1

Underground Facilities for Neutrinos

T. Bolton, M.P. Decowski, A. De Roeck*, G. Orebi Gann*, D. Speller
****Liaisons from other Snowmass Frontiers.***

(contributors from the community: Dongming Mei and others)

1.1 Accelerator neutrinos

The long baseline neutrino physics plan for the US for the next two decades is expected to largely follow from the 2014 P5 process. The science case is summarized by the Neutrino Frontier, and this section will accordingly focus on logistics and timing. Data taking will continue through most of the decade for the Noνa experiment, using neutrino beams directed from Fermilab to the Ash River, Minnesota far detector; and the T2K experiment utilizing the J-PARC neutrino beam on the east coast of Japan and the SuperK far detector in Kamiokande in the mountains of western Japan. In Japan, construction of HyperK has begun and will complete in the latter part of the decade. The US program is dominated by the Deep Underground Neutrino Experiment, DUNE. Currently the involvement of the US community in HyperK is limited, and future involvement is unclear at this time.

The international DUNE Collaboration is currently building the components of the first phase of the DUNE experiment: two 17 kiloton liquid argon TPC modules comprising the far detector to be installed at the Sanford Underground Research Facility (SURF) in Lead, South Dakota; and a multi-component near detector to be installed at Fermilab. The US contributions to DUNE are managed through the DOE's LBNF/DUNE-US project, which is responsible for excavating and outfitting laboratory space at SURF, for building the required conventional facilities at Fermilab, including a new wide band neutrino beam that will initially operate at 1.2 MW of proton beam power, and for contributing US components to the near and far detectors.

LBNF/DUNE-US is the largest project ever undertaken by the DOE Office of High Energy Physics, with an estimated cost of approximately 3.1 billion dollars. International partners contribute half the resources required for the DUNE detectors and provide substantial in-kind contributions to the facilities. Notably and historically, CERN is providing both of the $66 \times 19 \times 18$ m^3 far detector liquid argon cryostats. Mega-science projects built in the US have faced budget and schedule challenges, and LBNF/DUNE-US is no exception. Nonetheless, all signs to date indicate strong support for DUNE in the international neutrino science community, the DOE and partner international science agencies, and the executive and legislative branches of the US government. For example, in March 2022 the DOE Office of Science committed to a funding profile for LBNF/DUNE-US that supports the project's budget and keeps it on a competitive timeline. This discussion will assume that such support continues, and that DUNE will come online at SURF in its phase 1 configuration by 2030.

Perhaps the most interesting issue for DUNE in the Snowmass Underground Frontier context is its upgrade timetable, given that its first phase physics program is largely set. The LBNF/DUNE-US project will excavate space for four 17 kiloton liquid argon TPCs in two large ($>$ 140 m long) detector caverns, along with a central utility cavern between the two. Two of the slots will be left empty for the first phase of DUNE, leaving available considerable valuable scientific real estate. The DUNE collaboration would like to proceed to its full phase 2 configuration as soon as possible. This entails outfitting the SURF caverns with the third and fourth far detector modules, upgrading the near detector at Fermilab, and increasing the Fermilab proton beam power to 2.4 MW. However, the timeline for phase 2 is unclear, and one could consider use of the vacant DUNE cavern space for other science, either in cooperation with or independently of DUNE. Focusing on the far site at SURF, one could imagine several possible scenarios:

1. Funding would allow early construction of the two remaining DUNE far detector modules in, e.g., the 2032-2040 time frame. Practically speaking, given the limited time for further development, DUNE may have to stick close to one of its two existing detector technologies, “horizontal drift” or “vertical drift” single phase liquid argon TPCs. DUNE would benefit from the ability to acquire larger data sets quicker, but it might gain only modest new science capabilities, for example, by pushing energy measurement thresholds low enough to do solar neutrino physics. Furthermore, the ability of DUNE to utilize larger data sets for long baseline oscillation physics will depend on the ability to control systematic uncertainties with its near detector, which could result in prioritizing near detector upgrades at Fermilab.
2. Perhaps more plausibly, the final two DUNE far detector modules would be installed at some intermediate later date, e.g., 2036-2044. This would permit more time for development of new detector capabilities that could expand the DUNE science program. More intriguingly, the extra time could be used to design multi-use modules, i.e., ones that could support the DUNE long baseline physics while enabling physics beyond the original DUNE scope, such as neutrino-less double beta decay or direct dark matter searches.
3. If funding for the final DUNE far detector modules takes longer to appear, then new far detector module installation could be pushed beyond 2040. If this were the case, there may be time to build, execute, and dismantle experiments dedicated to neutrino-less double beta decay, direct dark matter searches, or other physics that utilize the LBNF cavern space but otherwise take place outside of the DUNE framework.

