CDEX-0νββ Program

(Public Domain Information Extracted from the Big-Science-Facility Letter-of-Intent)

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Abstract:

Studies of Neutrinoless Double Beta Decay (0νββ) are the best avenue to differentiate whether neutrinos are Majorana or Dirac particles. It provides measurements to the neutrino mass matrix and probes lepton number violation. The CDEX Program is pursuing 0νββ searches with germanium (Ge) detectors enriched in the isotope ^{76}Ge. The Ge-techniques, recognized to the most promising approach for next and next-next generations of 0νββ experiments, provide excellent energy resolution which greatly suppresses continuum background relative to measured peaks at energy of 2.039 MeV, the smoking-gun signature of 0νββ.

The CDEX program adopts a phased approach. An enriched ^{76}Ge experiment of target mass 300 kg is currently under preparation, to be commissioned in 2027. This would be followed by a 1-tonne experiment ready by 2033 to cover the neutrino inverted mass ordering, and then will evolve to a 10-tonnes program by 2040 with enough sensitivity to probe the neutrino normal mass ordering.

The CDEX program has several distinctive features. The experiments will be performed at the China Jinping Underground Laboratory (CJPL), the deepest underground research facility in the world, in which customized space is secured for the construction of a cryostat large enough to house experiments of all the future phases. Plans are made to build dedicated large-scale ^{76}Ge enrichment facilities in China, and further to perform Ge-crystal growth and Ge-detector fabrication underground in CJPL. These will greatly suppress background due to cosmic-ray activation on Ge-target, reduce their manufacture cost and enhance production rates – therefore mitigating the usual bottlenecks which has disfavored scale-up of the Ge-technology.

It can be envisioned that, as the program advances, international partnership with world-wide experimental-network will be established, while the domestic Ge-detector industry, as an active partner of the program, will benefit tremendously with state-of-the-art technology and expanded its user-market.

1. Scientific Motivations

This Big-Science-Facility Initiative targets to place China to the world's forefront position in the studies of Neutrinoless Double Beta Decay (0νββ), towards realization of experimental facilities with the scale of 10 tonnes germanium (Ge) detectors enriched in ^{76}Ge to achieve sensitivity of $T_{1/2} > 10^{29}$ yr, sufficient to probe the most parameter space of neutrino mass Normal Ordering. The CDEX collaboration, with Tsinghua University as the leading group, is the driver of this research program and vision. The pursuit of this program will lead to extensive international collaboration, and train generations of top research students to the frontier science and techniques. A Ge-detector manufacturing industry of world-standing will be established.

Neutrino is the least understood subject in the Standard Model of Particle Physics. The discovery of neutrino mass through neutrino oscillations in 1998 is the strongest indication of Physics beyond the Standard Model. Studies of neutrino properties and interactions are at the forefront basic physics research programs. They are intensely pursued by all the major basic physics research institutes. Advances in neutrino physics remain the benchmark for scientific achievement over the world.

One of the outstanding problems in neutrino physics is on its very fundamental nature – whether they are Majorana or Dirac particles denoting, respectively, whether neutrinos are and are not their own anti-particles. The answer to this question is expected to reveal the secrets of neutrino mass generation, as well as the structures of the Grand Unified Theory which targets to integrate weak, electromagnetic and strong interactions into a coherent framework – a Holy Grail in Basic Science.

The search of 0νββ is recognized to be the most sensitive avenue to probe the Majorana-versus-Dirac nature of the neutrinos. Many fundamental questions are probed by the 0νββ experiments. Positive signatures would imply that neutrinos are Majorana particles, provide measurements of the Majorana neutrino mass, reveal structures of the neutrino mass matrix and in particular the mass ordering. This will also be the first ground-breaking case of a lepton number violation process. Observation of 0νββ will be a scientific discovery of historical importance.

Searches of 0νββ have been pursued by the world's top research group since the 1980's. By 2022, the sensitivity is of ($T_{1/2} > 1.8\times10^{26}$ yr) and the current generation of experiments targets at achieving 10^{27} yr. Many techniques with different target isotopes have been adopted in 0νββ experiments. After many years of intense reviews, it is generally recognized that Ge ionization detectors are the best isotopes and technology for the next generation of 0νββ experiments and beyond. The most important merit for Ge-detectors is its excellent energy resolution (0.1% Full-Width-Half-Max). This can totally suppress the two-neutrino double beta decay background which is otherwise an irreducible background and greatly limits sensitivity improvement for most other techniques. The LEGEND Collaboration is building a 200-kg ^{76}Ge experiment at the Gran Sasso Underground Laboratory in Italy. Resources and logistics for the next phase of 1-tonne target to probe the neutrino mass inverted ordering are not secured yet.

