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

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Abstract. The theme of the TEXONO-CDEX research program is on the studies of low energy neutrino and dark matter physics at Kuo-Sheng Reactor Neutrino Laboratory and China Jin-Ping Underground Laboratory. The current goal is to open the “sub-keV” detector window with germanium detectors. The three main scientific subjects are neutrino magnetic moments, neutrino-nucleus coherent scattering, and dark matter searches. We highlight the status, results and plans in this article.

1. Physics Motivations and Goals
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. It is therefore highly motivated to look for and establish alternatives of neutrino sources and detection channels, especially in regions of parameter space which are experimentally unexplored.

In another arena, there are compelling evidence that about 20% of the energy density in the universe is composed of Cold Dark Matter[2] due to a not-yet-identified particle, generically categorized as Weakly Interacting Massive Particle (WIMP, denoted by \( \chi \)). A direct experimental detection of WIMP is one of the biggest challenges in the frontiers of particle physics and cosmology.

The TEXONO Collaboration has contributed in formulating the physics program and in making technical advances to open a detector window in the previously unexplored “sub-keV” regime[3] with low-energy germanium detectors. There is by now increasing interest worldwide. 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\(^{-1}\) (cpk/d). The neutrino physics program is being pursued at the established Kuo-Sheng Reactor Neutrino Laboratory (KSNL), while dark matter searches will be conducted at the new China Jin-Ping Underground Laboratory (CJPL)[4] where construction was recently (Fall 2010) completed. The two facilities are depicted schematically in Figures 1a&b.

1.1. Low Energy Neutrino Physics at KSNL
The various neutrino-induced interactions at KSNL are shown in Figure 2a. The TEXONO program has contributed to the studies of neutrino magnetic moments[5, 6] with a 1-kg high-
purity germanium detector (HPGe) and the measurement of neutrino-electron cross-section[7] with a 200-kg CsI(Tl) scintillator array. An important next goal with sub-keV germanium detectors is to study neutrino coherent scattering with the nucleus ($\nu N$)[8]: $\nu + N \rightarrow \nu + N$, a fundamental neutrino interaction which has never been observed. Measurement of the $\nu N$ coherent scattering is a sensitive test to the Standard Model[9]. It provides a probe to the weak nuclear charge and radiative corrections due to possible non-standard neutrino interactions or additional neutral gauge bosons. The coherent interaction plays an important role in astrophysical processes by being the dominant energy loss process. It is significant to the neutrino dynamics, energy transport and possible collective effects in supernovae and neutron stars[10]. It may be a promising avenue towards a compact and relatively transportable neutrino detector, an important application of which can be the real-time monitoring of nuclear reactors and supernovae detection[11].

The maximum nuclear recoil energy at momentum transfer much larger than neutrino masses is given by: $T_N^{\text{max}} = 2E_\nu^2/(M_N + 2E_\nu)$ The differential cross section for coherent scattering versus nuclear recoil energy for Ge target ($A=72.6$) with typical reactor $\bar{\nu}_e$ spectra is displayed in Figure 2a, where $T_N^{\text{max}} \sim 2$ keV.

In ionization detectors like Ge, the measure-able energy is only a fraction of the energy deposited in nuclear recoils due to their large $dE/dx$. The quenching factor ($QF$), defined as the ratio of the measure-able to the deposit energy, is about 0.2-0.25 for Ge in the $<10$ keV region[12]. Accordingly, the maximum measure-able energy for $\nu N$ in Ge due to reactor $\bar{\nu}_e$ is about 400-500 eV. At QF=0.25, the typical event rate at KSNL will be 11 kg$^{-1}$day$^{-1}$ or 4000 kg$^{-1}$yr$^{-1}$. The signal-to-background ratio will be $>22$ at the benchmark 1 cpk kd level.
Figure 2. (a) Left: The differential cross-section of the various neutrino interaction channels at KSNL with Ge as target, where $\phi(\bar{\nu}_e)=10^{13}$ cm$^{-2}$s$^{-1}$ and $\mu_\nu = 10^{-10}$ $\mu_B$. The background level of 1 cpkdd (kg$^{-1}$keV$^{-1}$day$^{-1}$) is also shown. (b) Right: The measured spectrum of ULEGe with 0.338 kg-day of data, after various background suppression procedures. Background spectra of the CRESST-I experiment and the HPGe are overlaid for comparison.

Figure 3. Exclusion plots of (a) Left: spin-independent $\chi N$ and (b) Right: spin-dependent $\chi N$ cross-sections versus WIMP-mass, displaying the KSNL-ULEGe limits and those defining the current boundaries. The DAMA allowed regions are superimposed. The striped region is that favored by SUSY models. Projected reach of experiments at benchmark sensitivities are indicated as dotted lines. The relevant region is presented with linear scales in the inset.

1.2. Cold Dark Matter Searches at KSNL and CJPL

The WIMPs interact with matter predominantly 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.
Supersymmetric (SUSY) particles are the leading WIMP candidates. The popular SUSY models prefer WIMP mass ($m_{\chi}$) of the range of $\sim 100$ GeV. Most experimental programs optimize their design in the high-mass region and exhibit diminishing sensitivities for $m_{\chi} < 10$ GeV, where there is an allowed region if the annual modulation data of the DAMA experiment[13] are interpreted as WIMP signatures. There are increasing theoretical interest in this light-WIMP region[14, 15], which include models on light neutralinos, non-pointlike SUSY candidates like Q-balls, as well as WIMPless, mirror, asymmetric, and singlet fermionic dark matter. 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.

