Neutrino Opportunities at the ORNL Second Target Station

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NF Topical Groups:

- ■ (NF1) Neutrino oscillations
- ■ (NF2) Sterile neutrinos
- ■ (NF3) Beyond the Standard Model
- ■ (NF4) Neutrinos from natural sources
- ■ (NF5) Neutrino properties
- ■ (NF6) Neutrino cross sections
- ■ (TF11) Theory of neutrino physics
- ■ (NF9) Artificial neutrino sources
- ■ (NF10) Neutrino detectors
- ■ (CF1) Dark matter: Particle-like
- ■ (IF1) Quantum Sensors
- ■ (IF2) Photon Detectors
- ■ (IF7) Electronics/ASICs
- ■ (IF8) Noble Elements

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Abstract: The Oak Ridge National Laboratory (ORNL) Spallation Neutron Source (SNS) First Target Station (FTS), used by the COHERENT experiment, provides an intense and extremely high-quality source of pulsed stopped-pion neutrinos, with energies up to 50 MeV. Upgrades to the SNS are planned, including a Second Target Station (STS), which will approximately double the expected neutrino flux while maintaining quality similar to the FTS source. We describe here several opportunities for neutrino physics, other particle physics, and detector development using the FTS and STS neutrino sources.

Neutrinos at the Spallation Neutron Source

The Oak Ridge National Laboratory Spallation Neutron Source First Target Station provides neutrons for diverse science goals by colliding GeV protons onto a mercury target. The protons arrive at the target in pulses several hundred ns wide at 60 Hz. The proton-Hg collisions create pions; π^- are largely captured by nuclei, whereas a very dominant fraction of π^+ come to a stop and then decay at rest. The primary decay products are a monochromatic 30-MeV ν_μ and a μ^+ on a short timescale; the μ^+ subsequently decays to a ν_e and a $\bar{\nu}_\mu$ with well-understood spectra ranging up to 50 MeV (below ν_μ charged-current (CC) threshold) with 2.2-μs decay time. The number of neutrinos produced amount to approximately 5×10^{14} neutrinos per flavor per MW-s. The quality of this source is excellent for neutrino physics, given the very high fraction of pions which decay at rest and a pulsed time structure allowing rejection of off-beam backgrounds at the $10^3 - 10^4$ level. The COHERENT experiment has already taken advantage of this beam [1, 2] with detectors deployed 16-25 m from the source in "Neutrino Alley", an underground corridor parallel to the proton beam, with substantial shielding reducing beam-related neutron flux and 8 meters-water-equivalent overburden. COHERENT is pursuing multiple physics goals with its suite of detectors [3–7] at the FTS.

The timing structure of the beam provides not only background rejection, but also opportunities for *flavor separation*. The prompt ν_μ are in-time with the proton beam flux, while the $\bar{\nu}_\mu$ and ν_e are delayed. The structure allows well-understood separation of prompt ν_μ neutral-current (NC) interactions from delayed ν_e CC and $\bar{\nu}_\mu$ and ν_e NC interactions. The timing also enables handle on systematics for BSM signals for which neutrinos are background (e.g., [8]).

Planned ORNL Upgrades: ORNL is planning an upgrade to the current 1.4-MW beam. The Proton Power Upgrade (PPU) project will double the power of the existing accelerator structure, to increase the brightness of pulsed neutron beams and provide new science capabilities. Furthermore, the Second Target Station (STS) includes a new neutron-production target (of tungsten) along with a new experimental hall and suite of neutron beam lines. Protons will be divided between the FTS and STS in a 3 to 1 ratio. The beam power is expected to be 1.7 MW in 2022 and 2.0 MW in 2024. In 2028, after STS construction is completed, the FTS will receive 2.0 MW at 45 Hz, and the STS will receive 0.7 MW at 15 Hz [9]. These upgrades provide exciting new opportunities. Neutrino flux is approximately proportional to proton power. Preliminary studies suggest similar neutrino production from the STS as the FTS [10]. Detectors sited in between the STS and FTS, at tens of meter baselines, will receive flux from both. It will be technically feasible to site 10-ton-scale detectors at the STS, with sufficient shielding and overburden.

Physics Motivations

We highlight briefly here multiple motivations for exploitation of the SNS FTS and STS neutrinos [11]. Some of these are described in COHERENT's LOIs [3–7], but others go beyond the scope of COHERENT.

Coherent elastic neutrino-nucleus scattering (CEvNS): CEvNS is the process in which a NC neutrino interaction results in the recoil of the nucleus as a whole [12, 13]. The COHERENT collaboration's program of CEvNS measurements for a range of nuclear targets, testing the N^2 dependence, has potential for a wide range of physics. CEvNS is a sensitive probe of non-standard interactions of neutrinos with heavy and light mediators. It can provide measurements of $\sin^2\theta_W$ and of neutrino electromagnetic properties. A percent-level precision, CEvNS can probe nuclear structure with unprecedented sensitivity. Furthermore, CEvNS is an effective tool for sterile neutrino oscillation searches [14, 15].

Accelerator-produced dark matter: CEvNS is a background for interactions of accelerator-produced BSM particles that create nuclear recoils. A new 10-tonne-scale recoil detector at the STS would have significantly enhanced sensitivity [8].

