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To cite this article: Alex Wright 2017 *J. Phys.: Conf. Ser.* **888** 012036

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Future Neutrinoless Double Beta Decay Search Experiments and Related R&D

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Abstract. The global program of neutrinoless double beta decay search experiments is reviewed, with a focus on those experiments not associated with another oral presentation described in these Proceedings.

1. Introduction

The detection of neutrinoless double beta decay would be a watershed moment in particle physics, demonstrating that neutrinos are Majorana particles and providing direct information about the absolute neutrino mass. As a result, the search for neutrinoless double beta decay has been given high priority by the particle physics community, and the global program of experiments seeking to detect neutrinoless double beta decay is rich and varied.

The central challenge in detecting neutrinoless double beta decay is the combination of the relatively low energy deposited in neutrinoless double beta decay ($< 5 \text{ MeV}$), and the extreme rarity of neutrinoless double beta decay events (current state-of-the-art experiments probe half lives $> 10^{26} \text{ yr}$). To address these issues, neutrinoless double beta decay search experiments must satisfy three main criteria:

- *A large mass of candidate isotope* to offset the long half life of the decay. The leading current generation experiments have fiducial isotope masses approaching 100 kg, and near-term experiments will have a few hundred kilograms. At these masses, experiments are able to probe to the top of the inverted neutrino mass hierarchy region, which corresponds to effective Majorana neutrino masses ($\langle m_{\beta\beta} \rangle$) in the $\sim 50 \text{ meV}$ range¹. To reach the bottom of the inverted hierarchy region ($\langle m_{\beta\beta} \rangle \sim 10 \text{ meV}$), experiments with fiducial isotope masses of $\sim 1 \text{ T}$ will be required. Experiments of this scale are expected to form the next generation of neutrinoless double beta decay search experiments on a likely time scale of a decade. To reach the normal mass hierarchy region, $\langle m_{\beta\beta} \rangle \sim 1 \text{ meV}$, would require experiments of order 10 T, and likely new technology.
- *Good energy resolution* to prevent the relatively numerous two neutrino double beta decay events, which have an endpoint very close to the neutrinoless double beta decay energy,

¹ $\langle m_{\beta\beta} \rangle$ can be used as a measure of experiment sensitivity because neutrinoless double beta decay half life scales as $\langle m_{\beta\beta} \rangle^{-2}$. The “inverted hierarchy” region refers to the region of parameter space in which $\langle m_{\beta\beta} \rangle$ must fall if neutrinos have an inverted mass hierarchy; for a recent review see [1].

from forming undue background in the region of interest. Better energy resolution can also aid background mitigation by making the mono-energetic neutrinoless double beta decay peak narrower and more easily distinguished.

- *Very low rates of background in the energy region of interest* to maintain the desired sensitivity to very low expected neutrinoless double beta decay rates. Leading current generation experiments have backgrounds in the 10^{-3} counts/keV/kg/yr range, with next generation experiments targeting background levels an order of magnitude lower still.

Satisfying these three conditions simultaneously necessarily involves tradeoffs, and different neutrinoless double beta decay search experiments have made very different optimizations. Table 1 lists the main current neutrinoless double beta decay search efforts. A subset of these experiments (those not affiliated with a separate oral presentation at the Neutrino 2016 conference) are described in more detail below. The descriptions are brief by necessity, and references to further information are provided in each case.

Table 1. A summary of current and planned neutrinoless double beta decay search experiments. The target isotope, experimental technique, and location (where determined) of each project are noted. Projects described further in this review are indicated with an '*'; for other projects, relevant references in these Proceedings are noted.

