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IsoDAR@Yemilab—A Definitive Search for Noble Neutrinos and Other BSM Physics [†]

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https://doi.org/10.3390/psf2023008021

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IsoDAR@Yemilab—A Definitive Search for Noble Neutrinos and Other BSM Physics [†]

Daniel Winklehner [‡]

Massachusetts Institute of Technology, 77 Massachusetts Ave., Cambridge, MA 02139, USA; winklehn@mit.edu

[†] Presented at the 23rd International Workshop on Neutrinos from Accelerators, Salt Lake City, UT, USA, 30–31 July 2022.

[‡] For the IsoDAR Collaboration.

Abstract: The IsoDAR neutrino source comprises a novel compact cyclotron capable of delivering 10 mA of 60 MeV protons in cw mode and a high-power neutrino production target. It has obtained preliminary approval to run at the new underground facility Yemilab in South Korea. IsoDAR will produce a very pure, isotropic $\bar{\nu}_e$ source, with a peak neutrino energy of around 6 MeV and an endpoint around 15 MeV. Paired with a kton-scale detector like the planned Liquid Scintillator Counter (LSC) at Yemilab, IsoDAR can measure $\bar{\nu}_e$ disappearance through the inverse beta decay (IBD) channel. We expect about $1.67 \cdot 10^6$ IBD events and 7000 $\bar{\nu}_e - e^-$ elastic scatter events in the LSC in five years of running, letting us distinguish many different models for noble (aka sterile) neutrinos and significantly improving existing limits for Non-Standard Interactions (NSIs). Finally, IsoDAR@Yemilab is sensitive to new particles produced in the target (such as light X bosons that decay to $\bar{\nu}_e\,\nu_e$). We describe the accelerator developments for IsoDAR that enable us to produce about a mole of neutrinos in five years of running. These include direct injection through a radiofrequency quadrupole, exploiting complex beam dynamics, and applying machine learning in accelerator design and optimization.

Keywords: neutrino oscillations; intensity frontier; cyclotrons; sterile neutrinos

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Citation: Winklehner, D. IsoDAR@Yemilab—A Definitive Search for Noble Neutrinos and Other BSM Physics. *Phys. Sci. Forum* **2023**, *8*, 21. https://doi.org/10.3390/psf2023008021

Academic Editor: Yue Zhao

Published: 25 July 2023

1. Introduction

IsoDAR@Yemilab (Isotope Decay-At-Rest experiment at the Yemilab underground facility in South Korea) is a proposed experiment to search for new types of neutrinos and other Beyond Standard Model (BSM) physics [1–3]. In this paper, we will use the term noble neutrinos (first heard from Chris Quigg at Neutrino 2022), because the neutrinos we are interested in—much like noble gasses do not easily form electron bonds—do not interact through weak forces. They are also known as sterile neutrinos and occasionally exotic neutrinos. The motivation for these noble neutrinos lies in a multitude of anomalies observed in neutrino oscillation experiments [4].

As seen in Figure 1, the IsoDAR neutrino source comprises a novel compact cyclotron and a high-power neutrino production target. The need for a high-current compact cyclotron to drive the IsoDAR neutrino experiment gave rise to the development of a new class of cyclotrons, the HCHC-XX (High-Current H_2^+ Cyclotron-XX), delivering 10 mA proton beams in continuous wave (cw) mode. With "-XX", we denote that we can slightly modify the design and build machines with arbitrary final energies from 2 MeV/amu to 60 MeV/amu, leading to many possible applications.

We discuss the detector and the physics case for IsoDAR@Yemilab in Section 2. We describe the cyclotron design, its novel aspects, and the use of machine learning for uncertainty quantification and optimization in Section 3.1. We describe the high-power neutrino production target in Section 3.2, and in Section 4 we briefly discuss several other applications of the HCHC-XX. All excavations for the Liquid Scintillator Counter (LSC) and cyclotron cavern are complete, and IsoDAR has preliminary approval to run at Yemilab.