Inelastic neutrino-nucleus cross sections: Neutrinos from stopped pions overlap significantly with the expected energy range of neutrinos from core-collapse supernovae, which go up to several tens of MeV. The SNS therefore offers excellent opportunities for the study of neutrino-nucleus interactions of relevance for supernova neutrino detection, as well as for understanding of processes within the supernova itself, including both astrophysical mechanisms and nucleosynthesis. The energy regime of interaction products is of the same order as the neutrino energies. Target nuclei of particular interest are Ar, O, Pb, Fe and C.

Solar neutrinos, which have energies up to about 15 MeV, are an interesting physics target for DUNE [16], and knowledge of the CC $\nu_e{-}^{40}$Ar cross section will enable interpretation of that signal also.

Measurement of inelastic neutrino-nucleus cross sections is also of intrinsic interest for study of the weak interaction and for nuclear structure physics [6].

A specific example of particular relevance to the U.S. community is argon, the material to be used in DUNE. DUNE has excellent sensitivity to the ν_e component of a supernova neutrino burst [17], for which an observation will yield rich physics and astrophysics. However, there currently exist *no* measurements of neutrino cross sections on ^{40}Ar in the relevant energy range. The dominant ν_e CC as well as the very-poorly-understood NC excitation cross sections are both of great interest. Uncertainties in these cross sections limit the quality of information which can be extracted from a burst observation.

Some existing and near-future COHERENT detectors, while optimized for low-energy recoils, have sufficient dynamic range to study some of these processes in argon, oxygen, lead and iron. However for precision cross section measurements, including full understanding of the distribution of final-state interaction products, fine-grained tracking detectors will be needed.

Possible Detectors and Facilities

Possible new detectors include those sensitive to keV-scale recoils at the tens of kg to 10-tonne scale. These include, for example, cryogenic crystals or large noble liquid detectors, such as those proposed by COHERENT [3, 4, 7], and large single-phase or dual-phase noble liquid detectors. Such detectors may also be sensitive to inelastic interactions [6]. A large heavy-water detector for flux normalization [18], similar to that planned for COHERENT in Neutrino Alley, is another possibility.

A fine-grained tracking detector such as a liquid argon TPC (for example, like CAPTAIN [19]) would be ideal for precision measurements relevant to DUNE low-energy physics. A several-tonne-scale detector could make cross section measurements with several percent statistical uncertainty. Such a detector could serve also as a test-bed for new LArTPC technology, such as novel pixellated readouts [20]. Other possible detector materials and configurations include liquid scintillator, water Cherenkov, lead-based detectors, directional CEvNS detectors, bubble detectors, high-pressure gas TPCs, and low-threshold bolometers.

Specific detectors may have specific needs, but generically, a hall of 4.5 m × 10 m × 4 m height would serve for a 10-tonne scale detector. For most physics topics, one wants to be as close as possible to the target, with as little background as possible; there is some tradeoff between proximity to the neutrino source and adequate shielding against neutrons. For some physics for which the signal is baseline-dependent, such as for sterile oscillations, specific locations may be desired. For accelerator-produced dark matter searches, angle with respect to the beam axis is important. In these latter cases, detector movability is also desirable. All of these are feasible at the STS for relatively modest investment.

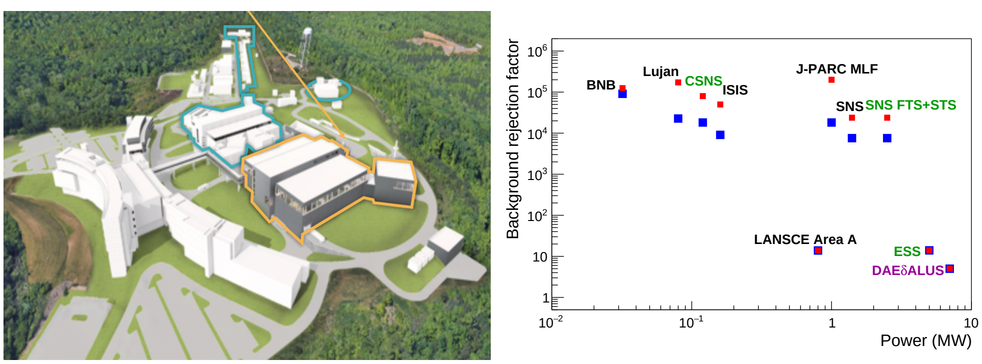

Fig. 1: Left: Spallation Neutron Source [21]. STS buildings are outlined in orange. Right: Approximate figures of merit for different stopped-π sources for neutrino physics. The upper right corner is the most desirable region. Proton power is approximately proportional to neutrino flux. Red squares represent prompt ν_μ flux; blue squares represent $\bar{\nu}_\mu$ and ν_e. The y-axis shows the reciprocal of the maximum of the beam pulse length and the parent particle decay timescale, times pulse frequency, which quantifies steady-state background rejection. Well-separated blue and red squares indicate that flavor separation is possible. Past facilities are indicated in black; future ones are in green; concepts are in purple.

Summary

With this letter we highlight several opportunities of broad relevance for particle physics and for detector development at the upgraded SNS. Neutrino facilities at the STS will be necessary to fully exploit the high-quality neutrino source.

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