The Fundamental Neutron Physics Facilities at NIST

P. R. Huffman, M. Arif, M. S. Dewey, T. R. Gentile,
D. M. Gilliam, D. L. Jacobson, J. S. Nico, and A. K. Thompson

National Institute of Standards and Technology, Ionizing Radiation Division, Gaithersburg, MD 20899, USA

Abstract. The National Institute of Standards and Technology (NIST) Center for Neutron Research (NCNR) is a national center that provides thermal and cold neutrons beams for activities such as materials science, biological, polymer, and fundamental physics research. Four beams are currently in use for fundamental physics experiments. These include a neutron optics and interferometry facility, a 0.496 nm monochromatic beam, a 0.89 nm monochromatic beam, and a high-intensity polychromatic beam. Experiments primarily focus on studies of the weak interaction using neutrons. This paper provides a general overview of the facilities and highlights some current experiments.

The NIST Center for Neutron Research (NCNR) is located in Gaithersburg, MD and houses a 20 MW research reactor that provides neutron beams for a wide variety of uses. These include materials science research, biological and polymer investigations, fundamental physics research, and neutron standards and dosimetry studies. Both thermal and cold neutron beams are available for use with instruments that include spectrometers, reflectometers, diffractometers, and small angle scattering chambers. Four beams are currently in use for fundamental physics experiments. These include three monochromatic neutron beams and a high-intensity polychromatic beam.

Neutrons are released in the reactor core from uranium fission products and are moderated to thermal energies by D_2O . Thermal beams are available for various neutron scattering instruments. One thermal beamport houses a large liquid hydrogen cold source. The cold source is a hollow shell with walls filled with liquid hydrogen at a temperature of ≈ 20 K. Neutrons partially thermalize with the hydrogen, then exit towards a series of eight neutron guides that feed a set of cold neutron instruments. The cold neutrons pass into the open end of rectangular ^{58}Ni -coated neutron guides 15 cm tall and 6 cm wide. ^{58}Ni has an effective neutron potential of 335 neV such that neutrons with low enough momentum perpendicular to the surface will be totally reflected and thus can be transported to the far end of the guides (that are typically 20 m to 60 m in length) with minimal losses. For a fixed neutron wavelength (or energy), the surfaces of the guide are reflecting up to a critical angle of ≈ 20 mrad nm^{-1} .

This paper will provide a brief description of the four cold neutron beams that are available for fundamental

FIGURE 1. Photograph of the neutron guide hall at the NCNR. This paper describes the NIOF and NG-6 neutron facilities. Three monochromatic beams and one polychromatic beam is available for use in fundamental physics research.

neutron physics research. Research includes investigations of the weak interaction and tests of the Standard Model through the study of neutron decay and neutron interactions. Highlights of some recent experiments per-

FIGURE 2. Spectrum of the filtered neutron wavelengths in the NG-6 polychromatic beam. The dips in the spectrum correspond to Bragg-edges from materials upstream, with the largest at 0.48 nm arising from an upstream monochromator. The data were taken with a 15 cm thick bismuth filter.

formed at the NCNR fundamental physics facilities will be presented.

BEAMLINES

Three of the fundamental physics beamlines reside at the end of cold neutron guide number six (NG-6): a polychromatic beam, a 0.89 nm monochromatic beam, and a 0.496 nm monochromatic beam. The fourth resides on neutron guide number seven (NG-7) and is directed into the NIOF.

Polychromatic Beam

Neutrons exiting from the upper 7 cm of the NG-6 guide pass through a ^6Li -loaded-glass collimator that defines a 6 cm diameter beam. The wavelength distribution of the beam is roughly Maxwellian with an average temperature of 30 K. To minimize backgrounds for neighboring experiments, single crystal, cooled (77 K) bismuth filters (5 cm to 15 cm long) are placed in the beam to attenuate gamma rays from upstream components in the guide. The neutron fluence rate with 15 cm of bismuth and no additional filters is $(1.5 \pm 0.1) \times 10^9 \text{ cm}^{-2} \text{ s}^{-1}$. The maximum fluence rate (ie. no filter) is approximately $2.3 \times 10^9 \text{ cm}^{-2} \text{ s}^{-1}$. A wavelength spectrum of the neutron beam is shown in Fig. 2 with 15 cm of single crystal bismuth filters in place.

The thermal energy (short wavelength) neutrons can be filtered from the beam using Bragg scattering from

polycrystalline materials; the most common being 5 cm to 15 cm thick of beryllium. Beryllium will Bragg reflect neutrons out of the beam whose wavelengths are less than 0.395 nm. Other filter materials that have been used are graphite and polycrystalline bismuth.

