The Center for Underground Physics (CUP)

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ABSTRACT

The Center for Underground Physics (CUP) was established as a research center of the Institute for Basic Science (IBS) in 2013. It aims to become an internationally prominent research center for basic particle astrophysics. Two major experimental programs are being pursued at CUP: the COSINE experiment, which searches, with high sensitivity, for dark matter; and AMoRE, which is a neutrinoless double-beta decay search.

INTRODUCTION

The discovery of the Higgs particle was a significant milestone in the quest to understand nature in that it completed the experimental confirmation of the Standard Model (SM) of elementary particle physics. The SM includes six quarks and leptons, four gauge bosons mediating weak, electromagnetic, and strong interactions, and finally the Higgs scalar boson as elementary particles. However, while the Standard Model's structure is experimentally well established, there are still major questions that remain unanswered. Among them, some of the most pressing and fundamental questions are as follows: (1) What is dark matter and what is dark energy? (2) What is the fundamental nature of neutrinos? What are their absolute mass values? Why are their masses so small? (3) What created a large asymmetry between matter and antimatter in the Cosmos? Why is the observed Universe comprised of matter, with no significant amounts of antimatter?

The answers to these questions will have implications for a more fundamental theory that goes beyond the current scope of the Standard Model (i.e., Beyond the Standard Model (BSM) theory) and provides a more profound understanding of nature. Experimental guidance is essential for progress in the development of a viable BSM theory. Energy-frontier experiments at CERN with the LHC accelerator aim at discovering new particles that may provide clues to the solutions to the above questions. The discovery of new elementary particles will likely revolutionize particle physics and deepen our understanding of nature and the Universe. In contrast to the physically giant and very expensive (≈ $10 billion) energy-frontier accelerator experiments, particle astrophysics experiments conducted deep underground at the low-background frontier, have been small-scale and relatively inexpensive. Nevertheless, these underground experiments made a number of very important discoveries, including: the first detection of neutrinos; the production of neutrinos in the core of the Sun and in supernova explosions; and the discovery of neutrino oscillation phenomena that confirm that neutrinos have mass. Underground experiments also were first to observe the two-neutrino beta decay mode of certain nuclei, and observe and measure very rare nuclear reactions that are important for understanding the nucleosynthesis of heavy elements in our Universe.

FACILITIES AT CUP

Expo HQ laboratory

The IBS Complex, which is currently under construction at Expo Science Park in Daejeon (Fig. 1), will serve as a global research hub for basic science with state-of-the-art research facilities and amenities. The total area of the complex is 260,000 m^2 with the gross floor area totaling

113,000 m^2. CUP will have a ground laboratory at this complex from May 2018. The laboratory will include facilities for crystal growing, chemical purification, low temperature detector R&D, inductively coupled plasma mass spectrometry (ICP-MS), sensor fabrication etc.

Fig. 1: Rendering of the IBS headquarters building, presently in development in Daejeon, Korea.

Low Temperature Detector Lab.

It has been shown that the technique of simultaneously measuring heat (phonon) and light (photon) signals with a setup composed of a scintillating crystal and metallic magnetic calorimeters (MMCs) offers great advantages in terms of energy resolution and background rejection, with good separation capabilities between alpha and beta particles (Fig. 2). We are developing low temperature detector techniques with dilution refrigerators to improve energy and timing resolution.

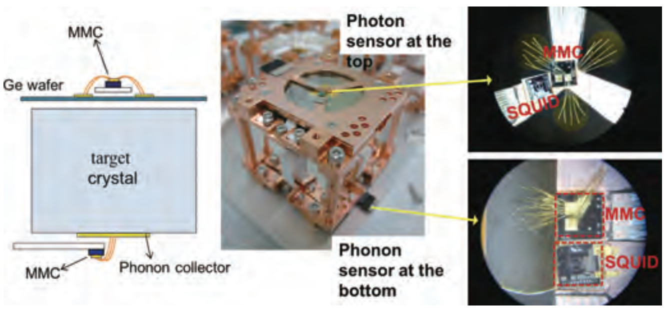

Fig. 2: A unit of a scintillating low-temperature detector using MMC. A phonon MMC sensor is connected to a gold-film phonon collector, while the photon MMC sensor is attached to a Ge wafer.

