ORNL Neutrino Sources for Future Experiments

Paul Langan[1], Chris Bryan[2], Marcel Demarteau[3], John Galambos[4], and Ken Herwig[4]

[1] *Associate Laboratory Director of Neutron Sciences, Oak Ridge National Laboratory*
[2] *High Flux Isotope Reactor, Oak Ridge National Laboratory*
[3] *Physics Division Director, Oak Ridge National Laboratory*
[4] *Spallation Neutron Source, Oak Ridge National Laboratory*

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Contact Information:
Jason Newby (Oak Ridge National Laboratory) [newbyrj@ornl.gov]
Andrew Conant (Oak Ridge National Laboratory) [conantaj@ornl.gov]

Additional Authors: COHERENT Collaboration and PROSPECT Collaboration

Abstract: Since 2013 the Oak Ridge National Laboratory has been developing the utilization of its neutron user facilities for fundamental neutrino science. The Neutron Science, Nuclear Science and Engineering, and Physical Sciences Directorates have collaborated with neutrino scientists to deploy two cutting edge neutrino experiments, PROSPECT and COHERENT, at HFIR and SNS respectively with the support of laboratory investments in site infrastructure, local supporting laboratories, computing and data storage, and administrative user support for visiting scientists and students.

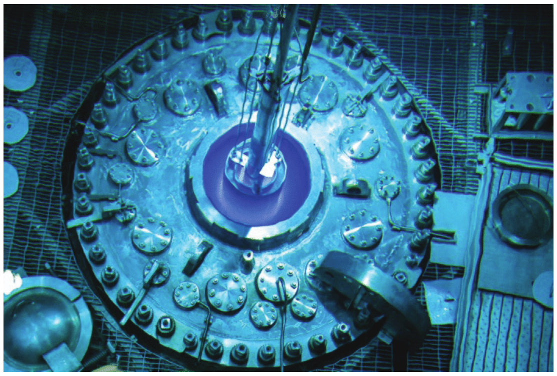
We have demonstrated that these facilities can deliver world class neutrino science while maintaining their commitments to their primary missions to the Office of Basic Energy Sciences. Both the SNS and HFIR are planned to operate at production levels beyond the next decade with significant power upgrades and a new target station planned for the SNS in the next five years that expand opportunities for the neutrino experimental program.

With continued support from the Office of High Energy Physics and ORNL management, we envision a thriving collaborative experimental neutrino program to deliver world-class science that utilizes the unique capability of these neutrino sources that is highly complementary to global neutrino experimental community efforts[1–12].

High Flux Isotope Reactor (HFIR)

The High Flux Isotope Reactor (HFIR) is an 85 MW research reactor that produces 10^{19} antineutrinos per second. The reactor is one of only a few reactors remaining in the United States fueled with highly-enriched uranium (HEU). The higher enrichment compared to commercial reactors results in $> 99\%$ of fissions coming from ^{235}U. The core is one of the most compact in the world, at 0.5 meters in diameter. Being a research reactor with a 50% duty cycle means there is ample opportunity to study backgrounds, which is critical for a short baseline experiment. Therefore HFIR is an excellent neutrino source to study neutrino properties and the ^{235}U spectrum.

HFIR will be undergoing a replacement of its permanent beryllium reflector in the mid 2020s. Following this replacement, HFIR will be able to continue operation for basic energy sciences for approximately another two decades. There are also potential plans to upgrade HFIR with new and improved scientific facilities, which would extend its lifetime for many more decades. The continued operation of the reactor will allow for use of the facility for subsequent neutrino experiments.



HFIR core during a defueling operation

HFIR already has experience with hosting a neutrino experiment. HFIR hosted the Precision Reactor Oscillation and Spectrum (PROSPECT) experiment in 2018[13–16]. The mission of PROSPECT is two-fold: to make a precision measurement of the ^{235}U spectrum and to search for sterile neutrino oscillations. The PROSPECT collaboration designed and constructed a ton-scale, segmented liquid scintillator detector that used inverse beta decay to see neutrinos coming from HFIR. PROSPECT has since achieved the highest statistics measurement of the ^{235}U spectrum and excellent signal-to-background for an above-ground, short-baseline detector. PROSPECT was also able to achieve short baseline (7-10 meters) from the core center.