Which, if any, of the scenarios described above actually plays out is anyone’s guess. Any path chosen would obviously require extensive consultation among multiple stakeholders. Given the scale, cost, and complexity of the choices, guidance from the DOE Office of Science will likely be essential. Indeed, one could imagine a recommendation emerging from the ongoing Snowmass/P5 process along the lines of “Establish a clear and transparent process to optimize the scientific utilization of excavated underground spaces at SURF.”

From the point of view of the Underground Frontier, the most important things to identify are requirements for any detectors placed in the DUNE caverns beyond the envisioned liquid argon TPC units. Several specific items should be assessed early:

1. No extraordinary procedures have been adopted for radiological mitigation by the LBNF/DUNE-US project. Hence, extra shielding required in the caverns, requirements for low radioactivity cryostat materials, radon mitigation systems, or other similar items would need to be planned for.
2. The two DUNE detector caverns are supported by a large central utility cavern that has been designed for four 17 kiloton liquid argon TPCs. Any additional utility requirements needed for possible detectors

that goes beyond what is provided for DUNE (cryogenics, power, cooling, etc.) need to be identified. Utilities could include items such as clean rooms or clean spaces.

3. Installation of any new detectors in the DUNE caverns would occur during operations of the first two DUNE modules, and conceivably other experiments in the SURF complex. Required access to the two SURF shafts, underground occupancy limits, and other working conditions would need to be understood.

4. Surface facilities at the SURF site are limited. These facilities include laboratory and office space, as well as the essential technical, business, and ESH services required to support an underground science program.

1.2 Neutrinos from astrophysical and geophysical sources

Each detection of neutrinos from geological and astrophysical sources is a unique opportunity to collect data from systems that are otherwise almost inaccessible, ranging from stellar interiors to the activity beneath the earth's mantle. Science drivers for these experiments and observatories typically center round probing far-reaching neutrino sources, including from cosmological, stellar, geological, atmospheric, and extragalactic origins, and from systems like core-collapse supernova and the diffuse supernova background. In addition to providing a handle to these systems, these observations also provide the opportunity to address fundamental questions about neutrinos, including providing constraints on neutrino behaviour and interactions with matter, the number of neutrinos, the sum of the neutrino masses, and data on collective oscillations. In turn, these studies yield new insight into flavor physics, new interactions, and often provide enhanced sensitivity to non-standard physics. This field has undergone significant growth since the last Snowmass [**?**], and is likely to continue to grow with the recent rise of multi-messenger astronomy [**?**].

Neutrinos from natural and astrophysical sources are a rich source of information on both neutrinos and their sources. Pursing the associated discovery potential requires access to clean, deep underground space. It is critical to proceed with planning now in order to address needs beyond the current Snowmass cycle.

1.2.1 Progress since 2013

Since 2013, several major experiments and observatories for neutrinos from natural sources (e.g. neutrinos of cosmological, astrophysical, and geological origin) have come online, produced results, or completed operations. Among the experiments with US participation that have been completed since the last report are LVD [**?**], Borexino[22], and SNO[**?**]. Ongoing experiments include Super Kamiokande [**?**] and CLEAN [**?**]; while several major next generation experiments are under development and construction, including Hyper-Kamiokande [**?**] JUNO [**?**], and SNO+[**?**]. Longer-term proposed experiments include a multi-tonne scale liquid Xenon experiment for the detection of natural neutrinos [3, 4], and a large hybrid scintillator detector called THEIA [**?**].

Honorable mention: Underwater Facilities for Neutrino Physics Several additional neutrino facilities exist world wide not just underground, but beneath water and ice. Recent projects with the largest contingents of U.S. collaborators include ANTARES (data-taking now ended as of February 2022), [19], IceCube [**?**]. A planned extension to IceCube known as IceCube-Gen2 is expected to begin taking first physics data after 2025 [19]. While these experiments play a major role in the future of US neutrino and high energy physics, requirements associated with their facilities lie beyond the scope of this report.

