Report of NIST to the CCRI Section III
Activities 2007-2008

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INTRODUCTION

The Ionizing Radiation Division, one of six divisions within the Physics Laboratory at the National Institute of Standards and Technology (NIST), develops, maintains and disseminates the national standards for ionizing radiation and radioactivity. The Division fulfills its mission through activities in three technical groups: Radiation Interactions and Dosimetry (led by Stephen M. Seltzer), Neutron Interactions and Dosimetry (led by Muhammad Arif), and Radioactivity (led by Michael P. Unterweger). In addition to promoting the accurate and meaningful measurements of dosimetric quantities pertaining to ionizing radiation (x and gamma rays, electrons, and energetic, positively charged particles), the Division maintains the national measurement standards for the Système International (SI) unit for radiation dosimetry (the *gray*) and activity (the *becquerel*). It also provides measurement services, standards, and fundamental research in support of NIST's mission as it relates to neutron technology and neutron physics for industrial research and development, national defense, homeland security, electric and alternative power production, and radiation protection, and maintains and disseminates measurement standards for neutron dosimeters, neutron survey instruments, and neutron sources. Finally, the Division is responsible for developing metrological techniques to standardize new radionuclides for research, and for exploring radiation and nuclear applications in health care, worker protection, environmental protection, and national defense.

The Division provides critical measurements and standards for all aspects of ionizing radiation in industry, health care, the environment, homeland security and defense, working closely with the user communities in all of these fields to define and prioritize our research and programs in metrology. Since our self-declaration of conformance in 2006, the Division maintains compliance to the relevant requirements of ISO/IEC 17025 and ISO Guide 34 as part of the NIST quality system in our calibration services and production of our Standard Reference Materials (SRMs®). Direct interactions with our international colleagues in metrology (by active participation in implementation of the Mutual Recognition Arrangement through intercomparisons, submission of Calibration and Measurement Capabilities for evaluation, and international meetings) as well as with community members (such as through the Council on Ionizing Radiation Measurements and Standards, CIRMS) serve to provide a strong basis for near-term planning and our current programs. Each year, generally in late October, NIST hosts the CIRMS Annual Meeting, which brings together more than 100 participants who provide perspectives on developments and needs in ionizing radiation research, measurements and standards in health care, homeland security, environmental and personnel protection, and industrial applications. The focus of the 16th Annual Meeting on measurements and standards for radiation-based imaging used in industry, academia and government, was of interest across the field of ionizing radiation: from health care applications such as in positron emission (PET) and computed (CT) tomography imaging used in diagnosis and treatment (planning and evaluation) to industry (x-ray imaging as a non-destructive tool to assess product integrity) and homeland security (for non-destructive screening). With the efforts of the Division to support quantitative medical imaging, the topic was particularly timely. In 2008, the 17th Annual Meeting ("Radiation Measurements and Standards at the Molecular Level") provided an opportunity for the entire ionizing radiation user community to meet and discuss recent developments and new trends related to measurements at the molecular level, particularly in biodosimetry, and included a special panel on the National Academy of Sciences report regarding the use and security of radioactive cesium salts as related to the evolving homeland security aspects of radiation protection.

The Division maintains a strong focus on addressing the needs in standards and measurements to support health care, particularly in radiation and nuclear therapies. Building on a long history of providing standards for medical x rays and radionuclides used in nuclear medicine, we have been expanding our efforts to better support the extensive use of medical physics in the US today, providing confidence in key results needed for drug and device development and marketing, therapy planning and efficacy, and disease screening. In particular, to support more quantitative medical imaging, we have taken the initial steps in developing phantoms for more accurate calibration of PET and CT systems, including standardizing ^{68}Ge, for the first time, calibrated to National measurement standards, for PET instrumentation. The ability to calibrate diagnostic imaging tools traceably to national standards will lead to a more quantitative approach and increased accuracy in treatment planning, increased patient safety, and greater confidence in results from clinical trials.

The Division continued to be actively involved in several international efforts over the last two years. In addition to our active participation in the three sections of the Consultative Committee on Ionizing Radiation (CCRI), we have participated in the EURAMAT key comparison (among approximately 26 countries) of air-kerma and absorbed dose to water from ^{60}Co gamma-ray beams, serving as the host laboratory for participants in the Sistema Interamericano de Metrología (SIM) regional metrological organization (including Canada, Brazil, and Argentina). The first primary standardization of ^{210}Pb performed by NIST, recently reported by Laureano-Perez, *et al.* [*Applied Radiation Isotopes* 65*, 1368-1380* (2007)], led to the development and dissemination of SRM 4337. A direct measurement comparison of this SRM with a UK national ^{210}Pb standard showed very good agreement, within measurement uncertainties, using five different methods.

Several facilities in the Division, used by a variety of internal and external users from industry, government, and academia as well as international colleagues, have expanded in continued support of research efforts in industrial and medical dosimetry, homeland security, and radiation-hardness and materials-effects studies. Significant progress has been made toward the development of the High-Energy Computed Tomography imaging system (with applications in homeland security), the Clinac accelerator (which will eventually serve as a high-energy calibration laboratory based on primary dosimetry standards for radiation therapy applications), and neutron interferometry (with measurements of 100 nm vertical coherence length for a single crystal neutron interferometer *via* path separation). To minimize operator exposures and expedite the standards-transfer process, a new, automated ionization chamber has been developed to measure up to 100 radioactive samples with minimal sample handling while maintaining the high precision and reproducibility of the manual instrument; the new instrument has successfully been used to measure the half-lives of ^{82}Sr and ^{99}Tc^{m}.

This document describes some of the significant activities and accomplishments of the Neutron Interactions and Dosimetry Group in 2007 and 2008. Contact information for the primary lead on each of these projects is provided and you are invited to contact the NIST staff for more details. In addition, please visit our website (http://physics.nist.gov/ird) for more information on these and other activities in the Division.

Strategic Element: *Develop and provide neutron standards and measurements needed for worker protection, nuclear power, homeland security, and fundamental applications.*

Neutron Standards and Measurements

The Neutron Interactions and Dosimetry (NI&D) group, located at the NIST Center for Neutron Research (NCNR), maintains and supports the nation's premier fundamental neutron physics user facilities, including a weak interactions neutron physics station, Neutron Interferometry and Optics Facility (NIOF), Ultra Cold Neutron Facility (UCNF) and a ^{3}He based Neutron Polarizer development facility, and have developed the nation's only high-resolution neutron imaging user facility (NIF) for fuel cell research. We maintain, and disseminate measurement standards for neutron dosimeters, neutron survey instruments, and neutron sources, and improve neutron cross-section standards through both evaluation and experimental work.

The group is at the forefront of basic research with neutrons. Experiments involve precision measurements of symmetries and parameters of the "weak" nuclear interaction, including measurement of the lifetime of neutrons using thermal and ultra-cold neutrons, improved cold neutron counting techniques, setting a limit on the time-reversal asymmetry coefficient and radiative decay of the neutron. The neutron interferometry program provides the world's most accurate measurements of neutron coherent scattering lengths important to materials science research and modeling of the nuclear potentials; during 2007-2008, new interferometry experiments to determine the charge distribution of the neutron, and reciprocal space imaging, were being carried out. We are developing and promoting the applications of efficient neutron spin filters based on laser-polarized ^{3}He, and are pursuing applications for these filters at the NCNR, the Intense Pulsed Neutron Source at Argonne National Laboratory, and the Los Alamos Neutron Science Center.

We are developing the necessary technical infrastructure to support neutron standards for national security needs. In addition, we are developing advanced liquid scintillation neutron spectrometry techniques for characterization of neutron fields and for detection of concealed neutron sources with low false-positive rates. We are planning to organize and lead a Consultative Committee for Ionizing Radiation (CCRI) comparison of thermal neutron fluence rate measurements, characterizing four different beam qualities at the NCNR, and carry out comparisons of NIST standard neutron sources and we are leading an effort that will result in a new international evaluation of neutron cross-section standards.

We are applying neutron-imaging methods for industrial research on water transport in fuel cells and on hydrogen distribution in hydrogen storage devices. This facility has provided critical services to major automotive and fuel cell companies during 2007-2008. This is a high demand and high profile nationally recognized program.

In summary, the NI&D group provides measurement services, standards, and fundamental research in support of NIST's mission as it relates to neutron technology and neutron physics. The national interests served include industrial research and development, national defense, homeland security, higher education, electric power production, and, more specifically, neutron imaging, scientific instrument calibration and development, neutron source calibration, detection of concealed nuclear materials, radiation protection, nuclear data, and particle physics data.

Neutron Physics

Precision Measurement of Radiative Neutron Decay Branching Ratio and Energy Spectrum

Beta decay of the neutron into a proton, electron, and electron antineutrino is accompanied by the emission of a soft photon. In 2006, we reported the first observation of this radiative decay mode in the journal *Nature*. The experiment was completed at the NG-6 fundamental physics end station. Since that time, we have worked to upgrade the apparatus to enable us to make a precision measurement (~1%) of both the branching ratio and energy spectrum of the decay photons. The experiment operates by detecting electron in prompt coincidence with a photon followed by a delayed proton. A beam of cold neutrons passes through the bore of a superconducting solenoid. Decay electrons and protons are guided out of the beam by the magnetic field and detected by a silicon detector. The primary improvement is increasing the solid angle of photon detection by constructing a 12-element annular BGO detector that surrounds the decay region of the cold neutron beam (see Figure 1). This allows us to accumulate about x12 more photon events than in the first run. The photon detector has been tested and is performing well. We also have constructed a second detector consisting of bare photodiodes. This detector should allow us to lower the energy detection threshold to about 200 eV, significantly lower than the 15 keV from the first run. The upgraded apparatus went on the NG-6 beam line in summer of 2006 (see Figure 2) and is acquiring preliminary data.

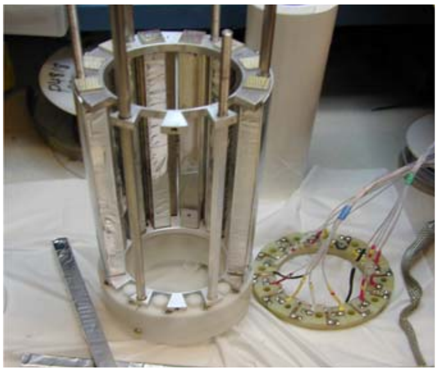

Figure 1: Photon detection is done by twelve BGO crystals viewed by avalanche photodiodes forming an annular ring around the neutron beam.