Sensor Fabrication Lab.

To optimize the low temperature detectors, we are trying to optimize the design of MMCs. To fabricate MMCs, we are installing fabrication equipment such as a radon-free e-beam evaporation system, ICP-RIE (inductively coupled plasma-reactive ion etching), Nb sputtering system etc. (see Fig. 3). All MMCs for the detectors of AMoRE and future experiments will be prepared in this lab.

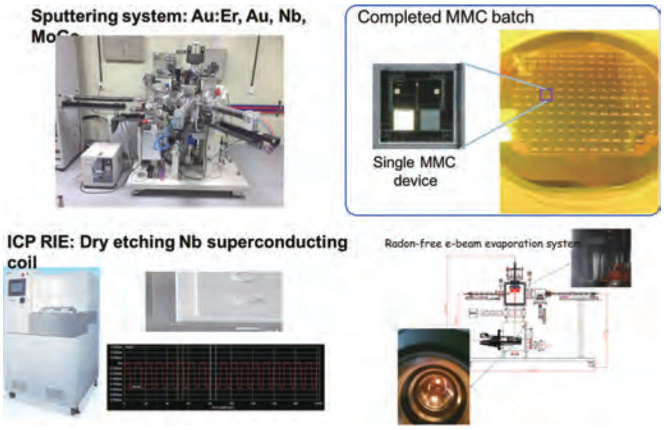

Fig. 3: Equipment for MMC sensor fabrication.

Crystal Growing Lab.

Since CUP concentrates on experiments utilizing heavy crystals, we are constructing and operating a crystal growing facility ourselves in the center (Fig. 4). We are growing crystals such as $CaMoO_4$, Li_2MoO_4, $Na_2Mo_2O_7$, NaI(Tl), etc.

Fig. 4: Czochralski crystal grower.

Purification Lab.

Most materials have contamination of various kinds of radioactive nuclides even though they are highly pure (99.99%). For example, NaI powder contains considerable amount of Pb and K, and $CaCO_3$ powder contains Th, U, and Sr etc. Many radiochemical analytical procedures have been developed based on radioactive nuclide separation techniques. In this chemical lab, we are developing various types of techniques for the purification of chemical compounds from radioactive nuclides; the techniques are listed as follows:

- Liquid Chromatography
- Precipitation
- Recrystallization
- Sublimation
- Zone melting

In addition to purification, we are also developing a measurement technique with ICP-MS for ultra-low levels of contamination (Agilent 7900). Currently, the ICP-MS machine has a detection limit of about 10 ppt for U, Th inside the MoO_3 powder due to the matrix existence. A new technique extracting the U, Th from the material under investigation will enhance the sensitivity down to the 0.1 ppt level with the same ICP-MS machine. The required level of the Th chain in the molybdate crystal for AMoRE-II experiment is about 0.3 ppt.

Yangyang Laboratory (Y2L)

CUP is managing Yangyang Underground Laboratory (Y2L), which is located on the east side of the Korean peninsula, about two hours driving time from Seoul, in a space provided by the Korea Hydro and Nuclear Power (KHNP) company. The underground laboratory is located in a tunnel where the vertical earth overburden is about 700m. The KIMS-CsI dark matter experiment was performed at this laboratory from 2003 to 2012 (Fig. 5).

