AS-TEXONO/05-09
31 October 2005

Research Program towards Observation of Neutrino-Nucleus Coherent Scattering

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Abstract. The article describes the research program pursued by the TEXONO Collaboration towards an experiment to observe coherent scattering between neutrinos and the nucleus at the power reactor. The motivations of studying this process are surveyed. In particular, a threshold of 100-200 eV has been achieved with an ultra-low-energy germanium detector prototype. This detection capability at low energy can also be adapted to conduct searches of Cold Dark Matter in the low-mass region as well as to enhance the sensitivities in the study of neutrino magnetic moments.

Results from recent neutrino experiments provide strong evidence for neutrino oscillations due to finite neutrino masses and mixings [1]. Their physical origin and experimental consequences are not fully understood. Experimental studies on the neutrino properties and interactions can shed light on these fundamental questions and constrain theoretical models, from which unexpected surprises may arise.

Neutrino coherent scattering with the nucleus[2]

$$\nu + \mathrm{N} \rightarrow \nu + \mathrm{N}$$

is a fundamental neutrino interaction which has never been experimentally observed. The Standard Model cross section for this process is given by:

$$(\frac{d\sigma}{dT})^{coh}_{SM} = \frac{G_F^2}{4\pi} m_N [Z(1-4\sin^2\theta_W) - N]^2 [1 - \frac{m_N T_N}{2E_\nu^2}] \quad \text{and} \tag{1}$$

$$\sigma_{tot} = \frac{G_F^2 E_\nu^2}{4\pi} [Z(1-4\sin^2\theta_W) - N]^2 \quad , \tag{2}$$

where m_N, N and Z are the mass, neutron number and atomic number of the nuclei, respectively, E_ν is the incident neutrino energy and T_N is the measure-able recoil energy of the nucleus. This formula is applicable at $E_\nu < 50$ MeV where the momentum transfer (Q^2) is small such that

$Q^2R^2 < 1$, where R is the nuclear size. Although the cross-section is relatively large due to the N^2 enhancement by coherence, the small kinetic energy from nuclear recoils poses severe experimental challenges both to the detector sensitivity and to background control. Various detection schemes using cryogenic[3] or gas detectors[4, 5] have been discussed.

Measurement of the coherent scattering cross-section would provide a sensitive test to the Standard Model[6], probing the weak nuclear charge and radiative corrections due to possible new physics above the weak scale. The coherent interaction plays important role in astrophysical processes where the neutrino-electron scatterings are suppressed due to Fermi gas degeneracy. It is significant to the neutrino dynamics and energy transport in supernovae and neutrons stars[7]. Being a new detection channel for neutrinos, it may provide new approaches to study other aspects of neutrino physics, such as that of supernova neutrinos[5]. Coherent scattering with the nuclei is also the detection mechanism adopted in the direct Dark Matter searches[1], such that its observations and measurements with the known particle neutrino is an important milestone as well.

Nuclear power reactors provide powerful and controllable source of electron anti-neutrinos, and can serve as optimal tool for the studies of neutrino-nucleus scatterings. A research program on low energy neutrino physics[8] is intensely pursued by the TEXONO Collaboration at the Kuo-Sheng (KS) Nuclear Power Station in Taiwan. The expected observable spectra due to $\bar{\nu}_e$-e and $\bar{\nu}_e$-N scatterings with Standard Model (SM) and magnetic moment (MM) interactions at KS are displayed in Figure 1. The maximum nuclear recoil energy T_{max} in $\bar{\nu}_e$-N coherent scatterings is given by:

$$T_{max} = \frac{2E_\nu^2}{M_N + 2E_\nu} \tag{3}$$

which corresponds to $T_{max} = 1.9$ keV in the case of Ge target (A=72.6) exposed to the typical reactor neutrino spectra.

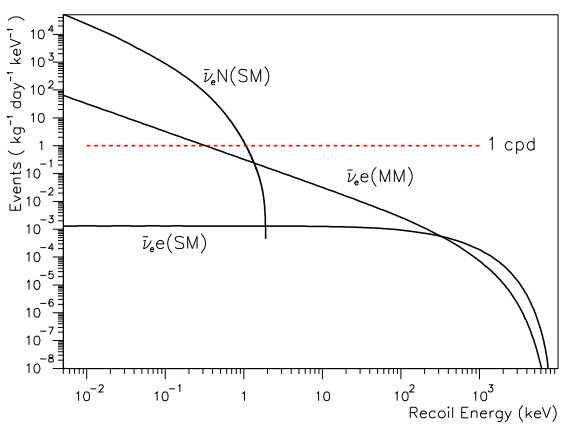

Figure 1. The differential cross-section of the various neutrino interaction channels, at KS-Lab with Ge as the target isotope. The background level of 1 cpd is also shown.