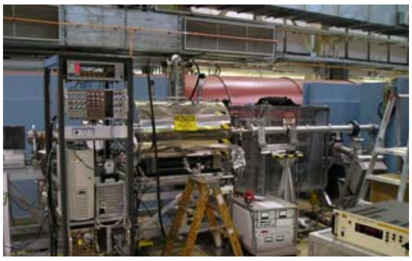

Figure 2: Photograph of the apparatus assembled on the NG-6 beam line. The superconducting solenoid is in the center and the beam line is seen entering on the right.

In the second run of this experiment, we expect to measure the radiative decay branching ratio to a 1 % total uncertainty. A new photon detector developed from a similar design to that utilized in the first run will measure the radiative decay for all photons above 10 keV to the endpoint energy of approximately 780 keV. An additional photon detector is being constructed to probe a lower photon energy regime for photon energies from approximately 200 eV to 10 keV. The radiative decay mode will be measured over nearly 4 orders of magnitude in photon energy. In addition, the photon energy spectrum over the proposed energy range will also be measured and compared to theoretical calculations. This experiment also represents an important exploration to future precision radiative decay experiments below 1 % uncertainty.

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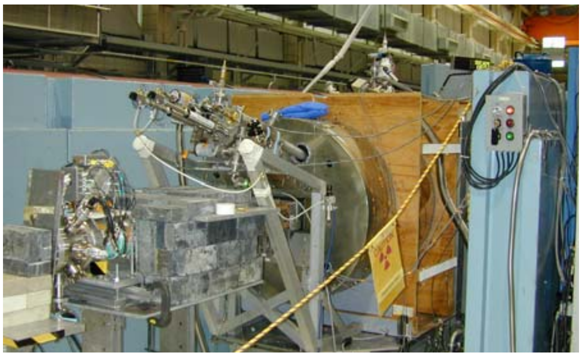
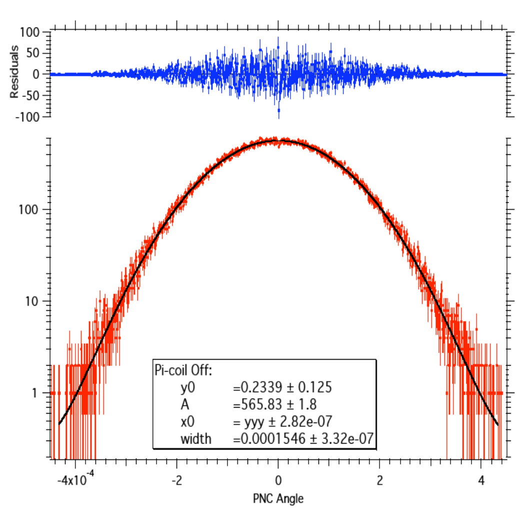
Measurement of the Parity Non-Conserving (PNC) Neutron Spin Rotation in Liquid Helium

We recently completed a successful run of an experiment to study the strong interaction using weak interaction properties of the neutron. The neutron spin-rotation experiment is based on the principle that a transversely polarized neutron beam will experience a parity-violating rotation of its polarization vector about its momentum axis in the target due to the weak interaction component of the forward scattering amplitude. To measure the small rotation, a neutron polarimeter was used in which the horizontal-component of the neutron beam polarization was measured for a neutron beam initially polarized along the vertical axis and traveling in the z direction. The challenge was to distinguish small parity-violating rotations from rotations that arise from residual magnetic fields.



Photograph of the apparatus on the NG-6 beam line. The magnetic shielding is shown surrounding the cryostat. The neutron beam exits the shielding after traversing the LHe targets and the polarization is analyzed in with the supermirror and He-3 ion chamber.

The collaboration acquired data on the rotation angle of neutrons traversing a 42-cm liquid helium target from the period of January through June of 2008. The apparatus included an adiabatic RF neutron spin flipper, input and output guides made from float glass, magnetic shielding, cryogenic targets, a data acquisition system, and a segmented He-3 ion chamber. The target was divided into four quadrants, front and back and side to side. This allows one to remove the beam fluctuations by operating two simultaneous experiments side-by-side and also to minimize the effect of magnetic field drifts by inserting between the upstream and downstream targets a magnetic pi-coil that rotates the spins by 180 degrees. The position of the targets is changed by pumping the liquid helium using a non-magnetic centrifugal pump. Data are acquired in three pi-coil states: off, +180 degree rotation, and -180 degree rotation.



Preliminary data from the experiment. Shown is a histogram of the calculated PNC angles for all the pi-coil-off sequences during running.

We acquired three reactor cycles (about 18 weeks) of data and are in the process of analyzing the data. We calculate rotation angles for each of the pi-coil and target states. The figure to the left shows a histogram of the PNC angle pi-coil off data for all the runs. One would expect the data to be distributed in a Gaussian peak centered on zero. The data are only preliminary but the pi-off data do show any anomalies at this point. We are currently studying the pi-on data for systematic effects that can producing rotations but are not a result of party-violation.

The Standard Model has been remarkably successful in describing weak interactions between leptons, leptons and hadrons, and in flavor-changing decays of hadrons. However, it has proven difficult both experimentally and theoretically to test the Standard Model with the nucleon-nucleon weak interaction. Strong and electromagnetic processes dominate at low energy so investigations are limited to parity non-conserving (PNC) observables, where weak currents must play a role. At low energies these processes are best described by an effective meson theory. Experiments measuring PNC spin rotations in low A nuclei are one of the few ways to access and test these fundamental theories. The goal of the run at NIST is a statistical precision of 3x10-7 rad/m with an anticipated 10-7 rad/m systematic uncertainty.

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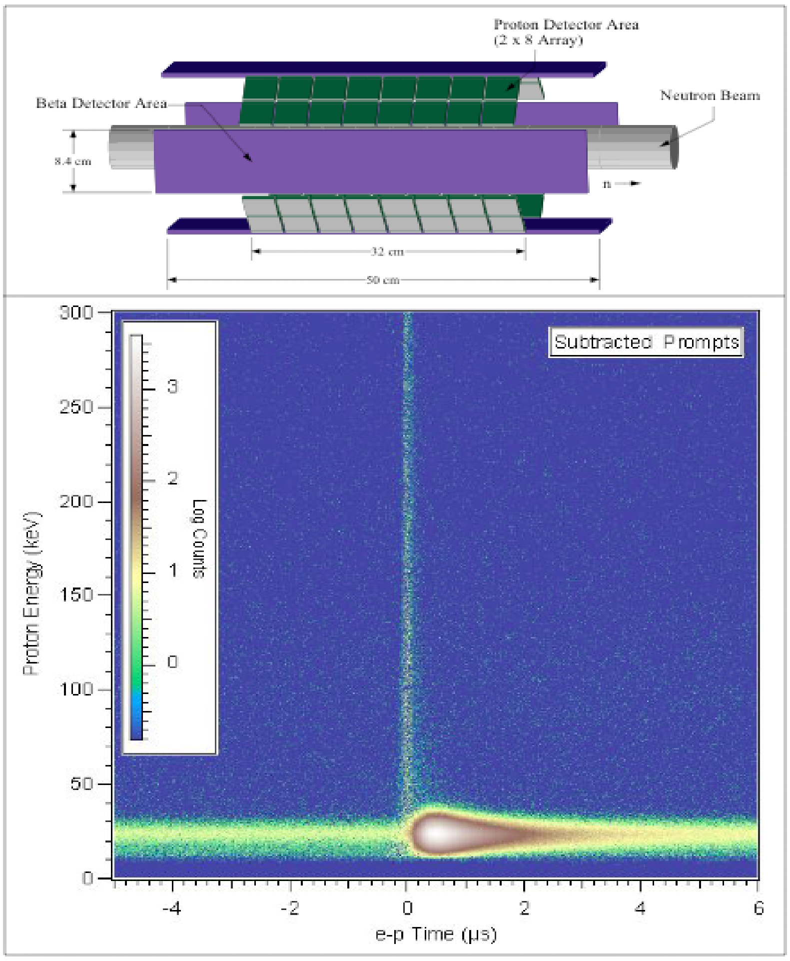
Search for Time Reversal Violation in Polarized Neutron Decay (emiT)

The “emiT” experiment searches for - or will set an improved upper bound on - the time-reversal asymmetry term in neutron beta decay. It does so by measuring electron-proton coincidence events from the decay of polarized neutrons. An asymmetry in coincidence pairs is formed as a function of the direction of the neutron spin. A measurement of a nonzero asymmetry would be an unambiguous indication of time-reversal violation.

The performance of the detector during the 2003 run is dramatically improved over its first run in 1997. The measured electron-proton coincidence rate is a factor of 10 higher than in this first run. In addition, the signal-to-background ratio is two orders of magnitude higher. These improvements were primarily due to better proton detectors, greatly reduced high voltage-induced backgrounds, and improved electronics. Since the experiment was expected to be statistics limited, the majority of the running time was devoted to reducing the statistical uncertainty on the asymmetry.



(Top) Schematic of the emiT apparatus. The beta detectors are plastic scintillator, the proton detectors consist of arrays of surface barrier diode detectors. (Bottom) Histogram of background subtracted coincidence events. The peak is due to neutron decay

Since the last run we have identified a number of systematic effects related to the acceleration and focusing of the protons that allows them to be efficiently detected. This has necessitated the development of a detailed Monte Carlo. Much of the last year has been devoted to validating this Monte Carlo and investigating a wide spectrum of possible systematic effects. Although a final systematic error budget is not yet complete, much progress has been made. Estimates of all systematic effects not related to proton detection have been shown to be smaller that the statistical sensitivity of the experiment and the Monte Carlo has been shown to perform well.