Experiments requiring unpolarized neutrons can use the exiting beam directly, while other experiments require the neutrons to be polarized. Two polarization technologies are available: supermirror and ^3He transmission polarizers. Polarizations of 96 % are typical for the supermirror device, with the polarized neutron beam slightly more divergent and reflected by an angle of approximately 1° with respect of the primary beam. ^3He transmission polarizers are generally superior for highly accurate neutron polarization measurements, polarization of large diameter beams, and polarization over a wavelength spectrum larger than can be accommodated by supermirrors.

0.496 nm Monochromatic Beam

Two monochromators are positioned in the lower 8 cm of the polychromatic beam exiting the NG-6 guide. The upstream monochromator consists of a piece of pyrolytic graphitic 5.1 cm by 5.1 cm by 0.2 cm thick with a mosaic of 0.8° . This crystal Bragg reflects a 0.496 nm beam at an angle of approximately 104° with respect to the primary beam.

Once the neutron beam reflects from the monochromator, it passes through 10 cm of cooled beryllium to remove the $\lambda/2$ component of the beam. The neutron fluence rate available at a typical experimental position (approximately 2 m from the crystal) is $6.5 \times 10^5 \text{ cm}^{-2} \text{ s}^{-1}$.

The 0.496 nm neutron beam is used for neutron calorimetry experiments, polarized ^3He development, and for neutron dosimetry work.

0.89 nm Monochromatic Beam

Downstream of the 0.496 nm monochromator resides a 0.89 nm stage 2 potassium-intercalated graphite monochromator. The outgoing 0.89 nm neutron beam is 6 cm by 6 cm and is directed at an angle of 60° with respect to the polychromatic beam.

The individual monochromator pieces have high stage purity and mosaics in the range of 1.1° to 2.1° . The reflectivity between 0.88 nm and 0.90 nm is $(85.4 \pm 0.5) \%$, yielding a capture fluence rate at 1 m from the crystal of $4.7 \times 10^6 \text{ cm}^{-2} \text{ s}^{-1}$.

Two additional wavelengths are present, one at $\lambda/2 = 0.45 \text{ nm}$ and one at $\lambda/3 = 0.30 \text{ nm}$. The $\lambda/2$ peak is re-

FIGURE 3. The wavelength spectrum of the 0.89 nm beam before and after filtering.

moved by a pyrolytic graphite crystal with a 10° mosaic positioned to reflect out the 0.45 nm neutrons. The $\lambda/3$ peak is minimized using Bragg reflection from polycrystalline bismuth. A time-of-flight spectrum of the 0.89 nm neutron beam before and after wavelength filtering is shown in Fig. 3. The 0.89 nm beam is used primarily for ultracold neutron production.

Neutron Interferometric and Optics Facility

The NIOF is one of the world's premier user facilities for neutron interferometry and related neutron optical measurements. A neutron interferometer (NI) splits, then recombines neutron waves. This gives the NI its unique ability to experimentally access the phase of neutron waves. Phase measurements are used to study the magnetic, nuclear, and structural properties of materials, as well fundamental questions in quantum physics. An overview of the facility can be found in Ref. [1].

Neutrons are extracted from the primary NG-7 beam using a dual-crystal parallel-tracking pyrolytic graphite monochromator system. Monochromatic beams (either unpolarized or polarized) with wavelengths from 0.2 nm to 0.48 nm are available. Neutrons are counted with integrating ^3He detectors or by high resolution position-sensitive detectors (with a resolution better than 50 μm). The sensitivity of the apparatus is greatly enhanced by state-of-the-art thermal, acoustical and vibration isolation systems. To reduce vibration, the NIOF is built on its own foundation, separate from the rest of the building. The result is a NI facility with exceptional phase stability (0.25 $^\circ/\text{day}$) and high contrast (90 %). The beam at the interferometer is 2 mm wide by 8 mm tall and has a fluence rate of $2 \times 10^5 \text{ cm}^{-2} \text{ s}^{-1}$. A picture of the facility is

FIGURE 4. Neutron Interferometer and Optics Facility

shown in Fig. 4.

EXPERIMENTS

Neutron Lifetime Measurements

Two experiments are underway to measure the lifetime of the free neutron. The first uses a Penning-trap technique and is nearing completion. The second technique is under development and involves three-dimensional magnetic confinement of neutrons.

In the Penning-trap technique, when a neutron in the beam decays while passing through the trapping region, the recoil proton is trapped. The proton is held in a 5 T magnetic field that provides radial containment and an electrode at each end to provide axial confinement. Periodically, one of the end electrodes is lowered to ground potential to allow the accumulated trapped proton(s) to exit the trap and be counted by a proton detector. By knowing precisely the number of neutrons that decay while in the trapping volume and the number that pass through, the neutron lifetime can be extracted. Additional details are found in Ref. [2].

Determination of the lifetime requires either an accurately known trap length or a variable trap length with accurately known differences in length. The latter is more easily realized physically and used in the current design. The required accuracy for determination of neutron flux (or density) is the primary systematic limitation. The neutron monitor employed is known as a $1/v$ detector, with an efficiency that is weighted by the reciprocal of the neutron velocity. This ^6Li detector is a transmission device that is nearly transparent to neutrons. By measuring rate of alpha production from this well-characterized foil, the neutron flux can be determined.