CJPL is the deepest and largest underground research facility in the world. The construction civil engineering and scientific research infrastructures have been supported by the National Science and Technology Infrastructure project of China in 2020 at 1.19 Billion RMB. The CDEX Collaboration has successfully performed the first-generation experiments at CJPL on Dark Matter searches with Ge-detectors at CJPL, producing a series of world-quality results. Several generations of research students have been trained. Working relations have been built up among CDEX research teams covering expertise on all aspects of Ge-detector production, operation and analysis, as well as the important low-radiation background instrumentation techniques. Connections are established with the world's leading industries on Ge-detector technologies and ^{76}Ge enrichment, as well as with international research scientists at the forefront of applying Ge-detector techniques to attend important scientific questions.

Standing on the solid platform established in the last decade, the CDEX Collaboration proposes to realize the vision of realizing a 10-tonnes Ge-0νββ experiment with enriched ^{76}Ge at CJPL. CDEX has already been assigned a 18m diameter and 18m height pit at CJPL and is constructing a 16-m diameter cryostat which is large enough to house the 10-tonnes of Ge-detectors. The first stage of 300-kg of enriched ^{76}Ge detectors is under construction, to be completed in 2027. Subsequent stages are expected to evolve to 1-tonne by 2033 and 5-tonne intermediate experiments and eventually to a 10-tonne Ge-0νββ experiment by 2040. Addition of target mass in various stages is cumulative without waste or overhead – an important merit of the Ge-detector technology over other contenders. An exposure of 100 ton-year with 10 years of data taking will bring the sensitivity to $T_{1/2} > 10^{29}$ yr.

Plans on the construction of Ge-crystal growing and Ge-detector fabrication facilities at CJPL is already at the advanced stage with funding committed from the National Science and Technology Infrastructure project of China in 2020 at roughly 40M RMB. In addition, plans on establishing a ^{76}Ge isotope enrichment facility in China are being pursued. All the Ge-facilities will add together to: (i) greatly reduce the intrinsic cosmic-ray induced long-lived radioactive background in the Ge-detectors; (ii) enhance the annual production capability by a factor of 3; and (iii) drive the overall cost of ^{76}Ge-detectors down by factor of 10. International partnership on a world-wide network of ^{76}Ge 0νββ experiments with China playing a leading role can be expected to be realized following these advances. Another natural impact is the further promotion in terms of advanced technology and market size to the Ge-detector manufacturing industries in China.

We elaborate in the following sections the status, plans, as well as the scientific, experimental and technical details of the CDEX-0νββ program.

2. Core Scientific Topics: 0νββ

Whether neutrinos are their own antiparticles, that is, to understand whether neutrinos belong to a class of exotic Majorana fermions, profoundly reveals new physics beyond the Standard Model of particle physics. Pursuing 0νββ decay is the unique and crucial test to answer this scientific question. Observation of 0νββ directly implies the lepton number violation and could provide a significant clue to some of the fundamental, big-picture scientific questions including the origin of small neutrino masses, potential explanation of the baryon asymmetry problem, as well as the Grand Unified Theory.

The experimental challenges of the 0νββ decay are the requirements of excellent energy resolution, extremely low background level, and an achievable large-scale detection system composed of tons or dozen tons of target material. The unique advantages of the enriched germanium experiment for the search of 0νββ decay are: (1) best energy resolution among all current techniques used in the 0νββ experiments. (FWHM=2.5keV@2.039MeV); (2) germanium detector as the 0νββ source and germanium-76 can be enriched and enjoy an intrinsic negligible natural radioactivity level of uranium and thorium (< 10 nBq/kg); (3) Easy to upgrade and integrate for a modular detection system. The advantage of such a system can continuously increase the data exposure volume. In the meantime, upgrading and optimizing the extremely low background front-end electronics and structural materials can be made continuously. For decades, the international scientific community has widely demonstrated that the enriched germanium detector array technology is the most competitive with best potentials of significant increase beyond the current sensitivity for the 0νββ experiments.

The CDEX collaboration proposes a multi-stage program with the ultimate goal of a total active germanium-76 mass of 10 tons for the 0νββ experiment at CJPL, having deepest rock overburden of around 2400 meter and largest space with a volume of 3 hundred thousand cubic meter in the world, in China. The technical design is to employ an enriched germanium-76 detector array immersed in the isotopically depleted liquid argon playing a role of cooling the enriched germanium array and providing an effective background rejection, to further reduce the background level of the enriched germanium system. R&D on the key technologies of the germanium detector and a lower radioactive cryogenic system are going to be investigated. Additionally, the diversity scientific targets such as direct dark matter searches, neutrino-nucleus coherent scattering from solar and cosmos as well as rare event phenomena will also be pursued. While key technologies of the enriched germanium detectors are intensively studied, the industrial effects and promotion on high-purity germanium semiconductor detector technology is foreseen. Meanwhile, the technology of CMOS-ASIC front-end electronics and large-scale enrichment of germanium isotope production capacity can be provided for international counterparts.

