China Jinping Underground Laboratory and Rare Physics Experiments Postprints

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Abstract

The China Jinping Underground Laboratory (CJPL) is currently the deepest underground laboratory in the world in terms of rock overburden, providing excellent shielding against cosmic-ray muons and exhibiting an extremely low cosmic-ray flux, making it exceptionally suitable for experimental detection of rare physical events. Currently, several experimental collaborations including the China Dark matter EXperiment (CDEX), the Particle and Astrophysical Xenon Experiments (PandaX), and the Jinping Underground Nuclear Astrophysics Experiment (JUNA) have established experiments at CJPL, conducting experimental searches for a series of rare physical events such as dark matter direct detection, neutrinoless double-beta decay, and astrophysical nuclear reactions, and have achieved numerous research results at internationally competitive levels. This paper summarizes the developmental history and background control status of CJPL since its establishment, presents an overview of the physical significance, experimental principles, key technologies, and scientific results of the experiments conducted by the various collaborations, and also outlines the future experimental plans of these groups.

Full Text

Preamble

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Rare Physical Events at China Jinping Underground Laboratory

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Abstract

China Jinping Underground Laboratory (CJPL) has the deepest rock overburden in the world, which considerably shields detectors from muons. Thus, it has an ultra-low radiation background level and is ideal for experiments investigating rare physical events. Previously, experiments including CDEX (China Dark matter EXperiment), PandaX (Particle and Astrophysical Xenon Experiments), JUNA (Jinping Underground Nuclear Astrophysics Experiment), and neutrino experiments have been carried out at CJPL, yielding excellent results in dark matter detection, neutrinoless double beta decay, and more. This review introduces the construction process of CJPL and describes the facilities, results, and future plans of the aforementioned experiments. CDEX employs a high-purity germanium detector array for dark matter detection and neutrinoless double-beta decay searches, whereas PandaX uses a dual-phase liquid xenon time projection chamber detector for the same purposes. JUNA utilizes a proton and helium accelerator to simulate four nuclear reactions that occur in the Universe. A 10^3-kg prototype was constructed by the neutrino experiment for feasibility verification. The CDEX, PandaX, and JUNA collaboration groups have reported their latest results, all of which have approached or surpassed the world' s best sensitivity.

These experiments demonstrate the extraordinary experimental conditions at CJPL. With the construction of CJPL-II, we anticipate an increase in the number of experiments based at Jinping and expect further significant achievements.

Keywords: China Jinping Underground Laboratory, Dark matter, Neutrinoless double-beta decay, CDEX, PandaX, JUNA

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Introduction

In physics, certain processes are termed "rare physical events" because they have extremely small reaction cross-sections or exceptionally long half-lives, resulting in very low expected event rates. To reduce environmental backgrounds, particularly interference from cosmic ray muons, such experiments are typically conducted in underground laboratories. Prior to 2009, China lacked such facilities, forcing related experiments to be carried out abroad. In 2009, Tsinghua University, in collaboration with Yalong River Hydropower Development Company, constructed the China Jinping Underground Laboratory (CJPL) in the middle of the 17.5 km-long Jinping traffic tunnel excavated for the Jinping Hydropower Station project. With a usable volume of 4,000 m^3 and a minimum vertical rock cover of 2,400 m, CJPL became the world' s deepest underground laboratory, providing Chinese scientists with an internationally first-class clean underground experimental space featuring minimal cosmic ray particle interference. Over the past decade, the laboratory has continued to develop, expanding from the original Phase I (CJPL-I) to a larger Phase II facility (CJPL-II), offering more convenient conditions for larger-scale experiments [Figure 1: see original paper].

CJPL's uniquely low-background environment has attracted numerous domestic experiments, including dark matter detection, neutrinoless double beta decay, neutrino, and nuclear astrophysics experiments. These experiments all require background reduction to achieve better sensitivity.

