Low Energy Neutrino and Dark Matter Physics with sub-keV Germanium Detectors

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Abstract. A TEXONO collaboration research program on low energy neutrino and dark matter physics is going on at the Kuo-Sheng Neutrino Laboratory (KSNL). Collaboration main goals are to measure the neutrino-nucleus coherent scattering cross section, neutrino magnetic moments, and the searches of WIMP dark matter. To achieve these goals various prototype detectors and their sub-keV background are under study. A threshold of 220 eV was achieved with prototype detectors at the KSNL. New limits were set for WIMPs with mass between 3-6 GeV. Data are being taken with a 500 g Point Contact Germanium detector, where a threshold of $\sim$350 eV was demonstrated. A 20 g ULEGe detector is taking data at CJPL in Sichuan, China.

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INTRODUCTION

The research program of TEXONO Collaboration on low energy neutrino and dark matter physics is pursued at the Kuo-Sheng Neutrino Laboratory (KSNL). The KSNL is located at a distance of 28 m from a 2.9 GWt (thermal) reactor core and has an overburden of about 30 mwe [1]. Results on neutrino magnetic moments and neutrino-electron scattering cross section have been obtained. The current goals are to develop novel detectors with kg scale target mass, 100 eV sensitivity and extremely low-background specifications for the searches of Weakly Interacting Massive Particles (WIMPs) and the studies of neutrino-nucleus coherent scattering. The design of Point-Contact Germanium (PCGe) detectors offers the potential merits of sub-keV sensitivities with kg-scale target mass. A PCGe of mass 900 g is collecting data at the KSNL. A limit on neutrino magnetic moments with a 1.06 kg germanium detector at a hardware threshold of 5 keV has been reported. A background level of $\sim$1 count $kg^{-1}keV^{-1}day^{-1}$ (cpd) at 20 keV has also been achieved. New results were recently obtained on the measurement of neutrino-electron scattering cross section and therefore the electroweak angle $sin^2\theta_W$ with a 200 kg CsI(Tl) scintillating crystal detector array.

ν-N COHERENT SCATTERING

Coherent elastic neutral current (NC) neutrino-nucleus scattering

$$\nu + N \rightarrow \nu + N \tag{1}$$

has never been observed prediction of the Standard Model (SM). This process is mediated by neutral currents and hence is flavor blind. Therefore, a neutrino of any flavor scatters off a nucleus at low momentum transfer (Q) such that the nucleon wavefunction amplitudes are in phase and add coherently. The SM cross section for this process is given by:

$$\frac{d\sigma}{dT} = \frac{G_F^2}{4\pi} M_N [Z(1-4sin^2\theta_w) - N]^2 [1 - \frac{M_N T_N}{2E_\nu^2}] \tag{2}$$

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 measurable recoil energy of the nucleus. Eq.(2) is applicable at neutrino energy (E_ν) < 50 MeV. At this neutrino energy the momentum transfer (Q^2) is small such that $Q^2R^2 < 1$, where R is the nucleus size. Corrections due to nuclear form factors can be neglected at low energies: $Q^2 \ll M_N^2$. As $sin^2\theta_w \approx 0.24$, the coherent effect due to scattering on protons is almost canceled. Total yield gives the total coherent neutrino-nucleus scattering cross section which is proportional to N^2. The count rate for coherent scattering versus nuclear recoil energy with typical reactor $\bar{\nu}_e$ spectra is displayed in Figure 1a. Contribution due to neutrino-electron scatterings from the SM and magnetic moment effects also display in Figure 1a. In HPGe, the measurable energy is only a fraction of the total energy deposit for the nuclear recoil events. The quenching factor (QF) is about 0.2-0.25 for Ge in the < 10 keV region. The maximum measurable energy for nuclear recoil events in Ge due to reactor $\bar{\nu}_e$ is about 400 to 500 eV.