Except for the existing key technologies in the current enrichment of germanium detectors, this project will explore two innovative and unique schemes to substantially suppress the dominated backgrounds: (1) The germanium crystal growth and detector fabrication for an enriched germanium detector at CJPL, to highly suppress the cosmogenic background in the enriched germanium crystal, in order to meet the requirements of reaching the half-life of germanium-76 0νββ decay to be greater than 10^{29} y. (2) Integrate an entire chain of germanium detector technologies, covering from the mass production on the raw materials of germanium dioxide in China, the growth of germanium crystals, detector fabrication, performance test to the installation in deep underground laboratory at CJPL. It will not only effectively suppress the background level of the device, but also significantly reduce the construction cost and increase production rate of the enriched germanium detectors, therefore addressing directly the challenges of scaling-up of the germanium techniques for 0νββ.

The ten-ton-scale enrichment germanium project proposed by the CDEX collaboration could be carried out in the form of international cooperation because the modular advantage of the germanium array system allows international counterparts to carry out various forms of international cooperation, including: (1) detector arrays distributed in multiple underground laboratories in the world and joint analysis data, or (2) the joint construction of the large-scale enrichment germanium experimental devices at CJPL, benefiting for deepest site and largest space.

The CDEX collaboration has established an internationally competitive research team through the R&D studies on key technologies for the 0νββ experiment. In particular, a growing number of the young scientists and doctoral students join in the group and a closely and extensively cooperation with international experts are built.

3. Technical design and main parameters

This project plans to build a germanium enrichment 0νββ experimental device in the 1725m^3 liquid nitrogen tank at Hall-C of the CJPL Phase-II, which will be implemented in three stages: CDEX-300, CDEX-1T and CDEX-10T. The conceptual layout is depicted in Figure 1.

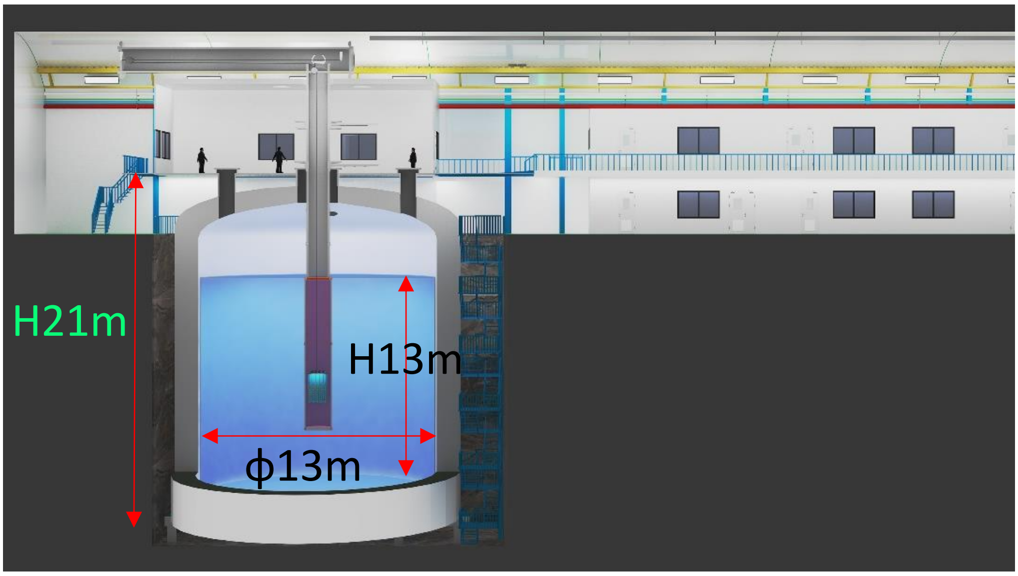

Figure 1: Schematic diagram of the 1725 m³ liquid nitrogen cooling and shielding system at Hall C1 of CJPL Phase-II.

(1) CDEX-300

Build a 300kg-scale enriched germanium detector array (^{76}Ge abundance>86%, and the total mass of germanium metal used in making detectors is about 300kg), high-purity germanium detectors are arranged in series, a total of 19 strings, each string of 10 or 11 detectors, a total of 200 detectors. The baseline of the detector is the Broad Energy Germanium (BEGe), with a single mass of about 1.12 kg and a total mass of about 225 kg.