China Jinping Underground Laboratory (CJPL)

CJPL was jointly constructed in May 2009 by Tsinghua University and Yalong River Hydropower Development Company, located in the middle section of the Jinping Mountain traffic tunnel in Sichuan [2]. The laboratory' s rock overburden exceeds 2,400 m, making it the deepest underground laboratory in the world. The extremely thick rock shielding substantially reduces cosmic rays, yielding a cosmic muon flux of only (61.7 $\pm$ 11.7) $m^{-2}s^{-1}$—approximately one hundred-millionth of the surface flux [3]. This ultra-low cosmic ray background provides superior conditions for a series of rare physical event detection experiments. Upon completion of Phase II, CJPL will become the world' s deepest underground laboratory with the lowest cosmic ray flux and largest available space. [Figure 3: see original paper] compares key parameters—including muon flux, rock overburden, equivalent water depth, and spatial volume—of major global underground facilities, where circle sizes represent laboratory volume, red indicates tunnel access (allowing convenient vehicular entry), and blue indicates shaft access (less convenient for transporting large experimental components).

CJPL currently consists of Phase I (CJPL-I) and Phase II (CJPL-II). Phase I was officially commissioned in December 2010, marking the establishment of China' s first ultra-deep underground laboratory and the world' s deepest such facility. The Phase II project was launched in August 2014 through an agreement between Tsinghua University and Yalong River Hydropower Development Company. The plan includes constructing four experimental halls (14 m $\times$ 14 m $\times$ 130 m each), expanding the total usable volume from 4,000 m^3 in Phase I to approximately 3$\times$10^{5}$ m^3. [Figure 2: see original paper] shows a schematic layout of CJPL-II [3].

Due to the special nature of experiments conducted at CJPL, stringent requirements are imposed on environmental background control. summarizes various environmental background measurements in the CJPL-I experimental hall. Because construction materials for CJPL-I were sourced from near the hydropower station without special radioactivity control, the radiation levels were slightly higher than those of other underground laboratories. During CJPL-II construction, radioactivity levels of multiple concrete samples were measured, and only low-radioactivity concrete was used. As shown in , CJPL-II' s environmental background levels are superior to those of CJPL-I [4].

In 2016, building upon Phases I and II, Tsinghua University and Yalong River Hydropower Development Company proposed constructing the "Ultra-deep Underground Ultra-low Radiation Background Frontier Physics Experimental Facility" (referred to as the Jinping Large Facility). The feasibility study report was officially approved by China' s National Development and Reform Commission in December 2018, and the project officially launched on July 20, 2019. The Jinping Large Facility is a major national scientific infrastructure prioritized during China' s 13th Five-Year Plan period. It represents China' s first ultra-deep underground laboratory infrastructure project and the world' s first large-scale construction of a comprehensive experimental facility with ultra-low radiation background conditions. The facility will provide internationally top-tier experimental platforms for particle physics, nuclear astrophysics, and deep-underground radiation biology. Construction began in December 2020, focusing on four major platforms: an underground experimental operation and maintenance support platform, an ultra-deep ultra-low radiation background shielding platform, and an ultra-deep ultra-low background analysis and testing platform, complemented by an aboveground auxiliary experimental platform. The facility is expected to be completed and operational by 2024, forming the world' s deepest, most comprehensively shielded, most capable radioactive material screening, and best-supported ultra-deep ultra-low radiation background physics experimental platform, comprehensively enhancing China' s scientific research support capabilities [5].

For deep underground laboratories, transportation convenience is an important metric alongside ultra-low background levels. CJPL enjoys unique geographical advantages with excellent accessibility. Located in the middle of the Jinping Mountain traffic tunnel, the laboratory is only 8.7 km from the east portal and 8.8 km from the west portal, allowing personnel direct vehicular access. The spacious tunnel permits construction vehicles, greatly facilitating large-scale physics experiments. External transportation is also convenient: CJPL is only 150 km from Xichang Qingshan Airport, with a highway and dedicated lane shared with Yalong River Hydropower Development Company providing approximately 2-hour travel time.