1.2.2 Underground facilities for neutrinos from natural sources

Astrophysical/Natural
Hyper-Kamiokande (Current)
Super-Kamiokande (Current)
SNO+ (Current)
G3 Liquid Xenon Detector (LOI)
THEIA (LOI)

Table 1-1. *Astrophysical and geological neutrino experiments responding to the UF4 underground supporting capabilities survey*

As new discoveries lead to new pathways for exploration, larger, cleaner, and more sophisticated detectors are required to probe with greater precision. To achieve the technical requirements on backgrounds required for these detectors, there is a continued need for clean, underground laboratory space with good facility support.

Because of the strong overlap between the underground facilities needs of experiments for neutrinos from natural sources and those for neutrinoless double-beta decay, discussion of both can be found in Section 1.4. A few needs specific to astrophysical, geological, and reactor neutrinos are outlined below.

1.2.2.1 Future needs and expectations for facilities

There is an ongoing need for space for research and development, prototyping, and demonstrators. There is also a need for new space for large detectors.

- THEIA is a large-scale natural source experiment proposed as a new DUNE module, or a standalone detector at the same site. THEIA's science program is substantially enhanced by accessing the LBNF neutrino beam at Sanford laboratory. In order to locate the experiment at SURF and to best take advantage of the beam and the deep site, a new, large cavern would need to be developed.
- A kiloton scale detector requires new space. An unenriched gaseous detector of xenon would be approximately as large as Super Kamiokande, with additional space required for shielding and utilities. These considerations must be taken into account in facilities planning.
- R&D paths for the extraction, production, and storage of Xe and underground Ar, for underground experiments is needed. More location flexibility would enhance global geoneutrino programs.

1.3 Neutrinoless double beta decay

Both the US and the international nuclear and particle physics community recognize neutrinoless double-beta decay ($0\nu\beta\beta$) as one of the highest-priority, non-accelerator-based searches with significant need for underground detector facilities. This priority has been repeated in meetings such as the North America-Europe Workshop on Double Beta Decay [13], following which laboratory directors, funding agencies, and leaders across countries voiced support for the establishment of next generation $0\nu\beta\beta$ detectors on both continents. The experimental investigation of the neutrino as a Majorana particle is an essential ingredient in the effort to understand the properties of neutrinos. The most promising laboratory technique to study the nature of neutrinos remains the search for neutrinoless double-beta decay. Most of these searches involve the measurement of the half-life of a decay-capable isotope through detection of a small excess in the event rate at the energy (Q-value) of the decay. These searches have to be conducted deep underground in clean environments. In this context, "deep" for near-term tonne-scale experiments indicates siting at depths on the order of XXX feet, while for next-generation experiments (order 100 tonnes), deep siting requires depths on the order of XXX feet. The recent improvement in sensitivity of $0\nu\beta\beta$ experiments, and the successful completion of several of those experiments, has demonstrated both the progress of the field and the need to plan for the future requirements of large-scale $0\nu\beta\beta$ searches.

The "timely development and deployment of a US-led ton-scale neutrinoless double-beta decay experiment" was also named as one of four high priority recommendations of the 2015 Long Range Plan for Nuclear Science [10]. The science drivers for $0\nu\beta\beta$ are discussed extensively in the Neutrino Properties Topical Group Report [8], and can be briefly summarized as:

- *Is the neutrino a Majorana fermion or a Dirac fermion?*
- *How can the sensitivity of neutrinoless double-beta decay searches best be improved beyond the inverted-ordering region targeted by the next generation of experiments?*

The detection of neutrinoless double-beta decay remains one of the most sensitive probes of neutrino properties and the Majorana nature of the neutrino mass. In the United States, two main tonne-scale experiments (expt & expt) have both listed the SNOLAB site as the preferred location—an indication of the high value placed on deep space by these experiments, and of the critical need for additional space to be developed for next-generation experiments. The community must begin planning now to accommodate the depth, space, and infrastructure requirements for experiments beyond the tonne-scale.

1.3.1 Progress Since 2013

Since the last report in 2013, a number of mid-scale ($\mathcal{O}(100\,\mathrm{kg})$ of isotope) experiments have been completed, placing increasingly stronger limits on 5 of the 32 main $0\nu\beta\beta$-capable isotopes. Interpreting these results in the neutrino-mixing framework, puts the limits of these mid-scale experiments at or near the top of the so-called Inverted Mass-Ordering of neutrinos, and also constrains the effective Majorana mass as a function of the mass of the lightest neutrino. For further details, see the the NF05 report [8].