The CDEX-300 experiment, as depicted schematically in Figure 2, is expected to be completed in 2027. It will have a background level of 1.0×10^{-4} cpkky. Operating under this background for 3 years, the exposure will reach 1 ton-year by 2030, and the half-life sensitivity will be greater than 10^{27} years, entering the sensitive parameter space of inverted hierarchy mass region.

The enriched germanium detector array will be immersed into the liquid argon with a diameter of 1.5m and a depth of 8m to maintain a low temperature. At the same time, the liquid argon will be purified to 9N, and the liquid argon scintillation light will be read by a wavelength-shift fiber system to provide the enriched germanium detector array a considerable background depression capability via anti-coincidence.

CJPL, where the device is located, has a rock overburden of 2400 m, which is about 1000 m thicker than the LNGS underground laboratory where LEGEND-200 is located. Therefore, the cosmic ray flux of the experimental platform of CDEX-300 (CJPL) is about 100 times lower than that of LEGEND-200, which can further reduce the cosmic background such as Ge-77m to negligible levels. The detection sensitivity of the CDEX-300 in operation for 3 years after its completion is expected to exceed that of the LEGEND-200 experiment (operation for 5 years), and the experimental results of the most sensitive half-life and effective neutrino mass of the germanium enrichment $0\nu\beta\beta$ experiment will be given.

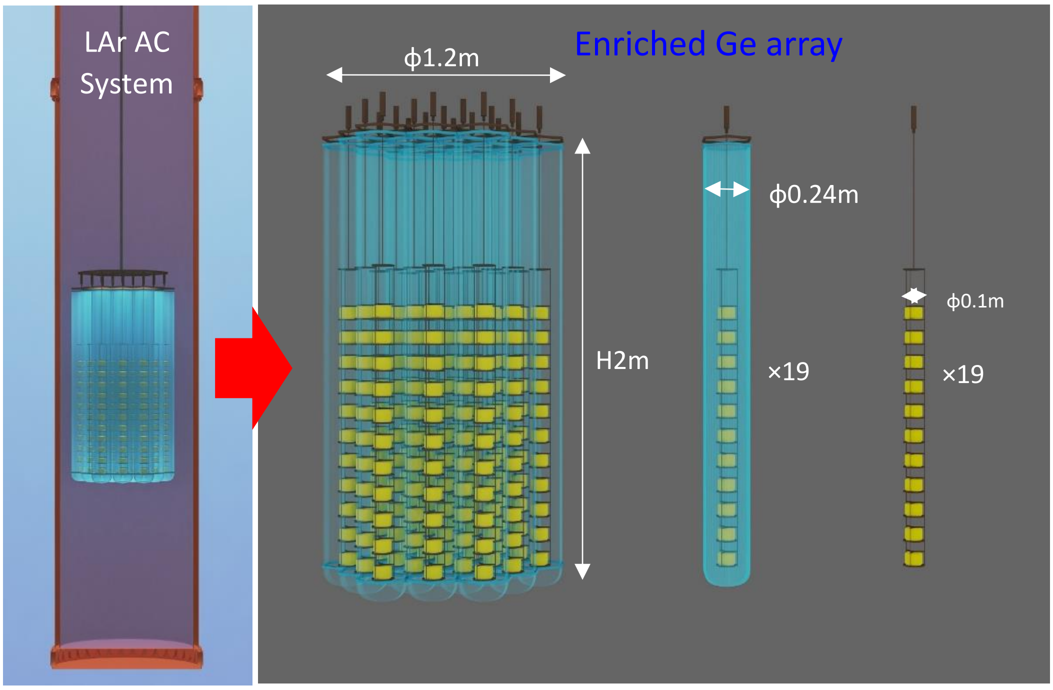

Figure 2. Schematic diagram of the 225kg Enriched ^{76}Ge detector array and its liquid argon active shielding system.

(2) CDEX-1T

In the CDEX-1T stage, three more enriched germanium arrays were added to the existing CDEX-300 liquid nitrogen cryostat, the target mass of each array will reach 250kg, and the total mass of the detector will reach about 1 ton. The liquid argon anti-coincidence system will be adopted with subterranean depleted argon, which can significantly reduce the background contribution of Ar radioisotopes. At this stage, most of the enriched germanium crystal growth and detector fabrication process will be completed in the underground laboratory, and the total background of CDEX-1T will be further reduced to 5.0×10^{-6} cpkky. After 5 years of operation, it will reach an exposure of 5 ton-year, the sensitivity of half-life measurement will increase to 10^{28} years, and a complete scan of the parameter space of inverted hierarchy neutrino mass region will be completed.