CJPL has significantly advanced China's deep-underground scientific research in dark matter detection, neutrinoless double beta decay (0 $\beta\beta$) searches, neutrino detection, and other fields, establishing a foundational experimental platform from scratch. Current experiments at CJPL include CDEX (China Dark Matter Experiment), PandaX (Particle and Astrophysical Xenon Experiments), the Jinping neutrino experiment, and JUNA (Jinping Underground Nuclear Astrophysics Experiment). More experimental groups are expected to join in the future.

Experimental Programs at CJPL

2.1 CDEX Experiment

The CDEX collaboration, led by Tsinghua University, employs a point-contact high-purity germanium detector array to search for dark matter and neutrinoless double beta decay events. High-purity germanium detectors are semiconductor devices offering low intrinsic background, excellent energy resolution, low energy threshold, and scalability—making them ideal for rare event detection. Dark matter detection and neutrinoless double beta decay experiments represent two typical rare physical event searches.

Dark matter is a form of matter in the universe that participates only in gravitational interactions, not electromagnetic or strong interactions, making it extremely difficult to detect. Experimentally, dark matter can be detected through direct detection of nuclear recoils caused by weak interactions between dark matter particles and target nuclei. Due to extremely low reaction cross-sections, these events are very rare, requiring background reduction. CDEX uses inherently low-background high-purity germanium detectors, further suppressing background through placement in CJPL, external shielding, control of support structure radioactivity, and anti-coincidence detection, achieving a background event rate below 1 count/(keV · kg · day) in the 0–2 keV region. The point-contact detector' s low energy threshold provides advantages for detecting light dark matter below 10 GeV, with the experimental threshold reaching 160 eVee (electron-equivalent), representing an internationally leading level.

Neutrinoless double beta decay (0 $\beta\beta$) is a process where certain nuclei undergo double beta decay without emitting neutrinos, producing only two electrons. This would demonstrate that neutrinos are Majorana particles, extending beyond the Standard Model. While double beta decay half-lives exceed 10^{20} years, 0 $\beta\beta$ half-lives are even longer, making it an extremely rare process. ^{76}Ge is a double beta decay isotope with high natural abundance and enrichment feasibility, making enriched ^{76}Ge high-purity germanium detectors ideal for 0 $\beta\beta$ searches. Without neutrinos carrying away energy, the two electrons carry the full decay energy, producing a monoenergetic peak at 2,039 keV for ^{76}Ge. Consequently, unlike dark matter experiments that focus on low-energy regions, 0 $\beta\beta$ experiments primarily investigate energies above 2,000 keV.

Since its establishment in 2009, CDEX has made substantial progress using high-purity germanium detectors for rare event searches, increasing detector mass from 20 g (CDEX-0) to single detectors of ~1 kg (CDEX-1A and CDEX-1B), and then to a 10-kg detector array (CDEX-10), delivering internationally leading physics results. In 2018, CDEX-10' s analysis of Weakly Interacting Massive Particles (WIMPs) provided the world' s most sensitive results for 4–5 GeV spin-independent couplings [FIGURE:4(a)] [7]. In 2019, annual modulation analysis of four years of CDEX-1B data yielded the world's best exclusion limits for dark matter below 6 GeV [FIGURE:4(b)] [8]. The collaboration has also achieved or exceeded world-leading sensitivity in analyses of inelastic WIMP scattering, axion-like particles, and dark photon models. In 0 $\beta\beta$ decay, CDEX-1 data analysis produced China' s first independent ^{76}Ge 0 $\beta\beta$ result, setting a lower limit on the half-life of $T^0{}_{1/2} \geq 6.43 \times 10^{22}$ yr (90% C.L.) [FIGURE:4(c)] [9].

Currently, the collaboration is conducting key technology research on low-background material preparation [10], cosmogenic radioactivity control [11], germanium crystal growth, detector design and fabrication, detector characterization, and pulse shape discrimination [12–14] to lay the experimental foundation for future larger-scale, lower-background high-purity germanium arrays.