The experimental search for $0\nu\beta\beta$ is an international effort, with strong US participation in a number of completed (Table 1-2) and ongoing (Table 1-3) searches. The results of these searches compare competitively with other worldwide efforts such as the completed CANDLES-III [?] (^{48}Ca at Kamioka, Japan) and CDEX (^{76}Ge, at CJPL, China), and the ongoing experiments COBRA[?] (^{116}Cd at LNGS, Italy), SuperNEMO[?] (^{82}Se at LSM, France), PandaX-III[?] (^{136}Xe at CJPL, China), and AMoRE /AMoRE II[?] (^{100}Mo) at Yangyang, South Korea). In addition, next-generation $0\nu\beta\beta$ detectors have been proposed that build on cross-collaborative strengths by combining efforts, including LEGEND[?] (GERDA [?] and Majorana[?]) and nEXO[16].

The experimental techniques break down in roughly four categories:

Experiment	Isotope	Location
CUPID-0 [14]	^{82}Se	LNGS, Italy
CUPID-Mo	^{100}Mo	Canfranc, France
EXO-200	^{136}Xe	WIPP, USA
GERDA	^{76}Ge	LNGS, Italy
KamLAND-Zen 400	^{136}Xe	Kamioka, Japan
MAJORANA Demonstrator [18]	^{76}Ge	SURF, US

Table 1-2. *Examples of of recently completed experiments with major US leadership or participation.*

Experiment	Isotope	Location
CUORE	^{130}Te	LNGS, Italy
AMORE-I	^{100}Mo	Yangyang, South Korea
KamLAND-Zen 800	^{136}Xe	Kamioka, Japan
LEGEND-200	^{76}Ge	LNGS, Italy
NEXT-xxx(white,10,100?)	^{136}Xe	LSC, Spain
SuperNEMO Demonstrator [20, 21]	^{82}Se	LSM, France
SNO+	^{130}Te	SNOLAB, Canada

Table 1-3. *Ongoing experiments with US leadership or participation.*

- Large-scale liquid scintillators doped with the $0\nu\beta\beta$ isotope, e.g. SNO+ and KamLAND-Zen experiments
- Gas and liquid time-projection-chambers filled with the $0\nu\beta\beta$ isotope, e.g. nEXO and NEXT experiments
- Semiconductors made from the $0\nu\beta\beta$ isotope, e.g. LEGEND
- Bolometers attached to crystals made from the $0\nu\beta\beta$ isotope, e.g. CUPID and CUORE

LEGEND, nEXO, and CUPID[**?**] (CUORE Upgrade with Particle Identification) are now three proposed experiments with major US involvement poised to begin either or both of commissioning and data collection within the next several years, and represent a concentration of US resources in extending the search for $0\nu\beta\beta$ to half-lives greater than 10^{28} yr. The infrastructure and supporting capabilities (see also Sections 4.1.1-4.4) necessary to undergird these efforts are key aspects of the planning process for each experiment and the laboratories that host them.

1.4 Underground Facilities for $0\nu\beta\beta$ and Experiments for Neutrinos from Natural Sources

The depth requirement for $0\nu\beta\beta$ and natural source experiments arises from the need for shielding from cosmic ray backgrounds. While some proposals for virtual depth enhancement have been proposed (e.g. through active background suppression [17]), such techniques are still under development, and suppression of backgrounds by physically siting deep underground is still critical for the science reach of these experiments. Ideally, this consideration is taken into account not only for the data-collection period of the experiment, but

$0\nu\beta\beta$
nEXO (Planned)
Majorana Demonstrator (Current)
NEXT-100 (Planned)
SNO+ (Current)
A possible $0\nu\beta\beta$ extension to DUNE (Conceptual)
NuDot (Current + Planned)
Kiloton Xe TPC for $0\nu\beta\beta$ (Conceptual)
CANDLES (current + planned)
NEXT-CRAB (Planned)
NEXT-HD (Planned)
NEXT with Ba-Tagging (Planned)
KamLAND-Zen (Current)
CUPID (Planned)
LEGEND (Planned)
THEIA (Planned)

Table 1-4. *Neutrinoless double-beta decay experiments responding to the underground survey*

in some instances, for materials handling and storage as well. Sections 4.1.1-4.4 in the Supporting Capabilities Topical Report (UF4) summarize the results of a survey of dark matter and neutrino experiments, including several searches for $0\nu\beta\beta$, regarding the supporting capabilities necessary for large scale low-background experiments. In this section, we discuss the particular needs of $0\nu\beta\beta$ and natural source experiments.

