Studies of neutrino interactions at the Kuo-Sheng Neutrino Laboratory with sub-keV Ge-detectors

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Abstract. Germanium detectors with point contact configuration is an exciting detector technology which provides sub-keV sensitivities as low as $100\, eV_{ee}$ with kg-scale detector mass. This detector technique offers a unique opportunity to realize experiments on dark matter, to enhance the sensitivity of electromagnetic properties of neutrino and coherent elastic scattering of neutrino nucleus with reactor neutrino source. The TEXONO collaboration have been pursuing this research program at the Kuo-Sheng Neutrino Laboratory (KSNL) in Taiwan. We will highlight our results on neutrino electromagnetic properties, search of sterile neutrinos, as well as studies towards observation of neutrino-nucleus coherent scattering. The detector R&D programs which allow us to experimentally probe this new energy window will be discussed. The efforts set the stage and complement the CDEX dark matter experiment at the new China Jinping Underground Laboratory (CJPL) in China.

1. Introduction

Detectors with sub-keV threshold, low background and high energy resolution can significantly enhance sensitivities on several important research programs in neutrino and dark matter physics. This motivates the development of point-contact germanium detectors with kg-scale mass. This novel detector technique have been demonstrated as efficient means to probe Weakly Interacting Massive Particles (WIMP) [1, 2, 3]. The experimental signatures of WIMP and neutrino-nucleus coherent scattering are nuclear recoils which require extremely low background and low threshold detectors. The TEXONO collaboration has developed several p-type (pGe) and n-type (nGe) germanium detectors and studied their operational performance. 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 $100\, eV_{ee}$; (3) background at the range of $\sim 1\, kg^{-1}\, keV^{-1}\, day^{-1}\, (cpkkd)$ in sub-keV energy region.

2. Experimental Configuration

The research program of the TEXONO collaboration [4] on neutrino electromagnetic properties, neutrino-nucleus coherent scattering and dark matter physics is pursued at the KSNL which is situated at the northern shore of Taiwan. The detector facilities are located at a distance of 28 m from a 2.9 GWt nuclear reactor core and the 30 meter-water-equivalent concrete overburden eliminates the hadronic components of cosmic rays. Ge-detector is surrounded by 38.3 kg NaI(Tl) anti-Compton (AC) detector. This Ge and NaI-detector setup is placed inside the 50 ton shielding house, which is further mounted with plastic scintillators panels to veto...
cosmic ray muons (CR). A detail description of the shielding and the detector development at KSNL can be found in [5]. In order to achieve a 100 eVee threshold, the collaboration has studied operational characteristics and performance of several Ge-detectors with different configurations under ultra low background environment [2]. Experimental sensitivity for several research programs in neutrino and dark matter physics is not only limiting by signal detection threshold of the detectors, but also due to degradation of background rejection capability at sub-keV recoil energy region. The anomalous surface events in pGe arise from a few milli-meter thick transition layer with weak electric field. The poor charge collection in this region reduces the ionization yield of the events and enhance the background at sub-keV energy region. In order to avoid the anomalous surface effect, a nGe detector is constructed. The surface conductive contact of nGe is prepared by p+ boron implantation technique. The thickness of p+ contact on the outer surface of crystal is the order of \( \mu \)m.

The data were acquired with 500g fiducial mass of nGe detector. Three categories of selection criteria are adopted. Firstly we used physics versus noise events (PN) cuts to differentiate physics signals from spurious electronic noise. In second step, we applied anti-Compton(AC) and cosmic(CR) cuts to identify events with activities only at the Germanium target. The signal from neutrino and dark matter would be single hit. Therefore, third and final step was single hit versus multiple hit events cut. The energy calibration from sub-keV to 14 keV is achieved by the combination of precise-pulser measurement and X-ray peaks (10.37 keV and 1.29 keV) originate from cosmogenic induced \(^{68,71}\)Ge-isotope decay via electron capture.

3. Neutrino Electromagnetic Properties
Investigations of neutrino properties continue to be an accretive field for both theoretical and experimental physicists. Their nonzero masses, as suggested by neutrino oscillation experiments with various sources, has triggered intensive studies of nontrivial electromagnetic properties in both theoretical and experimental framework [6]. The massive neutrinos acquire non-vanishing tiny charge radii squared, magnetic dipole moments, anapole moments (require parity violation in addition), and electric dipole moments (require both parity and time-reversal violation in addition) through electroweak radiative corrections. The Minimally-extended Standard Model (MSM) predicts value of neutrino magnetic moments \( (\mu_\nu) \): \( \mu_\nu \approx 3 \times 10^{-19} \mu_B \) [m_\nu / 1 eV] in units of the Bohr magneton(\( \mu_B \)). The current upper limits set on \( \mu_\nu \) are several orders of magnitude larger than this MSM prediction.

