Dark Matter Searches with sub-keV Germanium Detectors

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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 for dark matter searches. We highlight the status, results and plans in this article.

1 Physics Motivations and Goals

There are compelling evidence that about 20% of the energy density in the universe is composed of Cold Dark Matter[1] due to a not-yet-identified particle, generically categorized as Weakly Interacting Massive Particle (WIMP, denoted by χ). 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[2] with low-energy germanium detectors. The generic 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 $\mathrm{kg^{-1}keV^{-1}day^{-1}}$ (cpkkd). The neutrino physics program and dark matter searches is being pursued at the established Kuo-Sheng Reactor Neutrino Laboratory (KSNL), while underground dark matter searches will be conducted at the new China Jin-Ping Underground Laboratory (CJPL)[3]. The two facilities are depicted schematically in Figures 1a&b.

1.1 Cold Dark Matter Searches at KSNL and CJPL

The WIMPs interact with matter pre-dominantly via: $\chi + \mathrm{N} \rightarrow \chi + \mathrm{N}$. There may be both spin-independent and spin-dependent interactions.

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[4] are interpreted as WIMP signatures. There are increasing theoretical interest in this light-WIMP region[5, 6], which include models on light neutralinos, non-pointlike SUSY candidates like Q-balls, as well as WIMPless, mirror, asymmetric, and singlet fermionic dark matter.

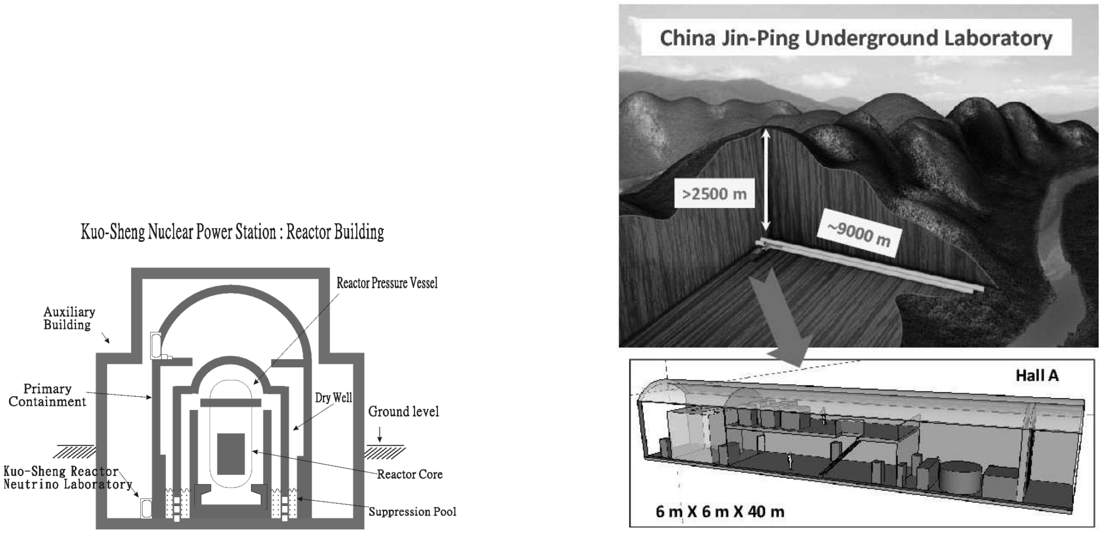

Figure 1: Schematic diagrams of the two facilities where our experiments are conducted: (a) Left: Kuo-Sheng Reactor Neutrino Laboratory (KSNL) (b) Right: China Jin-Ping Underground Laboratory (CJPL).