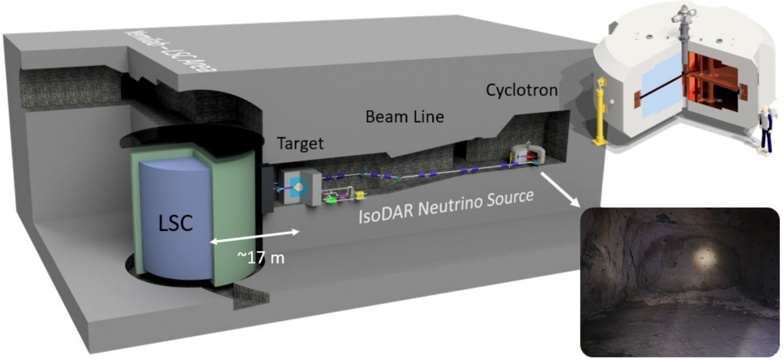

Figure 1. CAD model of the Liquid Scintillator Counter (LSC) and IsoDAR areas in the Yemilab facility. From right to left: The cyclotron provides a 10 mA proton beam that is guided through the beamline to the target where $\bar{\nu}_e$ are produced. The LSC counts inverse beta decay (IBD) events. All caverns are excavated (an example can be seen in the photograph).

2. IsoDAR Physics—Noble Neutrinos and Beyond

The LSC is envisioned to be a 2.3 kton liquid scintillator detector (15 m × 15 m cylinder) using inverse beta decay (IBD) as the primary detection mechanism. With an assumed performance similar to KamLAND [5,6] ($\sigma[E] = 6.4\%/\sqrt{E\ (\mathrm{MeV})}$ and $\sigma[\mathrm{vertex\ (cm)}] = 12/\sqrt{E\ (\mathrm{MeV})}$) and with the IsoDAR neutrino target placed roughly 17 m center-to-center from the LSC, we expect about $1.67 \cdot 10^6$ IBD events and over 7000 $\bar{\nu}_e - \mathrm{e}^-$ elastic scatter events at low Q in 5 years of running. The physics reach with IsoDAR@Yemilab and the estimated event rates above was recently reported on in much detail [7,8]. To summarize:

The noble neutrino search is the flagship analysis of IsoDAR. With the expected resolution, we can trace out the survival probability of $\bar{\nu}_e$ as a function of L/E (distance traveled over neutrino energy) for more than two periods, allowing a shape analysis (see Figure 2). This comfortably covers the global fits and allowed regions from other experiments for eV-scale noble neutrinos with $>5\sigma$ in 5 years of running.

For $\bar{\nu}_e - e^-$ elastic scattering, we expect a $\delta \sin^2\theta_W$ sensitivity of 0.0045 (1.9% measurement). This uses rate and energy shape information and includes statistical and systematic uncertainties. This result will improve the global reactor measurement of $\sin^2\theta_W = 0.252 \pm 0.030$ [9] by almost an order of magnitude. We would also greatly improve the sensitivity to Non-Standard Interactions (NSI) compared to global fits.

Axion-like particles. Mono-energetic photons created in the neutrino production target could potentially convert to axions that then interact or decay in the LSC, producing peaks above the $\bar{\nu}_e - e^-$ elastic scattering signal and the expected background [8].

Bump hunting in the IBD spectrum. In the IsoDAR target, excited nuclei could de-excite, producing a light X particle, a *low mass mediator*. The X could then decay, producing a $\bar{\nu}_e\ \nu_e$ pair, the $\bar{\nu}_e$ of which would be detected through IBD and show up as a bump in the IsoDAR IBD spectrum. These X particles are well-motivated in the literature [10–14].

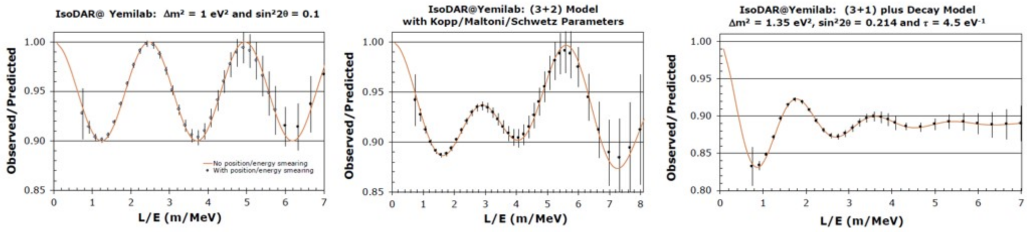

Figure 2. From left to right: A 3 + 1, a 3 + 2, and a 3 + 1-with-decay (of the noble neutrino) model. The decay model (right) does not include position and energy smearing expected from the Yemilab detector, while the other two do. The decay time is consistent with recent IceCube results [15]. From [7].