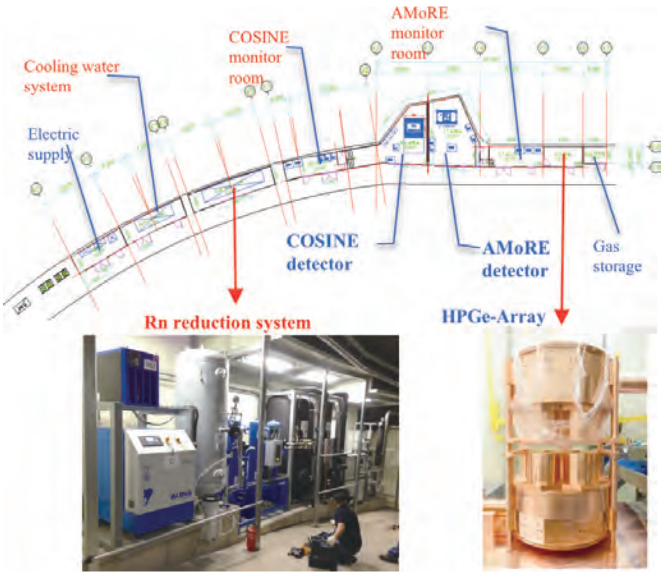

Fig. 5: A5 tunnel floor where both COSINE-100 and AMoRE-Pilot experiments are running. A radon reduction system (150 m^3/hr) and HPGe-array detector are shown.

Handuk Underground Laboratory

The Y2L laboratory was built in year of 2003 utilizing tunnels unused in the underground hydro-electric power plant. The COSINE-100 and AMoRE-pilot experiments are on-going in the lab, but with limited space of about 300m^2. CUP proposed to build another large area underground laboratory at an active iron mine, Handuk mine in Korea. Fig. 6 shows the planned underground laboratory with an area of more than 2000 m^2. We will have two water tanks with a 10 m diameter and 10 m height. One tank will be used for AMoRE-II experiment with a cryostat system including detectors will be immersed in the water tank to minimize the backgrounds. Another tank will be used for potential research with large volume of liquid scintillator mainly for dark photon search experiment and neutrino detection. There will be dedicated room for crystal growing at underground to avoid cosmic excitation in the crystals, and there will be extra space for future proposals.

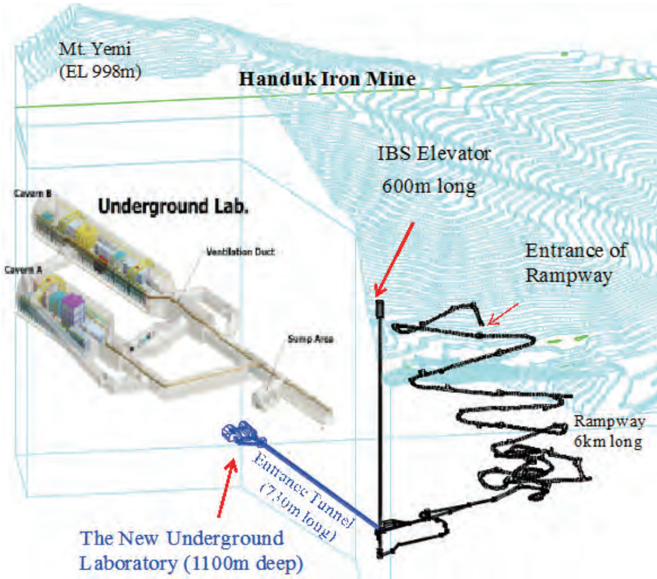

Fig. 6: Schematic diagram for the planned underground laboratory in Handuk's active iron mine. IBS will build a dedicated vertical elevator, 730m entrance tunnel, underground laboratory, and ground-level laboratory. Construction will be finished by the end of 2019.

DARK MATTER SEARCHES

There is much evidence that our Universe is mainly composed of dark matter and dark energy; the standard model particle energy density makes up only about 5% of the total energy density, and the remaining 95% is unknown. There are numerous theoretical models about what dark matter is; axions and weakly interacting massive particles (WIMPs) are strong candidates among them [1]. Since Witten's 1985 proposal to search for direct signals from the interaction of WIMPs using terrestrial detectors [2], many underground experiments have searched for these hypothesized dark-matter particles since the energy deposition by the WIMP-nucleus scattering, order of ~10 keV, is "easily" detectable with ordinary particle detectors. Now, after three decades of searching by experiments with sensitivities that have improved by almost ten orders of magnitude, no clear signs for WIMPs have been uncovered. However, they may show up anytime in the data with upcoming, more sensitive detectors. Underground experiments will continue to play critical roles in attempts to answer questions about dark matter.

