The CDEX Dark Matter Program at the China Jinping Underground Laboratory

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Abstract.
The China Jinping Underground Laboratory (CJPL) is a new facility for conducting low event-rate experiments. We present an overview of CJPL and the CDEX Dark Matter program based on germanium detectors with sub-keV sensitivities. The achieved results, status as well as the R&D and technology acquisition efforts towards a ton-scale experiment are reported.

1. China Jinping Underground Laboratory
The China Jinping Underground Laboratory (CJPL)[1] is located in Sichuan, China, and was inaugurated in December 2012. With a rock overburden of about 2400 meter, it is the deepest operating underground laboratory in the world. The muon flux is measured to be 
\[ (2.0 \pm 0.4) \times 10^{-10} \text{cm}^{-2} \text{s}^{-1} \]

The drive-in tunnel access can greatly facilitate the deployment of big experiments and large teams. Supporting infrastructures of catering and accommodation, as well as office and workshop spaces, already exist.

As depicted schematically in Figure 1, the completed CJPL Phase-I consist of a laboratory hall of dimension 6 m(W) × 6 m(H) × 40 m(L). This space is currently used by the CDEX[3] and PandaX[4] dark matter experiments, as well as for a general purpose low radiopurity screening facility.

Additional laboratory space for CJPL Phase-II, located about 500 m from the Phase-I site, is currently under construction. Upon the scheduled completion by early 2017, it will consist of four halls each with dimension 14 m(W) × 14 m(H) × 130 m(L). The tunnel layout is as displayed in Figure2a.

2. CDEX Dark Matter Program
About one-quarter of the energy density of the Universe can be attributed to cold dark matter [5], whose nature and properties are unknown. Weakly interacting massive particles (WIMPs

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Figure 1. Schematic diagram of CJPL Phase-I inaugurated in 2012, showing the space allocation to the CDEX and PandaX Dark Matter experiments, as well as to the radiopurity screening facilities.

denoted by $\chi$) are its leading candidates. The WIMPs interact with matter pre-dominantly via elastic scattering with the nucleus: $\chi + N \rightarrow \chi + N$. The unique advantages of CJPL make it an ideal location to perform experiments on dark matter searches.

Germanium detectors sensitive to sub-keV recoil energy were identified and demonstrated as possible means to probe the “light” WIMPs with mass range $1 \text{ GeV} < m_\chi < 10 \text{ GeV}$[6]. This inspired development of p-type point-contact germanium detectors (pPCGe) with modular mass of kg-scale[7], followed by various experimental efforts[8, 9, 10]. The scientific theme of CDEX (China Dark matter EXperiment)[3] is to pursue studies of light WIMPs with pPCGe. It is one of the two founding experimental programs at CJPL.

2.1. First Generation CDEX Experiments

As depicted in Figure 3, the first-generation experiments adopted a baseline design[9] of single-element “1-kg mass scale” pPCGe enclosed by NaI(Tl) crystal scintillator as anti-Compton detectors. These active detectors are further surrounded by passive shieldings of OFHC copper, boron-loaded polyethylene (PE(B)) and lead, while the detector volume is purged by dry nitrogen to suppress radon contamination.

The pilot CDEX-0 measurement is based on a 20 g prototype Ge detector at 177 (eV$_{ee}$) threshold with an exposure of 0.784 kg-days[11]. The CDEX-1 experiment adopts a pPCGe detector of mass 1 kg. The first results are based on an analysis threshold of 475 eV$_{ee}$ with an exposure of 53.9 kg-days[12]. After suppression of the anomalous surface background events and measuring their signal efficiencies and background leakage factors with calibration data[13], all
residual events can be accounted for by known background models, as illustrated in Figure 4. Dark Matter constraints on $\chi N$ spin-independent cross-sections were derived for both data set, and are displayed in Figure 5, together with other selected benchmark results [14]. In particular, the allowed region from the CoGeNT [8] experiment is probed and excluded with the CDEX-1 results.

Analysis is currently performed on CDEX-1 data set with year-long exposure. Annual modulation effects as well as other physics channels are being studied. New data is also taken with an upgraded pPCGe with lower threshold.

2.2. Current Efforts and Future Goals
The long-term goal of the CDEX program will be a ton-scale germanium experiment (CDEX-1T) at CJPL for the searches of dark matter and of neutrinoless double beta decay ($0\nu\beta\beta$)[15]. A pit of diameter 18 m and height 18 m will be built at one of the halls of CJPL-Phase II to house such an experiment, as illustrated in Figure 2b.

Towards this ends, the “CDEX-10” prototype has been constructed with detectors in array structure having a target mass at the 10-kg range. This would provide a platform to study the many issues of scaling up in detector mass and in improvement of background and threshold. The detector array is shielded and cooled by a cryogenic liquid. Liquid nitrogen is being used, while liquid argon is a future option to investigate, which may offer the additional potential benefits of an active shielding as anti-Compton detector.
In addition, various crucial technology acquisition projects are pursued, which would make a ton-scale germanium experiment realistic and feasible. These include:

(i) detector grade germanium crystal growth;
(ii) germanium detector fabrication;
(iii) isotopic enrichment of $^{76}\text{Ge}$ for $0\nu\beta\beta$;
(iv) production of electro-formed copper, eventually underground at CJPL.

The first detector fabricated by the Collaboration from commercial crystal that matches expected performance will be installed at CJPL in 2016. It allows control of assembly materials placed at its vicinity, known to be the dominant source of radioactive background, as well as efficient testing of novel electronics and readout schemes. The benchmark would be to perform light WIMP searches with germanium detectors with "$0\nu\beta\beta$-grade" background control. This configuration would provide the first observation (or stringent upper bounds) of the potential cosmogenic tritium contaminations in germanium detectors, from which the strategies to suppress such background can be explored.

The projected $\chi N$ sensitivity for CDEX-1T is shown in Figure 5, taking a realistic minimal surface exposure of six months. The goal for $0\nu\beta\beta$ will be to achieve sensitivities covering completely the inverted neutrino mass hierarchy.
Figure 5. Exclusion regions derived from the CDEX-0 and CDEX-1 experiments, and comparison with other benchmark results. Projected sensitivities of the current detectors and future projects are superimposed.

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