3. IsoDAR Technology—High Power Cyclotron and Target

3.1. The 60 MeV/amu High Current H_2^+ *Cyclotron (HCHC-60)*

For IsoDAR to be definitive within 5 years of running, we require a beam current of 10 mA, cw, with a minimum of 80% duty factor. This is a factor of 10 higher than current commercially available cyclotrons can deliver. The main challenge with high beam currents is space charge—the Coulomb repulsion of the particles making up the beam from each other. Space charge leads to beam growth and halo formation, leading to controlled and uncontrolled beam loss. Another challenge for the IsoDAR experiment is the underground installation, making compactness a requirement. The HCHC-XX design addresses these challenges [16–18]. It is a room temperature compact cyclotron design with four double-gap RF cavities driven at the 4th harmonic at 32.8 MHz. This leads to a high energy gain per turn, increasing inter-turn separation. A deliberate resonance at the highest radius excites a small precessional motion which further increases this separation at the location of the extraction septum. In addition to these standard methods, we use three novel approaches to achieve the highest beam currents:

- Acceleration of 5 mA of H_2^+. This molecular ion can be stripped of the binding electron after extraction, yielding 10 mA of protons, alleviating space charge [19].
- RFQ Direct Injection. Direct axial injection through a short linear buncher accelerator (a radiofrequency quadrupole or RFQ operating at the cyclotron frequency) [20] that has the highest bunching efficiency available (see Figure 3).
- Vortex Motion. This collective beam dynamics effect only occurs in high-current isochronous cyclotrons. If the current and beam parameters are matched to the external focusing forces, the bunch exhibits rotation about its vertical axis in its local frame. This leads to a round steady-state distribution that facilitates clean extraction [16].

Two examples of the HCHC-XX design are shown in Figure 3 together with a zoom into the central region where the spiral inflector [18] (a set of two electrodes, shaped to follow the beam path, create an electric field that guides the beam) is located. Our recent publication shows the feasibility of the design through Particle-In-Cell (PIC) simulations [16]. All the challenging aspects are located before the beam reaches 2 MeV/amu; thus, it is straightforward to modify the design for any final energy between 2 and 60 MeV/amu and we speak of a family of cyclotrons. During the design process, we used machine learning to create so-called surrogate models, replacing our (costly) high-fidelity simulation decks to facilitate fast RFQ optimization [21] and perform uncertainty quantification [16] of the cyclotron design. We create these surrogate models by either training a neural network or using polynomial chaos expansion on high-fidelity simulation data.

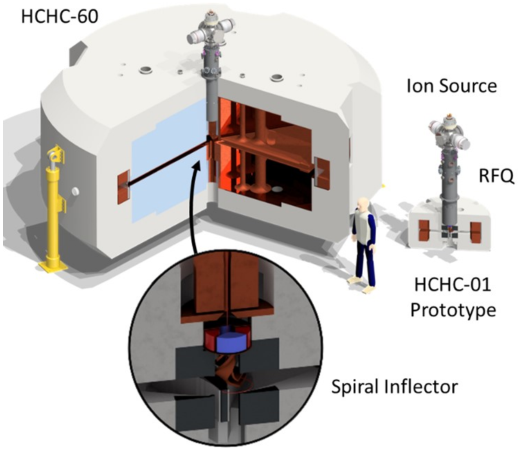

Figure 3. CAD rendering of an HCHC-60 and the HCHC-01 prototype. The beam is created in the ion source, pre-accelerated and bunched in the RFQ, and injected into the cyclotron through the spiral inflector (see text).

3.2. The Neutrino Production Target

The neutrino production target will have to sustain a continuous proton beam power deposition of 600 kW (10 mA, 60 MeV, cw). Our design comprises three nested Be hemispheres that act as spallation targets, producing neutrons. In between these shells, heavy water flows at a rate of 0.031 m^3/s to transfer away heat. Furthermore, we spread out the beam to about 20 cm before it impinges on the target, where it is completely stopped. The shells and the full target structure are shown in Figure 4 and more details of the target design and structural analysis were recently published [2]. Here, we briefly summarize them.