1.4.1 Infrastructure

Infrastructure needs of $0\nu\beta\beta$ and natural source experiments are based on long-term occupation of very clean underground environments. Many detector technologies also require stable long-term cryogenic operations, and most require remote computing, and safe and efficient site access for investigators. Underground electrical systems should provide clean power and fail-overs to backup power in case of a power outage.

To facilitate the design and construction of experiments, the underground location should be well-characterized. This includes 3D geographical scans of the cavern, rock sampling and characterization of the radioactive backgrounds of the area.

Many $0\nu\beta\beta$ and natural source experiments will also require gas consumables, e.g., liquid nitrogen or N_2-boil off. These facilities could be shared in underground locations.

1.4.2 Cleanrooms

All $0\nu\beta\beta$ and natural source experiments will require long-term occupation of dedicated cleanrooms, typically for the full period of installation and operation of the experiment. However, the cleanroom requirements vary per experiment. The cleanliness spec is from Class-1(ISO-3) to Class-10000(ISO-7), with a surface area of 50–200 m^2 and 3–10 m headroom. The radon requirements in the cleanroom also range from a very challenging 1 $\mathrm{mBq/m}^3$ to a more modest 10 $\mathrm{Bq/m}^3$. The lower limit is only achievable with dedicated Rn-abatement systems or synthetic air. Some of the cleanrooms will need to be equipped with gloveboxes to further reduce the Rn concentration and/or fume hoods for chemical procedures. Humidity and temperature control are essential.

Given the long-term occupation and varying requirements, most $0\nu\beta\beta$ and natural source experiments will need their own dedicated cleanrooms. Shared cleanrooms could be useful for additional short-term needs, such as very high cleanliness specification during the assembly of critical components.

1.4.3 Muon veto systems

- Water muon Cherenkov veto systems
- Active muon tagging

1.4.4 Clean environments for materials

Commissioning of large low-background experiments requires careful materials handling protocols to maintain the radiopurity of the materials and detectors during assembly. Production of clean materials directly underground mitigates some of the cost and logistical complications associated with transporting materials above ground and minimizes cosmogenic activation that might occur during transit. The copper used in shielding and cryogenic infrastructure often directly faces active detector volumes in low-background experiments, and is often the source of non-negligible backgrounds due to such activation [23, 24]. Underground electroformation facilities provide a means of producing copper with minimal surface exposure, resulting in lower backgrounds.

Similar considerations exist for the crystals used in bolometric detectors used several of the largest neutrino, $0\nu\beta\beta$, and dark matter detectors. As experiments move to tonne and multi-tonne scale detector masses, a main source of backgrounds arises from cosmogenic activation of the detector material [**?**]. As a particular example, while Ge detectors lead the world in detection thresholds for dark matter searches and have excellent energy resolution in discriminating $2\nu\beta\beta$ events, providing discovery potential for $0\nu\beta\beta$ searches, the cosmogenic production of tritium, ^{68}Ge and ^{60}Co are a main source of background for dark matter experiments and constrain the sensitivity of Ge $0\nu\beta\beta$ experiments beyond the scale of LEGEND [25, **?**, **?**], and may be a significant source of backgrounds in next-generation tonne-scale experiments in other isotopes (e.g. CUPID-1T) as well.

A laboratory for underground crystal growth could be located at depths ranging from 300-ft at the SURF to very deep at SNOLab, as long as the hadronic components of cosmic rays are significantly reduced. Such a laboratory should include zone refining for Ge ingots, and detector fabrication facilities. In addition, a mechanical lab should be attached to the crystal growth facility because the mechanical process of crystals is part of the entire production chain. Locating the entire production chain underground at the underground labs where the experiments will be built will provide significant reduction in the cosmogenic production of radioactive isotopes [25]. An underground facility for crystal growth and fabrication requires sufficient space (4 labs for a total of 1000 square feet), underground safety in terms of exhausting hydrogen gas (ambient gas for processing Ge in zone refining and crystal growth) and handling the waste of acids (clean and etching of Ge). However, there are safety protocols that we have established and implemented for more than 10 years at the surface labs. Those challenges can be overcome [25].

Production of deionized ultra-pure water underground is also needed not only for cleaning but in order to fill muon-veto water tanks, and means of production in sufficient quantities is a facilities issue that should be considered with other infrastructure needs and background mitigation strategies.