Of particular interest is that an Italian group, DAMA, has claimed that they have observed persistent yearly modulation signals in their NaI(Tl) crystal detectors for last 14 years [3]. Their signal is the yearly ups and downs in the count rates between the 2-6 keV energy region, and they have claimed that there is no other explanation possible for this result, except WIMP-Na(I) nuclei interaction. However, no other experiments could see the same annual modulation, even with much lower background and more sensitive detectors. Since the DAMA group themselves confirmed the annual modulation signal with two independent experiments with different sets of NaI(Tl) crystals, the modulation itself seems to be confirmed, so this contradiction is an anomaly. The DAMA group will release an additional six years' worth of data in 2018, with different sets of photomultipliers this time.

At the Center for Underground Physics (CUP) of the Institute for Basic Science (IBS), we tried to confirm or reject the DAMA's claim by repeating the same NaI(Tl) experiment at Yangyang underground laboratory (Y2L). The COSINE experiment is divided into two phases. The COSINE-100 experiment, which began last September, houses 100 kg of NaI(Tl) crystals at Y2L [4.5] (See Fig. 7). The background rates in these crystals are higher than DAMA, ~ 2-4 dru (differential rate unit, counts/keV/kg/day), compared to ~ 1 dru in DAMA's data. However, DAMA's modulation signal is clearly observed over null modulation, which makes the COSINE-100 experiment a possible means for determining whether we are seeing the same modulation or not with two years of data. The background spectra obtained with NaI(Tl) crystals at Y2L are shown in Figure 8. While we run the COSINE-100 experiment, we are growing NaI(Tl) crystals at CUP's ground-level laboratory in cooperation with a French expert on crystal growing for the second phase of the COSINE experiment. It is very challenging to grow large single crystals of good quality and low backgrounds; presently, such high quality NaI(Tl) crystals are not available commercially. In second phase of COSINE, we aim to have crystals with backgrounds lower than 1 dru.

Fig. 7: COSINE-100 setup. (Left) The figure shows overall setup including the shielding. (Right) The rfigure shows the NaI(Tl) detectors inside liquid scintillator veto system.

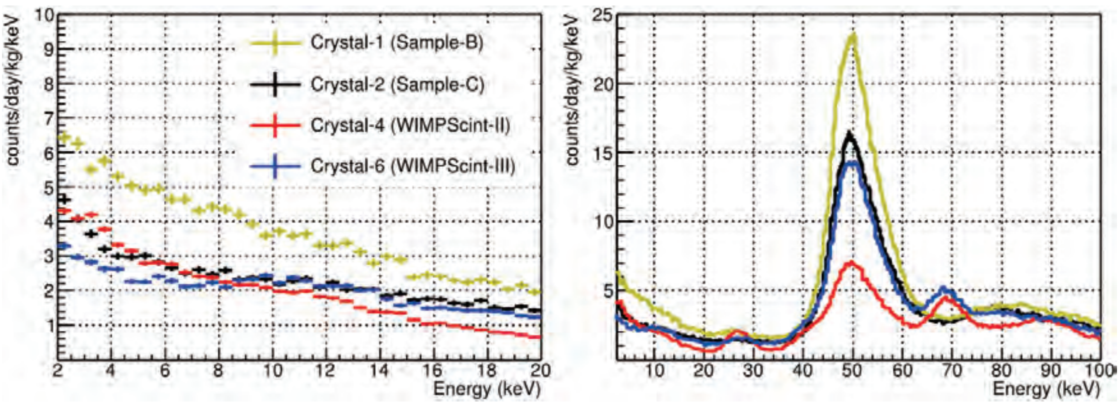

Fig. 8: Energy spectrum comparison for four crystals from different powder samples. (Left) A zoomed view of the E<20 keV region of the spectrum. The spectra were made after the application of the three noise rejection criteria. (Right) The peak near 50 keV reflects the Pb-210 contamination level in each crystal. Crystal-4 and Crystal-6 have been underground for less than one year and so cosmogenic peaks (e.g. 125I at 67.8keV) are additionally seen. Ref. [4]