Experiment	Isotope	Technique	Location	References
Majorana Demonstrator	^{76}Ge	Point contact Ge	Sanford	[2–5]
GERDA II	^{76}Ge	Semicoax/BE Ge + veto	LNGS	[6–8]
CDEX	^{76}Ge	Point contact Ge	CJPL	*
NG-Ge76	^{76}Ge	Point contact Ge		*
COBRA	^{116}Cd	CdZnTe	LNGS	*
CANDLES	^{48}Ca	CaF_2 scintillator + veto	Kamioka	*
AMoRE	^{100}Mo	Low-T MMC	Y2L	*
DCBA/MTD	^{100}Mo	Foils + tracker	KEK	*
MOON	^{100}Mo	Foils + scintillator		
EXO200	^{136}Xe	LXe TPC	WIPP	[9, 10]
nEXO	^{136}Xe	LXe TPC	SNOLAB	[9, 11–15]
NEXT	^{136}Xe	High-P TPC	LSC	*
PandaX III	^{136}Xe	High-P TPC	CJPL	*
KamLAND-Zen	^{136}Xe	Liquid scintillator	Kamioka	[16, 17]
SuperNEMO	^{82}Se	Foils + tracker		[18–28]
CUPID	$^{130}\text{Te}, {}^{82}\text{Se}$	Hybrid bolometers		[29–34]
CUORE/CUORE-0	^{130}Te	TeO_2 bolometers	LNGS	[29, 35–38]
SNO+	^{130}Te	Liquid scintillator	SNOLAB	*

2. CDEX

The China Dark Matter Experiment (CDEX) is a relatively new germanium-based experiment that is currently being developed at Tsinghua University, and which will be deployed at the China Jinping Underground Laboratory (CJPL) [39]. The collaboration is currently accruing experience in Ge enrichment, crystal growth, diode fabrication, and production of electro-formed copper as it works towards a 10 kg-scale deployment, with an eventual goal of a 1 T experiment. The first goal of the experiment is dark matter detection; however, the collaboration plans to

include a neutrinoless double beta decay search as part of the physics program in a future 1 T experiment [40].

3. NG-Ge76

The NG-Ge76 collaboration [41] is a recently formed effort aimed at producing a single future tonne-scale neutrinoless double beta decay experiment combining the best technologies of the current generation experiments to achieve a target background rate of ~ 0.1 counts/tonne/year in the neutrinoless double beta decay energy region of interest. An initial meeting of interested parties was held in Munich in April 2016.

4. COBRA

As the name suggests, the CdZnTe 0ν Double Beta Research Apparatus (COBRA) experiment is based on CdZnTe, an intrinsic semiconductor containing five neutrinoless double beta decay isotopes: ^{114}Cd , ^{128}Te , ^{70}Zn , ^{130}Te , and ^{116}Cd . The somewhat challenging charge drift properties of CdZnTe means that COBRA must use smaller crystals than other semiconductor experiments and deploy them in large arrays. The collaboration has operated a $4 \times 4 \times 4$ array of 1 cm^3 (6 g) crystals at the Gran Sasso Laboratory (LNGS) in Italy since November 2013, accruing 216 kg-days of exposure [42]. Using this data, the collaboration has published limits on the neutrinoless double beta decay half lives of all five candidate isotopes [43], including a world-leading 1.8×10^{21} yr (90% C.L.) limit for ^{114}Cd .

Moving forward, the COBRA collaboration envisions a roughly 1 m^3 array composed of 415 kg of larger $2.0 \times 2.0 \times 1.5\text{ cm}$ (36 g) crystals. The collaboration has identified a commercial supplier of such crystals and has tested their performance with segmented readout [44, 45]. Funding has been received for a 3×3 crystal test array with enhanced readout.

5. CANDLES

The CAlcium fluoride for studies of Neutrino and Dark matters by Low Energy Spectroscopy (CANDLES) experiment searches for neutrinoless double beta decay in ^{48}Ca using an array of CaF_2 crystals suspended in a liquid scintillator based active veto. A single system of photodetectors is used for both the crystals and the veto, with the signals from the two systems separated using pulse shape discrimination.

The collaboration is currently operating the CANDLES III experiment, which contains 305 kg of CaF_2 crystals in 2 m^3 of liquid scintillator and features an upgraded passive external shielding system, in the Kamioka underground laboratory. The initial results and background performance [46] indicate that CANDLES III should achieve sensitivity corresponding to an $\langle m_{\beta\beta} \rangle$ of 0.5 eV.

Moving forward, the collaboration believes that an $\langle m_{\beta\beta} \rangle$ sensitivity at the ~ 0.1 eV level can be achieved using the current crystals-in-liquid approach; to extend sensitivity to $\langle m_{\beta\beta} \rangle$ in the 10 meV range the collaboration intends to transition to scintillating CaF_2 crystal bolometers [47]. An important step in improving the future sensitivity of the experiment was recently realized in the demonstration of calcium enrichment of ^{48}Ca using a chemical technique [48].

