Recent status and prospects of CDEX dark matter search at CJPL

Xu Rui
Tsinghua University
On behalf of the CDEX collaboration
2023 Jun.12 @ PPC2023, Daejeon, Korea
Outline

• Dark Matter (DM) and its Direct detection (DD)

• Introduction to CDEX and CJPL

• Recent status of CDEX

• Prospect of CDEX

• Summary
Dark Matter

- Direct
- Indirect
- Accelerator
Dark Matter Direct Detection

• Advantage of Ge detector:
  ✓ Lower Background
  ✓ Lower Energy threshold
  ✓ Better Energy Resolution
  ✓ Long-time stability

\[
\frac{dR}{dE_R} = N_T \frac{\rho \chi}{m_{\chi}} \int d^3 \vec{v} v f_v (\vec{v} + \vec{v}_E) \frac{d\sigma}{dE_R}
\]
China Dark matter EXperiment

- Formed in 2009, 11 institutions and 100 persons now;
- Direct detection of light DM by High Purity Germanium detectors (HPGe);
World’s deepest underground lab, CJPL

- Constructed by Tsinghua U. and Yalong Hydropower Company in 2009-2010
- Extension project, CJPL-II, final exam and expected to be completed in 2024
CDEX Experiment

- DM detection with Ge prepared since 2003 and started in 2005 in Y2L (5g);
- **CDEX-1**: Development of **PPC Ge detector**, bkg understanding, since 2011;
- **CDEX-10**: Performances of **Ge array detector** immersed in LN$_2$, since 2016;

P-type Point-Contact (PPC) Germanium detector
CDEX-1 Status

- 2 sub-stages: **CDEX-1A** (2011) → **CDEX-1B** (upgraded, 2013);
- Traditional single-element ~1kg PPC Ge detector;
- Low-bkg Pb&Cu passive shield + NaI veto detector;
- Located in PE room at CJPL-I;

![CDEX-1A&B: 1kg PPC Ge×2](image_url)
CDEX-10 Status

- Array detectors: 3 strings with 3 detectors each, ~10kg total;
- Direct immersion in LN2 for cooling and shielding;
- Prototype system for future hundred-kg to ton scale experiment
  - Light/radio-purer LN2 replacing heavy shield i.e. Pb/Cu;
  - Arraying technology to scalable capability;
Dataset of CDEX-1B&10B

- **Threshold:**
  - ✓ 160 eVee (electron equivalent energy)

- **Background level:**
  - ✓ 2.5 cpkqd@2-4 keVee (cts/(keV·kg·day))

- **Exposure:**
  - ✓ CDEX-1B: 1107.5 kg\(\cdot\)day
  - ✓ C10-B1: 205.4 kg\(\cdot\)day

Measured C1B(red) and C10B1 spectrum. The combined efficiency is shown in the inset.

CDEX-1 & CDEX-10 Results

- **WIMP search**
  - $\chi - N$ elastic scattering
  - Annual modulation *PRL 123, 221301 (2019)*
  - Migdal effect *PRL 123, 161301 (2019)*
  - Boosted WIMP: down to $\mathcal{O}(10 \text{ keV})$ *PRD 106, 052008 (2022)*
  - $\chi - e$ scattering down to $\mathcal{O}(10 \text{ MeV})$ *PRL 129, 221301 (2022)*

- **New physics beyond the WIMP**
  - Axion like particle: down to $\mathcal{O}(100 \text{ eV})$ *PRD 101, 052003 (2020); PRD 95, 052006 (2017)*
  - Dark photon: down to $\mathcal{O}(100 \text{ eV})$ *PRL 124, 111301, (2020)*
  - Exotic DM: down to $\mathcal{O}(1 \text{ MeV})$ *PRL 129, 221802, (2022)*
χ−N elastic scattering from CDEX-1B&10

- **CDEX-1B:**
  - First extended the mass to 2 GeV among Ge experiments.
  - The most sensitive result on SD χ−N elastic scattering below 4 GeV.
  - The best result on the WIMP annual modulation below 6 GeV.

- **CDEX-10:**
  - The most sensitive result on SI χ−N elastic scattering at 4-5 GeV.

**Chin. Phys. C** 42, 023002 (2018)  
Annual Modulation analysis from CDEX-1B

- AM provide smoking-gun signatures for WIMPs independent of background modeling, while only requires background is stable with time;
- CDEX-1B excludes CoGeNT’s signal region, also DAMA/LIBRA phase-1’s interpretation with the WIMP SI interaction under Standard Halo model in Germanium crystal.


Best-fit of modulation amplitude w/ phase=152.5 day

SI Limits from AM

2023/6/12
WIMP searches with Migdal effect

- **Migdal effect (ME):**
  - Elastic scattering: $\chi + N \rightarrow \nu + N(E_R)$
  - Migdal effect: $\chi + A \rightarrow \chi + N(E_R) + e^-(E_{EM})$

- Time-Integrated Analysis with Migdal: 737.1 kg-d, w/ Eth 160 eVee;
- AM Analysis: 1107.5 kg·day, w/ Eth 250 eVee;
- Leading sensitivity in 50-180 MeV;

Cosmic Ray Boosted DM (CRDM)

- DM particles can be boosted to relativistic momenta by elastic scattering with CR nucleus in the Galaxy;
- Using CDEX-10 205.4 kg·day data and the CRDM scenario to exclude region from $1.7 \times 10^{-30}$ to $10^{-26}$ cm$^2$, most sensitive results from solid detector baed experiment;
- Earth shielding effect is evaluated by the Monte-Carlo sim package CJPL_ESS

*Phy. Rev. D 106, 052008 (2022)*
\( \chi-e \) scattering in Ge detectors

- Light \( \chi \) can potentially pass most of the energy onto electrons, depositing observable energy via \( \chi - e \) scattering.
- Using EXCEED-DM to evaluate \( \chi - e \) scattering in crystal;
- Leading results for the heavy mediator/electric dipole coupling scenario among solid-state detector-based experiments in high mass range.
- Revealing the vast potential of such technical route in probing the \( \chi-e \) scattering.