DOUBLE BETA DECAY

Although (aside from photons of light) neutrinos are the most abundant particles in nature, and an essential and well-established component of the Standard Model, they remain the most poorly understood of the elementary particles. The very small neutrino mass suggests that the source of its mass is different from the well understood Higgs mechanism. Also, many theoretical ideas for understanding the asymmetry of matter versus antimatter in the current Universe invoke the neutrino sector [6]. However, their basic frameworks depend critically on whether neutrinos are two-component Majorana spinors or four-component Dirac spinors. Moreover, although we know that neutrinos have mass, and despite having successfully measured the two mass differences between three neutrinos by neutrino oscillation experiments, we do not know their absolute mass values. The only practical method to resolve this dilemma is by measurement of the ultra-rare zero-neutrino double beta decay processes (0nDBD). The signal of 0nDBD is a mono-energetic energy deposition from the nuclear decay in the energy range of ~ a few MeV depending on the nuclei. The half-life of 0nDBD is inversely proportional to the neutrino mass squared and found to be larger than 10^{25} years. Future experiments will require deep underground experiments with background levels well beyond current state of the art technologies.

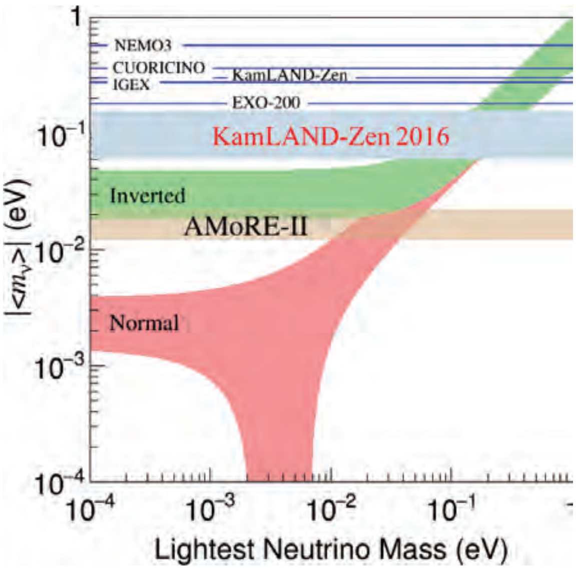

Fig. 9: The green (inverted hierarchy) and red (normal hierarchy) colored regions show the predictions on effective neutrino mass from oscillations as a function of the lightest neutrino mass. The most stringent experimental limits, the KamLAND-Zen result and the predicted AMoRE experiment sensitivity are shown as horizontal bands.

At CUP, we are preparing the AMoRE (Advanced Molybdenum Rare Decay Experiment) experiment, which is an experiment trying to discover 0nDBD from ^{100}Mo nuclei [7]. We have 110 kg of enriched ^{100}Mo powder produced by the Russian company ECP, and we are trying to grow molybdate single crystals to measure the mono-energetic (3034keV) events occurring in the crystal. The AMoRE experiment will proceed in three different phases, increasing the crystal mass up to 200 kg for the AMoRE-II phase. In AMoRE-II, the expected sensitivity of the 0nDBD lifetime is 8.2×10^{26} years and the neutrino mass sensitivity can be as low as 13-25 meV as shown in Fig. 9 and Table 1. The crystal is cooled down to a temperature of 10 mK, and sensitive phonon sensors have been developed and are shown in Fig. 2. We have installed six doubly enriched $^{40}Ca^{100}MoO_4$ crystals at Y2L and began to take data in August 2016 [8]. To avoid the vibrational noise from pulse tube coolers, we installed a spring suspended still (SSS) and a mass spring damper (MSD) as shown in Fig. 10. We have successfully grown the appropriate molybdate crystals for the AMoRE-II experiment at CUP, such as Li_2MoO_4 or $Na_2Mo_2O_7$ crystals. The AMoRE-II experiment will have 200 kg of the crystals. In Fig. 11, the scatter plot of rising time versus the energy and the rising time distribution of high energy events

