COHERENT LOI 1: Future COHERENT physics program at the SNS

COHERENT collaboration

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NF Topical Groups:

- ■ (NF2) Sterile neutrinos
- ■ (NF3) Beyond the Standard Model
- ■ (NF5) Neutrino properties
- ■ (NF6) Neutrino cross sections
- ■ (NF7) Applications
- ■ (TF11) Theory of neutrino physics
- ■ (NF9) Artificial neutrino sources
- ■ (NF10) Neutrino detectors
- ■ (CF1) Dark Matter: particle-like

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Abstract: The COHERENT experiment has established a low-background experimental area near the SNS pulsed proton beam in which to study coherent elastic neutrino nucleus scattering (CEvNS) and other low-energy neutrino scattering processes with state-of-the-art low-threshold detectors. The initial success of this program has been demonstrated with the discovery of CEvNS with a CsI detector (2017) and the recent confirmation of the N^2-dependence of CEvNS on argon (2020). The next phase of this program will utilize a diverse suite of large-scale detectors of modest costs enabling a far-reaching and impactful physics program including: tests of beyond-standard-model physics, nuclear structure measurements, understanding neutrino behavior in astrophysical environments, and searches for dark-matter particles.

Introduction

Coherent elastic neutrino-nucleus scattering (CEvNS) was predicted in 1974 as a consequence of the newly discovered neutral weak current [1, 2]. The Standard Model CEvNS cross section has a characteristic dependence on the square of the number of neutrons in the target nucleus, $\sigma \sim N^2$, owing to the small weak charge of protons; this coherent enhancement of the cross section makes it the dominant interaction mechanism for neutrinos of energies between ∼10 and ∼100 MeV. Measurements of this process enable exploration of a dense and diverse suite of physics topics ranging from searches for beyond-standard-model interactions to a measurement of the neutron density distribution in nuclear matter (see Ref. [3] and references therein). The COHERENT program complements searches for dark matter (DM) by confirming cross-section predictions for neutrino backgrounds expected in future large-scale WIMP searches (the so-called "neutrino floor" [4]) and also has sensitivity to accelerator-produced DM [5, 6]. The COHERENT suite of experiments includes measurements of ν processes beyond CEvNS including interactions on ^{40}Ar, ^{127}I, ^{208}Pb, and ^{56}Fe with possible connections to nuclear structure, nucleosynthesis, and supernova neutrino detection. In particular, neutrino-argon inelastic interactions will be particularly relevant for the DUNE supernova sensitivity.

Currently

The observation of CEvNS is quite challenging due to the technical requirements: $\mathcal{O}$(10 keV) nuclear recoil energy thresholds, intense neutrino sources, and low backgrounds. The COHERENT collaboration has surmounted these challenges using state-of-the-art detector technology combined with the intense, pulsed, stopped-pion neutrino source available at the Spallation Neutron Source (SNS) at Oak Ridge National Laboratory (ORNL), and a well-shielded, low-background area "neutrino alley", 20-30 m from the 1.4 MW beam. These experimental features enabled the first measurement of CEvNS with a CsI crystal in 2017 [7]. In addition, COHERENT recently reported a measurement of CEvNS on argon [8, 9], demonstrating the expected N^2 dependence of the event rate, confirming that the signal is indeed CEvNS and providing additional constraints on non-standard neutrino interactions (NSI).

The next goal of COHERENT is to build upon these first measurements, which are currently statistically limited at ≈ 30%, by moving to a precision CEvNS program that can realize this suite of physics topics. Currently in neutrino alley: the CENNS-10 LAr detector continues to collect data; two detectors are studying neutrino-induced-neutrons ("NINs") on Pb/Fe; a 185-kg NaI detector is currently measuring the ^{127}I CC inclusive cross section and has studied backgrounds as a prototype experiment for CEvNS; and an ongoing measurement of SNS-pulse-coincident neutron backgrounds along neutrino alley using the Multiplicity and Recoil Spectrometer (MARS).

Future Program

We are proposing a neutrino alley configured as shown in Fig. 1 that will allow a dense program of new results from CEvNS and related physics on a time scale of 5-10 years [3]. The MARS neutron detector and NIN cubes are currently installed and will continue to run with only modest changes. The Ge array will consist of 16 kg of PPC Ge detectors enabling a measurement of CEvNS on an intermediate-mass nuclei with the lowest detection threshold ($\mathcal{O}$(1 keVnr)) in neutrino alley. This detector is funded, and installation will begin in next year. Current plans also contain a multi-ton NaI array using existing individual 7.7-kg NaI[Tl] modules with sensitivity to charged-current ^{127}I interaction and, potentially, for CEvNS. This detector is also funded with installation planned for the near future.