(3) CDEX-10T

In the CDEX-10T stage, the detector mass will be increased to 10 tons on the basis of the CDEX-1T. In the foundation pit of the large liquid nitrogen cryostat in Hall C1 of CJPL-II, a new large liquid argon cryostat will be designed and constructed, and 17 underground high-purity depleted argon (ULAr) experimental chambers will be installed inside. In each of ULAr experimental chamber, an enriched germanium arrays will be installed in and the ULAr will be served as an external shield and anti-coincidence detector. There are 17 enriched germanium arrays, each with 300 Inverted Coaxial Point Contact (ICPC) detector units, with a single mass of 2kg and a single array mass of 600kg. The total target mass will reach 10 tons.

At this stage, all the fabrication processes of germanium detectors and related materials will be completed in the underground laboratory, the performance of the pulse shape discrimination method and the anti-coincidence of liquid argon will be further improved. The background level of CDEX-10T will be further controlled and lower than 1.0×10^{-6} cpkky. After 10 years of operation, an exposure of 100 ton-year will reach, which will increase the half-life measurement sensitivity to 1.3×10^{29} years, initially covering the parameter range of normal hierarchy neutrino mass order with an effective mass above 5meV, and realizing scanning most of the parameter space of normal hierarchy mass order.

4. Additional Technical Outputs

This project proposes to build enriched germanium 0νββ experimental devices CDEX-300/CDEX-1T/CDEX-10T in stages, master a number of key experimental techniques including the fabrication of enriched high-purity germanium detectors, liquid argon detectors, CMOS ASIC front-end electronics, high-precision waveform sampling electronics, the production and control of the low-background material et al., build a ^{76}Ge neutrinoless double-beta decay measurement experimental device with the world's largest mass, the best energy resolution, and the lowest background in CJPL, and carry out researches on major frontier issues of multi-physics targets including the neutrinoless double-beta decay measurement, direct detection of dark matter, solar physics research, supernova neutrino detection, electron decay and other rare physical event searches et al., obtain cutting-edge physics research results at the international leading level, and promote the deep-underground frontier research in China which will provide significant support to become an international research highland and leader.

Running the device will complete the scanning of the parameter space of inverted hierarchy mass region, and enter the normal hierarchy mass parameter space, and give the most internationally competitive physical results at each stage. Multidisciplinary cutting-edge physics researches, such as the dark matter detection and solar neutrino measurement, will reach the international leading level as well. The project will establish an internationally advanced enriched germanium device for deep-underground rare physical events detection, cultivate a high-level talents team, and make China one of the world's leader in deep-underground frontier researches.

This project aims at the major frontier scientific issues of 0νββ, and develops large-scale scientific instruments and devices at the international leading level, which can not only achieve major cutting-edge physical achievements, but also achieve a series of key technological innovations and breakthroughs during the construction of high-purity germanium detector arrays, which will contribute to the development of neutrino physics, dark matter, nuclear physics and other research in China via providing cutting-edge experimental equipment and related technologies. Through the implementation of this project, China will independently realize the capacity building of 100 kilograms or even tons of germanium-76 isotope separation, and autonomous mastery of a series of cutting-edge technologies, including the high-purity germanium crystal growth and detector manufacturing, low-temperature, low-background and low-noise front-end electronics, large-volume liquid argon anti-coincidence detection system, etc.

Several key technical benefits in particular are as follows:

(1) Independently master the manufacturing technology of high-purity germanium detectors, form the production capacity of high-purity germanium detectors, with the relevant technical indicators reaching the international advanced level, breaking the monopoly of foreign technology; effectively promoting the nuclear physics gamma spectroscopy, ultra-low background measurement, radiation environment monitoring, nuclear emergency and other fields of development and technological progress in China.

(2) Drive the development of domestic ^{76}Ge stable isotope separation technology, promote the construction and operation of domestic large-scale ^{76}Ge stable isotope separation devices, and promote the development of stable isotope industry in China.

(3) In terms of ultra-low background technology, promote the development of domestic low-background electronics substrates, underground low-background electrolytic copper and other material's manufacturing technologies, and provide ultra-low background technology support for larger-scale rare physical events detection experiments in the future.

It should be noted that Ge-detectors is not only a technique, it is a very important industry with huge market in nuclear science. There are tremendous potential benefits in investing in domestic Ge expertise and industries. It can be expected that, through active partnership, the CDEX-0νββ program will help to realize an industry in germanium detectors with world-standing in China which masters all aspects of the technologies. This is an important industrial, commercial and strategic advance in its own right.

5. Status of the Key Technologies

The key technologies of this project include advanced semiconductor detector technology for high purity germanium, low-temperature low-background low-noise electronics technology and liquid argon anti- Compton technology.