In all, the new data set is approximately 25 times larger than the 1997 run. We anticipate the completion of data analysis in FY09 with a value that is a factor of 4 better than the current limit. This result would represent the most sensitive test of T-violation in beta decay. It is well established that new sources of CP (and T) violation are required by the observed baryon asymmetry of the universe. However, CP violation has been observed so far only in the decays of neutral kaons and B mesons (recently evidence for the implied T violation in the neutral kaon system has also been reported). These effects are consistent with a phase in the Standard Model quark mixing matrix and thus do not explain the baryon asymmetry. The emiT experiment searches for new sources of CP violation whose signature would be a T-odd correlation in the decay of free neutrons.

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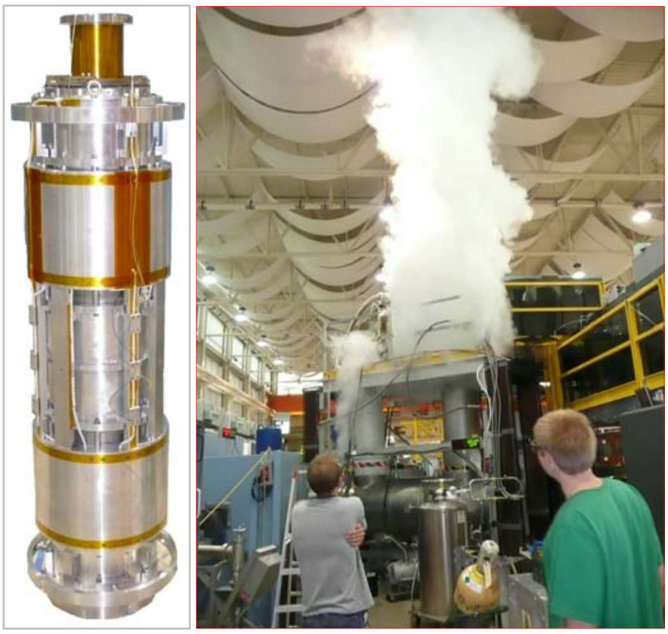
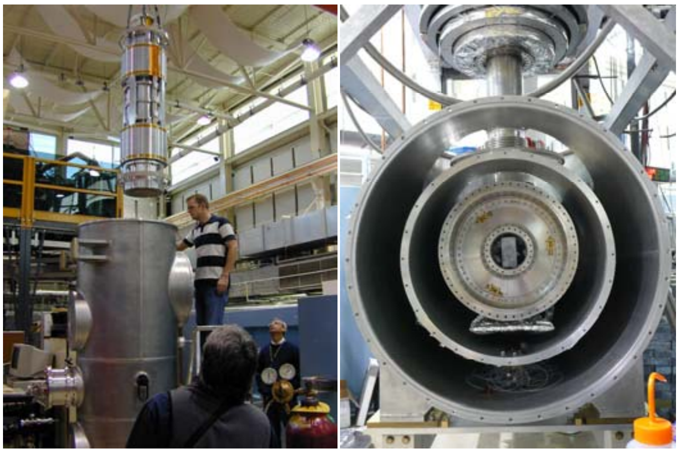
Magnetically Trapped Neutron Lifetime Experiment

This program is a collaborative effort, involving two U.S. National Laboratories (NIST and ORNL) and three universities (NC State, Harvard, and Yale). It is designed to measure the neutron beta-decay lifetime τ_n using a substantially new technique. Our method confines Ultra Cold Neutrons (UCN) within a three-dimensional magnetic trap. Cooling of the neutrons occurs within the conservative trap when 12 K neutrons (0.89 nm) down-scatter in superfluid ^{4}He to near rest via single phonon emission (superthermal production). The UCN then interact only with the magnetic field via their magnetic moment and when the spin is parallel to the magnetic field, they will seek to minimize their potential energy by moving towards low field regions. By cooling to temperatures of approximately 100 mK, the population of UCN becomes thermally detached from the helium bath allowing accumulation of UCN to a density as high as Pτ, where P is the superthermal production rate and τ is the UCN lifetime in the source. Neutron decay is detected by turning off the cold neutron beam and observing the scintillation light resulting from the beta-decay electrons. When an electron moves through liquid helium, it ionizes helium atoms along its track. These helium ions quickly recombine into metastable He^*_2 molecules. About 35 % of the initial electron energy goes into the production of extreme ultraviolet (EUV) photons from singlet decays, corresponding to approximately 22 photons/keV. These EUV photons are frequency down-converted to blue photons using the organic fluor tetraphenyl butadiene (TPB) coated onto a diffuse reflector surrounding the trapping region. This light is transported via optics to room temperature and detected by two photomultiplier tube (PMT)s operating in coincidence. This unique trapping and detection method allows us to observe neutron decay events *in situ*, and therefore directly measure the decay curve.



(Left) Ioffe type magnetic trap (Right) Successful test quench of the full magnetic trap in its final horizontal position.



(Left) Lowering the new magnetic trap into the cryostat. (Right) After installation the end view of the magnet helium bath and heat shields on the NG6-u beamline. The thermally isolated ultra-pure helium cell (with test weight) is seen suspended from three Zylon

The decay of the free neutron is the simplest nuclear beta decay and is the prototype for all charged current semi-leptonic weak interactions. The decay parameters, the neutron lifetime in particular, provide essential inputs to investigations of the weak interaction. A precise value for the neutron lifetime is required for several internal consistency tests of the SM including searches for right-handed currents and tests of the unitarity of the CKM mixing matrix. Measurements of neutron decay coefficients provide information on the vector and axial-vector coupling constants g_v and g_a. The neutron lifetime is also an essential parameter in the theory of Big Bang Nucleosynthesis.

At present, there is a 6.5 σ discrepancy between the two most precise UCN bottle experiments that is not understood. It is essential to resolve this disagreement, which can best be accomplished through measurements using systematically different techniques. As beam-type experiments are limited by measurements of the neutron flux, and material bottle experiments are complicated by wall interactions, magnetic trapping techniques offer the best possibility for both solving this discrepancy and improving the precision of the neutron lifetime.

In addition, the work performed over the course of this program has played a major role in the development and design of a number of other significant experiments, including the neutron EDM effort and CLEAN, a neutrino experiment that seeks to both directly measure the rate of pp reactions in the sun and search for dark matter events. In addition, we developed and tested new technologies, for example, a long wavelength neutron monochromator the basis of which is being used at the Spallation Neutron Source and at the ILL. We have also tested a variety of methods of detecting light at cryogenic temperatures and are pushing the development of accelerator mass spectrographic methods to measure the isotopic abundance of helium samples.

Finally as this and other neutron lifetime experiments relying on magnetic trapping move forward, one must fully understand the dynamics of neutrons in magnetic traps. Our studies of marginally trapped neutrons are helping to guide the design other experiments in the field.

We are nearing completion of the upgraded apparatus. Most systems have now been fully tested and we expect to demonstrate neutron trapping by the end of 2008. Estimates of background and increased counts rates indicate that we should reach a sensitivity of 2-3 s with approximately four cycles of data collection.

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Wide-angle neutron polarization analysis with ^{3}He spin filters

Apparatus for wide-angle polarization analysis. On the left is the conceptual design: the neutron beam (yellow) enters from the right and is polarized by a ^{3}He spin filter. This polarizer is enclosed by an electrically shielded radio frequency solenoid that will be used to invert the ^{3}He polarization (and thus the neutron polarization). After being scattered from a sample housed in the cryostat shown, two curved ^{3}He cells analyze the polarization of the widely scattered neutrons. The center photograph shows a top view of the prototype apparatus that has been tested off-line; the metal box contains the compensated RF solenoid and polarizer cell that are shown on the right.

The capabilities of many neutron scattering instruments would be greatly enhanced by neutron polarization analyzers that can cover a wide angular range. Many of these instruments do not have any polarization capability and there are space constraints for the addition of new instrumentation. We have developed a polarizer-analyzer-spin flipper system based solely on ^{3}He spin filters. The entire system is housed by a 40 cm long, 70 cm diameter end-compensated solenoid that provides a uniform magnetic field with homogeneity of better than 2 parts in 104 over the relevant region. Adiabatic fast passage (AFP) nuclear magnetic resonance (NMR) is used to flip the ^{3}He polarization in the ^{3}He polarizer, thereby inverting the polarization of the incoming neutron beam. Curved ^{3}He cells to analyze the polarization of the scattered neutrons have been constructed. The ^{3}He polarization in each cell can be monitored using free induction decay NMR. The overall system as been demonstrated off-line. Currently we are constructing an on-line apparatus that will be tested on the Multi Axis Crystal Spectrometer (MACS). Improving cell relaxation times is an ongoing effort.

Successful demonstration of wide-angle polarization analysis is the first step towards implementation for neutron scattering. This capability will greatly enhance the range and depth of both fundamental and applied studies of magnetic materials.

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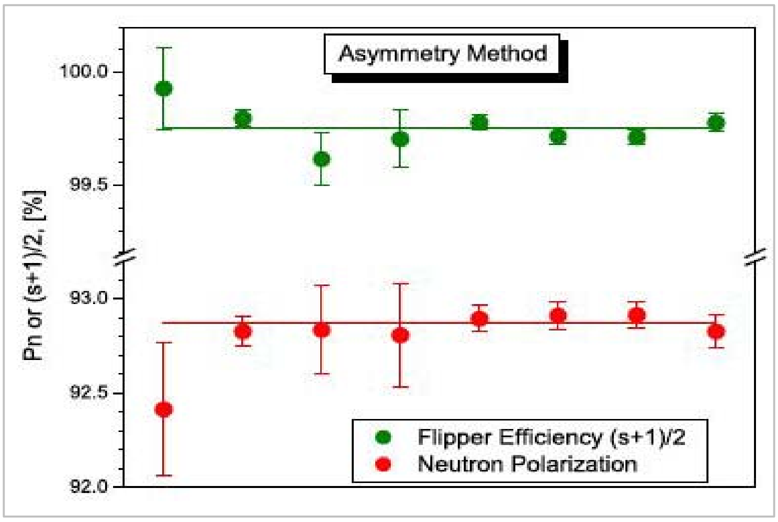
Polarized ^{3}He for neutron interferometry and neutron polarimetry



Top - precision cells that were located in the neutron interferometer (before gas filling). Bottom -Determination of the neutron polarization (Pn) and spin flip efficiency (s) to better than 0.1% using transmission measurements using a polarized ^{3}He analyzer.