To realize the full potential of CEvNS physics in neutrino alley at the SNS, in addtion to the planned detectors described above, the COHERENT collaboration is proposing two additional, ton-scale, few-million-$-scale apparatus.

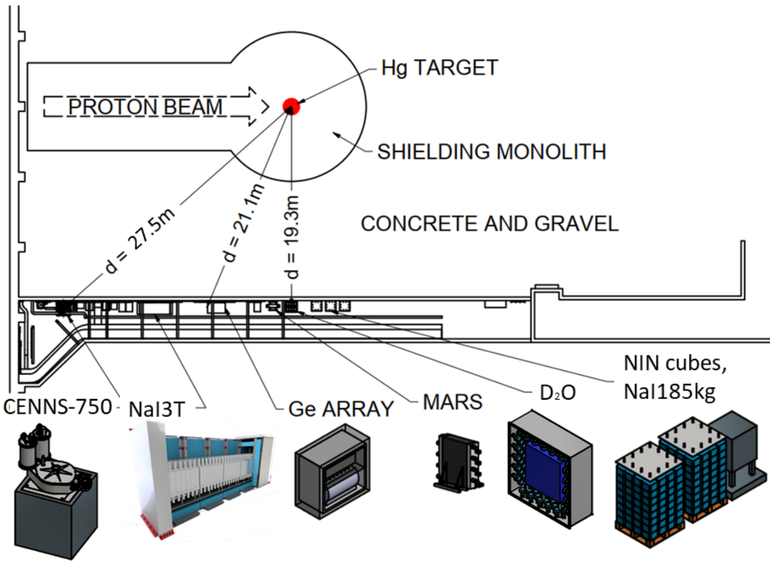

Fig. 1: Proposed SNS ν-alley configuration.

A heavy water (D_20) detector [10] will allow an improved uncertainty of $\approx$ 3% on the normalization of the neutrino flux via the known rate of the charged-current $\nu_e + d \rightarrow p + p + e^-$ reaction [11]. This will be a significant improvement over the current value of 10% which will ultimately become the dominant uncertainty[7, 9] as larger and more sensitive detectors are deployed with and other systematic errors are reduced. Additionally, charged-current ν_e interactions on ^{16}O may be explored. This device employs $\mathcal{O}(1$ ton) of D_2O in an acrylic vessel surrounded by light water and 8-inch PMTs and will collect $\approx$ 1000 signal events/year.

The ton-scale liquid argon detector [3], CENNS-750, is a 750 kg (610 kg fiducial) scintillation-only device with a large coverage fraction of high-sensitivity photodetectors such as 3" cryogenic PMTs or VUV-sensitive SiPMs enabling an energy threshold of $\sim$ 20 keVnr. We are planning for the use of underground argon [12] to reduce the dominant non-beam-related (^{39}Ar) background. This device will build upon on experience with the currently-running CENNS-10 detector [13] and would be a complementary effort to the global LAr dark matter enterprise [12, 14]. CENNS-750 is expected to provide $\approx$ 3500 CEvNS events/year allowing more precise energy spectra and substantially furthering the precision of the resulting measurements on the large CEvNS and related physics program.

Conclusion

The COHERENT collaboration, with ongoing support of the SNS facility and management, has established neutrino alley as the world's best facility in which to measure the CEvNS interaction. "First-light" measurements from CsI[Na] and argon have confirmed the existence of the CEvNS process. Near-future, funded Ge and NaI detectors will continue to build the physics portfolio. Beyond this, COHERENT is proposing two additional, low-cost, ton-scale detectors. These devices will provide precision CEvNS cross section measurements, placing world-leading constraints on beyond-standard-model neutrino interactions; will search for accelerator-produced dark matter [6]; and will provide direct measurements of the nuclear response to low-energy neutrinos, informing nuclear structure/modeling efforts and aiding with he planning and interpretation of future neutrino experiments [15, 16].

References

[1] Daniel Z. Freedman. Coherent Neutrino Nucleus Scattering as a Probe of the Weak Neutral Current. *Phys. Rev. D*, 9:1389–1392, 1974. doi: 10.1103/PhysRevD.9.1389.

[2] V. B. Kopeliovich and L. L. Frankfurt. Isotopic and chiral structure of neutral current. *JETP Lett.*, 19:145–147, 1974. [Pisma Zh. Eksp. Teor. Fiz.19,236(1974)].

[3] D. Akimov et al. COHERENT 2018 at the Spallation Neutron Source. 2018. arXiv:1803.09183 [physics.ins-det].

[4] M.C. Gonzalez-Garcia, Michele Maltoni, Yuber F. Perez-Gonzalez, and Renata Zukanovich Funchal. Neutrino Discovery Limit of Dark Matter Direct Detection Experiments in the Presence of Non-Standard Interactions. *JHEP*, 07:019, 2018. doi: 10.1007/JHEP07(2018)019.