PROSPECT detector at HFIR

HFIR is a dedicated user facility with world-class operational excellence. The compact core and facility allow for very short baselines (< 10 meters) from the core and a variety of deployment locations. Additionally, the HFIR core is also well-modeled with state-of-the-art simulation tools [17]. Many HFIR staff are familiar with the efforts of neutrino science and have consistently demonstrated support for groundbreaking science experiments. The tacit knowledge and experience is invaluable to neutrino experiments seeking to measure reactor neutrinos.

Spallation Neutron Source (SNS)

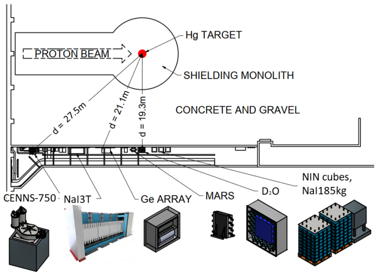
The Spallation Neutron Source at the Oak Ridge National Laboratory is an extraordinary machine and user facility supporting the mission of the DOE Basic Energy Sciences in materials and biological research.

The SNS is also the world's most intense source of neutrinos from stopped-pion decays. These neutrinos were recently used by the COHERENT collaboration to make the first observation of a neutrino interaction that had eluded experimental detection for over 40 years, coherent elastic neutrino-nuclear scattering (CEvNS)[18]. The success of the COHERENT experiment[19, 20] was primarily due to the intensity, pulsed time structure, and total annual neutrino production of the neutrino source.

The Spallation Neutron Source Complex

As currently operating, the SNS utilizes a superconducting linear accelerator to bring hydrogen ions to a kinetic energy of 1 GeV. The ions are stripped of their electrons and the protons stored in a 1 microsecond period storage ring. Within a millisecond, 1200 of these proton pulses are accumulated before the beam is extracted and directed on a massive liquid mercury target with a width of only 350 ns. This entire process is repeated 60 times a second to deliver 1.4 MW of protons to spallate neutrons off the target nuclei. The neutrons are heavily moderated and sent down beam lines to neutron scattering instruments and a single fundamental neutron physics experiment hall. The SNS operates 5000 hours per year with exquisitely consistent beam conditions with a premium on reliable, scheduled operations for the user program.

For every 300 neutrons produced in the target, you also get a positively charged pion that decays to three flavors of neutrinos with a characteristic energy and time structure that is preserved by the short proton pulses. The proton beam energy is fortuitously in a sweet-spot to efficiently produce pions without producing too many kaons and the target is sufficiently thick to minimize decays-in-flight. This results in an extremely clean (>99%) source of neutrinos from decay-at-rest pions that is well understood.



Neutrino Alley at SNS First Target Station with planned COHERENT instruments

The SNS Proton Power Upgrade (PPU) project to be completed by 2024 will provide 2.0 MW of proton power at the currently operating First Target Station. The proton pulses will be delivered at a rate of 60 pulses per second until the completion of the Second Target Station(STS) in 2028. When the STS comes online that same 2MW will be delivered in 45 pulses per second to the first target and 15 pulses will be directed at the new tungsten target at the Second Target Station. The civil design of the target building is now underway and Second Target Station project management is working with the neutrino scientists to understand facility requirements for future neutrino experiments. The second target station will expand opportunities for neutrino science in several ways:

- Purpose designed laboratory spaces will allow for a factor of 10 larger detector masses for high precision experiments to probe topics including non-standard interactions, neutrino magnetic moment, and the weak mixing angle, and
- On-axis and off-axis locations will provide highly competitive searches for accelerator produced dark matter[21].

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COHERENT Authors:

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

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[1] Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of National Research Centre "Kurchatov Institute", Moscow, 117218, Russian Federation

[2] National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), Moscow, 115409, Russian Federation

[3] Department of Physics, Indiana University, Bloomington, IN, 47405, USA

[4] Department of Physics, Duke University, Durham, NC 27708, USA

[5] Triangle Universities Nuclear Laboratory, Durham, NC 27708, USA

[6] Department of Physics and Astronomy, University of Tennessee, Knoxville, TN 37996, USA

[7] Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA

[8] Sandia National Laboratories, Livermore, CA 94550, USA

[9] Center for Experimental Nuclear Physics and Astrophysics & Department of Physics, University of Washington, Seattle, WA 98195, USA