	AMoRE-Pilot	AMoRE-I	AMoRE-II
Mass (kg)	1.5	5	200
Backgrounds	10^{-2}	10^{-3}	10^{-4}
$T_{1/2}$(year)	1.0×10^{24}	8.2×10^{24}	8.2×10^{26}
m_{2b} (meV)	380-719	130-250	13-25
Schedule	2015-2017	2018-2019	2020-2023

Table 1: The expected sensitivities and other parameters of the phases of the AMoRE experiment.

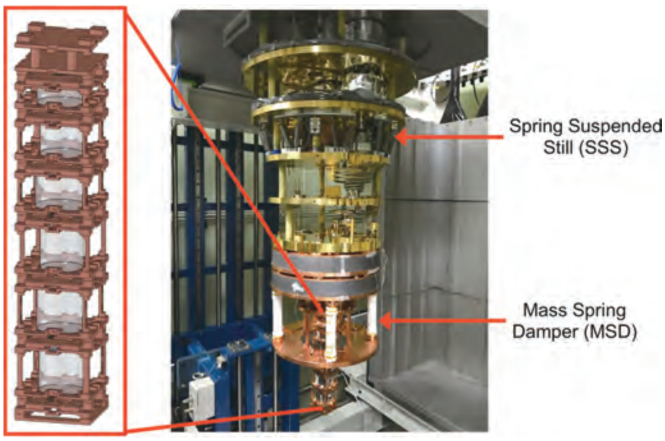

Fig. 10 : A setup of the AMoRE-pilot experiment. Six $^{40}Ca^{100}MoO_4$ crystals are at the bottom of the setup.

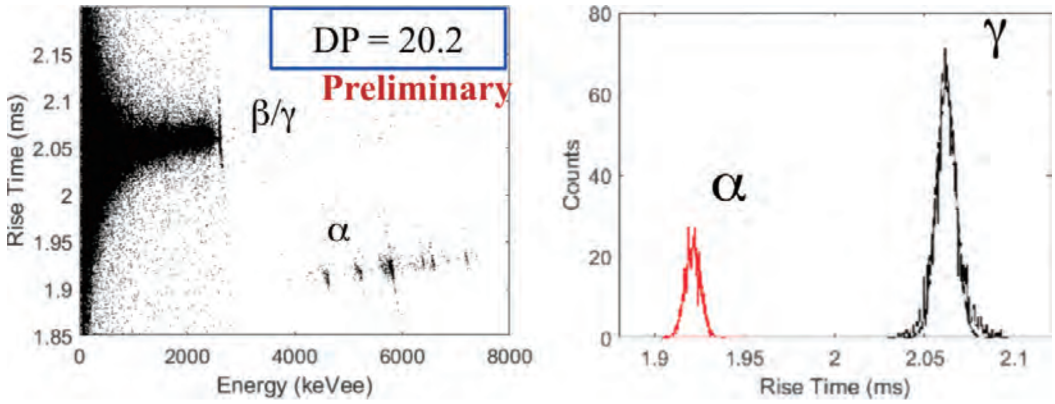

Fig. 11: (Left) Rising time of the pulse as a function of the energy. (Right) Rising time distribution of high energy events including 2.6 MeV gammas.

including 2.6 MeV gammas are shown. The separation power between gamma(beta) events from alpha backgrounds at the region of interests reached up to 20 σ.

The first double beta decay experiment began more than 70 years ago. Since then, numerous experiments have attempted to discover the 0nDBD, but no event has been found yet and the race is continuing [9]. The best present results on 0nDBD for eight of the most promising nuclei are summarized in Table 2.