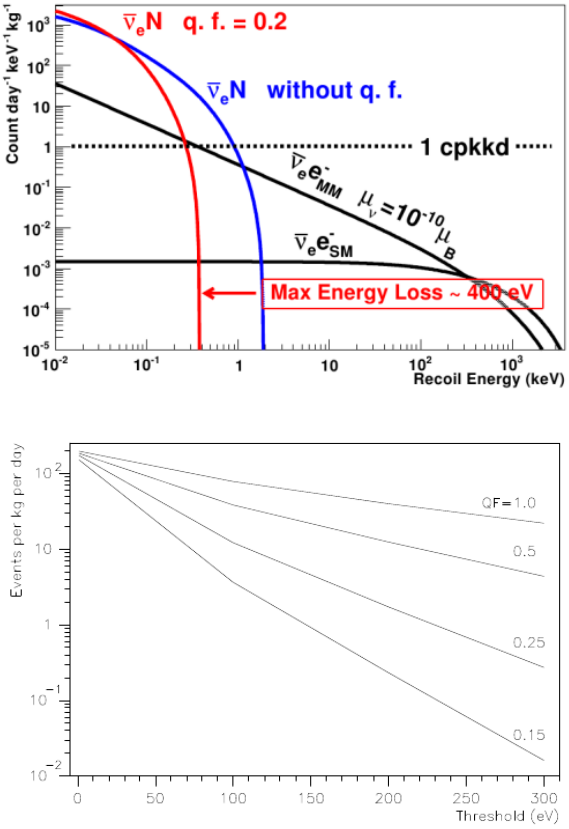


FIGURE 1. (a) Top: The differential cross section of the various neutrino interaction channels at KSNL with Ge as the target isotope. (b) Bottom: The variations of the neutrino coherent scattering event rate versus threshold at different quenching factors for a 1 kg ULEGe detector at KSNL.

Measurement of the coherent scattering cross section would provide a sensitive test to the SM probing the weak nuclear charge and radiative corrections due to possible non-standard neutrino interactions or additional neutral gauge bosons. The coherent interaction plays 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. This scattering may be a promising avenue towards a compact and relatively transportable neutrino detector, an application of which can be for the real-time monitoring on the operation of nuclear reactors, a subject of paramount global importance in the non-proliferation of nuclear materials.

PERFORMANCE OF PCGe DETECTOR

The design of Point-Contact Germanium (PCGe) detectors was first proposed in the 1980 Ref.[3], offering the potential merits of sub-keV sensitivities with kg-scale target mass. There are successful demonstrations of the detector technique [4]. The trigger efficiencies depicted in Figure 2 correspond to the fractions of the distributions above the discriminator threshold level, while the studies on the amplitude distributions of in situ data contributed to the other. The relative timing between the PCGe and anti-Compton (ACV) NaI(Tl) detectors is shown in Figure 3, for sub-noise edge events at 200-400 eV before and after the pulse shape discrimination (PSD) selection. Events in coincidence with ACV at the 50-200 ns window are due to multiple Compton scatterings, which are actual physical processes having similar pulse shapes as the neutrino and WIMP signals. It can be seen that only these events have substantial probabilities of surviving the cuts, and the fractions constitute to the PSD efficiencies. The threshold at ~50% combined efficiencies is ~300 eV. Intensive background and optimization studies with the PCGe at KSNL are underway.

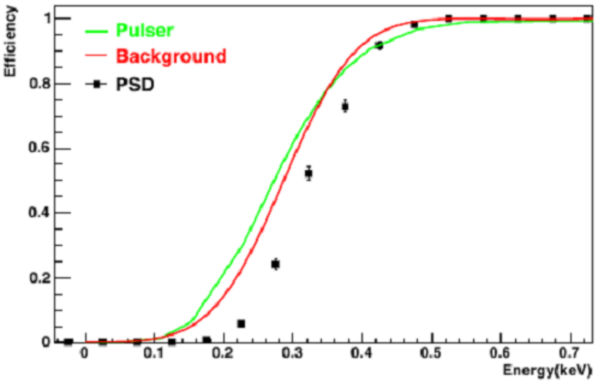


FIGURE 2. The trigger and analysis efficiencies of the 500 g PCGe detector, as derived from the test pulser and in situ events, respectively.

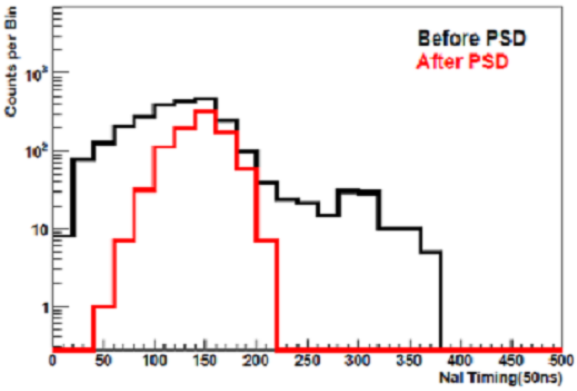


FIGURE 3. Events as a function of relative timing between ACV-NaI(Tl) and PCGe systems before and after PSD selection.

