Low Energy Neutrino Physics with sub-keV Ge-Detectors at Kuo-Sheng Neutrino Laboratory

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Abstract. Germanium detectors with sub-keV sensitivities offer a unique opportunity to study neutrino interactions and properties, as well as search for light WIMP Dark Matter. The TEXONO Collaboration has been pursuing research program on low energy neutrino interactions and light WIMP Dark Matter at the Kuo-Sheng Neutrino Laboratory (KSNL) in Taiwan and in the China Jinping Underground Laboratory (CJPL) in China. We present highlights the physics program on the studies of neutrino electromagnetic interactions as well as neutrino-nucleus coherent elastic scattering.

1. Introduction
Neutrinos have been always captivating physicists because of their elusiveness and exciting new properties. Electromagnetic interactions and neutrino-nucleus coherent scattering have a lot of potential in making precision tests of physics within and beyond the Standard Model. The research program of TEXONO Collaboration [1] on neutrino electromagnetic properties, neutrino-nucleus coherent scattering and dark matter physics is pursued at the Kuo-Sheng Neutrino Laboratory (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 has 30 meter-water-equivalent concrete overburden [2]. In order to achieve the 100 eV threshold, the collaboration has studied operational characteristics and performance of several Ge detectors with different configurations under ultra low background environment [3].

2. Electromagnetic Properties of Neutrino
The conservation of lepton number and absence of right-handed neutrino fields in Standard Model lead to the conclusion that the neutrino should be exactly massless. But the experimental verification of the existence of a non-zero neutrino mass and mixing between different neutrino flavors has triggered intensive studies of non-trivial electromagnetic properties such as anomalous neutrino magnetic moments ($\mu_\nu$) and neutrino millicharged. 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 due to anomaly cancellation. However, it is no longer ensured in many extensions of Standard Model. The bottom line is neutrinos become electrically millicharged particles ($q_\nu$), when electric charge is de-quantized.

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
Figure 1. The observable spectra due to neutrino interactions on Ge target with reactor $\bar{\nu}_e$ at $\phi_{\bar{\nu}_e} = 10^{13} \text{ cm}^{-2}\text{s}^{-1}$, 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 [4].

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 [4].

| Data Set       | Reactor-$\bar{\nu}_e$ $10^{13} \text{ cm}^{-2}\text{s}^{-1}$ | Data Strength (kg-days) | Threshold (keV) | Bounds at $\langle \mu_\nu \times 10^{-11} \rangle$ (kg-days) | Bounds at $\langle q_\nu \times 10^{-12} \rangle$ |
|----------------|-----------------------------------------------------------|------------------------|-----------------|-------------------------------------------------|------------------|
| 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 pPCGe  | 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             | $< 0.023$                                       | $< 0.0004$       |

of the incoming neutrino. Both $\mu_\nu$ and $q_\nu$ contributions are enhanced in sub-keV energy region, illustrated in Fig. 1a. To include the atomic effect in the analysis, we adopted the ab-initio Multi-Configuration Relativistic Random-Phase Approximation theory [4]. It is observed that $q_\nu$ contribution has enhancement in cross-sections when atomic effects are properly calculated, as shown in Fig. 1b. The upper bounds on $\mu_\nu$ and $q_\nu$ are listed in Table 1 for different data taking. The potential sensitivities of realistic next-generation measurements with novel Ge techniques when a 1\% measurement of the SM cross section could be achieved, at a threshold of 0.1 keV are also shown in last row of the Table 1.

Sterile neutrinos are Standard Model gauge singlets and they can only interact via their mixing with the active neutrinos. The transition magnetic moment of a sterile neutrino 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, manifesting experimentally as peaks in the measurable energy spectra [5]. The constraints on sterile neutrino mass and its transition magnetic moment are derived from data taken with low-background and low-threshold germanium detectors as shown in Fig. 2a. The exclusion plot of transition magnetic moment ($\mu_{\nu_{sa}}$) versus mass ($m_{sa}$) at 90\% C.L. is illustrated in Fig. 2b.
3. Coherent Elastic Neutrino-Nucleus Scattering

Coherent Neutrino Nucleus Scattering (CENNS) is a neutral current process which is well-predicted by the Standard Model. This process has not yet been experimentally observed, but is actively pursued with the TEXONO program with reactor neutrinos [6]. A generic scale of $E_\nu < 50$ MeV is usually taken to characterize the requirement of coherency. The degree of coherency ($\alpha$) and relative change in cross section ($\xi$) are further parameterized [7]. The variations of $\alpha$ and $\xi$ with respect to $E_\nu$ and nucleus $A(Z,N)$ are shown in Fig. 3.

References
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