NEUTRINO OSCILLATIONS

The Neutrino Experiment for Oscillation at Short Baseline (NEOS), which searches for light sterile neutrinos, is being conducted at a reactor with a thermal power of 2.8 GW located at the Hanbit nuclear power complex in South Korea as a CUP neutrino program [18]. The search is being done with a detector consisting of a ton of Gd-loaded liquid scintillator shown in Fig. 12. in a tendon gallery approximately 24 m from the reactor core. The measured antineutrino event rate is about 2000 per day with a signal to background ratio of about 22. Data was taken for 6 months. The shape of the antineutrino energy spectrum obtained from the eight-month data-

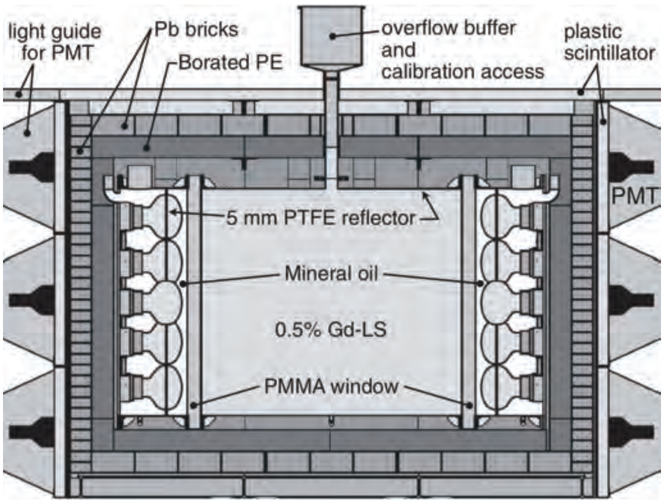

Fig. 12: A cross-sectional view of the NEOS detector.

Mother	Q (keV)	Abun. (%)	$T_{1/2}(2n)$ (10^{20} Y)	Exp	$T_{1/2}(0n)$ (10^{24} Y)	M (meV)	Ref.
^{48}Ca	4270.0	0.187	0.44	CANDLES	> 0.058	3.1-15.4	[10]
^{76}Ge	2039.1	7.8	15	GERDA-II	>53	0.15-0.33	[11]
^{82}Se	2997.9	9.2	0.92	NEMO-3	> 0.36	1-2.4	[12]
^{100}Mo	3034.4	9.6	0.07	NEMO-3	>1.1	0.33-0.62	[13]
^{116}Cd	2813.4	7.6	0.29	AURORA	> 0.19	1-1.8	[14]
^{130}Te	2527.5	34.5	9.1	CUORE-0	> 4.0	0.26-0.97	[15]
^{136}Xe	2458.0	8.9	21	KamLAND-Zen	> 107	0.06-0.16	[16]
^{150}Nd	3371.4	5.6	0.08	NEMO-3	> 0.02	1.6-5.3	[17]

Table 2: Best present results on the neutrino mass (M) from 0nDBD experiments (limits at 90% C.L.). To calculate M, g_A = 1.27 has been used.

taking period was compared with a hypothesis of oscillations due to active-sterile antineutrino mixing. No strong evidence of sterile neutrino oscillation was found. An excess around the 5 MeV prompt energy range was observed as seen in existing longer-baseline experiments. The mixing parameter $\sin^2 2\theta_{14}$ was limited up to less than 0.1 for $\Delta(m_{41})^2$ ranging from 0.2 to 2.3 eV^2 with a 90% confidence level [19]. We plan to run NEOS-II experiment at the same tendon gallery to take data for a whole fuel cycle, 1.5 years. The new data will clarify the reactor anomaly.

In summary, the Center for Underground Physics will pursue discoveries of 0nDBD and dark-matter WIMPs, with the goals of reaching the most significant regions of the still unexplored parameter space by continuously advancing the state-of-art of the techniques necessary for achieving these goals, with low temperature detectors, ultra-low background crystals, and ultra-low radioactivity measurements.

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