[10] Physics Department, University of South Dakota, Vermillion, SD 57069, USA

[11] Los Alamos National Laboratory, Los Alamos, NM, USA, 87545, USA

[12] Department of Physics, Laurentian University, Sudbury, Ontario P3E 2C6, Canada

[13] Department of Physics, North Carolina State University, Raleigh, NC 27695, USA

[14] SLAC National Accelerator Laboratory, Menlo Park, CA 94205, USA

[15] Center for Neutrino Physics, Virginia Tech, Blacksburg, VA 24061, USA

[16] Department of Mathematics and Physics, North Carolina Central University, Durham, NC 27707, USA

[17] Department of Physics, Carnegie Mellon University, Pittsburgh, PA 15213, USA

[18] Enrico Fermi Institute and Kavli Institute for Cosmological Physics, University of Chicago, Chicago, IL 60637, USA

[19] Department of Physics and Astronomy, Tufts University, Medford, MA 02155, USA

[20] Department of Physics at Korea Advanced Institute of Science and Technology (KAIST), Daejeon, 34141, Republic of Korea

[21] Center for Axion and Precision Physics Research (CAPP) at Institute for Basic Science (IBS), Daejeon, 34141, Republic of Korea

PROSPECT Authors:
M. Andriamirado [22], A. B. Balantekin [23] H. R. Band [24], C. D. Bass [25], D. E. Bergeron [26], D. Berish [27], N. S. Bowden [28], J. P. Brodsky [28], C. D. Bryan [29], R. Carr [30], T. Classen [28], A. J. Conant [31], G. Deichert [29], M. V. Diwan [32], M. J. Dolinski [33], A. Erickson [31], B. T. Foust [24], J. K. Gaison [24], A. Galindo-Uribarri [34, 35], C. E. Gilbert [34,35], C. Grant[36], B. T. Hackett [34,35] S. Hans [32], A. B. Hansell [27], K. M. Heeger [24] D. E. Jaffe [32], X. Ji [32], D. C. Jones [27], O. Kyzylova [33], C. E. Lane [33], T. J. Langford, [24], J. LaRosa [26], B. R. Littlejohn [22], X. Lu [34,35], J. Maricic [37], M. P. Mendenhall [28], A. M. Meyer [37], R. Milincic [37], I. Mitchell [37], P. E. Mueller [34] , H. P. Mumm [26], J. Napolitano [27], C. Nave [33], R. Neilson [33], J. A. Nikkel [24], D. Norcini [24], S. Nour [26], J. L. Palomino [22], D. A. Pushin [38], X. Qian [32], E. Romero-Romero [34,35], R. Rosero [32], P. T. Surukuchi [24], M. A. Tyra [26], R. L. Varner [34], D. Venegas-Vargas [34,35], P. B. Weatherly [33], C. White [22], J. Wilhelmi [24], A. Woolverton [38], M. Yeh [32] A. Zhang [32], C. Zhang [32], X. Zhang [28]

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[22] Department of Physics, Illinois Institute of Technology, Chicago, IL, USA

[23] Department of Physics, University of Wisconsin, Madison, Madison, WI, USA

[24] Wright Laboratory, Department of Physics, Yale University, New Haven, CT, USA

[25] Department of Physics, Le Moyne College, Syracuse, NY, USA

[26] National Institute of Standards and Technology, Gaithersburg, MD, USA

[27] Department of Physics, Temple University, Philadelphia, PA, USA

[28] Nuclear and Chemical Sciences Division, Lawrence Livermore National Laboratory, Livermore, CA, USA

[29] High Flux Isotope Reactor, Oak Ridge National Laboratory, Oak Ridge, TN, USA

[30] Department of Physics, Massachusetts Institute of Technology, Cambridge, MA, USA

[31] George W. Woodruff School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA USA

[32] Brookhaven National Laboratory, Upton, NY, USA

[33] Department of Physics, Drexel University, Philadelphia, PA, USA

[34] Physics Division, Oak Ridge National Laboratory, Oak Ridge, TN, USA

[35] Department of Physics and Astronomy, University of Tennessee, Knoxville, TN, USA

[36] Department of Physics, Boston University, Boston, MA, USA

[37] Department of Physics & Astronomy, University of Hawaii, Honolulu, HI, USA

[38] Institute for Quantum Computing and Department of Physics and Astronomy, University of Waterloo, Waterloo, ON, Canada