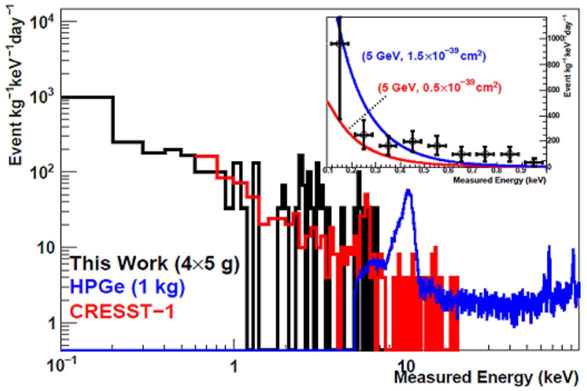
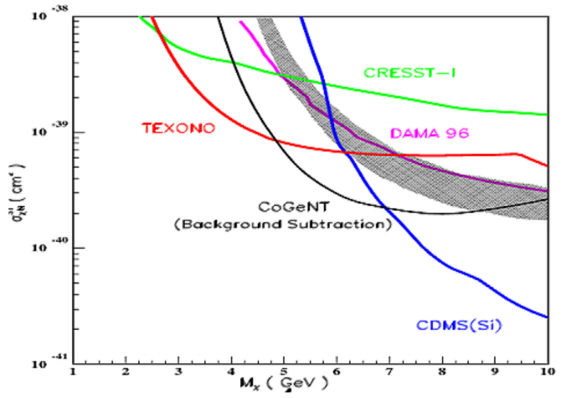


FIGURE 4. The measured spectrum of ULEGe after cosmic-ray and anti-Compton vetos as well as PSD selections with 0.338 kg-day of data.



Results on Dark Matter Searches

WIMPs are the potential dark matter candidates. The popular SUSY models prefer WIMP mass m_χ in 10 to 100 GeV range. Most of the experimental programs optimize their design in the higher mass region and exhibit diminishing sensitivities for $m_\chi < 10$ GeV. A 4-channel Ultra-Low-Energy Germanium (ULEGe) detector with a total active mass of 20 g has collected low-background data at KSNL [2]. The background spectrum with 0.338 kg-day of exposure is shown in Figure 4. Constraints on WIMP-nucleon spin-independent $[\sigma_N^{SI}]$ and spin-dependent$(\sigma_N^{SD}(n))$ couplings as a function of WIMP-mass (m) were derived as depicted in Figures 5(a)&(b), respectively. The KSNL limits improve over previous results at $m \sim 3$ to 6 GeV. Sensitivities for full-scale experiments at 1 cpd background level are projected as dotted lines. The observable nuclear recoils at m = 5 GeV and σ_N^{SI} = 0.5 × 10^{-39} cm^2(allowed) and 1.5 × $10^{-39} cm^2$ (excluded) are superimposed with the measured spectrum.

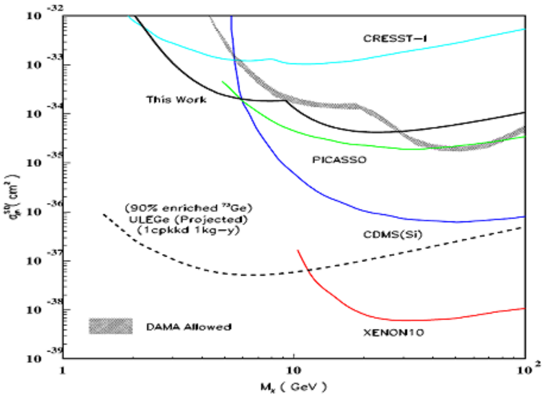


FIGURE 5. Exclusion plot of the spin-independent $\chi-$neutron cross section versus WIMP-mass (b) Exclusion plot of the spin-independent χN cross section versus WIMP-mass.

CHINA JIN-PING UNDERGROUND LAB

The dark matter limits of Ref. [2] are by-product results of an experimental configuration optimized for neutrino physics. It is essential that the program evolves into a dedicated dark matter search experiment in an underground location. China Jin-Ping Laboratory (CJPL), located in Sichuan province of China having more than 2500 m of rock overburden and accessible by a road tunnel built for public traffic and supported by excellent infrastructure already available near the entrance, is about to start. A 4×5 g ULEGe detector has been installed to study the background level since mid 2010.

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