As described in this section of this report, we have completed an experiment to measure the spin dependence of the scattering length for ^{3}He via neutron interferometry. The experiment was conducted using polarized ^{3}He cells, such as those shown below, that were located between the blades of the interferometer. The 2.5 cm diameter, 4.2 cm long precision cells were constructed with flat, polished windows so as to provide a uniform path length for the neutron beam. It is known that it is difficult to reliably obtain the best relaxation times with this type of construction, in which the cell is not constructed from fully blown glass. Nevertheless we were able to produce one cell with a relaxation time of 340 hours, close to the theoretical limit set by dipole-dipole relaxation. Because of the time scale of months required to obtain sufficient statistics for the desired level of precision in this experiment, and the need to polarize cells off line and transport them to the interferometer, this long lifetime proved to be of great benefit.

Polarized ^{3}He was also used for highly precise measurements of the neutron polarization, another requirement for the success of the experiment. For these measurements, the interferometer was removed and replaced by a ^{3}He cell with sufficient gas density to yield a high analyzing power. A ^{3}He spin filter's analyzing power can be determined precisely with relative transmission measurements of unpolarized neutrons. Using four measurements of the cell transmission (unpolarized neutrons for gas polarized and unpolarized, polarized neutrons for gas polarized parallel or antiparallel), we were able to determine the neutron polarization and spin flip efficiency to better than 0.1 %. The use of polarized ^{3}He allowed for the first determination of the spin dependence of then scattering length for ^{3}He by neutron interferometry. The use of ^{3}He spin filters for highly accurate measurements of neutron polarization, which can have other applications, was tested at a very precise level.

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Continuous spin-exchange optical pumping in high flux neutron beams

Most of our work to date has been with ^{3}He cells optically pumped off-line, and transported to the neutron beam line. These permits spin filters to fit into a small space, and ancillary equipment such as an oven and lasers need not be installed in the tight space constraints of many neutron scattering instruments. However, we aim to optically pump continuously on beam lines where possible. For most fundamental neutron physics applications, continuous operation is a necessity due to the long time scale required for these experiments and the need for a stable polarization.

"Double cell" for continuous optical pumping in high flux beams. The spherical volume is maintained at ~200 C and illuminated with laser light for optical pumping, and only the flat-windowed, spin filter cell is in the neutron beam

We recently collaborated on an experiment at the Los Alamos Neutron Science Center (LANSCE) in which a ^{3}He polarizer was operated continuously a year. It was observed that the neutron beam caused both short term and long term effects on the ^{3}He polarization. The short term loss is due to increased relaxation of the optically pumped alkali metal used in spin-exchange optical pumping (SEOP), while the long term effect is due to a beam-induced deposit inside the cell that decreases the transmission of laser light. Since the neutron flux at LANSCE is relatively low, we collaborated on a test run on a high flux beam line at the Institut Laue-Langevin.

The results allowed the magnitude of the effects and their scaling with flux to be quantified, but also raised new questions that will be addressed in continuing studies. In parallel, we are developing "double cells", which can potentially bypass this issue by separating the optical pumping volume from the spin filter volume. Such cells have other advantages for continuous pumping, but also present greater demands on the laser power required for maximum polarization. We are currently studying what is achievable.

Neutron beam effects on SEOP will be understood and addressed, allowing the advantages of ^{3}He spin filters to be exploited for high flux experiments at the NCNR and other US and overseas laboratories. New cell approaches that will be useful for the general goal of continuous optical pumping will be developed.

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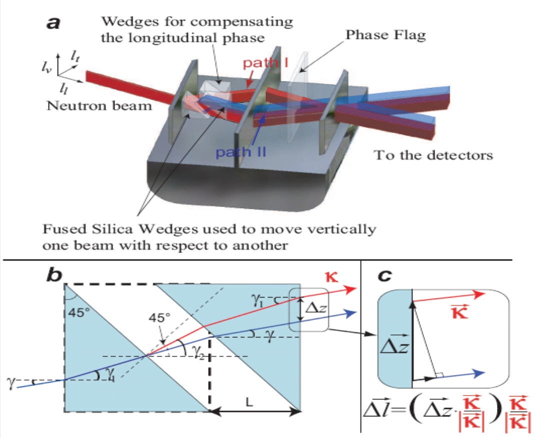
Measurements of the vertical coherence length of a neutron interferometer setup at NIST



Schematic of the coherence length experiment.

We report the measurement of about 100 nm vertical coherence length for a single crystal neutron interferometer. We introduce a path separation via a pair of prisms placed in the legs of interferometer and measure the loss in contrast as this separation is increased. We show that the measured coherence length is consistent with the experimental distribution of the incoming neutron beam momentum in the vertical direction. Finally, we demonstrate that the loss in contrast with beam displacement in one leg of the interferometer can be recovered by introducing a corresponding displacement in the second leg of the interferometer. The schematic of the coherence length experiment is shown at left; a neutron beam, entering at left, is coherently divided via Bragg diffraction on the 1st blade of the neutron interferometer into two paths (paths I and II). The phases which neutron accumulates over each path are experimentally controlled by rotating the phase flag. In one of the paths we install two 45° prisms, which at 0 distance separation form a cube. By separating the prisms we shift the neutron beams in path I and II vertically with respect to each other. We observe a loss in contrast with displacement, which we measure with the help of phase shifter (shown on the figure) and neutron detectors behind interferometer. **b**: A schematic diagram of the neutron paths through the prisms. The neutron beam enters from the left and depending on the separation between the prisms is shifted vertically. The angles shown on the figure correspond to the calculations for path separation and phase shifts of the neutron described in the text. **c**: Zoom in on the neutron beam as it exits the prism.

Neutron interferometer is a practical example of macroscopic quantum coherence. We will describe this via neutron wave-function over the Mach-Zehnder interferometer. At the1st blade the neutrons are split by Bragg scattering into two paths. The neutron wave-function is |path; p>, where neutron with momentum p is spanned path I and path II (shown in “a”). The phase which the neutron accumulates over each path is experimentally controlled via rotation of the phase flag. The wave-function of a neutron over the interferometer will then be

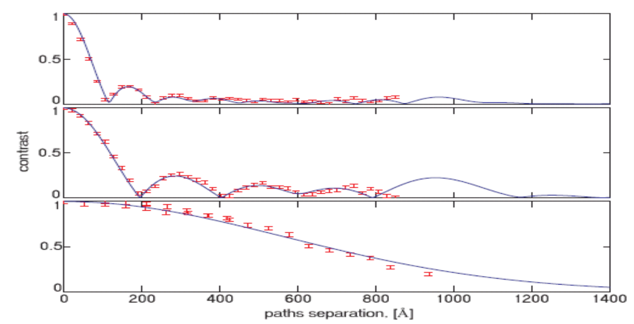
$$\Psi = e^{ikr}e^{i\varphi_1}C_1\left|I\right\rangle + e^{ik(r+\Delta z)}e^{i\varphi_2}C_2\left|II\right\rangle,$$

where φ_1 and φ_2 are the phases over path I and path II in the absence of the prisms. The coefficients C_1 and C_2 are parameters of the neutron interferometer which account for the attenuation and scattering losses of the neutron beam. The measured contrast originates from the constructive interference of the two paths. For an incoherent sum of plane waves, then intensity on the detector is,

$$I_0(\varphi_0) = \int \rho(k_z)\left(A + C_1C_2\cos(\varphi_0 + k_z\Delta z)\right)dk_z,$$

where ρ(kz) is the neutron vertical momentum distribution and $A = 1/2\left(C_1^2 + C_2^2\right)$. The contrast is contained in the second term of the integral and the loss of a contrast is a result of averaging over a momentum distribution.

The figure below shows contrast variation as a function of momentum distribution of the beam. As expected the contrast length increases as we narrow the momentum distribution of the incoming neutron beam. Notice that in the narrowest case the contrast remains up to 1000 Å in the vertical separation of the paths. Here we also show with straight lines contrast curves obtained by approximating the wave-function of the neutrons as a plane wave and integrating over the vertical momentum distribution.



Contrast plots for three different vertical beam divergences. In each subplot data are shown with closed circles. The lines are contrast curves derived as a sum of plane waves using the vertical momentum distribution (k_z) measures independently with a help of position sensitive detector. The beam profiles data is very closely described by sum of plane waves with measured and approximated vertical beam distributions.

We have measured the vertical coherence function of a single crystal neutron interferometer via path separation and for different vertical beam distributions. We extended this measurement to 1000 Å. Having a single crystal neutron interferometer with a long coherence length provides new opportunities for experiments such as Fourier Spectroscopy and coherence scattering over scales that are not easily accessible by other approaches.

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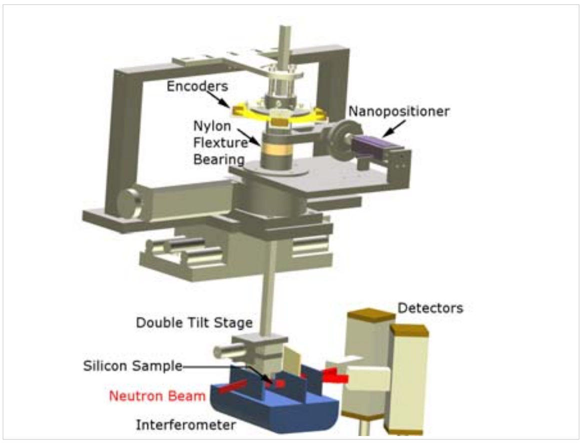
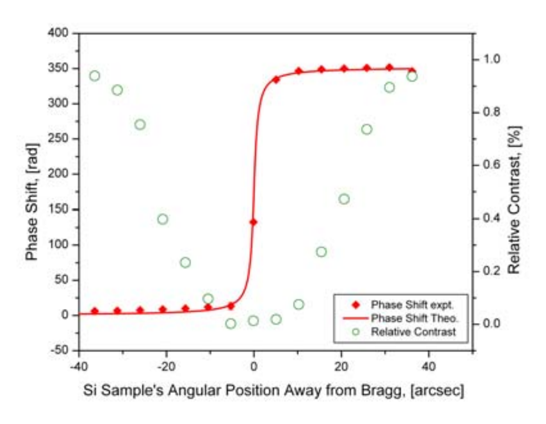
Measurement of the neutron charge radius

The neutron is electrically neutral, but being composed of charged quarks it has an internal charge structure. There exists a large program in nuclear physics devoted to understanding the substructure of the proton and neutron. The neutron charge radius $\langle r_n^2 \rangle$ represents a spherically symmetric charge distribution inside the neutr on and so a successful measurement of $\langle r_n^2 \rangle$ would provide insight into the quark distribution of the neutron. The neutron charge radius is directly proportional to the neutron-electron scattering length b_e and a series of known constants. Using dynamical diffraction techniques we can measure the neutron-electron scattering length and hence $\langle r_n^2 \rangle$ to 0.3 % relative uncertainty.