[5] D. Akimov et al. Sensitivity of the COHERENT Experiment to Accelerator-Produced Dark Matter. 2019. arXiv:1911.06422 [hep-ex].

[6] COHERENT collaboration. COHERENT LOI 3: COHERENT Sensitivity to Dark Matter. 2020. Snowmass LOI.

[7] D. Akimov et al. Observation of Coherent Elastic Neutrino-Nucleus Scattering. *Science*, 357 (6356):1123–1126, 2017. doi: 10.1126/science.aao0990.

[8] D. Akimov et al. First Constraint on Coherent Elastic Neutrino-Nucleus Scattering in Argon. *Phys. Rev. D*, 100(11):115020, 2019. doi: 10.1103/PhysRevD.100.115020.

[9] D. Akimov et al. First Detection of Coherent Elastic Neutrino-Nucleus Scattering on Argon. 2020. arXiv:2003.10630 [nucl-ex].

[10] Rebecca Rapp. COHERENT Plans for D_2O at the Spallation Neutron Source. In *Meeting of the Division of Particles and Fields of the American Physical Society*, 2019. arXiv:1910.00630 [physics.ins-det].

[11] S. Nakamura, T. Sato, S. Ando, T.S. Park, F. Myhrer, Vladimir P. Gudkov, and K. Kubodera. Neutrino deuteron reactions at solar neutrino energies. *Nucl. Phys. A*, 707:561–576, 2002. doi: 10.1016/S0375-9474(02)00993-4.

[12] Rahaf Ajaj. Low Radioactivity Argon for Dark Matter and Rare Event Searches. *PoS*, LeptonPhoton2019:084, 2019. doi: 10.22323/1.367.0084.

[13] R. Tayloe. The CENNS-10 Liquid Argon Detector to measure CEvNS at the Spallation Neutron Source. *JINST*, 13(04):C04005, 2018. doi: 10.1088/1748-0221/13/04/C04005.

[14] C.E. Aalseth et al. DarkSide-20k: A 20 tonne two-phase LAr TPC for direct dark matter detection at LNGS. *Eur. Phys. J. Plus*, 133:131, 2018. doi: 10.1140/epjp/i2018-11973-4.

[15] COHERENT collaboration. COHERENT LOI 4: Inelastic Neutrino-Nucleus Interaction Measurements with COHERENT. 2020. Snowmass LOI.

[16] COHERENT collaboration. COHERENT LOI 5: Instrumentation Development. 2020. Snowmass LOI.

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D. Akimov[1,2], P. An[3,4], C. Awe[3,4], P.S. Barbeau[3,4], B. Becker[5], I. Bernardi[5], V. Belov[1,2], M.A. Blackston[6], L. Blokland[5], A. Bolozdynya[2], R. Bouabid[3,4], A. Bracho[3,4], B. Cabrera-Palmer[7], N. Chen[8], D. Chernyak[9], E. Conley[3], J. Daughhetee[5], J.A. Detwiler[8], K. Ding[9], M.R. Durand[8], Y. Efremenko[5,6], S.R. Elliott[10], L. Fabris[6], M. Febbraro[6], A. Galindo-Uribarri[5,6], A. Gallo Rosso[11], M.P. Green[4,6,12], K.S. Hansen[8], M.R. Heath[6], S. Hedges[3,4], M. Hughes[13], T. Johnson[3,4], L.J. Kaufman[13,14], A. Khromov[2], A. Konovalov[1,2], E. Kozlova[1,2], A. Kumpan[2], L. Li[3,4], J.T. Librande[8], J.M. Link[15], J. Liu[9], A. Major[3], K. Mann[4,6], D.M. Markoff[4,16], O. McGoldrick[8], P.E. Mueller[6], J. Newby[6], D.S. Parno[17], S. Penttila[6], D. Pershey[3], D. Radford[6], R. Rapp[17], H. Ray[18], J. Raybern[3], O. Razuvaeva[1,2], D. Reyna[7], G.C. Rich[19], D. Rudik[1,2], J. Runge[3,4], D.J. Salvat[13], K. Scholberg[3], A. Shakirov[2], G. Simakov[1,2]W.M. Snow[13], V. Sosnovtsev[2], B. Suh[13], R. Tayloe[13], K. Tellez-Giron-Flores[15], R.T. Thornton[13,10], J. Vanderwerp[13], R.L. Varner[6], C.J. Virtue[11], G. Visser[13], C. Wiseman[8], T. Wongjirad[20], J. Yang[20], Y.-R. Yen[17], J. Yoo[21,22], C.-H. Yu[6], and J. Zettlemoyer[23,13]

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