The ($\epsilon_X, \lambda_X$) of BS correction are calibrated by three sources - (a) the bulk-rich cosmic-ray induced neutrons, (b) surface-rich $\gamma$-rays $^{241}$Am and (c) $^{137}$Cs. The bulk spectra from pGe with these sources are compared to reference bulk spectra acquired via simulations for $\gamma$-rays and n-type Germanium detector measurement for cosmic-neutrons [2, 5].

The observed and actual rates are denoted by ($B', S'$) and (B, S), respectively. The observed and actual rates are denoted by ($B', S'$) and (B, S), respectively. Events with ($\tau$) less (larger) than a certain rise-time cut ($\tau_0$) are categorized as $B'$ ($S'$). ($B', S'$) and (B, S) are related by the coupled equations:

$$B' = (\epsilon_{BS})B + (1 - \lambda_{BS})S$$

and

$$S' = (1 - \epsilon_{BS})B + \lambda_{BS}S$$

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

By comparing the measured in situ Ga-L x-ray peak at 1.3 keVee after BS selection to that predicted by the corresponding K peak at 10.37 keVee, a consistent $\epsilon_{BS}$ is independently measured.

Measurements of B are stable and independent of ($\tau_0$), as indicated by the small variations relative to the uncertainties, while ($\epsilon_{BS}, \lambda_{BS}$) exhibit significant shifts in the expected directions. This show that the BS calibration procedures are valid and robust [2].
High energy $\gamma$-rays from ambient radioactivity produce flat electron-recoil background at low energy, together with the L-shell X-ray lines predicted by the higher energy K-peaks, are subtracted. The residual spectrum corresponds to $\chi^N$ candidate events. The event rates of $\chi^N$ spin-independent interaction cannot be larger than the residual spectrum. The quenching function in Ge is derived with the TRIM software which matches well with existing data [8]. The results are described in Rf. [5, 6]. In particular, the allowed region from the CoGeNT-2013 [11] data is probed and excluded with the CDEX-2014 results [6].

3. Low Energy Neutrino Physics

The physical origin and experimental consequences of finite neutrino masses and mixings are not fully understood. Investigations on anomalous neutrino properties and interactions are crucial to address these fundamental questions and may provide hints or constraints to new physics beyond the Standard Model. To explore the neutrino electromagnetic properties like neutrino magnetic moments $\mu_\nu$ [8] and neutrino milli-charge $q_\nu$ [4] with neutrino-electron scattering at low energy regime we need the detectors which have low threshold, low background and high energy resolution. These requirements lead towards high-pure Germanium (Ge) detector, which has excellent energy resolution and low detection threshold.

![Figure 1](image1.png)  
**Figure 1.** The observable spectra due to neutrino interactions on Ge target with reactor $\bar{\nu}_e$ at $\phi_{\bar{\nu}_e} = 10^{13}$ cm$^{-2}$s$^{-1}$, with current experimental bound on neutrino magnetic moment, neutrino millicharge, together with the SM $\bar{\nu}_e - e$ and coherent scattering $\bar{\nu}_e - N$. (b) Differential cross sections for Ge-ionization by $q_\nu$-interaction with 1 MeV neutrino incident energy.

![Figure 2](image2.png)  
**Figure 2.** Differential cross sections for Ge-ionization by $q_\nu$-interaction with 1 MeV neutrino incident energy.

The experimental studies on $\mu_\nu$ and $q_\nu$ is make use of neutrino interactions with bound electrons of detectors. We adopted the Multi-Configuration Relativistic Random-Phase Approximation theory, to include the atomic effect in the analysis. It also provide the better description for the structure of Ge atoms as well as photo-absorption data of Ge crystal at photon energy $\geq 80$ eV [4]. The differential cross section due to $q_\nu$ has $(1/T^2)$-dependence which is different from that of $(1/T)$ for $\mu_\nu$ at $T \ll E_\nu$ where T is the measurable recoil energy of electron and $E_\nu$ is the energy of the incoming neutrino. Fig. 1 showing that both $\mu_\nu$ and $q_\nu$ contributions are enhanced as T decreases. It was recently identified [4] that $q_\nu$ contribution has enhancement in cross-sections when atomic effects properly calculate as shown in Fig. 2 and the known ratios
Table 1. Summary of experimental limits at 90% CL on $\mu_{\nu}$ and $q_{\nu}$ parameters studied in this work using selected reactor neutrino data. The projected sensitivities of measurements at the specified realistically achievable experimental parameters are also shown [4, 8].