Schematic of the experimental setup



Phase plot showing rapid change in dynamic phase near Bragg orientation of the sample

A Laue-Laue-Laue type interferometer is used to measure the dynamical phase shift of a neutron as it diffracts from a perfect silicon crystal sample near the Bragg angle θ_B. A neutron entering a material at an angle θ near the Bragg angle experiences a complicated dynamical phase shift ϕ'_{sam} that is valid for angles within the Darwin width of the reflection which is only a few arcsecs.The strength of this interaction is represented by the nuclear scattering length b_n. The factor $\Delta_{0,H}$ is called the Pendellösung length. Where as Δ_0 is directly proportional to the nuclear scattering length of the material, Δ_H contains a small contribution from the neutron-electron interaction. Namely,

$$\Delta_H = \frac{N\lambda^2}{\pi}[b_n + 14(1-f)b_e]$$

where f is known form factor. The neutron-electron scattering length is smaller than that of b_n by a factor of 1000. Measuring the phase shift near and away from the Bragg angle we can extract the neutron-electron scattering length (shown in the phase plot to the left).

Experiments done in the last thirty years to measure $\langle r_n^2 \rangle$ have mainly measured the total transmission of neutrons through dense materials like lead, bismuth, and xenon with typical precision of a few percent. In general these experiments do not agree within standard uncertainties of each other. This experiment using neutron interferometry to measure the $\langle r_n^2 \rangle$ has inherently different systematic uncertainties from transmission methods and will help resolve this discrepancy. Since phase shifts can be measured precisely using neutron interferometry our value should also be a tenfold improvement of the current world average of $\langle r_n^2 \rangle = (-0.1161 \pm 0.0022)$ fm.

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Precision measurement of the neutron - ^{3}He incoherent scattering length

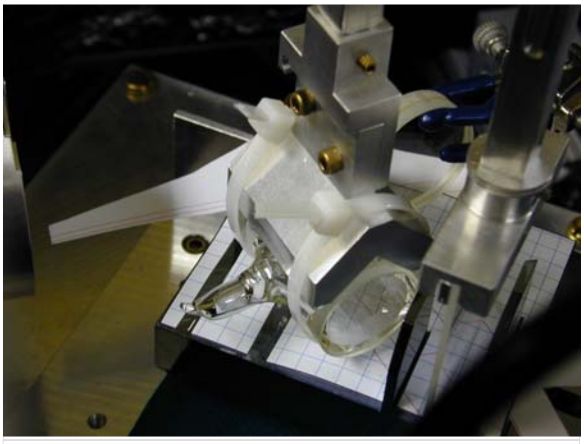

Figure 1: The He-3 cell inside the interferometer

The Neutron Interferometer and Optics Facility performed a precision measurement of the n-^{3}He incoherent scattering length. Quantum chromodynamics describing the strong interaction between quarks is non-perturbative making rigorous direct calculations at low energies impossible. Instead complex, multi-parameter phenomenological models have been developed to tackle nucleon-nucleon (NN) interactions. In systems with more than two nucleons poorly understood three nucleon (3N) interactions must be included with NN models to match the experimental data on binding energies which is known to great precision. Neutron scattering lengths, which describe a neutron's s-wave interaction with a target nucleus, are predicted by NN+3N models, and therefore provide crucial benchmarks in the testing of various theoretical approaches. Neutron scattering lengths of light nuclei also play an important role in effective field theories (EFT) since EFTs' use low-energy observables to constrain mean-field behavior. This experiment used neutron interferometry to determine the spin-dependent incoherent scattering length b_i of n-^{3}He, and was the first neutron interferometric experiment to use a polarized gas sample.

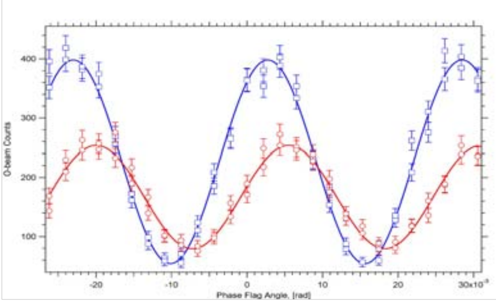

Figure 2: Graph of with samle cell in (red) and out (blue) of the beam

Neutrons were polarized to P_n=93% using a transmission-mode supermirror. The neutron spin state could be flipped 180° with a precession coil. The neutron polarization was measured periodically during the experiment by replacing the interferometer with an optically thick ^{3}He cell which provided analyzing powers of up to 99%. Two different techniques were used to measure P_n and the spin flipper efficiency s to 0.04% relative uncertainty.

This experiment used a target cell filled with ^{3}He gas (see figure 1) placed in one path of the interferometer (see figure 2). The NIST glass shop fabricated four boron-free glass target cells. Each cylindrical cell had outer dimensions of 25.4 mm diameter x 42 mm and was sealed with approximately 2 bar of ^{3}He gas. The ^{3}He gas was polarized in two days to an initial polarization of P_{3He} = 65% using spin exchange optical pumping techniques at a separate facility. The cell was transferred to the interferometer using a portable battery power solenoid with typical transport loss in P_{3He} of only a few percent. The largest cell lifetime at the interferometer, which had non-ideal magnetic field gradients, was 115 h.

We measured b_i= (-2.417 ± 0.012 (statistical ± 0.014 (systematic)) fm which is in 2σ disagreement with the one previous measurement of b_i, where σ is the standard uncertainty. This result and the previous one are systematically limited by the small but nonzero triplet absorption cross section of ^{3}He known only to one percent. Known NN+3N models do not match the current data on coherent and incoherent scattering lengths (including this work) for n-^{3}He by several σ showing the need for greater theoretical work.

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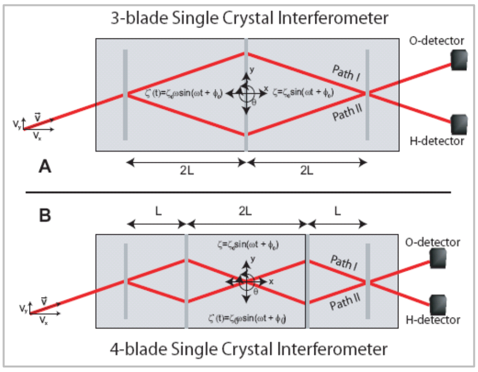
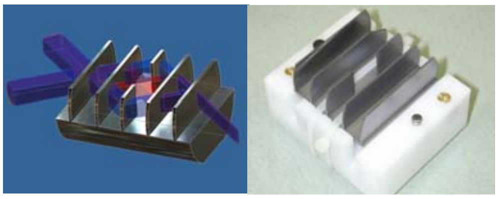
Use of quantum error coding in a 4-blade neutron interferometer

Single crystal neutron interferometers are extremely sensitive to environmental noise, including vibrations. Sensitivity is a result of 1) many wavelengths combined in interferometer, 2) slow velocities of neutrons, 3) long measurements times. Most neutron interferometers require vibration isolation, which is usually a big and massive system (especially for low frequency vibrations). We have designed a type of neutron interferometer, which will be less sensitive to slow vibrations. Not only will this design improve the interferometer contrast but it will also make it easier to adopt the use of it in many systems.





A schematic diagram of the proposed interferometer with 4 blades.

The figure at left shows a schematic diagram of a “standard” (LLL-type) 3-blade interferometer (A) and the proposed 4 blade interferometer (B). A neutron beam (with neutron velocity **v**) comes from the left, is split by the first blade, is diffracted on the second blade, and recombines at the third. After passing through the interferometer, the beam is captured by the O and H detectors. We model vibrations as oscillations of/around the center of mass of the interferometer, as $\zeta(t)=\zeta_0\sin(\omega t+\varphi_0)$, where ζ could be y - transverse vibrations, x - longitudinal, and θ -rotation. From the simulations we can conclude that the new proposed (4 blade) setup is less sensitive to the environmental disturbances. Thus we would like to cut the test 4 blade interferometer for 2.35 A wavelength and test it at the NIST NIOF facilities at different vibration environments.

In order to compare both types of interferometers (3-blade and 4-blade), we designed a new 5 blade interferometer, where by blocking some neutron path, we can realize both cases. In this case we the contrast of both should not depend on the quality of different crystals and different mechanical and chemical polishing.

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Measurements of the neutron magnetic dipole moment (MDM) using Schwinger scattering.

This experiment will measure Schwinger scattering in silicon. Previous attempts done by Shull and others did not produce the expected results. The successful realization of Schwinger scattering experiment in Si will give the value of the neutron magnetic dipole moment.

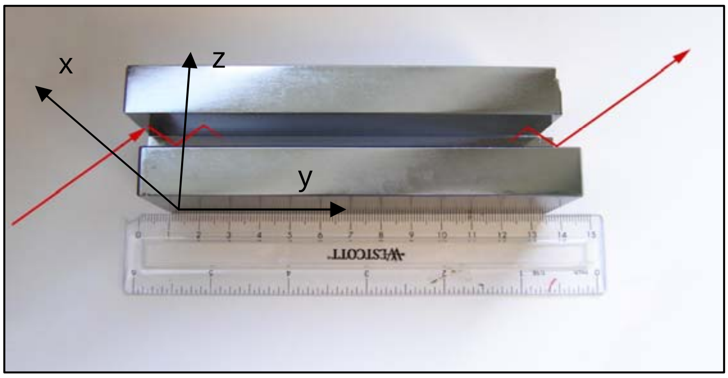

Figure 1: The crystal for the MDM experiment

Schwinger scattering is caused by the interaction between the neutron’s magnetic dipole moment (MDM) and the atomic electric field silicon crystal. The atomic electric field of the silicon induces a tiny magnetic field in the rest frame of the moving neutron which rotates the neutron polarization by a very small angle (about 3.2×10^{-4} radians). To magnify this rotation a neutron beam is Bragg reflected down a narrow slot cut from perfect silicon. At each of consecutive reflection a magnetic field will rotate of the neutron polarization by $\pi/2$ in order for the Schwinger scattering effect to accumulate. For 135 successive reflections off of the (220)-planes of our crystal a 3.84 Å neutron will produce a total rotation of 0.043 radians.