Future plans include utilizing the C1 experimental hall in CJPL-II, immersing detectors in liquid nitrogen within a 13 m × 13 m volume to achieve cooling and external background shielding, with the goal of reaching a background level of 1 count/(keV · kg · yr) near 2 MeV. The collaboration plans to use enriched ^{76}Ge detectors, increasing the array mass to 300 kg and eventually 10^3 kg, to push the 0 $\beta\beta$ half-life limit to 10^{27}-10^{28} yr [15]. [Figure 5: see original paper] shows the planned CDEX-300 experimental setup.

2.2 PandaX Experiment

The PandaX collaboration, established in 2009, employs a dual-phase liquid xenon time projection chamber (TPC) for dark matter direct detection. [Figure 6: see original paper] illustrates the dual-phase xenon TPC structure: ionization events in liquid xenon produce excited xenon atoms and electron-ion pairs. De-excitation of excited xenon and recombination of electrons and ions produce scintillation light (S1 signal), while electrons drift under electric fields into the gas phase, generating electroluminescence (S2 signal) [16]. This dual-phase design provides two signals per event, offering inherent advantages for three-dimensional position reconstruction and discrimination between electron and nuclear recoils. Xenon' s large atomic mass and high reaction cross-section also provide high recoil rates and experimental sensitivity for WIMPs around 100 GeV.

PandaX has completed multiple detector upgrades since 2009. In the completed Phase I (PandaX-I) and Phase II (PandaX-II) experiments, the liquid xenon effective masses reached 120 kg and 580 kg, respectively, achieving internationally leading results. PandaX' s 3.3$×10^{4}$ kg · day low-background data released in 2016 and 2017 produced the world' s best exclusion limits, with a final total exposure of 1.32$×10^{5}$ kg · day pushing the upper limit on dark matter reaction cross-section at 30 GeV to 2.2×10^{-46} cm^2 [Figure 7: see original paper] [17].

The currently operating PandaX-4T experiment represents a further upgrade of PandaX-II, with an effective liquid xenon mass of 4,000 kg. Located in the B2 experimental hall of CJPL-II, the detector is housed in a cryostat maintaining -100°C, which is immersed in high-purity water shielding to reduce environmental gamma and neutron backgrounds. PandaX-4T was completed in 2020 and began commissioning in November of that year, with the first data-taking period lasting 94.9 days and achieving 0.63×10^{3} kg · day exposure. Analysis of this data constrained WIMP-nucleon spin-dependent cross-sections to 5.8×10^{-42} cm^2 (neutron) and 1.7×10^{-40} cm^2 (proton) [18], and set a lower limit on the 0 $\beta\beta$ half-life of ^{136}Xe at 2.27×10^{21} yr [19].

The PandaX-III project plans to use 200–1,000 kg of high-pressure gaseous xenon to search for 0 $\beta\beta$ decay in ^{136}Xe. A prototype detector containing 20 kg of gas at 1 MPa pressure has been designed and tested since 2016, validating operational gas parameters and track reconstruction capabilities. Based on this, PandaX-III aims to reduce background near 2,457 keV to 3.5×10^{-3} counts/(keV · kg · yr) and improve the ^{136}Xe 0 $\beta\beta$ half-life limit to 8.5×10^{25} yr.

2.3 JUNA Nuclear Astrophysics Experiment

JUNA (Jinping Underground Nuclear Astrophysics Experiment), led by the China Institute of Atomic Energy, is China' s first deep-underground nuclear astrophysics program. Nuclear astrophysics experiments focus on nucleosynthesis processes in the universe, studying reactions including ^{12}C(α,γ)^{16}O, ^{13}C(α,n)^{16}O, ^{25}Mg(p,γ)^{26}Al, ^{19}F(p,α)^{16}O, and ^{19}F(p,γ)^{20}Ne [20–22]. The project moved into CJPL-II in 2020, and in December of that year, the required hydrogen-helium ion accelerator achieved first beam.

