PROCEEDINGS OF SCIENCE

Low-Mass Dark Matter Searches with Sub-keV Germanium Detectors

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1. Introduction

The theme of the CDEX-TEXONO research program is on the studies of low energy neutrino and dark matter physics. The current objectives are to open the "sub-keV" detector window with germanium detectors [1]. 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 $kg^{-1}keV^{-1}day^{-1}$ (cpkkd). The neutrino physics program [2, 3] is pursued at the established Kuo-Sheng Reactor Neutrino Laboratory (KSNL), while dark matter searches will be conducted at the new China Jinping Underground Laboratory (CJPL) [5] officially inaugurated in December 2010. The three main scientific subjects are neutrino magnetic moments [2, 4], neutrino-nucleus coherent scattering [1], and dark matter searches [6]. We highlight the status and plans of the dark matter program in this article.

2. Dark Matter Searches at CJPL

There are compelling evidence that about one-quarter of the energy density in the universe is composed of Cold Dark Matter [6] 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 WIMPs interact with matter pre-dominantly via elastic coherent scattering like the neutrinos: $\chi + \mathrm{N} \rightarrow \chi + \mathrm{N}$. There may be both spin-independent ($\sigma_{\chi N}^{SI}$) and spin-dependent ($\sigma_{\chi N}^{SD}$) interactions between WIMP and matter.

The facility CJPL [5] is the deepest operating underground laboratory in the world, having $\sim$2400 meter of rock overburden and tunnel drive-in access, as shown schematically in Figure 1, It is located at southwest Sichuan, China, reachable from the provincial international airport at Chengdu via a 50 min flight to Xichang followed by a 90 min drive on a private two-lane motorway. The laboratory is owned by the Ertan Hydropower Development Company, and managed by Tsinghua University, China. Excavation and construction of the first experimental hall ("Hall A") of dimension 6.5 m(width)X6.5 m(height)X40 m(length) with 50 cm of concrete lining was completed in summer 2010. By Fall 2011, the ventilation system, high-speed internet connections, as well as the necessary surface infrastructures (office and dormitory spaces, liquid nitrogen storage system) have been installed. There are intense efforts at CJPL to characterize the background. Measurements are being performed on the ambient radioactivity as well as fast and thermal neutron fluxes. Residual cosmic-ray events have been observed, at a rate (several events per month per square-meter) consistent with the expectation for a location with 2400 m rock overburden. The first generation experimental program at CJPL will include two projects: the CDEX-TEXONO experiment described here, and the dark matter project PandaX with liquid xenon detector. A facility for measuring and screening low-radiopurity materials will be installed. Future expansions of the laboratory are foreseen. New ideas are being discussed and explored.

An experiment with 100 eV threshold would open a window for Cold Dark Matter WIMP searches [6] in the unexplored mass range down to several GeV [1]. Based on data taken at KSNL with the 20-g prototype Ultra-Low-Energy Germanium detector (ULEGe), limits were derived in this low WIMP mass region improving over those from the previous experiments at $3 < m_{\chi} <$

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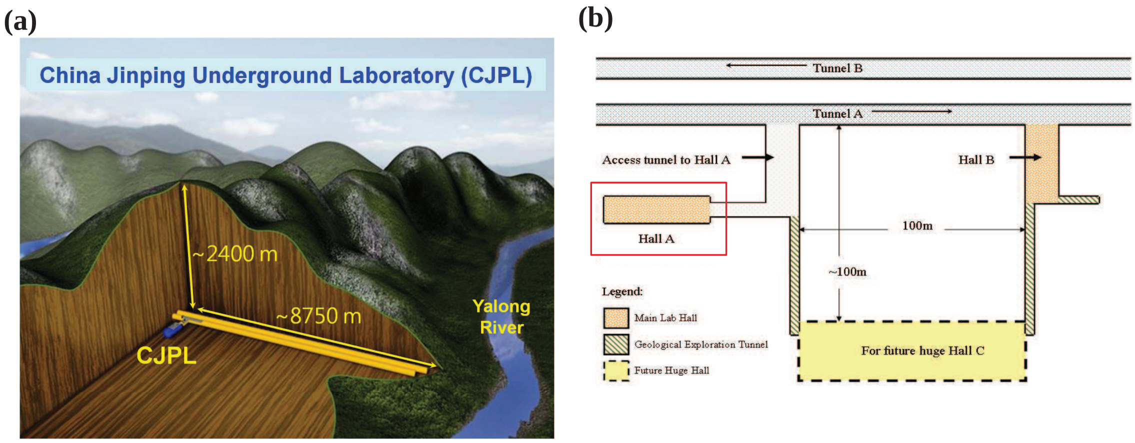

Figure 1: Schematics diagrams displaying the essential features of CJPL: (a) Geographical setting showing tunnel length and overburden; (b) Floor Plan of the present Hall-A and expected future expansions;

6 GeV [7]. The $\sigma_{\chi N}^{SI}$ versus m_χ and $\sigma_{\chi N}^{SD}$ versus m_χ exclusion plots are depicted in Figures 3a&b, respectively. Also displayed are the various results defining the exclusion boundaries, together with allowed regions implied by the DAMA/LIBRA, CoGeNT and CRESST-II data [8, 9]. In particular, interpretations of the recent CoGeNT low-energy spectra as positive signatures of low-mass WIMPs [9] have stimulated intense theoretical interests and speculations on this parameter space.