| Data Set               | Reactor-$\bar{\nu}_e$ Flux | Data Strength ON/OFF (kg-days) | Analysis Threshold (keV) | $\mu_{\nu}$ | $q_{\nu}$ | % C.L. |
|------------------------|----------------------------|-------------------------------|--------------------------|--------------|----------|--------|
| TEXONO 1 kg Ge         | 0.64                       | 570.7/127.8                   | 12                       | < 7.4        | < 8.8    |        |
| GEMMA 1.5 kg Ge        | 2.7                        | 1133.4/280.4                  | 2.8                      | < 2.9        | < 1.1    |        |
| TEXONO Point-Contact Ge| 0.64                       | 124.2/70.3                    | 0.3                      | < 26.0       | < 2.1    |        |
| Projected Point-Contact Ge | 2.7                  | 800/200                      | 0.1                      | < 1.7        | < 0.06   |        |
| Sensitivity at 1% of SM| 1.0                        | —                             | 0.1                      | < 0.023      | < 0.0004 |        |

of peaks at discrete binding energies provide smoking gun signatures for positive observations. Fig. 1 reveal that the experimental sensitivity to both $\mu_{\nu}$ and $q_{\nu}$ values critically depend on lowering the energy threshold of the detector employed for measurement of the recoil-electron spectrum.

The expected differential event rate ($dR/dT$) are convoluted with the neutrino spectrum ($d\phi/dE_{\nu}$) as follows,

$$
\frac{dR}{dT} = \rho_e \int_{E_{\nu}} \left[ \frac{d\sigma}{dT} \right] \left[ \frac{d\phi}{dE_{\nu}} \right] dE_{\nu},
$$

where, $\rho_e$ is the electron number density per unit target mass.

The observable spectra due to weak interactions, neutrino magnetic moments at $\mu_{\nu} = 2.9 \times 10^{-11} \mu_B$ and milli-charges at $q_{\nu} = 1.1 \times 10^{-12} e_0$ ($e_0$ is charge on electron) with a reactor flux of $10^{13} \text{ cm}^{-2} \text{ sec}^{-1}$ are depicted in Fig. 1. A 500 g n-type point contact Germanium detector at KSNL site had been deployed for neutrino millicharge searches. The positive signal of neutrino millicharge will be excess count on reactor-ON subtract reactor-OFF data, as plotted in Fig. 3 and Fig. 4. Comparisons and results from different data taking with MCRPRA calculations [4] are listed in Table I. The potential sensitivities of realistic next-generation measurements are also shown. Low threshold detector is also crucial in the studies of neutrino nucleus coherent scattering at the reactor [1, 7, 3]. At 100 eV$_{ee}$ threshold, the range of 10 events/kg-keV-day can be expected. The observation of this channel is the current theme of the program at KSNL.

4. Summary and Prospects

Data taking and analysis with sub-keV germanium detectors continue at KSNL and CJPL. R&D programs are pursued, including advanced detector hardware configurations, electronic components and pulse shape techniques for signal-noise differentiation. Beyond light WIMP searches in 10 GeV range, sub-keV Germanium detection have been an efficient means to study neutrino interactions and properties as well as studies of neutrino-nucleus coherent scattering with reactor neutrinos. Those interaction shown enhancement of excess count at sub-keV if non Standard Model properties existed.
Figure 3. Reactor ON-OFF spectrum.

Figure 4. Residual plot of ON-OFF spectrum with \((2\sigma)\) best-fit region of neutrino millicharge.

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