The accelerator can produce various ion beams (hydrogen, helium, etc.) with continuously adjustable energies from 70–400 keV, providing a foundation for experimental success. CJPL' s excellent shielding against environmental gamma rays and neutrons benefits experiments that precisely detect these particles from nuclear reactions, reducing backgrounds and enabling more sensitive measurements. In December 2021, JUNA published its first results, achieving the world' s highest sensitivity and precision [23]. For the "holy grail reaction" ^{12}C(α,γ)^{16}O, which had not been previously measured, JUNA provided an upper limit on the cross-section at 538 keV, reaching internationally leading levels. shows count rates and backgrounds for other reactions in their respective energy regions.

2.4 Neutrino Experiment

The Jinping neutrino experiment, led by Tsinghua University, aims to build a hundred-ton-scale liquid scintillator detector at CJPL for multi-physics studies including solar and geoneutrinos, achieving world-leading sensitivity [26]. CJPL offers the lowest reactor neutrino background, largest geoneutrino signal, lowest environmental radioactivity, and longest solar neutrino baseline through Earth [27], providing exceptional advantages for low-energy neutrino experiments.

The collaboration first designed a ton-scale prototype to validate experimental performance [28]. Located in the CJPL-I experimental hall, the prototype [Figure 8: see original paper] features 103 kg of liquid scintillator at the sphere’ s center to produce scintillation light during nuclear reactions. Thirty photomultiplier tubes uniformly cover the sphere’ s exterior to convert light signals to electrical signals [28]. High-purity water between the sphere and outer stainless steel container provides environmental background shielding.

Future plans include achieving physics goals in solar neutrinos, geoneutrinos, supernova and supernova relic neutrinos. For solar neutrinos, the experiment can precisely measure the vacuum-to-matter transition region of neutrino oscillation, testing matter effect theories. Detection of neutrinos from the Sun’ s CNO cycle can resolve the solar core metallicity problem. For geoneutrinos, Jinping can clearly distinguish contributions from uranium and thorium decay chains. Combined with results from Borexino and KamLAND, this will determine the mantle neutrino flux, revealing mechanisms of plate tectonics, mountain formation, and distribution of heat-producing elements.

2.5 Summary and Outlook

The CDEX, PandaX, JUNA, and Jinping neutrino experiments have leveraged CJPL’ s environment to achieve results leading or comparable to similar international experiments in dark matter, neutrinoless double beta decay, and geoneutrino detection, demonstrating CJPL’ s exceptional low-background performance. Currently, the CJPL-II experimental halls are nearing completion. As the world’ s largest underground laboratory, CJPL-II provides ideal space for larger-scale experiments.

CDEX’ s CDEX-300 and CDEX-1T projects are planned for CJPL-II, while PandaX-4T is already operational. Both collaborations expect increased sensitivity and reduced backgrounds through larger detector volumes to achieve leading results in dark matter and $0\beta\beta$ searches. JUNA has established China’ s first continuously tunable 400 keV hydrogen-helium ion accelerator in CJPL-II, with plans for a MeV-scale high-precision electrostatic accelerator to achieve superior results and drive technological breakthroughs. Following prototype validation, the Jinping neutrino experiment plans larger-scale construction in CJPL-II, aiming for a 2×10^{6} kg spherical liquid scintillator detector for more sensitive neutrino detection.

Additional experiments plan to utilize CJPL-II’ s low-background and large-space advantages, such as radiobiology dose-effect studies that will exploit CJPL’ s cosmic ray shielding to reveal objective dose-effect relationships at low dose rates, providing more reliable scientific foundations for cancer radiotherapy.

Upon completion of CJPL-II and the Jinping Large Facility, China Jinping

Underground Laboratory will become the world' s premier deep-underground comprehensive experimental platform, serving particle physics, nuclear astrophysics, deep-underground radiation biology, and other fields, driving vigorous development of China' s deep-underground scientific research.

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Author Contributions

WANG Yufeng and LIU Jiaxuan wrote and revised the manuscript; YANG Litao reviewed and revised the manuscript and participated in laboratory construction and experimental research; ZENG Zhi, MA Hao, and YUE Qian were responsible for laboratory design and construction, project guidance, and management.

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Note: Figure translations are in progress. See original paper for figures.