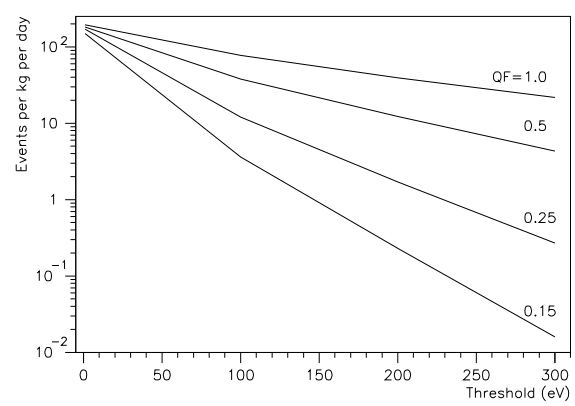

Figure 2. The variations of the neutrino coherent scattering event rates versus threshold at different quenching factors for a 1 kg ULEGe detector at KS Lab.

High-Purity Germanium(HPGe) detectors have been widely and successfully used in various areas of low energy neutrino physics and cold dark matter searches. These detectors are

kilogram-scale in mass, and with a detection threshold ("noise edge") of several keV. A sensitive direct search of neutrino magnetic moments[9] was recently performed with a 1 kg HPGe detector at KS. A physics threshold of 12 keV and a background level of ~ 1 day^{-1}kg^{-1}keV^{-1}(cpd) comparable to underground dark matter experiments were achieved, from which sensitive limits of the ν_e and $\bar{\nu_e}$ magnetic moments were derived[10].

For ionization detectors like germanium, the measure-able energy of nuclear recoil events is only a fraction of their energy deposited due to charge recombination or "quenching" at large dE/dx. The expected event rates for neutrino-nucleus coherent scattering at different threshold and quenching factors (QF) at KS are depicted in Figure 2. The measured QF for Ge is typically 0.25 in the several keV region, such that the maximum measure-able energy for nuclear recoil events is only about 480 eV.

"Ultra-Low-Energy" Germanium (ULEGe) detectors, developed originally for soft X-rays detection, are candidate technologies to meet these challenges of probing into a previously unexplored energy domain. These detectors typically have modular mass of 5-10 grams while detector array of up to N=30 elements have been successfully built. Various prototypes based on this detector technology have been constructed. As illustrations, the measured energy spectrum with a 5 g ULEGe prototype is depicted in Figure 3. After applying pulse shape discrimination (PSD) criteria as illustrated in Figure 4, the electronic noise edge can be suppressed and a threshold of 100-200 eV was achieved.

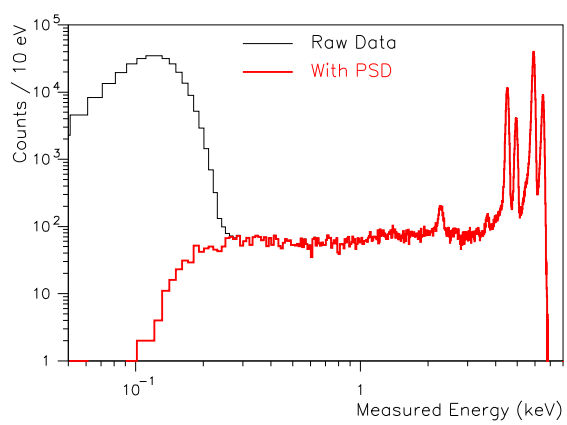

Figure 3. Measured energy spectra with ^{55}Fe source with X-rays from Ti by the ULEGe prototype. The threshold is 100-200 eV after PSD which suppresses the electronic noise edge.