A detector with 100 eV threshold will therefore open a window for Cold Dark Matter WIMP searches[2] in the unexplored mass range down to several GeV[3]. The uniqueness and advantages of having a low-threshold detector are twofold. Firstly, a new window of observation is opened for low-mass WIMPs. Secondly, the minimum velocity of WIMPs that produces $\chi N$ is proportional to the recoil energy. Therefore, a lower threshold allows a larger range of WIMPs to contribute in an observable interaction and hence results in better sensitivities for all values of $m_{\chi}$.

Based on data taken at KSNL with the 20-g prototype Ultra-Low-Energy Germanium detector (ULEGe), competitive limits were derived in the low WIMP mass region ($3 < m_{\chi} < 6$ GeV)[16] exceeding those from the previous CRESST-I experiment[17]. The $\sigma_{SI}^{\chi N}$ versus $m_{\chi}$ and $\sigma_{SD}^{\chi N}$ versus $m_{\chi}$ exclusion plots are depicted in Figures 3a&b, respectively. The various results[18] defining the exclusion boundaries are also shown. The shaded region is a still-disputed allowed parameter space claimed by the DAMA group[13]. Projected sensitivities of a 1-kg ULEGe detector are also displayed. The CoGeNT experiment[19] first realized the Point-Contact Germanium detectors (PCGe)[20] which offer sub-keV sensitivities with detector of kg-size modular mass. Their 2010 results[19] at the Soudan Underground Laboratory, where both limit and allowed region were reported, inspire a host of theoretical investigations on possible low-mass WIMPs[15].

The underground facility CJPL[4], shown in Figure 1b, is located at Sichuan, China, with $\sim 2500$ meter of rock overburden and tunnel drive-in access. It is owned by the Ertan Hydropower Development Company, and managed by Tsinghua University, China. Construction of the first experimental hall (“Hall A”) of dimension 6 m(width)$\times 6$ m(height)$\times 40$ m(length) and the first shielding structures were completed in September 2010. By the end of 2010, the necessary infrastructures, office and dormitory spaces are being installed. The first experiment with the 20 g ULEGe is being set up, followed by the 1-kg PCGe to be installed in 2011. Upgrades of detector to the 10-kg mass range at the 2012−2013 frame are planned. Potential reaches with benchmark sensitivities are depicted by dotted lines in Figures 3a&b.

2. Sub-keV Germanium Detector

Several R&D directions are intensely pursued towards improvement on the threshold and background for sub-keV germanium detectors:

(i) Pulse Shape Analysis of Near Noise-Edge Events:

It has been demonstrated that by studying the correlation of the Ge signals in two different shaping times[16] as depicted in Figure 4a, the threshold can be further reduced below the hardware noise edge via Pulse Shape Discrimination (PSD). The achieved thresholds at 50% signal efficiency are 220 eV and 310 eV for 20-g ULEGe and 500-g PCGe, respectively. As illustrations, the relative timing between the PCGe and anti-Compton (AC) NaI(Tl) detectors is shown in Figure 5a, for “sub-noise edge” events at 200-400 eV before and after PSD. Events in coincidence with AC 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. The PSD selection efficiencies depicted in Figure 5b
Figure 4. (a) Left: Scattered plots of the $SA_6^P$ (shaping time 6 µs with partial integration) versus $SA_{12}^P$ (shaping time 12 µs with partial integration) signals, for both calibration and physics events. The PSD selection is shown. (b) Right: Rise time plots, as characterized by the amplitude of timing amplifier (TA) signals, showing different behaviour between surface (faster) and bulk (slower) events.

Figure 5. (a) Left: Selection of relative timing between AC-NaI(Tl) and PCGe systems, before and after PSD selection. The “50–200 ns” is the coincidence window where the signals at PCGe are mostly due to physics events correlated with the AC detector. (b) Right: The trigger efficiencies of the 500 g PCGe detector, as derived from the test pulser and \textit{in situ} background events, respectively. PSD selection efficiencies were derived from the survival probabilities of AC-tagged events of (a).

were derived from the survival probabilities of these AC-tagged samples in the coincidence window. The trigger efficiencies were measured with two methods. The fractions of calibrated pulser events above the discriminator threshold provided the first measurement, while the studies on the amplitude distributions of \textit{in situ} background contributed to the other. Further improvement are being made both on PSD algorithms and on efficiency measurement.

(ii) Pulse Shape Analysis of Surface Vs Bulk Events:
The surface and bulk events in PCGe can be separated by the rise time of the pulses as characterized by the amplitude of timing amplifier (TA) signals. It is illustrated in Figure 4b.
(iii) Background Understanding and Suppression:
The MeV-range background was understood to the percent level in our previous neutrino-electron measurement with CsI(Tl) scintillating crystal array\cite{7}. However, the measured sub-keV spectrum of Figure 2b at KSNL could not be explained with standard background modeling on ambient radioactivity. Intense efforts on hardware cross-checks, further simulation and software analysis are underway. Data taking at CJPL, where the cosmic-induced background will be absent, will also elucidate the origin of the observed sub-keV events.

3. Prospects and Outlook
A detector with 1 kg mass, 100 eV threshold and 1 cpkkd background level has important applications in neutrino and dark matter physics, as well as in the monitoring of reactor operation. Crucial advances have been made in adapting the Ge detector technology towards these requirements. Relevant limits have been achieved in prototype studies at KSNL on the WIMP couplings with matter. The sub-keV events are still to be understood. Intensive research programs are being pursued along various fronts towards realization of experiments which can meet all the technical challenges. Detectors with kg-scale are being deployed at KSNL and CJPL.

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