A polyethylene (PE) shielding structure with thickness 1 m and interior dimension 8 m(length)×4.5 m(width)×4 m(height) has been constructed for the CDEX-TEXONO program at CJPL. A 20-g ULEGe array and a 1-kg PCGe have been installed within OFHC copper shielding inside this PE-housing. Data taking has commenced in February 2011. Design and construction of the next-generation PCGe array with total mass at the 10-kg range is proceeding. This new detector will be shielded and enclosed in a liquid argon chamber which serves as both cryogenic medium and active shielding and anti-Compton detector where the scintillation light will be read out by photomultipliers. The conceptual design of this "CDEX-10" is shown in Figure 2. Commissioning is planned in 2013.

Potential reaches are depicted by dotted lines in Figures 3a&b. The projected sensitivities assume Ge detectors at 100 eV threshold (equivalent to about 500 eV nuclear recoils), 10 kg-year of exposure and that the achieved background level of the order of 1 cpkkd at the few keV range can be extrapolated down to threshold.

3. Sub-keV Germanium Detectors

Point-Contact Germanium detectors (PCGe) [10] offer sub-keV sensitivities with detector of kg-size modular mass, an improvement over the conventional ULEGe design. WIMPs with mass down to a few GeV can be probed.

Several R&D directions [11] are intensely pursued towards improvement on the threshold and background for sub-keV germanium detectors:

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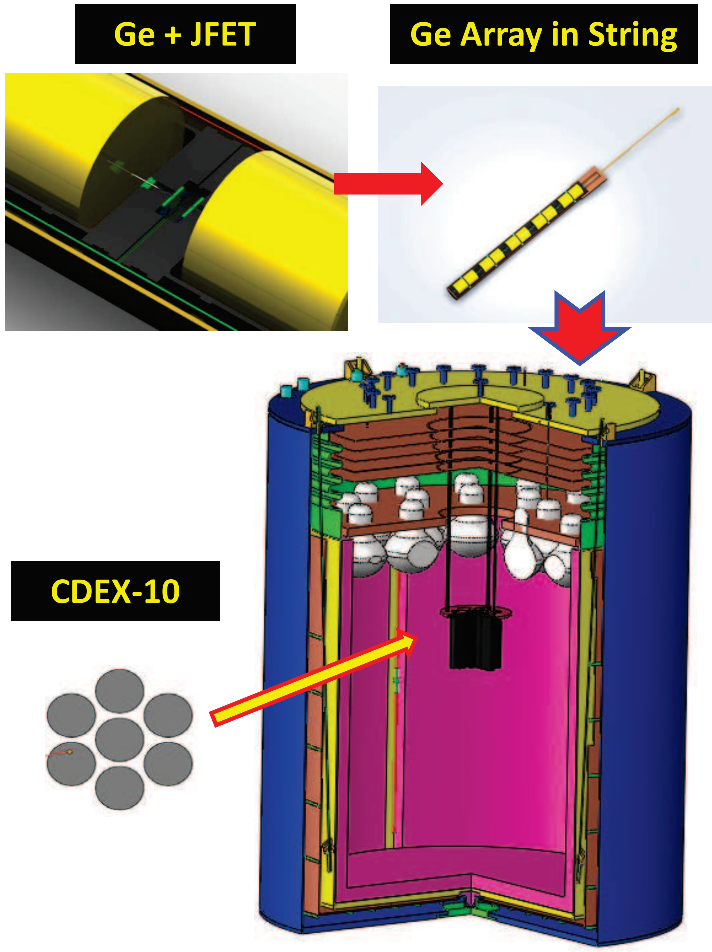

Figure 2: Conceptual design drawings of the CDEX-10 detector with the range of 10 kg germanium sensor array enclosed by a liquid argon anti-Compton detector.

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 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.

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 4b.