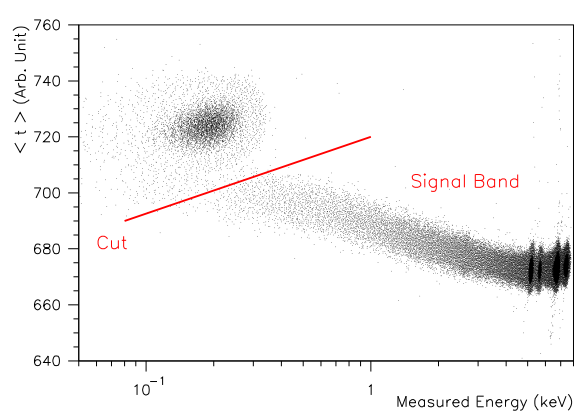

Figure 4. Pulse shape discrimination: mean time versus energy of recorded ULEGe events. Simple selection cuts can be devised to effectively suppress the electronic noise background.

The goal of the ν-N coherent scattering experiment is to develop a ULEGe detector with a total mass of $\sim$1 kg and a modular threshold as low as 100 eV, and a background level below 1 keV in the range of 1 cpd. From Figure 2, at the typical QF=0.25, the event rate for such configurations and projected background levels at KS will be 11 per day, at a signal-to-background ratio of $>$22. A by-product of such an detector would be to further enhance the searches of neutrino magnetic moment at reactors. An improved sensitivity range down to 2×10^{-11} μ_B can be expected. Such detector can also be adopted for Cold Dark Matter

searches, probing the unexplored low WIMP-mass region, as indicated in Figure 5.

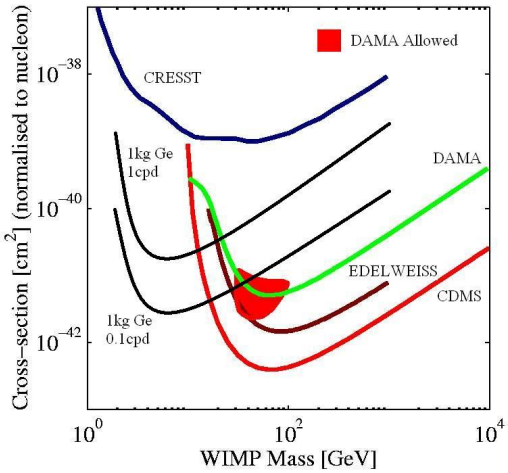

Figure 5. Expected sensitivity region for Cold Dark Matter searches using a ULEGe detector with a total mass of 1 kg.

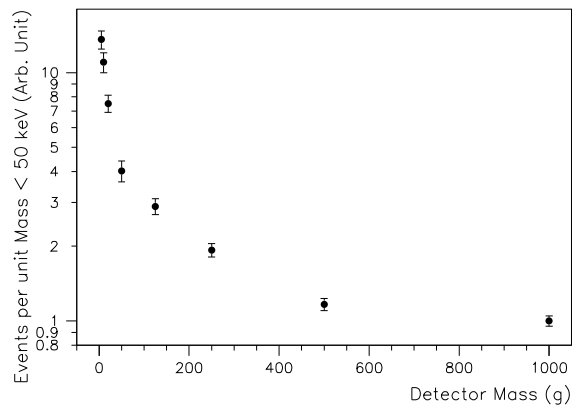

Figure 6. Simulated results on the variations of background per unit mass versus detector mass at the same external γ-background level.

An R&D program towards realization of these experiments is being pursued. As indicated in Figure 6, simulation studies show that background per unit mass can increase by a factor of 10 between Ge-detectors with mass 1 kg and 10 g. The individual elements of the ULEGe can be built into an array form to scale up the target mass to the kg-range. However, they must be assembled within a compact space in order to maintain the same background level of $\sim$1 cpd achieved by the 1 kg HPGe detector at KS. Alternatively, the "segmented" Ge technology, using integrated circuitry approach, is being investigated. Meanwhile, in situ measurements are performed at both KS as well as the Yang-Yang Underground Laboratory in South Korea. A quenching factor measurement for nuclear recoils in Ge with sub-keV ionization energy is being prepared.

This work is supported by contracts NSC93-2112-M-001-030 and NSC94-2112-M-001-028 from the National Science Council, Taiwan, as well as by the Pilot Project Scheme 2004-06 from the Academia Sinica, Taiwan.

[1] See the respective sections in *Review of Particle Physics*, Phys. Lett. **B 592**, 1 (2004), for details and references.

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