Figure 1 shows the slotted Si crystal for the experiment. Here the (220)-planes of the Si oriented perpendicular to the z-axis. The slot is aligned with y-axis and x-axis is the vertical direction. A constant magnetic field directed along z-axis is provided by four coils is. Additional coils in the y and z directions null any external magnetic fields. The neutron polarization is adjusted in such way so it will be along y-axis when the neutron hits the Si crystal. Schwinger interaction will rotate the neutron polarization around x-axis creating measured neutron polarization along z-axis. A schematic of Schwinger setup can be seen in Figure 2. A supermirror polarizer polarizes monochromatic neutron beam which can be flipped by an RF flipper. The neutron polarization is analyzed by a Heusler crystal at the end of the experimental apparatus.

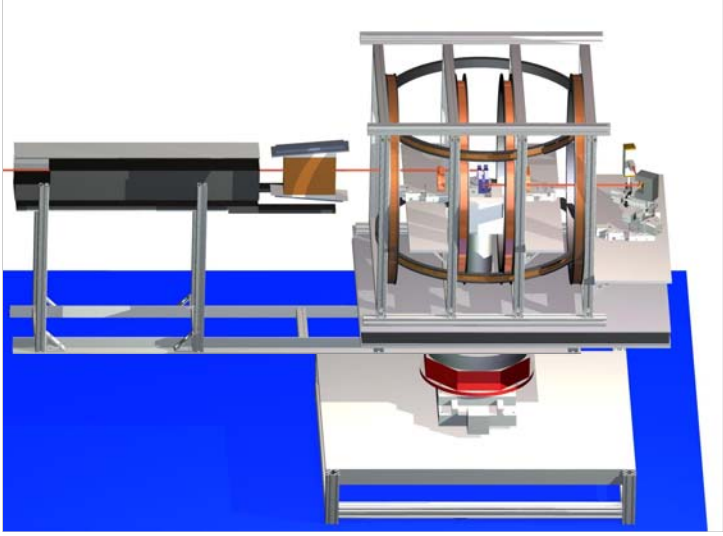

Figure 2: A schematic of the experiment. Four vertical coils provide a constant low gradient field around the crystal region.

A successful Schwinger scattering experiment provides "proof of principle" for measuring of the neutron electric dipole moment (EDM) using a similar technique. This technique is completely different from standard neutron EDM experiments which use UCN in high magnetic fields thus providing a different prospective on systematic errors of EDM experiments.

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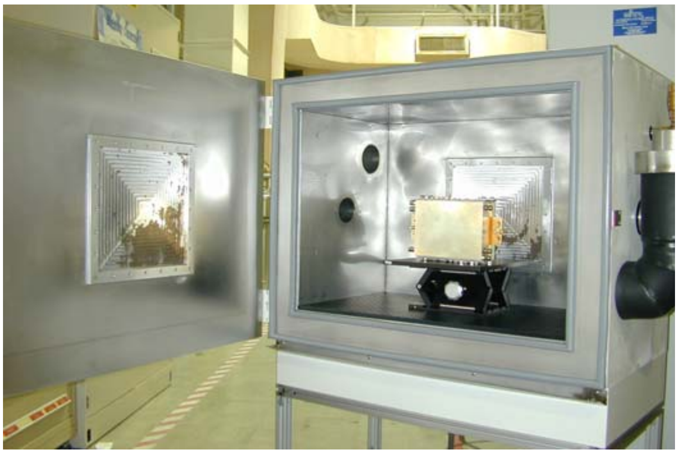
Neutron Imaging

Advanced Neutron Imaging Facility

Freeze chamber installed inside BT2.

The NIST Neutron Imaging Facility (NNIF) at the NIST Center for Neutron Research (NCNR) is one of the most advanced neutron imaging facilities in the world and it is the best of its kind in the USA. The facility is a national user facility that provides extensive infrastructure for performing fuel cell experiments as well as world class neutron radiography facilities to groups from industry, national laboratories and universities. These groups compete for beam time through a competitive external peer review process. Since the facility became operational in 2006 there have been several notable improvements and accomplishments. These include: Incorporation of large environmental chamber into facility for in situ neutron radiography of cold startups and freeze-thaw testing, stack stimulation with a single cell, development of advanced neutron imaging equipment and techniques, development of 25 micrometer resolution as a standard capability for testing with fuel cells, 30 % improvement in spatial resolution demonstrated with prototype 10 micrometer detector system and increased neutron intensity by a factor of two by optimizing the single crystal bismuth fast neutron and gamma filter.

In 2007, 18 groups using the facility, nearly doubled the use of the facility by fuel cell research group. In 2008, 7 new research groups are involved with using the facility for a total of 25 groups.



Sample chamber with 100 cm^2 cell inside. Windows on front and back are for neutron transmission.

The topics being studied at the facility have expanded significantly. The facility uses cover a diverse set of topics that include the following: Fuel Cells, Hydrogen Storage Beds, Biology, Geology, and Heat Pipes, Industrial proprietary and Neutron Imaging Methods and Devices Development

On average facility users spend five days to setup and carry out experiments at the facility. The facility staff train, assists and collaborate scientifically with the users providing all the needed assistance and expertise to utilize the neutron radiography technique effectively in their research. Facility users are trained in radiation safety as well as using software written by NNIF scientists for analyzing image data. Users of the facility have access as well to dedicated expert technicians to setup and assemble mechanical equipment used in experiments. There have been over 40 published peer reviewed journal articles and/or conference presentations on the research performed at the facility in the last two years so far.

This facility allows industrial/academic researchers to study systems using the most advanced neutron radiography capabilities. This is the only facility of its kind in the world with this level of support for studying fuel cells with neutron radiography.

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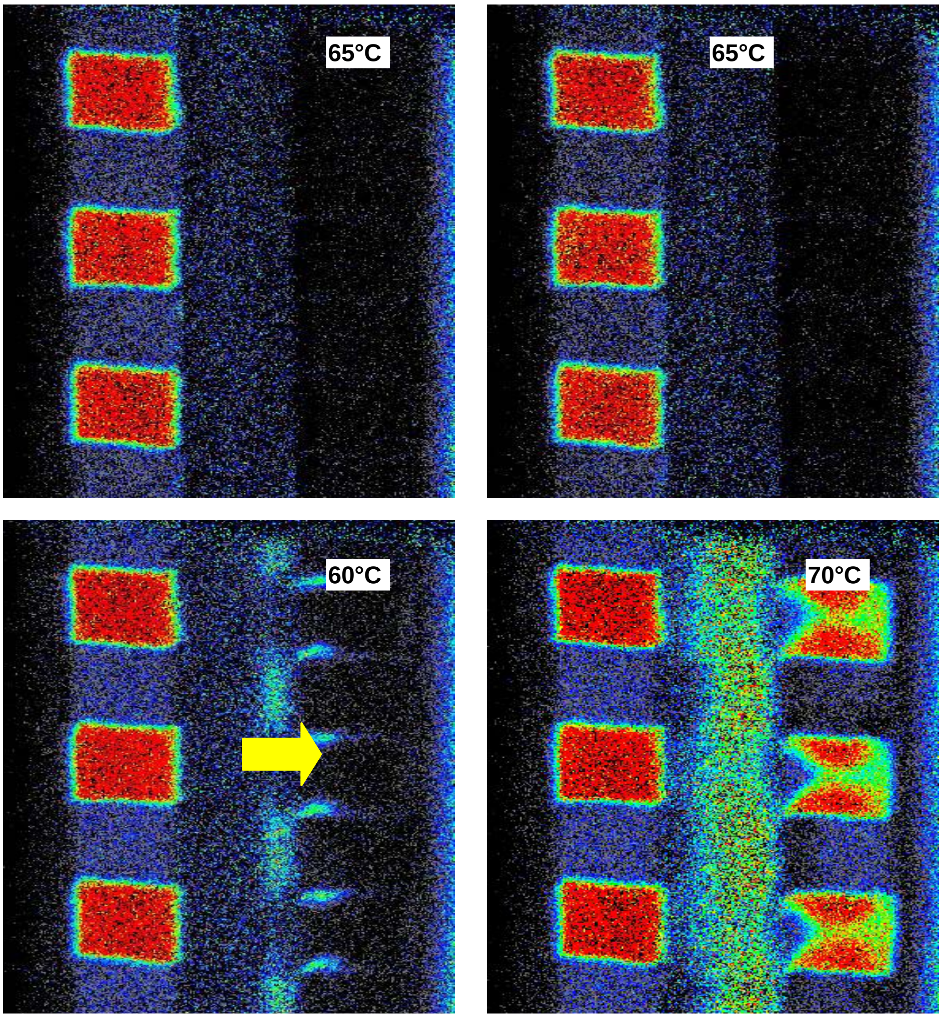
Driving water transport in fuel cells with temperature gradients

Removing water from fuel cells is critical during winter when temperatures are below freezing. To do this energy must be pumped in to the fuel cell by forced air advection of water from the flow fields of a fuel cell. This process can be complicated by the use of structured hydrophobic parts that prevent the transport of water in a fuel cell.



High resolution images demonstrate the effectiveness of temperature driven flow to overcome barriers to water transport in fuel cell designs. Top images are side view of fuel cell at a constant temperature. Bottom images show transport of water when the two sides are maintained at a different temperature.