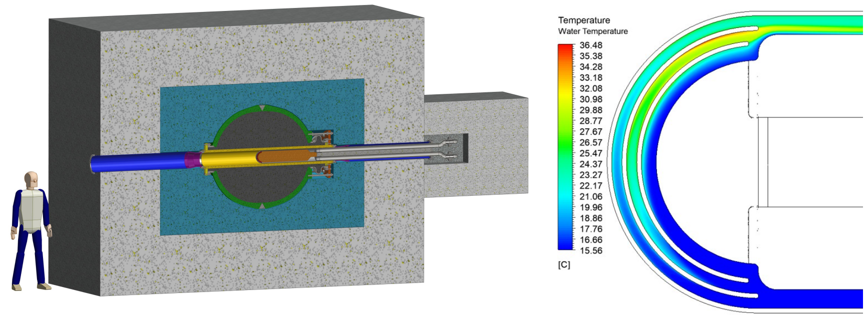

Figure 4. (**Left**): CAD rendering of the IsoDAR high-power neutrino target. The beam enters from the left and strikes the torpedo with three hemispherical shells (orange). Neutrons flood into the surrounding sleeve (stainless steel vessel, green, filled with a mix of Li and Be) where neutrinos are produced. (**Right**): Close-up of the shells making up the beam target and temperature distribution in the water (heavy water is pumped through the shells to take away the 600 kW of power). From [2].

In the center of the target structure is the so-called torpedo, which houses the cooling water pipes and which is inserted into the beam pipe, forming a vacuum seal. The head of the torpedo is where the three shells are attached. The torpedo can be removed (at the end of its lifetime) and stored in temporary storage pipes drilled into the nearby rock. The handling of the torpedo will be remote due to its high activation. The beam pipe is surrounded by a pressure vessel holding a mixture of 99.99% isotopically pure ^{7}Li and ^{9}Be. The neutrons produced on the hemispheres and other Be in the target assembly capture the ^{7}Li and the resulting ^{8}Li beta-decays, yielding the desired $\bar{\nu}_e$ source.

We calculated the cooling of the target with computational fluid dynamics and used finite elements analysis to determine the stresses in the involved materials. We showed that we stay well below the safety limits [2]. We optimized the mixture of Li and Be as well as the shape of the sleeve to obtain the maximum number of $\bar{\nu}_e$ per proton [22] using Monte Carlo simulations in Geant4. We also performed detailed studies to ensure that adequate shielding is put around the target, minimizing the number of neutrons in the detector and avoiding activation of the surrounding rock above the natural background [23]. We used the ENDF/B-VIII.0 library. Possible reaction channels not in this library include breakup reactions (cf., e.g., ref. [24]) which are not considered yet but may be in the future.

4. Outlook and Conclusions

The IsoDAR design is mature for both the cyclotron and target. Preparations for the installation of IsoDAR at the Yemilab underground facility are ongoing. Several prototypes are currently being constructed: the ion source to demonstrate the generation of the needed 10 mA of 80% pure H_2^+ beams, the RFQ for the demonstration of direct injection into a compact cyclotron, and a target test bench to investigate the properties of the Li–Be mixture in the target sleeve to test the high-pressure injection of molten Li.

The IsoDAR cyclotron has multiple applications beyond neutrino physics. Among them is its capability to produce medical isotopes in large amounts [25,26], which can be used for imaging and cancer therapy. Furthermore, there is interest from the material sciences to use similar machines for testing the radiation hardness of devices and materials relevant to fusion research [27,28].

Funding: This work was supported by NSF grants PHY- 1707969, PHY-1912764, and PHY-1626069 and the Heising–Simons Foundation. Winklehner was also supported by funding from the Bose Foundation.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Supporting data are available from the author upon reasonable request.

Conflicts of Interest: The author declares no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

IsoDAR	Isotope Decay-At-Rest
HCHC-XX	High-Current H_2^+ Cyclotron-XX
BSM	Beyond Standard Model
RFQ	Radiofrequency Quadrupole
LSC	Liquid Scintillator Counter
IBD	Inverse Beta Decay
NSI	Non-Standard Interactions
PIC	Particle-In-Cell

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