The preliminary lifetime value obtained in this experiment is $\tau_n = (884.6 \pm 4.1) \text{ s}$ [3]. Continuing efforts to measure the neutron count rate are underway by calorimetry.

metric techniques, that should reduce the final uncertainty by a factor of two.

The second experiment under development for measuring the neutron lifetime uses magnetic trapping techniques. In brief, ultracold neutrons (UCN) are produced by inelastic scattering of cold (0.89 nm) neutrons in a reservoir of superfluid ^4He (the “superthermal” process) [4]. These neutrons are then confined by a three-dimensional magnetic trap. As the trapped neutrons beta decay, the energetic electrons produced generate scintillations in the liquid He [5], that should be detectable with nearly 100 % efficiency. τ_n can be directly determined by measuring the scintillation rate as a function of time. A proof-of-principle demonstration of this technique has been performed [6]. The apparatus has been upgraded and is now equipped with a larger magnet that will be used to make a measurement of the neutron lifetime at the 10^{-3} level.

The Penning-trap measurements were performed on the polychromatic beam, while the UCN lifetime work is underway on the 0.89 nm monochromatic beam.

Time-Reversal Violation

The EMIT experiment searches for the time-reversal violating D -coefficient in neutron beta decay. A description of the experiment can be found in Ref. [7].

The detection region consists of four 50 cm long electron detectors and four 30 cm long proton detectors arranged octagonally around the polarized neutron beam. The decay electrons and protons are detected in coincidence for neutrons polarized perpendicular to the direction of the neutron momentum. A difference in the coincidence rate for neutrons in one spin direction versus the opposite spin direction is a direct indication of time-reversal violation.

Data was taken in initial runs and set a limit of $D = [-0.6 \pm 1.2(\text{stat}) \pm 0.5(\text{syst})] \times 10^{-3}$. Substantial improvements have been made with a number of components including the proton detectors and the experiment is presently taking data on the polychromatic beam. These improvements are expected to produce a factor of ten higher data rate with significantly reduced systematic effects. It should be feasible to reduce the statistical uncertainty on D to 2×10^{-4} .

Polarized ^3He program

Polarized neutrons are preferred or required for many of the experiments underway. The ^3He spin filter, that operates by the absorption of one spin state, does not affect the other spin state so no deflection or divergence

is introduced into the beam. Because of the simple $1/v$ ^3He -neutron cross section, it can serve well as a broad-band neutron polarizer.

We are developing practical neutron spin filters based on two different techniques for polarizing ^3He : metastability-exchange optical pumping and spin-exchange optical pumping. An overview of the two polarization techniques and a description of the neutron ^3He program at NIST can be found in Ref. [8].

Polarized ^3He spin filters are based on the spin dependence of the ^3He -neutron capture cross section. Because the two neutrons in the ^4He nucleus are spin paired, only neutrons of one spin state are absorbed by the ^3He nucleus to form a ^4He nucleus. For the ^3He spin parallel to the neutron spin, the thermal capture cross section is essentially zero, whereas for the spins anti-parallel, the cross section is 10666 b.

Using both techniques, we have demonstrated 50 % to 60 % ^3He polarization under the conditions that are relevant to neutron polarizers. For a ^3He polarization of 60 %, the neutron polarization is 90 % and the transmission is 18 %. We are also able to analyze the neutron polarization using ^3He -based techniques.

SUMMARY

We operate one end-guide position that is wholly dedicated to fundamental neutron physics research. This station presently consists of a primary high-flux polychromatic beam, a 0.49 nm monochromatic beam, and a 0.89 nm monochromatic beam for ultracold neutron production. In addition, we have a state-of-the-art neutron interferometry and optics facility.

The neutron beams are available to users for experiments that fall in line with the general missions of the facility.

REFERENCES

1. Arif, M., *et al.*, in *Proceedings of the SPIE - The International Society for Optical Engineering*, edited by C. G. Gordon, Proc. SPIE **2264**, 1994, pp. 20-26.
2. Snow, W. M., *et al.*, *Nucl. Instrum. Meth. A* **440**, 528-534 (2000).
3. Dewey, M. S., *et al.*, *NIST Special Publication* **977**, 6 (2002).
4. Golub, R. and Pendlebury, J. M., *Rep. Progr. Phys.* **42**, 439-501 (1979).
5. Stockton, M., Keto, J. W., and Fitzsimmons, W. A., *Phys. Rev. Lett.* **24**, 654-657 (1970).
6. Huffman, P. R., *et al.*, *Nature* **403**, 62-64 (2001).
7. Lising, L. J., *et al.*, *Phys. Rev. C* **62**, 055501 (2000).
8. Rich, D. R., *et al.*, *Physica B* **305**, 203-207 (2001).