6. AMoRE

The Advanced Mo-based Rare process Experiment (AMoRE) uses cryogenic calcium molybdate bolometers to search for neutrinoless double beta decay in ^{100}Mo . Both optical and heat readout are accomplished using metallic magnetic calorimeters (MMCs), which are thin pads of an Au:Er material whose magnetization changes with temperature. These changes in magnetization are then read out using a SQUID device. The MMC for temperature measurement is placed directly

on the calcium molybdate crystal, while optical readout is accomplished by suspending a thin Si wafer a short distance away from the crystal surface to act as a photon absorber. A second MMC on the Si wafer measures the optical signal via the heat induced in the Si wafer from photon absorption.

The collaboration is currently operating the AMoRE-Pilot experiment, which includes five $^{40}\text{Ca}^{100}\text{MoO}_4$ (i.e. the material is enriched in ^{100}Mo and also depleted in ^{48}Ca which could induce background from its higher energy two neutrino double beta decay events) crystals totaling 1.5 kg at the YangYang underground laboratory (Y2L). The observed pulse shape discrimination, energy resolution, and background levels suggest that AMoRE-Pilot should achieve a sensitivity to $\langle m_{\beta\beta} \rangle$ in the 0.21–0.49 eV range [49, 50].

An upgraded experiment, AMoRE I, with 5.0 kg of $^{40}\text{Ca}^{100}\text{MoO}_4$ crystals is currently being installed at Y2L and is expected to be operational before the end of 2016. AMoRE I is expected to achieve sensitivity to $\langle m_{\beta\beta} \rangle$ in the 70–140 meV range and act as a step towards the 200 kg AMoRE II experiment, which could deploy in 2018, and which is expected to have sensitivity to $\langle m_{\beta\beta} \rangle$ in the 12–22 meV range [50].

7. DCBA

The Drift Chamber Beta-ray Analyzer (DCBA) is a tracking detector consisting of thin source foils sandwiched between gas-filled drift regions with wire readouts. A uniform magnetic field (0.8 kG in the most recent DCBA-T2.5) in the tracking region enables charge and momentum to be measured [51].

The DCBA collaboration has pursued a staged scale-up program at the KEK Laboratory in Japan, initially with ^{150}Nd as the target isotope [52, 53] and most recently in DCBA-T2.5 with 30 g of ^{nat}Mo . The operation of these detectors in the surface building at the KEK laboratory has allowed the collaboration to demonstrate the powerful background rejection enabled by the magnetic tracking technique [54].

The collaboration is currently working towards the Magnetic Tracking Detector (MTD) experiment, which is envisioned as consisting of modules containing 32 kg of Mo foil each in a layered source foil and tracking region geometry within a cylindrical magnetic coil. Components of MTD are currently under development at KEK.

8. NEXT

The Neutrino Experiment with a Xenon TPC (NEXT) searches for neutrinoless double beta decay in ^{136}Xe . As the name implies, the project is based around high pressure (\sim 10 bar) xenon gas time projection chambers. Energy readout is accomplished by detection of the xenon scintillation light with an array of photomultiplier tubes, while track reconstruction is achieved by drifting the ionization electrons under an applied electric field to one end of the cylindrical field cage where they produce electroluminescence light which is detected using an array of silicon photomultipliers.

NEXT is pursuing a staged scale-up program. Between 2010 and 2014 the collaboration operated \sim 1 kg prototype detectors to demonstrate the energy resolution [55, 56] and topological track identification [57, 58, 59] required for larger detectors. The collaboration is currently commissioning the 10 kg scale NEXT-White (NEW) detector in the Canfranc underground laboratory (LSC) [60]. NEW will be operated with natural xenon until mid 2017 to characterize backgrounds and detector response, after which the detector will be filled with enriched xenon with the goal of measuring the $2\nu\beta\beta$ decay rate.

Concurrently with the deployment of NEW, the collaboration is developing the 100 kg scale NEXT-100 detector [61]. Based on the results of current NEXT detectors, NEXT-100 is expected to be sensitive to neutrinoless double beta decay half lives of 6×10^{25} years (90% C.L.) in a three

year run, which corresponds to $\langle m_{\beta\beta} \rangle$ in roughly the 80–150 meV range. Backgrounds are expected to be $< 4 \times 10^{-4}$ counts/keV/kg/yr in the region of interest [62, 63].