In the aspect of advanced semiconductor detector technology for high purity germanium, the key points are the large-mass-scale enrichment of ^{76}Ge, the growth of high purity germanium crystal and the germanium detector fabrication technology. In recent years, China gradually has the capacity for large-mass enrichment of ^{76}Ge. China Nuclear Energy Industry Corp., for example, has successfully achieved the ^{76}Ge isotope separation with 95% abundance, and recently reached the industrial production level. Therefore, through the implementation of the project, it will promote the production capacity of germanium-rich materials in China, which is expected to reach several hundred kilograms per year, and it will provide strong guarantee for the raw enriched germanium materials of 1 ton and 10 tons of germanium neutrinoless double beta decay experiment.

In recent years, General Research Institute for Nonferrous Metals (GRINM GROUP), Guangdong Vital Materials Corp., Tsinghua University, Shenzhen University in China have made good progress in the growth of high purity germanium crystal, and successfully grown high purity crystals that meet the requirements of detector fabrication. In addition, growing crystals underground can greatly decrease the cosmogenic isotopes produced by the irradiation of cosmic rays, which is one of the main background sources in double beta decay experiment. Through the knowledge accumulation of previous CDEX experiment and simulation, we have mastered the background control method of cosmogenic isotopes in germanium during crystal growth, detector processing and transportation. The study indicates that to achieve the half-life measurement sensitivity to ~10^{29} years, the physical goal of 10T, crystals must be grown in an underground laboratory. CJPL will provide an ideal deep underground place for crystal growth. CJPL has already been funded by the "National Major S&T infrastructure of China" project of the National Development and Reform Commission (NDRC) to carry out research on the underground growth of germanium crystals and the fabrication of detectors, aiming to significantly reduce the cosmogenic radioactivity and develop new techniques for large unit detectors.

After more than ten years of intensive research, Tsinghua University has achieved variety of germanium detector fabrication techniques such as BEGe, Coaxial, Point Contact (PCGe) and ICPC. Their key performance especially energy resolution has reached the international advance level, comparable to the current best-performing commercial products, and have put on the market. Broad Energy Germanium (BEGe) detector, for instance, which is adopted by the Gerda Phase II detectors, has the advantages of low noise, better energy resolution, and good pulse shape discrimination to differentiate single hit and multi-hits events. Our plan is to develop new 1kg BEGe detector with a ^{76}Ge abundance of over 86%, with a diameter of 80mm and a height of 40mm, and an energy resolution of FWHM<500eV@122keV and 2.5 keV @ 2039 keV. Inverted Coaxial Point Contact (ICPC), a new technique of point contact detector for larger mass crystal unit and multi-purpose experiment, combining both advantages of BEGe and PCGe, with higher mass, lower capacitance, lower energy threshold and efficient pulse shape discrimination. An ICPC detector has been successfully made by Tsinghua University with a mass of 1.5 kg and an energy resolution (FWHM) of 500 eV @122keV and 1.7 keV @ 1332 keV. It is planned to develop >2kg ICPC detectors with energy resolution up to 2.5 keV@2039 keV. In addition, we have accumulated a lot of experience in development of low-mass, low-background detector materials and low-temperature, low-background low-noise front-end electronics. For example, in order to minimize the radioactive background from surrounding materials of germanium crystals, our design solution uses a modular mechanical structure consisting of lightweight oxygen-free high-conductivity (OFHC) copper and PTFE to hold the detector structure; and the signal is read by a low-background, low-noise CMOS ASIC preamplifier. The OFHC copper component mainly provides mechanical support, fixation and connection between unit detectors. PTFE parts are mainly used for fixing crystals and isolating high voltage.

As to the front-end electronics, CMOS ASIC pre-amplifier uses custom-designed CMOS Integrated Circuit process. Compared to traditional JFET, CMOS pre-amplifier can operate directly at germanium detector work temperatures of about 77 K, thus reducing the connection length and its parasitic capacitance, and achieving the same or better noise performance as JFET pre-amplifier. CMOS pre-amplifier also offer the natural advantage of achieving low background, due to all circuits of CMOS pre-amplifier are integrated into a single chip and use fewer materials. In 2010, serval international experiments paid attention and carried out to develop ASIC pre-amplifiers based on CMOS technology. By now, the ASIC pre-amplifier is the preferred choice for future ton-scale Ge experiments. Tsinghua University began ASIC technology research in 2004 and has always been the leading position in the world. At present, based on 0.35 μm CMOS process, ASIC pre-amplifier has achieved the goals of low background, stable operation at liquid nitrogen temperature and best low noise result (ENC ~ 10e) under the condition of connecting with ~1kg germanium detector.