Space and facilities are also needed for handling of fluids such as organic liquid scintillator, including filling, recirculation, and purification capabilities.

1.4.5 Clean environments for detector construction

Of the respondents to the survey, the most concentrated use of cleanroom environments was for detector assembly and construction, with a few experiments also expressing continued need for cleanroom space for the purposes of calibration/operations, supplementary measurements, parts cleaning, and clean storage. During the construction and assembly phases, clean space is used to prevent contamination of parts with radon, a long-lived radioactive daughter of the U/Th chain. Cleanroom classes particularly suitable for these needs are ISO5, ISO 6, and radon-free clean rooms. Experiments that can be assembled from smaller modules typically reported plans to assemble detectors in glove boxes, mitigating the need for special requirements from the facility. The few responding experiments with specified environmental radon levels typically reported requirements on the order of $1\,\mathrm{mBq\,m^{-3}}$, with one experiment specifying a flow of 180-220 meter^3/h. KamLAND-Zen requires $10\,\mathrm{Bq\,m^{-3}}$ or better.

1.4.6 Material Assay Facilities

In general, neutrino experiments constructed and installed in underground laboratories are highly sensitive to radioactive backgrounds. Background budgets and projections rely on accurately quantifying the expected background rates, including though material assay of the detector components. A variety of assay techniques are employed by neutrino experiments. High-purity germanium (HPGe) detectors are commonly used by individual institutions and experiments, and as a result there is little underground-lab-supplied capacity for HPGemeasurements. Existing facilities are usually oversubscribed. Dedicated assay facilities play a larger role in measurements involving alpha-counting, inductively-coupled plasma mass spectrometry (ICP-MS), neutron activation, and dedicated cryogenic bolometers for characterizations requiring sensitivity on the order of $\mathrm{\mu Bq\,kg^{-1}}$. Future neutrino experiments will need to screen 10s to 100s of samples a year and compete for assay facilities with dark matter experiments requiring similar screening efforts.

1.4.7 Storage facilities

The 2013 report contained a recommendation to reserve underground space for materials assay and storage [9].

Underground facilities facilities for storage continue to play a role in mitigating cryogenic activation, including muon-activation, of materials.

1.4.8 Environmental monitoring and safety

The growing scale of underground neutrino experiments requires the development of clear strategies for environmental monitoring and safety protocols to maintain sustainable operations. Sensitive radon detectors would provide ongoing information regarding levels relevant to experimental backgrounds and human health [**?**, **?**]. Several experiments rely on storing large amounts of liquid cryogens underground, which carries hazards associated with handling extremely cold materials and asphyxiation. Since the experiments are run in underground caverns, they are often located in active mines, and must be coordinated with mining activity. Associated with this are challenges involving ease of access for equipment and personnel, and ease of egress or access to refuge chambers in the event of an emergency.

1.4.9 Underground Testing and R&D Facilities

Future experiments often need long-term R&D and prototyping efforts. For neutrino experiments, this may mean that the R&D setup needs to be shielded from cosmic rays and placed underground. The space requirements are typically modest in comparison to the actual experiment and do not necessarily have to be in the same underground laboratory, proximity to the home institution is often desired.

1.4.10 Underground User Facilities and International Collaboration

While the collaborative nature of neutrino physics requires cooperation from scientists around the world, many face practical barriers ranging from

- lack of computing account access for foreign-national collaborators from "countries of concern"

SURF is applying to be a DOE user facility [15]. There is strong community support for such facilities to improve access to on-site and computing resources to encourage international collaboration.

1.4.11 Other considerations: Domestic Impacts and broader participation

- broadening participation, access to underground facilities for users from smaller/less-resourced institutions

- public and community engagement on underground science; public awareness and support of tax-funded facilities; emphasis on communication of purpose

1.4.12 Goals

Major goals of the neutrinoless double-beta decay program include establishing full coverage and beyond of the Inverted Ordering mass region. Several major goals are incorporated within the scope of the underground frontier, and overlap with the needs of the cosmic frontier and the search for new physics. Neutrinos from natural sources are used both to probe the source, and to study neutrino properties. In both cases, the goals for this frontier are to establish and provide sufficient underground space and facilities to support these programs into the next decade and beyond.