The origin of neutrino millicharged is related to electric charge quantization which one of the profound mystery of nature. The electric charge is quantized within Standard Model (SM) of particle physics due to anomaly cancellation. However, it is no longer ensured in many extensions of SM. The bottom line is neutrinos become electrically millicharged particles \( (q_\nu) \), when electric charge is de-quantized. The non-vanishing value of \( q_\nu \) would imply neutrinos are Dirac particles. The study of electromagnetic characteristics of neutrino may shed light on Dirac or Majorana nature and also act as probe of new physics that might exist beyond SM.

As the kinematic parameters in neutrino-electron scattering like energy transfer starts to overlap with atomic scale, the proper treatment of the atomic effects in neutrino scattering is necessary. There is no known experimental measurement of the response of atomic systems to the neutrino scattering. Therefore, we have to rely on a pure theoretical analysis in interpreting the low energy neutrino-electron scattering data. We adopted the Multi-Configuration Relativistic Random-Phase Approximation (MCRRPA) theory, to include the atomic effect in the analysis. It also provides the better description for the structure of Ge atoms as well as photo-absorption data of Ge crystal at photon energy \( \geq 80 \) eVee [7]. 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 \( T << E_\nu \), where T is the measurable recoil energy of the electron and \( E_\nu \) is the energy of the incoming neutrino. Both \( \mu_\nu \) and \( q_\nu \) contributions are enhanced as T decreases, is illustrated in Fig. 1a. It was
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 [8].

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 tabulated [8].

| Data Set       | Reactor-$\bar{\nu}_e$ 10$^{13}$ cm$^{-2}$ s$^{-1}$ | Data Strength (kg-days) | Threshold (keV$_{ee}$) | Bounds at $\mu_\nu \times 10^{-11}$ | Bounds at $q_\nu \times 10^{-12}$ |
|----------------|---------------------------------------------------|-------------------------|------------------------|-------------------------------------|----------------------------------|
| 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 nPCGe  | 0.64                                              | 124.2/70.3              | 0.3                    | $< 26.0$                           | $< 2.1$                          |
| Projected pPCGe| 2.7                                               | 800/200                 | 0.1                    | $< 1.7$                            | $< 0.06$                         |
| Sensitivity at 1% of SM | 1.0                                           | ——                      | 0.1                    | $< 0.023$                          | $< 0.0004$                        |

recently identified that $q_\nu$ contribution has enhancement in cross-sections when atomic effects are properly calculated [8]. The differential cross section due to the interaction with $q_\nu$ on Ge target under various schemes for monochromatic incident neutrino at $E_{\nu} = 1$ MeV, a typical range for reactor $\bar{\nu}_e$ is shown in Fig. 1b. A unique “smoking gun” signature is also identified for $q_\nu$ interactions which can be observed through K- and L-shell peaks at the specific binding energies and with known intensity ratios. These intensity ratios of K- and L-shell peaks would be different from cosmic-activation electron-capture background. The upper bounds on $\mu_\nu$ and $q_\nu$ are listed in Table 1 for different data taking. The last row of Table 1 illustrates the effective lower bounds to the sensitivities when a 1% measurement of the SM cross section could be achieved, at a threshold of 0.1 keV$_{ee}$ by next-generation Ge-based experiments.

4. Dark Matter Sterile Neutrino Search
Sterile neutrinos are singlets in the SM gauge groups. Their masses, mixing angles and couplings are unknown. Reactor and short baseline experiments anomalies motivate the very light sterile neutrinos in the eV mass range. Sterile neutrinos in the keV mass range are motivated as dark matter candidates. Sterile neutrinos are described via their mass ($m_{sa}$) and active-sterile mixing amplitude ($\sin^2(\theta)$). Therefore, massive sterile neutrinos can undergo radiative decays.
via mixing with the active SM light neutrinos. This process is considered as one of the golden modes to look for keV-scale sterile neutrinos.

![Figure 2](image-url)

**Figure 2.** (a) The differential scattering cross section of sterile neutrinos and Ge-atoms through the $\mu_{\nu_{\text{sa}}}$. (b) Exclusion curve at 90% C.L. for the transition magnetic moment of sterile neutrinos.