The CDEX Collaboration has studied liquid argon time projection chamber (TPC) and liquid argon anti-Compton system for many years. Sun Yat-sen University and Tsinghua University have been deeply participated in the research and development of the liquid argon dark matter experimental facility, responsible for the design and installation of the core liquid argon detector, developed a ton-scale liquid argon dark matter detection system, and has rich experience in single-phase liquid argon detection and low threshold dual-phase argon TPC technologies. In addition, the prototype of liquid argon anti-Compton system has been developed by Sichuan University and Tsinghua University, and rich experience has been accumulated in liquid argon scintillation readout and liquid argon purification.

6. CDEX-0νββ in the International Context

Several isotopes used to derive the competitive results of the 0νββ decay include ^{76}Ge, ^{136}Xe, ^{130}Te and ^{100}Mo. Whereas, the international production capacity of enriched germanium and xenon has been formed and meets the experimental needs of 0νββ based on large-scale ^{76}Ge or ^{136}Xe. Meanwhile, ^{130}Te isotope has a cost advantage due to the high natural abundance.

There is consensus on the baseline of the enriched germanium detection technology for future 0νββ experiments -- a cosmogenic-control enriched germanium-76 array immersed in an anti-Compton capability, isotopically depleted liquid argon and employed in low-radioactivity front-end electronics, supporting material and cables. On the other hand, there are a variety of technical solutions and experimental approaches to advance for the isotopes such as ^{136}Xe and ^{130}Te in the world. The most comprehensive competitive experimental technology might be determined in the next 5 to 10 years. Future cross-examination between the results of 0νββ experiments based on different isotopes is crucial to have the complementary results of the 0νββ decay.

Compared to other technologies used in the searches of the 0νββ decay, the germanium-76 detector has the merits of having the best energy resolution. While the search of the 0νββ decay sustains null results, the detectors with poor energy resolution will be interfered or even overspread by an irreducible 2νββ background. Besides, the uranium and thorium chains of germanium crystals themselves are extremely low. The upper limit of 90% CL measurement of ^{226}Ra is 8.6×10^{-23} *g/g*. Therefore, the background control is focused on the front-end electronics, support materials, installation process contamination, cosmic radioactivity and anti-Compton detector materials. It is generally recognized that, following details reviews among the different experimental concepts and readiness, the enriched germanium detector array offers the best prospects for the next generation of 0νββ experiments and beyond.

At present, in the international enrichment germanium detector array 0νβ experiment, European and United States scientists jointly established the LEGEND cooperation group to promote the 0νββ experiment based on enriched germanium in two stages of 200kg and tonnage. At present, the LEGEND-200 experiment is building a 200kg enriched germanium experimental device in the LNGS underground laboratory in Italy, with an expected half-life target of 10^{27} years. The LEGEND-1000 project is expected to have a half-life of more than 10^{28} years, and the goal is to scan all parameter spaces in inverted mass ordering, but the current experiment location and project funding are not yet fully secured.

The CDEX collaboration will conduct the 0νββ experiments at CJPL. As a pilot analysis, the first 0νββ experimental results based on a natural abundance of germanium-76 single germanium detector was published in 2017. Due to the by-product result, the sensitivity of the effective neutrino mass in the CDEX collaboration is weaker by about 1 order of magnitude higher from the results of the European GERDA experimental group at that time. Over the past decade, the CDEX collaboration has accumulated a solid foundation in high-purity germanium detector technology, successfully prepared different types of detectors, and the key energy resolution performance parameters are comparable to the current best-performing commercial high-purity detectors. At the same time, the Tsinghua University team is supported by the "National Major Scientific and Technological Infrastructure of China", the funding agency of the National Development and Reform Commission of China. Several types of the germanium detector fabrication and some key technologies at CJPL, together with the promotion on China's capacity for the production of large-scale enriched germanium materials, has been made. The realization of these projects will place China to the international leading positions in many aspects of the germanium detector technology. They will address the key technical challenges that have long plagued scientists engaged in Ge-0νββ in Europe and the United States – cosmogenic background, high fabrication cost, slow production rate. They will allow the CDEX program to take the driving roles in future evolution of the subject, and serve as an important platform for international cooperation in future experiments on enriched germanium 0νββ in one-tonne to ten-tonne scales, including scientists from China, Europe and the United States.

The CDEX cooperation group will seek in-depth cooperation with the world's expertise and key players in 0νββ while acquiring the key technologies for ^{76}Ge 0νββ experiment in China and promoting future one-tonne and even ten-tonne ^{76}Ge 0νββ experiments in an international collaborative manner.