1.4.13 Synergies with Dark Matter Experiments and Quantum Information Science

1.4.13.1 Synergies with Dark Matter

Neutrino experiments share many of the same radioactivity and activation requirements as direct detection dark matter (DM) experiments. Here also lie several synergies between neutrino experiments themselves, but also with the DM community. Underground facilities could take a lead on further fostering these interactions.

There are already efforts underway to collect and store material assay results in a publicly accessible database, e.g., radiopurity.org. These efforts could be further strengthened so that experiments can more easily decide on construction materials. However, the usefulness of the stored information is often complicated due to, e.g., large batch to batch screening variations for the same material (even from the same manufacturer) or possibly for (scientific) competitiveness reasons. In addition, standardization of some screening methodologies, such as for Rn and plate-out measurements is required in order to compare across different labs and facilities.

Activation studies is another area where neutrino and DM experiments could share expertise. These require the collection of various muon and neutron-related cross sections and tools to analyze them. There are virtually no community tools and databases at the moment and also here it seems that every experimental collaboration starts anew.

Another area of synergy is in the use of underground test facilities for cryogenic and liquid scintillation detectors (see also Section 2.1.3). Research and development on these detectors is often impossible in surface laboratories due to high background rates.

1.4.13.2 Synergies with Quantum Information Science

- sensor development
- underground cryogenic test and prototyping/R&D space

1.5 Conclusions

- Preservation of competitiveness in the US neutrino program is dependent on future access to clean, deep underground space. Planning for future needs must begin now.

- Local, expert support at underground facilities is critical for success.

  Guidance and local expertise on site-specific deployment details, environmental health and safety requirements, fluid handling, shipping, and administration are vital components of executing and maintaining operations in underground experiments (especially those of larger scales)

- Supporting underground facilities is critical to achieving science goals for neutrino physics experiments

  Several common themes arise with respect to the resources and facilities needed for successful underground neutrino physics. This includes capabilities that are not unique to these experiments but are critical in assessing underground-specific needs such as depth, environmental backgrounds, materials handling and storage (and whether items must be prepared and stored underground - space needs) and cleanliness requirements:

  - Robust computing/connectivity in labs underground;
  - Centralised data for cosmogenic activation;
  - Centralised radiopurity database;
  - Shared data and simulations;
  - Facilities for radio-assays, low-background counting;
  - Support for laboratory access for equipment and personnel;
  - Support to understand and implement seismic safety requirements;
  - Additional supporting facilities such as space for prototypes, R&D etc. A need for cryogenic facilities has synergies with dark matter and QIS.

- Plans to pursue neutrino science beyond the tonne-scale $0\nu\beta\beta$ program require inter-agency planning efforts for future underground facilities, particularly with respect to the preparation and allocation of deep underground space.

- There is a need to compile results from $0\nu\beta\beta$, G2 dark matter, and natural source experiments, and to perform simulations regarding the sufficiency of depth of existing laboratories to host future-generation experiments.

  As referenced in the 2013 report [9], depth requirements for neutrino and dark matter experiments depends on which technology is employed. In keeping with the several avenues of research and development currently being pursued by $0\nu\beta\beta$ experiments, simulations corresponding to suitable combinations in each major category (e.g. detector substrate, sensor, etc) may also inform whether current depth and experimental space constraints require more concentrated development of a particular technology for a planned experiment to be sited, or if underground facilities must be expanded.

- There is a need for central coordination of radio assay capabilities, perhaps by one of the underground laboratories.

- There is strong community support for better user facility support for international collaborators.

Bibliography

[1] R. Abraham et al, "Forward Physics Facility", https://www.snowmass21.org/docs/files/summaries/EF/SNOWMASS21-EF9_EF6_EF10_EF5-NF6_NF3_NF10-RF6_RF0-CF7_CF0-AF5_AF0-UF1_UF2_ForwardPhysicsFacility-193.pdf (2021)

[2] P. Huber, J. M. Link, C. Mariani, T. O'Donnell, M. Pitt, R.B. Vogelaar, "KURF: The Kimballton Underground Research Facility", https://www.snowmass21.org/docs/files/summaries/UF/SNOWMASS21-UF1_UF4-RF4_RF3_ODonnell-007.pdf

[3] R. Gaitskell, K. Palladino, "The Exploitation of Xe Large Scale Detector Technology for a Range of Future Rare Event Physics Searches", https://www.snowmass21.org/docs/files/summaries/CF/SNOWMASS21-CF1_CF2-NF5_NF4-IF8_IF0-CompF0_CompF0-UF2_UF3_Matthew_Szydagis-236.pdf