3. **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 [3]. However, the measured sub-keV spectrum at KSNL [7] could not be explained with standard background modeling

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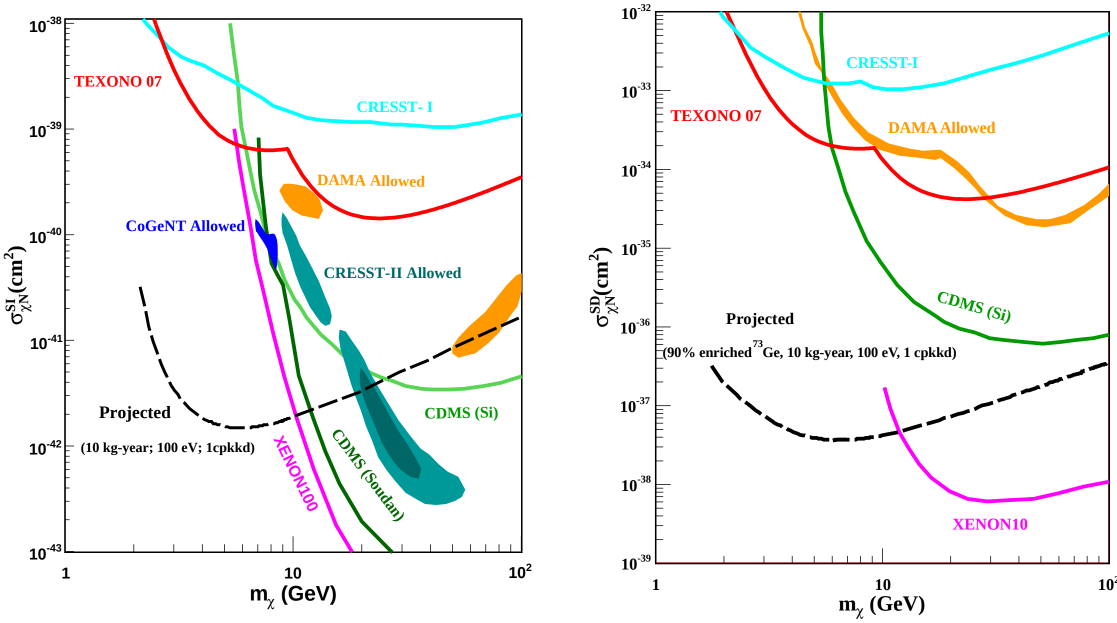

Figure 3: Exclusion plots of (a) Top: spin-independent χN and (b) Bottom: spin-dependent χN cross-sections versus WIMP-mass, displaying the KSNL-ULEGe limits [7] and those defining the current boundaries [6, 8]. The DAMA, CoGeNT and CRESST-II allowed regions [8, 9] are superimposed. Projected reach of experiments at benchmark sensitivities are indicated as dotted lines.

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.

4. **Fabrication of advanced electronics for Ge detectors:** R&D program is being pursued to produce advanced JFET and pre-amplifier electronics with goals of further reducing threshold and improving energy resolution. Data acquisition and trigger systems with real time analysis capabilities using Field Programmable Gate Arrays (FPGA) are being installed.

4. 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.

† The CDEX-TEXONO Collaboration consists of groups from China (Tsinghua University, China Institute of Atomic Energy, Nankai University, Sichuan University, Ertan Hydropower Development Company), Taiwan (Academia Sinica, Institute of Nuclear Energy, Kuo-Sheng Nuclear Power Station, National Tsing-Hua University), India (Banaras Hindu University) and Turkey

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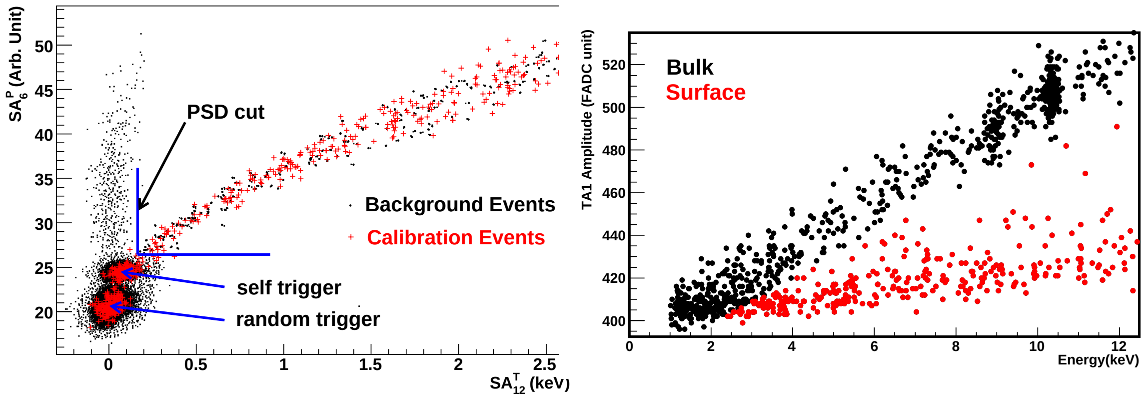

Figure 4: (a) Top: Scattered plots of the SA_6^P (shaping time 6 μs with partial integration) versus SA_{12}^T (shaping time 12 μs with partial integration) signals, for both calibration and physics events. The PSD selection is shown. (b) Bottom: Rise time plots, as characterized by the amplitude of timing amplifier (TA) signals, showing different behaviour between surface (faster) and bulk (slower) events.

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