COHERENT LOI 5: Instrumentation Development

COHERENT Collaboration

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NF Topical Groups:

☐ (NF1) Neutrino Oscillations
☐ (NF2) Sterile Neutrinos
■ (NF3) BSM
☐ (NF4) Neutrinos from Natural Sources
☐ (NF5) Neutrino Properties
☐ (NF6) Neutrino Interaction Cross Sections
☐ (NF7) Applications
☐ (TF11) Theory of Neutrino Physics
■ (NF9) Artificial Neutrino Sources
■ (NF10) Neutrino Detectors

IF Topical Groups:

☐ (IF1) Quantum Sensors
■ (IF2) Photon Detectors
■ (IF3) Solid State Detectors and Tracking
☐ (IF4) Trigger and DAQ
☐ (IF5) MPGDs
☐ (IF6) Calorimetry
☐ (IF7) Electronics/ASICs
■ (IF8) Noble Elements
■ (IF9) Cross Cutting and System Integration
☐ (IF10) Radio Detection

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Abstract: The Spallation Neutron Source (SNS) at the Oak Ridge National Laboratory (ORNL), as the most powerful and precise neutrino source in the world, provides a unique platform for the R&D of novel instrumentation ideas. The current detector R&D efforts in the COHERENT collaboration are associated with various Snowmass topical groups, and other research fields, such as direct dark matter searches, neutrinoless double beta decay and neutrino oscillation experiments. The planned Second Target Station (STS) at the SNS would become an even better detector R&D environment. The collaboration is welcoming new ideas towards more powerful particle detectors.

1 Introduction

The COHERENT collaboration is actively developing low-threshold, low-background, large-target-mass, high-precision detectors for the search of a broad range of new physics through the detection of Coherent Elastic neutrino(ν)-Nuclear Scatterings (CEvNS) in Neutrino Alley at the SNS, ORNL.

2 Noble Liquid Detectors

Liquid argon (LAr) detectors continue to be instrumental in high energy physics. Efforts to reduce thresholds and inform the LAr detector response are crucial for future WIMP searches, long baseline experiments, and CEvNS measurements. We have performed detailed studies of the 24 kg fiducial mass CENNS-10 LAr scintillator detector [1] and performed the first detection of CEvNS in a light nucleus, advancing our understanding of neutrino-nucleus interactions and constraining non-standard interactions [2]. Detailed background studies and lowering the scintillation threshold were crucial for these results, laying the groundwork for the 610 kg fiducial mass CENNS-750 detector [3]. The CENNS-750 detector will provide precision measurements of the CEvNS cross section on argon, probe processes such as the charged-current (CC) response of argon nuclei, and search for accelerator-produced dark matter with unprecedented sensitivity [4].

We are pursuing novel techniques to enhance CENNS-750's scientific reach. We continue to study high-efficiency PMTs and SiPMs to reduce thresholds, and explore highly-segmented photodetector geometries to improve event selection and particle ID. We are investigating machine-learning-based analyses for more robust CEvNS and CC event selection, and are investigating high-yield wavelength shifting techniques such as Xe-doping to further increase scintillation light yield and localize events in the detector. In addition, we are planning on use of underground argon [5] to reduce the dominant non-beam related background in the experiment.

3 Solid State Detectors

Continued development over the past decade of P-type Point-Contact (PPC) High-Purity Germanium (HPGe) detectors has resulted in devices with masses in excess of 2 kg each and sub-keV energy resolution and thresholds [6, 7]. Combined with the well-understood systematics and measured quenching factors, the resolution allowed by PPC detectors enables precision measurements of spectral shape distortions due to nuclear form factors or new physics. The drawbacks of these detectors are primarily in their relatively high cost to manufacture, and in the case of SNS operation, the limited timing resolution afforded due to the wide range of drift times in larger mass detectors (up to $\sim 2\mu$sec).