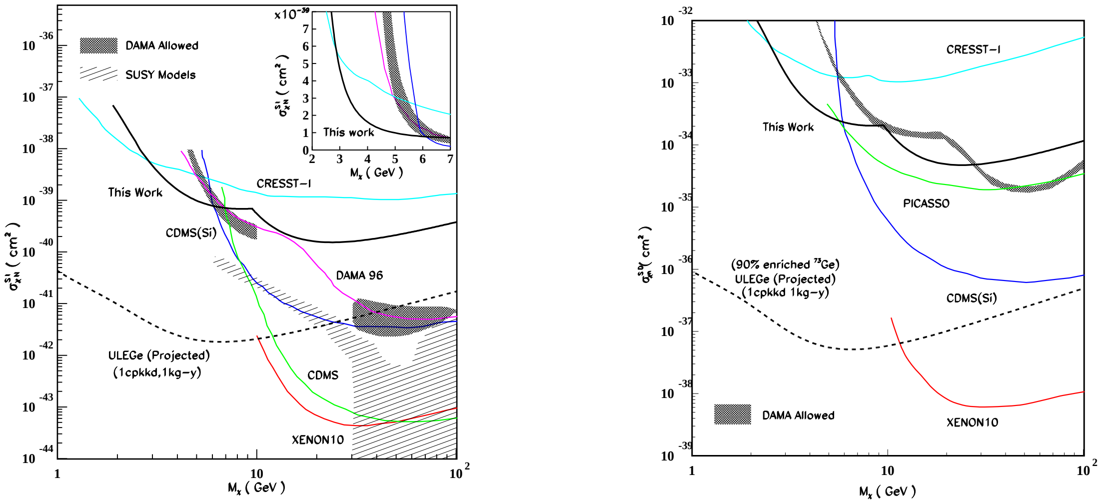

Figure 2: Exclusion plots of (a) Left: spin-independent χN and (b) Right: spin-dependent χN cross-sections versus WIMP-mass, displaying the KSNL-ULEGe limits and those defining the current boundaries The DAMA allowed regions are superimposed. The striped region is that favored by SUSY models. Projected reach of experiments at benchmark sensitivities are indicated as dotted lines. The relevant region is presented with linear scales in the inset.

A detector with 100 eV threshold will therefore open a window for Cold Dark Matter WIMP searches[1] in the unexplored mass range down to several GeV[2]. 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 χN 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_χ.

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)[7]. The $\sigma_{\chi\mathrm{N}}^{\mathrm{SI}}$ versus m_χ and $\sigma_{\chi\mathrm{N}}^{\mathrm{SD}}$ versus m_χ exclusion plots are depicted in Figures 2a&b, respectively. The various results[8][9][10] defining the exclusion boundaries are also shown.

The underground facility CJPL[3], shown in Figure 1b, is located at Sichuan, China, with ∼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)×6 m(height)×40 m(length) and the first shielding structures were completed in September 2010. By the mid of 2011, the necessary infrastructures, office and dormitory spaces are being installed. The first experiment with the 20 g ULEGe and 1-kg PCGe are being set up 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 2a&b.

2 Sub-keV Germanium Detectors

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

1. **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[7] as depicted in Figure 3a, 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. The PSD selection efficiencies were derived from the survival probabilities of these anti-Comptoni(AC)-tagged samples in the coincidence window[7]. The trigger efficiencies were measured with the fractions of calibrated pulser events above the discriminator threshold provided the first measurement and the studies on the amplitude distributions of *in situ* background[7].

2. **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 3b.

3. **Background Understanding and Suppression:**
   The measured sub-keV spectrum at KSNL [7] could not be explained with standard background modeling on ambient radioactivity. Intense efforts on hardware cross-checks, further simulation and software analysis are underway.

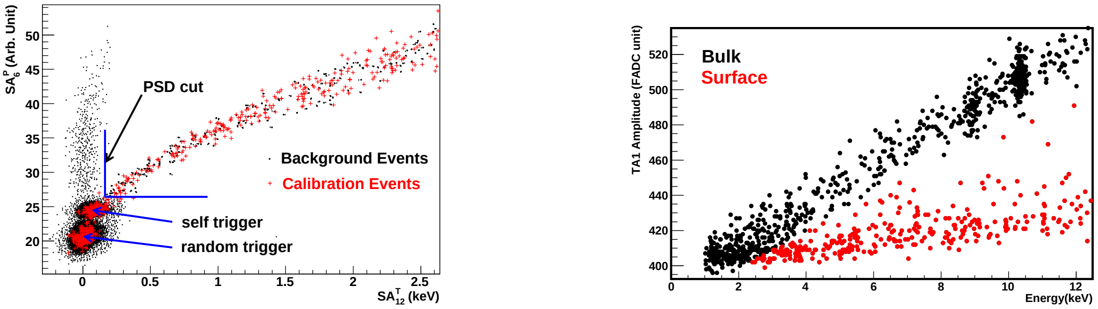

Figure 3: (a) Left: Scattered plots of the SA$_6^P$ (shaping time 6 μs with partial integration) versus SA$_{12}^T$ (shaping time 12 μs with partial integration) signals, for both calibration and physics events. The PSD selection is shown. (b) Right: Rise time plots, as characterized by the amplitude of timing amplifier (TA) signals, showing different behaviour between surface (faster) and bulk (slower) events.

3 Prospects and Outlook

A detector with 1 kg mass, 100 eV threshold and 1 cpkkd background level has important applications in dark matter physics. 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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