9. PandaX-III

With the next generation detector, PandaX-III, the Particle and Astrophysical Xenon (PandaX) collaboration plans to branch from its initial focus on direct dark matter detection with two-phase xenon TPCs to searching for neutrinoless double beta decay. PandaX-III will be a high pressure xenon gas TPC with a central cathode plane and charge readout via arrays of Micromegas detectors at either end of the cylindrical drift region [64].

The collaboration envisions a 1 T experiment consisting of 5 modules deployed in a large water tank at CJPL. With a predicted background of 1×10^{-4} counts/keV/kg/yr, the experiment is projected to achieve a half life sensitivity of 10^{26} yr (90% C.L.) in 3 years of running. A 20 kg-scale prototype was recently commissioned by the PandaX team at Shanghai Jiao Tong University, the first batch of 20 cm \times 20 cm Micromegas modules has been produced and commissioned, and 200 kg of enriched xenon has already been procured. The first PandaX-III module is projected to be deployed in 2017, with the full array of five modules expected to be online by 2022.

10. SNO+

The SNO+ experiment is a 780 T liquid scintillator based neutrino experiment located at SNOLAB. The experiment has a broad physics program including low energy solar neutrinos, supernova neutrinos, geo-neutrinos, and reactor antineutrinos, but has a main focus on neutrinoless double beta decay [65, 66].

SNO+ will search for neutrinoless double beta decay in ^{130}Te by dissolving ^{nat}Te into the liquid scintillator in the form of a novel organometallic tellurium complex that will be synthesized underground from purified telluric acid [67, 68]. In the first phase of the experiment the scintillator will be loaded with tellurium at 0.5% by weight, which corresponds to 3.9 T of tellurium or 1.3 T of ^{130}Te (260 kg fiducial). Coupled with the low expected background levels, 13.4 counts/year, in the region of interest (corresponding to 3×10^{-4} counts/keV/yr/kg of isotope or 1×10^{-6} counts/keV/yr/kg of scintillator) [69, 70], this loading level is expected to allow SNO+ to achieve a half life sensitivity of 2.0×10^{26} yr (90 % C.L.), corresponding to an $\langle m_{\beta\beta} \rangle$ sensitivity of 38–92 meV in a 5 year run.

The SNO+ experiment is currently being readied for data taking [71, 72, 73]. The detector is being filled with ultra-pure water, after which it will be operated in the water-filled state for a few months. The liquid scintillator purification system is concurrently being commissioned, and it is expected that the filling of the detector with scintillator will begin early in 2017. The tellurium purification and loading systems are expected to be installed underground beginning in autumn 2016, with tellurium deployment beginning early in 2018. Roughly 4 T of telluric acid has already been procured and is being stored underground at SNOLAB as an additional safety factor against cosmogenic activation.

Further in the future, the excellent optical transmission of the Te-loaded scintillator raises the prospect of increasing the neutrinoless double beta decay sensitivity of SNO+ by increasing the tellurium loading level. Scintillator cocktails with Te concentrations as high as 15–20% have been produced, and R&D towards reducing the scintillation quenching observed at these higher loadings is ongoing. Since internal backgrounds in SNO+ are expected to be sub-dominant to the background provided by the ^{8}B solar neutrino signal, the total background level will not scale directly with tellurium loading and the sensitivity of the experiment is expected to scale roughly linearly with loading level. Increasing the loading level to 5%, therefore, might increase the half life sensitivity to the vicinity of 10^{27} yr, allowing SNO+ to probe a large portion of the inverted hierarchy phase space.

Acknowledgments

The author wishes to acknowledge those who provided slides and information used here and in the related presentation: Juan José Gómez Cadenas, Michel Sorel and Paola Ferrario; Mark Chen and Steven Biller; Nobuhiru Ishihara; Yeongduk Kim and Hyon-Suk Jo; Tadafumi Kishimoto and Saori Umehara; Stefan Schönert and Steven Elliott; Xiangdong Xi and Han Ke; Qian Yue; and Kai Zuber and Stefan Zatschler.

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