To assist and overcome resistances to water transport two temperature driven mechanisms have been proposed and studied by researchers from Pennsylvania State University. The two mechanisms are thermo-osmosis and phase-change flow (also known as the heat pipe effect). Thermo-osmosis involves colder water being driven by osmosis to hotter reservoir. However, for the heat pipe effect transport occurs as hot vapor is transported away to condense on a colder part of the fuel cell. The researchers from Penn. State showed separately that the thermo-osmosis effect only contributed weakly to the transport of water when purging fuel cells. However, using the 25 micrometer capability of the NNIF, they were able to demonstrate that the heat pipe effect is a much more effective means to transport water in the fuel cell.

Neutron imaging proved that the heat pipe effect could be used to overcome hydrophobic barriers to water transport in the fuel cell. This means that purging the cell is more effective when colder gases are used to advectively remove water from the cell. These measurements will aid in the design of more energy efficient water purging techniques in automotive fuel cells that will improve durability and lifetime in sub-zero climates.

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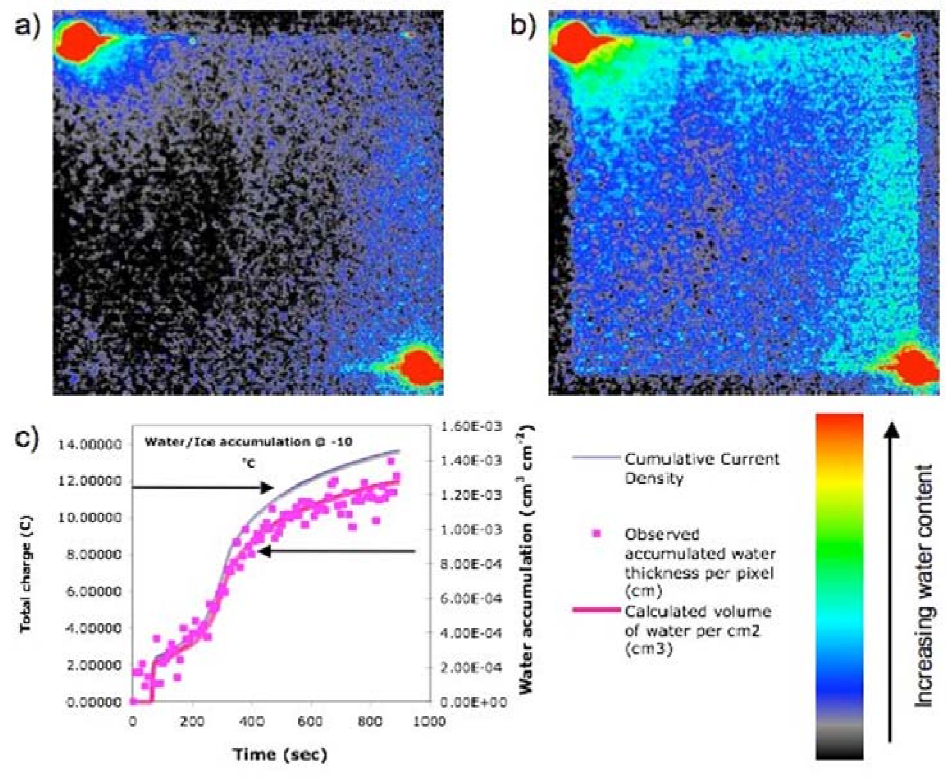
Fuel cell water management below the freezing point

A freeze chamber installed in the NIST neutron imaging beam line provides academic and industrial researchers with the world's only neutron imaging facility of realtime freeze effects in hydrogen fuel cells. Building hydrogen fuel cell powered vehicles that operate reliably in arctic climates requires a good understanding of how to remove water from the fuel cell during shutdown and startup. Residual water trapped in the cell can cause damage to the fuel cell as the water freezes. The volume expansion of the ice formed can result in irreversible damage to the catalyst layer, such as delamination from the membrane. In order to assess water removal strategies, such as purging the cell with dry gas, it is necessary to measure the water content before and after a purge using neutron radiography. When starting up the fuel cell at temperatures below 0 °C, the water formed will freeze in the fuel cell gas flow paths causing the cell to shutdown.



Measurement of the water content as a PEMFC is operated at -10 °C until failure. Comparing the initial image (a) to one near the cell shutdown (b), it is seen that the product water does not escape into the gas channels, but is frozen inside the GDL, catalyst layer or membrane. Eventually, enough of the pores are clogged with water and oxygen can no longer reach the catalyst layer and the fuel cell stops producing current. (c) The measured water from neutron radiography indicates that all the product water (calculated from the generated current) is frozen inside the cell. Data ration with LANL.

To study these effects and design optimal hardware and strategies to mitigate their impacts users are able to measure the water content while the freeze chamber maintains the temperature of the fuel cell as cold as -40 °C. The freeze chamber can accommodate commercial scale fuel cells, as well as a high resolution imaging detector. Collaborative efforts between NIST and Los Alamos National Laboratory (LANL) and between NIST and General Motors Fuel Cell Activities are focused on developing a greater understanding of this problem. In the initial experiments with LANL it was shown that when operating the fuel cell at -10 °C, all of the product was frozen in the cell, and eventually resulted in cell failure. Recent experiments have used high resolution neutron imaging to study where the ice forms in the fuel cell sandwich. Work with GMFCA has focused on optimizing the gas purge sequence to remove enough liquid water from the GDL and membrane so as to enable efficient fuel cell start up at freezing temperatures. Optimizing strategies for proper water removal from a fuel cell at temperatures below 0°C will increase product durability and performance.

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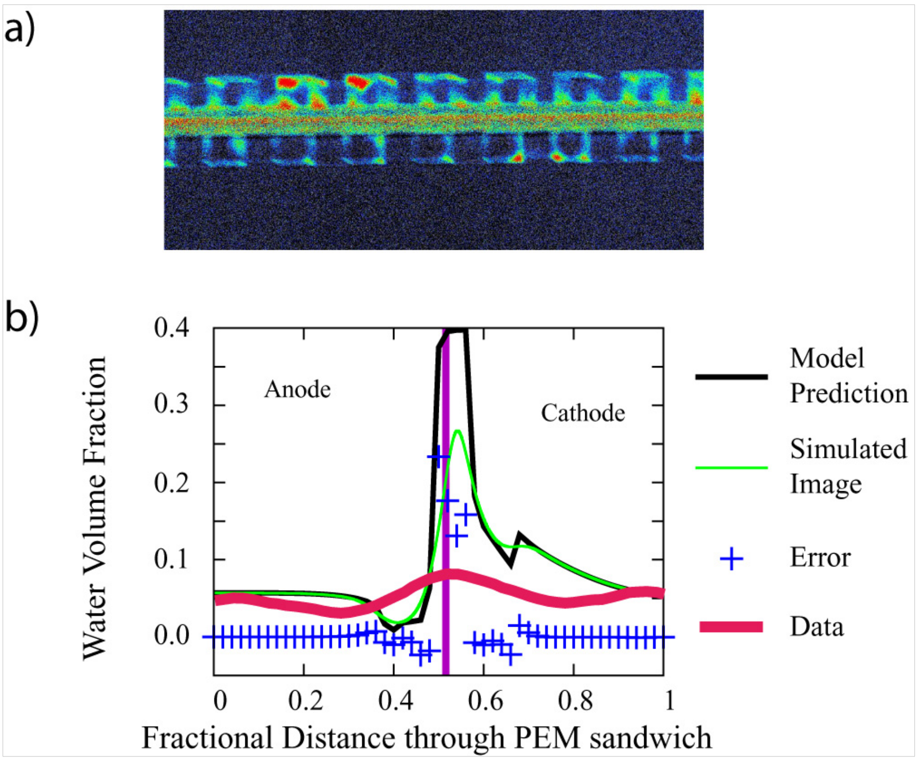
Understanding the through-plane water content of an operating fuel cell

High resolution neutron radiography provides much needed input on the "through-plane" water content in proton exchange membrane fuel cells. Although great advances have been made in engineering fuel cells for use in consumer applications much of the fundamental understanding of water transport in the cell is based on unvalidated computer models. Models of the water content in a PEMFC guide material scientists in fine tuning fuel cell component properties, such as gas diffusion layer pore diameter and hydrophobicity, to facilitate water management, and thereby increase fuel cell performance. To validate these models with neutron radiography it is necessary to have spatial resolution of order 25 micrometers or less, which is an order of magnitude greater that what has been available to date. Using newly developed high resolution neutron radiography, the through-plane water content of a small scale PEMFCs can be directly measured at the NIST neutron imaging facility. A wide range of measurements have been compared to simple one- and two- dimensional models of the steady-state water content.



a) High resolution neutron image of water viewed edge on. b) Comparison of the measured, modeled, and simulation of the measured water content of a fuel cell operating at 60 °C and 0.75 A cm^{-2}. The model over predicts the membrane water content by about a factor of four, even when the instrumental resolution is considered

One initial result of this comparison is that there is a large discrepancy in the membrane water content, with the model predicting significantly more water than is measured. We have performed a second calibration procedure, based the known water uptake by a membrane exposed to humidified gas. The initial results demonstrate that there is a systematic effect of measuring less water than is actually present due to the finite image resolution. This image resolution can be used to simulate neutron images for a given model prediction of the through-plane water content to estimate the size of the potential systematic error. Doing so, we have shown that this instrumental broadening does not account for the full discrepancy.

There is an ongoing effort with Lawrence Berkeley National Laboratory and Los Alamos National Laboratory to make fundamental measurements of the water transport and proton conductivity *in situ* to provide better input data to the current model. Understanding the dominant fundamental mechanisms of the through-plane water transport in PEMFC will allow researchers to optimize the porous media properties of the gas diffusion layer and catalyst layer in order to improve PEMFC performance and reduce PEMFC production costs. Institutions / people:

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Neutron Computed Tomography of Organic Inclusions in Carbonate Rocks

The 3D distribution of organic inclusions in carbonate rocks can reflect the original growth morphology of ancient microbial communities when the rocks are well preserved (e.g. Sumner, 1997). However, characterizing their distribution is difficult without destroying the sample. Early results from neutron computed tomography demonstrate that there is a difference in attenuation between some organic inclusions, which contain hydrogen, and the hosts carbonate minerals, which have a moderately low linear attenuation coefficient (0.35 cm-1 for calcite). The scientific goal of neutron computed tomography of ancient rocks is to use the images to reconstruct the morphology of ancient microbial communities preserved in these rocks. However, a number of noise and resolution issues need to be addressed with imaging and data processing techniques.