7. CDEX Collaboration

CDEX collaboration was formed in 2009 and mainly consists of Tsinghua University, Sichuan University, Peking University, Beijing Normal University, IHEP, Nankai University, Sun Yat-sen University, CIAE, NUCTECH Company, YaLong River Hydropower Development Company, Academia Sinica, Banaras Hindu University (India) and Dokuz Eylül University (Turkey). The collaboration has performed experiments in light dark matter searches at CJPL with germanium detectors, and is promoting experiment research on 0νββ in ^{76}Ge.

Tsinghua University has a good track record in research on particle physics and nuclear technique application. Tsinghua group started dark matter detection using HPGe detectors in Y2L in 2004. The group designed the first single-element point contact germanium detector with a mass of 1kg in 2009. To further reduce background and scale the detector mass, we developed a germanium detector array with three detectors in one string in CJPL. Based on the detector array, the stringent limit on spin-independent WIMP-nucleus interaction. Incorporating the Migdal effect, we successfully excluded the parameter space between 50 and 180 MeV/c^2. In addition, the low threshold germanium detector was also applied to directly detect solar dark photons. In a parallel with dark matter detection, we initiated 0νββ search with a natural germanium detector and published the first result of ^{76}Ge half-life limit in China.

Germanium detector and related technologies have been developed by CDEX. We have successfully made our germanium detectors and low background electronics. The first point contact germanium detector equipped with a CMOS ASIC pre-amplifier came to true in Tsinghua University. We also set up isotope separation cascade in the laboratory and produced several kilograms of enriched ^{76}Ge material with an abundance of about 90%.

CJPL is jointly operated by Tsinghua and Yalong river company and ready to provide sufficient experiment space and logistic support for next phase of CDEX.

For international cooperation, Tsinghua and Sichuan University was founding institutes of LEGEND collaboration and establish good connection with international colleagues on the development of detector and electronics and the coordination of underground labs. At the moment, CDEX at CJPL and LEGEND at LNGS are promoting 200-300 kg ^{76}Ge 0νββ, respectively. The cooperation between two groups is natural and desirable for future ton scale experiment to probe the neutrino inverted mass ordering, and beyond.

8. Budget and Schedule

The CDEX collaboration proposes the construction of a next-generation ^{76}Ge 0νββ experiment (CDEX-300) in CJPL. It consists of 225 kg Ge detectors enriched to more than 86% in ^{76}Ge, a liquid argon (LAr) anti-veto background suppression system, CMOS ASIC front-end electronics specified for low-noise, low-background, and low-temperature use, and a set of high precision data acquisition system. The CDEX-300 experiment setup is planned to install in the center of a 1725 m^3 liquid nitrogen cryostat in the C1 hall of CJPL-II. The Ge detector array, liquid argon, and scintillation light readout devices are kept in a reentrant tub submerged in the liquid nitrogen cryostat. An over 6 m liquid nitrogen surrounding the reentrant tub can provide an effective shield against radioactivity outside the reentrant tub. Based on the technology innovations acuminated during the operation of CDEX-300, utilizing the modular features of Ge detector array, and via international cooperation, future experiments with larger detector mass and lower background, CDEX-1T with 1-ton detector mass and CDEX-10T with 10-tons detector mass, could be constructed in a running / construction parallel mode and achieve half-life sensitivity of $>10^{28}$ yr (CDEX-1T) and $>10^{29}$ yr (CDEX-10T).

The budget of this project mainly consists of the acquisition of ^{76}Ge, the growth of high purity Ge crystal, production of Ge detector, research and development of electronics and DAQ, travel expenses, and service fees. Based on the current cost projection, the budget is approximately 1.5 Billion RMB for CDEX-1T and 10 Billion RMB for CDEX-10T.

The modular feature of the Ge detector array allows us to start data taken before reaching the full detector mass. Batches of detectors can be installed into the cryostat as detector strings. Assuming the construction of CDEX-300 starts in 2023, the sequence of actions is as follow:

- From 2023 to 2027: construction, data taking of CDEX-300 to 2030, reaching a ^{76}Ge 0νββ half-life sensitivity of $>10^{27}$ yr at the end of its operation, probing the neutrino inverted mass ordering, that is $m_{\beta\beta}<30$ meV.
- From 2027 to 2033: construction of CDEX-1T experiment.
- From 2033 to 2040: data taking of CDEX-1T, reaching a ^{76}Ge 0νββ half-life sensitivity of $>10^{28}$ yr at the end of its operation, covering entirely the neutrino inverted mass ordering, that is $m_{\beta\beta}<10$ meV.
- From 2033 to 2040: construction of CDEX-10T experiment while operating CDEX-1T.
- From 2040 to 2050: data taking of CDEX-10T, reaching a ^{76}Ge 0νββ half-life sensitivity of $\sim1.3\times10^{29}$ yr at the end of its operation, start probing the neutrino normal mass ordering, that is $m_{\beta\beta}<5$ meV.