*Phys. Rev. Lett.* 129, 221301 (2022)
Solar Axions, ALPs

- Background assumption: continuous background + X-rays
- Profile likelihood method
- Excellent energy resolution of Ge is suited for the monochromatic DM axion and Fe-57 axions
- Competitive $g_{Ae}$ constraints exist for $m_a$: 100 eV ~ 1 keV

Solar Dark Photon

- Solar is the most significant dark photon source.
- Detection method: $V + A \rightarrow A^+ + e^-$;
- The most stringent limits on $\kappa$ with mass of 10 to 300 eV for solar dark photon;

Exotic DM results

- Low mass dark matter ($\chi$) may interact with nucleon ($N$):
  - Neural current fermionic DM absorption:
    $$\chi + N \rightarrow \nu + N$$
  - DM-nucleus 3$\rightarrow$2 scattering:
    $$\chi + \chi + N \rightarrow \phi + N$$

$$E_R \approx \frac{m_\chi^2}{2M}$$

$$E_R = (4 - \xi^2) \frac{m_\chi^2}{2M}$$

$$\chi + N \rightarrow \nu + N$$

$$\chi + \chi + N \rightarrow \phi + N$$

Neural current absorption
$$\chi + N \rightarrow \nu + N$$

DM-nucleus 3$\rightarrow$2 scattering
$$\chi + \chi + N \rightarrow \phi + N$$
CDEX Roadmap

- **CDEX-1** (2011-2018): Development of PPC Ge detector, bkg understanding
- **CDEX-10** (2016-2022): Performances of Ge array detector immersed in LN2
- **CDEX-50** (2021-202X): 50kg Ge detector arrays for DM searches
- **CDEX-300ν** (2021-202X): 300kg enriched Ge detector arrays for 0νββ Exp.

See Dr. Wang Li’s talk (Neutrino 2)
CDEX-50

- Ge detectors array directly immerse into Liquid Nitrogen for cooling and shielding;
- Composed of 5 strings, 10 detectors/string;
- Target mass (Ge) reaches ~50kg;
- Two types of Ge detectors: Broad Energy Ge (BEGe) & PPCGe;
CDEX-50 Projected Sensitivity

- **Bkg level**: $<0.01 \text{ cts/(keV}\cdot\text{kg}\cdot\text{day}) @1 \text{ keV}$
- **Energy threshold** for data analysis: 100 eV
- **Exposure** reaches $\sim 50 \text{ kg}\cdot\text{year}$
- **WIMP SI sensitivity** reaches $10^{-44} \text{ cm}^2$
- **Multi physics channel analysis**: axions, dark photons…

---

Simulated Background Spectra

![Simulated Background Spectra](image)
Technical R&D towards next stage

✓ Ge detector fabrication: Various types, ~20 has been successfully done.

✓ HPGe crystal growth: On-going project

✓ Ultra Low bkg very-front-end ASIC + Bare Ge immersed in LN$_2$: New ASIC tested; Bare BEGe successfully perform in LN$_2$

✓ ULB-Copper production in underground lab: Goal: < 0.1 μBq/kg

✓ Cosmogenic background control: $\sim 10^{-2}$ cpkkd@2-4 keV(sim)
Ge Detector Fabrication & ULB ASIC

- **Ge detector fabrication**

  Key technical Steps:
  ✓ Commercial Ge crystal;
  ✓ Structure machining;
  ✓ Li-drift and B-implanted;
  ✓ Home-made ASIC PreAmp;
  ✓ Underground EF-Cu;
  ✓ Underground assemble;
  ✓ Underground testing...

  ![Bare HPGe detectors](image1)
  ![Bare HPGe in LN₂](image2)
  ![Home-made different Ge detectors](image3)
  ![ASIC Front-end Electronics](image4)
E-forming Copper production Underground

• Prototype setup for underground EF-Cu production
  ✓ Goal: Majorana copper, U/Th content $\sim O(0.1\mu Bq/kg)$;
• Test run in Tsinghua U. and moved to CJPL-I;
• U/Th Analysis by ICP-MS
Cosmogenic Background Control

- **New detectors cooperated with commercial companies**
  - Particularly cosmogenic bkg control during detector fabrication and transportation above ground;

- **Home-made detectors**
  - Improve with low bkg material and low noise electronics;
  - Set up underground fabrication and testing facility;

Detector production: 45 days +
Ground transportation: 60 days +
Underground cooling: 180 days →

Cosmogenic bkg: $\sim 10^{-2}$ cpk/d (sim.)
• **CJPL-I to CJPL-II**
  - ✓ Volume: 4000 m³ to 300,000 m³;
  - ✓ 1 main hall (6.5x6.5x42m) to 8 main halls (14x14x60m each);
  - ✓ Additional pit for next-generation CDEX;
• Major infrastructure construction will be completed **by the end of 2023**.
• Expected the construction of the laboratory will be completed **by the end of 2024**.
Summary

- CDEX: unique advantages of Ge detectors for DM searches at CJPL;
- CDEX has made diverse and significant contributions: WIMP, axions, dark photons, exotic DM, AM, Migdal effect, boosted DM, $\chi$-e scattering…..
- CDEX-50, the next stage experiment, at Hall C-1 of CJPL-II;
- Technical R&D developments to facility future experiments.
Thanks for your attention!