[4] X. Xiang, D. Khaitan, R. Gaitskell, M. Szydagis et al, "Extracting Physics from Natural Neutrinos with G3 Liquid Xenon Detector", https://www.snowmass21.org/docs/files/summaries/NF/SNOWMASS21-NF4_NF0_Matthew_Szydagis-163.pdf

[5] M. Askins, Z. Bagdasarian, N. Barros, E. W. Beier, et al. "Theia: Summary of physics program", arXiv:2202.12839. (2022)

[6] Jaret Heise. "The Sanford Underground Research Facility", arXiv:2203.08293. (2022)

[7] T. Akindele, T. Anderson, E. Anderssen, M. Askins, M. Bohles, A. J. Bacon, et al. "A Call to Arms Control: Synergies between Nonproliferation Applications of Neutrino Detectors and Large-Scale Fundamental Neutrino Physics Experiments", arXiv:2203.00042. (2022)

[8] C. Giunti, J. Gruszko, B. Jones, L. Kaufman, A. Pocar, and D. Parno. "Snowmass NF05 Report: Neutrino Properties, Draft 2" (2022)

[9] M. Gilchriese et al. "Chapter 7: Underground Laboratory Capabilities", Planning the Future of U.S. Particle Physics, Report of the 2013 Community Summer Study, arXiv:1401.6115v1 (2014)

[10] A. Aprahamian et al. "Reaching for the horizon: The 2015 long range plan for nuclear science". (2015)

[11] A. Giuliani, J.J. G. Cadenas, S. Pascoli, E. Previtali, R. Saakyan, K. Schäffner, S. Schönert. Astroparticle Physics European Consortium, "Double Beta Decay APPEC Committee Report, v3", 2020.

[12] M. Agostini, G. Benato, J. A. Detwiler, J. Menéndez, F. Vissani. "Toward the discovery of matter creation with neutrinoless double-beta decay", arXiv:2202.01787. (2022)

[13] APPEC, North America - Europe Workshop on the Future of Double-Beta Decay, https://agenda.infn.it/event/27143/

[14] O. Azzolini et al, "Final Result of CUPID-0 Phase-I in the Search for the ^{82}Se Neutrinoless Double-β Decay, Phys. Rev. Lett. 123, 032501 (2019)

[15] U.S. Department of Energy Office of Science, "User Facilities", https://science.osti.gov/User-Facilities

[16] G Adhikari et al. "nEXO: neutrinoless double beta decay seaerch beyond $10^2$8 year half-life sensitivity", J. Phys. G: Nucl. Part. Phys. 49 015104 (2022)

[17] C. Wiesinger, L. Pandola, S. Schönert. “Virtual depth by active background suppression: Revisiting the cosmic muon inducerd background of GERDA Phase II” https://arxiv.org/pdf/1802.05040.pdf (2018)

[18] I.J. Arnquist et al. “Final Result of the MAJORANA DEMONSTRATOR’s Search for Neutrinoless Double-β Decay in ^{76}Ge”, arXiv:2207.07638v1 (2022)

[19] C. Spiering, “Neutrino Detectors Under Water and Ice”, Particle Physics Reference Library, Springer, Cham. https://doi.org/10.1007/978-3-030-35318-6_17 (2020)

[20] R. Arnold, C. Augier, J. Baker et al., “Probing new physics models of neutrinoless double beta decay with SuperNEMO”, Eur. Phys. J. C 70, 927-943 (2010)

[21] A. Rakhimov et al, “Development of methods for the preparation of radiopure ^{82}Se sources for the SuperNEMO neutrinoless double-beta decay experiment, Radiochimica Acta, vol. 108, no. 2, 2020, pp.87-97 (2021)

[22] G. Alimonti et al, “The Borexino detector at the Laboratori Nazionali del Gran Sasso”, Nucl. Instr. Meth. A, 600, 3, pp568-593 (2009)

[23] She, Z., Zeng, Z., Ma, H. et al. “Study of cosmogenic activation in copper for rare event search experiments”. Eur. Phys. J. C 81, 1041 (2021). https://doi.org/10.1140/epjc/s10052-021-09827-w

[24] Baudis, L., Kish, A., Piastra, F. et al. “Cosmogenic activation of xenon and copper”. Eur. Phys. J. C 75, 485 (2015). https://doi.org/10.1140/epjc/s10052-015-3711-3

[25] D. Mei, personal communication.