Currently, the COHERENT Collaboration is deploying an array of 8 PPC germanium detectors with a total mass in excess of 16 kg. To enable a next-generation effort, we propose the development of new classes of PPC detectors with larger masses and a narrower range of drift lengths, while maintaining reasonable depletion/operating voltages and the low-noise performance that enables excellent energy resolution and low thresholds. New prototype detectors developed in coordination with detector manufacturers can be directly evaluated in the germanium detector array currently being deployed at the SNS, while plans for a future experiment evolve.

4 Photon Detectors

4.1 Low-threshold cryogenic scintillators

The most serious limitation in reducing the energy threshold of the COHERENT CsI(Na) detector was the Cherenkov radiation originated from its PMT quartz window by natural radiation and cosmic rays [8], which can be completely eliminated by replacing PMTs with SiPM arrays. Cryogenic operation is needed to reduce the dark count rate of SiPM arrays [9], which also calls for the replacement of doped crystals with undoped ones due to much higher intrinsic light yield of the latter [10–15]. The light yield of such a combination is expected to be at least 4 times higher than that of the CsI(Na) detector [14], and the energy threshold would be at least three times lower.

With such a low threshold, even a ~ 10 kg prototype can detect a thousand CEvNS events annually [14]. Its sensitivity to detect [0.1, 10] MeV dark matter particles produced at the SNS through a new vector boson [16, 17] surpasses any existing experiment [14]. Significant improvement in constraining non-standard neutrino interactions is also expected [18], which can be used to break the degeneracy in neutrino oscillation parameters (dark [19] and conventional LMA solutions) that cannot be solved by oscillation experiments alone.

4.2 D_2O detector for precise neutrino flux normalization

The neutrino flux at the SNS arises from π^+ production by a 1-GeV proton beam incident on a thick, liquid Hg target; each π^+ ultimately produces three neutrinos through decay at rest. COHERENT has assigned a 10% systematic uncertainty on the neutrino flux, due to the complete lack of world data for Hg in this energy range, and to discrepancies in model predictions for the process [8]. This shared systematic applies to every neutrino cross-section measurement at the SNS. It was the second largest systematic for the discovery of CEvNS on CsI [8], and the largest for the measurement on LAr [2].

To benchmark the neutrino flux, COHERENT plans to construct a 1300-kg D_2O detector in two modules. Its operation is based on detecting Cherenkov light from CC ν_e reactions with d. Each module will consist of an upright cylinder, with D_2O contained inside a central acrylic cylinder, contained inside a steel tank with 10 cm of H_2O tail catcher. Twelve PMTs view the volume from above. The essential detector concept is not novel – in fact, a D_2O detector was deployed at a stopped-pion neutrino source forty years ago [20] – but the use of Tyvek reflectors to achieve good light collection with minimal instrumentation is new. With the theoretical cross section known at the 2-3% level [21, 22], it will be a powerful tool. We anticipate more than 500 CC $\nu_e - d$ events per module per SNS beam-year, with the predominant background arising from CC interactions on oxygen. We plan to acquire flux-normalization data not only in the present SNS operational mode, but also with 1.3-GeV protons on liquid Hg (after a planned beam upgrade), and with 1.3-GeV protons on tungsten at the planned STS [23].

5 Cross cutting and future prospects

Low-threshold, low-background technologies developed for CEvNS detections are widely used for direct dark matter searches as well. The development of such detectors at the SNS benefits from the fact that the nuclear recoil signals associated with the SNS proton beam spills are well understood. The well shielded Neutrino Alley can hence be used as a perfect test bed for new technologies. Additionally, the PPC germanium detectors used in COHERENT are a technology under consideration for a ton-scale neutrinoless double beta decay search experiment (LEGEND); development of larger mass detectors is synergistic with that effort.

The COHERENT collaboration welcomes new ideas beyond the collaboration's nominal to-do list, and would like to share the detector R&D opportunity enabled by the planned STS at the SNS that could provide generous well-shielded experimental spaces and more powerful, better controlled, pulsed neutrino source. For instance, a LAr TPC can be tested there, verifying some of the key DUNE technologies, and measuring low energy neutrino cross sections relevant for e.g., supernova neutrino detection [24].

6 References

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