The recent observations of an X-ray spectrum by the XMM-Newton and Chandra satellites from nearby galactic clusters and the Andromeda galaxy claim the presence of a monochromatic 3.5 keV photon line [9]. This anomalies X-ray line triggered a huge amount of theoretical interpretations, as a signal of a 7 keV sterile neutrino dark matter candidate decaying into a photon and an ordinary neutrino. Motivated by this anomalous X-ray emission line, we studied transition magnetic moment of a sterile neutrino which can rise from its conversion to an active neutrino through radiative decay or non-standard interaction with matter. It is found that this inelastic scattering process for a non-relativistic sterile neutrino has a pronounced enhancement in the differential cross section at energy transfer about half of its mass as shown in Fig. 2a for $m_{\text{sa}} = 7.1$ keV [10]. The signal would appear as peaks in the measurable energy spectra. The constraints on sterile neutrino mass and its transition magnetic moment are derived from data taken with low-background and low-threshold germanium detectors. The exclusion plot of transition magnetic moment ($\mu_{\nu_{\text{sa}}}$) versus mass ($m_{\text{sa}}$) at 90% C.L. is illustrated in Fig. 2b.

5. **Coherent Neutrino Nucleus Elastic Scattering**

Coherent neutrino nucleus elastic scattering ($\nu A_{el}$) is a neutral current process which is well-predicted by the SM. This process has been recently observed by COHERENT collaboration using the pion-decay-at-rest neutrino source at the Spallation Neutron Source in Oak Ridge [11]. TEXONO collaboration is also actively pursuing this program with reactor neutrinos [1]. The differential cross section of $\nu A_{el}$ in the SM is given by

$$
\frac{d\sigma_{\nu A_{el}}}{dq^2} = \frac{1}{2} \left[ \frac{G_F^2}{4\pi} \right] \left[ 1 - \frac{q^2}{4E_q} \right] \left[ \epsilon Z F_z(q^2) - NF_N(q^2) \right]^2
$$

(1)

where $F_z(q^2)$ and $F_N(q^2)$ are, respectively, the proton and neutron nuclear form factors, while $\epsilon \equiv [1 - 4sin^2\theta_w]$. A generic scale of $E_\nu < 50$ MeV is usually taken to characterize the requirement of coherency. The departure from coherency for $\nu A_{el}$ is characterized by deviations from the $[\epsilon Z - N]^2$ scaling as $q^2$ increases. The scattering amplitude of individual nucleons adds with a finite relative phase angle to contribute to the cross section. The average phase misalignment...
angle of any nucleon pairs contributes to deviation from coherency for $\nu A_{el}$ [12]. The degree of coherency can therefore be quantified by a measurable parameter $\alpha \equiv \cos\langle \phi \rangle \in [0,1]$. The limiting conditions are that (a) $\alpha = 1$ implies full coherency or $\sigma_{\nu A_{el}} \propto (\epsilon Z - N)^2$, while (b) $\alpha = 0$ brings total incoherency or $\sigma_{\nu A_{el}} \propto [\epsilon^2 Z + N]$. The relative change in cross section is an alternative parameter to characterize partial coherency.

$$\xi \equiv \frac{\sigma_{\nu A_{el}}(\alpha)}{\sigma_{\nu A_{el}}(\alpha = 1)} = \alpha + (1 - \alpha) \left[ \frac{(\epsilon^2 Z + N)}{(\epsilon Z - N)^2} \right]$$

The variations of $\alpha$ and $\xi$ with respect to $E_{\nu}$ and nucleus A(Z,N) are shown in Fig. 3. The low energy reactor $\bar{\nu}_e$ and solar-$^8B\nu_e$ probe the full coherency region ($\alpha > 0.9$), while the intermediate energy DAR-$\pi\nu$’s allow measurements in the transition regions ($0.9 > \alpha > 0.1$).

6. Summary and Prospects

Ge-detectors with 300 eV$_{ee}$ threshold have been used to study neutrino properties and interactions, where the signatures are enhanced at sub-keV. Data taking and analysis are continuing at KSNL, complemented by the CDEX experiment at CJPL on WIMP and axion dark matter searches [13]. Intensive R&D programs are being pursued including the understanding and suppression of sub-keV background and advanced detector hardware configurations, electronic components and pulse shape analysis techniques for signal-noise differentiation.

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