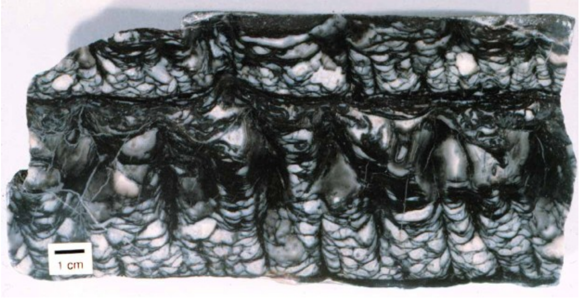

Figure 1: Ancient microbial structures. Black areas consist of organic inclusions encased in calcite crystals. White areas lack organic inclusions. The structures grew from the bottom to the top of the image.

The imaged samples are 2.52 billion years old and come from the Gamohaan Formation, South Africa. They contain the remnants of complex microbial communities in the form of organic inclusions encased in calcite with trace dolomite, quartz, pyrite, fluorite and hematite (Fig. 1). The morphology of the structures in the rocks reflects the growth behavior of the component microbial communities (Sumner, 1997; 2000). In the five cores imaged using the NIST neutron tomography system, the contrast between the mineral matrix and organic inclusions varied among samples, correlating with the extent of preservation of organics in the sample. The samples with less evidence of organic decay (and associated hydrogen loss) had higher contrast and microbial structures are more apparent (Fig. 2). The largest structures are clearly visible in the reconstructed volumes, and with careful visualization, some of the finer microbial textures are schematically present.

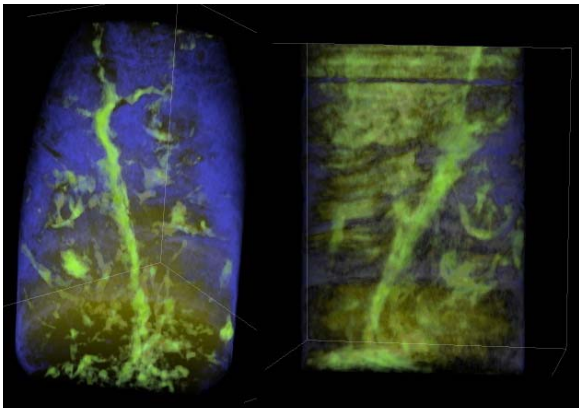

Figure 2: Neutron computed tomography image of ancient microbial structures like those shown in Figure 1. Concentrations of organic inclusions are rendered in green, and calcite lacking inclusions is rendered in blue. The samples are 2.5 cm across and the microbial structures grew from the bottom to the top of the images. The lowest part of each sample has a texture like the bottom of the sample in Figure 1, transitioning upward into areas with denser inclusions. The strong green feature that is oriented somewhat vertically represents the core of one of the cone-shaped structures in the middle of the sample in Figure 1. Hints of the laminae draping over the cone are visible in the neutron image on the right. Dish-shaped structures, which define the edges of white areas in Figure 1, are visible in places in both neutron images. It is unclear why only some are visible. Serial sectioning on the samples imaged with neutrons may provide insights into how the neutron images can be interpreted in terms of microbial growth structures.

Two approaches will improve data quality. First, better reconstruction techniques, tailored to each sample, will reduce noise. Specifically, bad pixels and individual high or low responses can be identified individually in images and replaced with average values to reduce ring artifacts and streaking. This process has been started for the highest quality data set. Second, successive slices need to be better calibrated. The heterogeneity in the samples affects the average attenuation in different slices. Some of these variations can be normalized during data processing. However, a better approach would be to image a standard with two uniform attenuations that spans all slices when imaging each microbial sample. This standard could be used to scale the attenuation of each slice to the appropriate range in values. Such calibration will be very helpful for low contrast, variable samples such as these natural rocks.

Overall, the neutron computed tomography images obtained at NIST in 2008 are the best obtained to date. They provide significant information on the 3D morphology of the ancient microbial communities in a non-destructive manner. Results have much lower resolution than volumes created by serially slicing the rock, but this process is labor intensive and destroys the samples. Results are substantially better than X-ray computed tomography, which is ineffective for these samples because the density differences are very small. Thus, results obtained at NCNR are a significant step toward both developing neutron computed tomography for imaging organic inclusions in rocks and developing techniques for studying the morphology of ancient microbial structures. Research was carried out by Dawn Sumner from UC-Davis at the BT-2 neutron imaging station.

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Phase gradient imaging with gratings

We have developed and tested a new phase imaging technique that will be incorporated into a cold neutron imaging facility as part of the NIST Center for Neutron Research expansion initiative. Traditional radiographic imaging relies on absorption of neutrons to produce contrast in radiographs of the object being studied. Phase imaging relies on small changes in the phase of the unattenuated neutron wave to achieve phase contrast. Small changes in material thickness or density can result in more significant phase contrast than absorption contrast in some materials. This means that phase imaging is more sensitive to changes in material density than transmission imaging. In the case of neutron phase imaging, this enhancement can be up to 1000 times. Previous work at NIST utilized small pinhole apertures to produce phase contrast, but the reduced beam intensity resulted in exposure times as long as a day. Recently, it has been demonstrated that by using a grating line source, rather than a pinhole, one can create an intense neutron beam with high transverse coherence in one-dimension that allows rapid acquisition of differential phase contrast images. The method uses the Talbot effect, where one illuminates a phase-modulating grating with monochromatic plane waves, to measure the neutron wave phase gradient along the coherent direction. The phase gradient is directly is proportional to the gradient in the number density of the object.

In a collaborative effort between NIST and the Korean Atomic Energy Research Institute, we have fabricated high quality gratings at the NIST Nanofabrication facility and developed a prototype imaging instrument have to study this technique for a new cold neutron imaging facility to be built as part of the NCNR expansion. The gratings used in the experiment are shown in Figure 2.

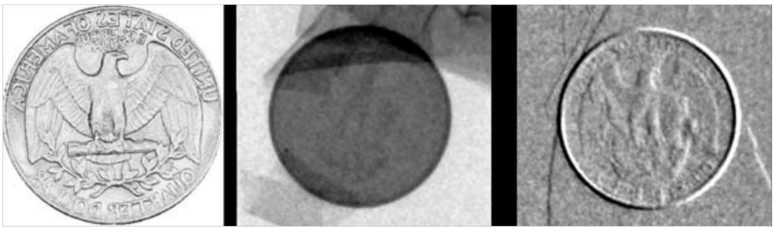

Figure 1. Standard transmission radiograph (center) and phase gradient image(right) of a U.S. quarter (left). The standard radiograph cannot resolve the subtle changes in attenuation from the stamped features, whereas the phase gradient image easily resolves these. There is the potential for the method to analyze normal (compressive or tensile) residual stresses in materials in a more rapid fashion than is currently achievable with diffraction methods.

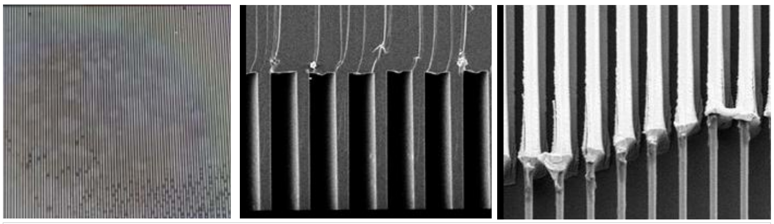

Figure 2. Gratings fabricated at the NIST Nanofab facility. The source grating (R) is composed of two gratings with 5 μm lines of Gd deposited on quartz with a 0.774 mm period at a 40 % duty cycle. The phase grating (M) requires combs with a 4 μm width, to a 40 μm depth, on a 8 μm period. In order to achieve this high aspect ratio, the gratings were etched with KOH along the Silicon (111) direction. The analyzer grating (L) is about 4 μm of Gd deposited on narrow silicon combs to a width of 2 μm with a 4 μm period.

A phase gradient object refracts a neutron beam, resulting in a very small angular deflection of the transmitted beam. If placed in front of a phase-modulating grating, this deflection results in a lateral shift of the Talbot self image. Since the period of the Talbot self image is smaller than current state-of-the-art neutron detector resolution, an absorbing mask enables one to measure the intensity profile. By scanning any grating in the system through one period of the structure, one obtains a sinusoidal variation in the intensity in each pixel. The mean of the variation is the usual transmission radiograph, the phase angle is related to the neutron phase gradient, and the amplitude is the dark-field, which is related to the amount of small angle scattering.

Shown in Figure1 is a demonstration of the phase gradient technique's sensitivity to small variations in the sample as compared to standard transmission imaging.

Phase imaging results in different forms of contrast, improving the sensitivity of neutron imaging to small changes in the local number density. A new cold neutron imaging facility will be built as part of the NCNR expansion, and will be optimized for phase gradient imaging.

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Homeland Security

New Manganese Sulfate Bath

A new reduced-volume manganese bath permits calibration of low-intensity neutron sources as required for DHS applications.

Description: Many neutron sources required by Homeland Security have a lower neutron emission rate than is appropriate for the NIST calibration facility, a Manganese Sulfate Bath system. The Manganese Sulfate Bath uses a sphere of neutron-absorbing material which surrounds a neutron source. The induced radioactivity is a measure of the neutron source strength. The lower intensity of the DHS sources provides less manganese activation, resulting in a reduced signal over background. NIST developed a smaller bath so that more of the manganese is close to the source and therefore induces higher manganese activity. Unfortunately, the smaller bath also has a higher neutron leakage. The fraction of neutron leaking from the sphere depends on the neutron spectrum. NIST uses the new bath only as a means to compare one Californium source against another so that the spectrum remains constant. High-fluence Californium sources calibrated in the existing Manganese Sulfate Bath will be used to calibrate the new bath. A more direct calibration is also being developed, based on Cf-252 NUBAR, the average neutron emission per fission in Cf-252. paper was presented on progress in this NUBAR calibration method at the 13th International Symposium on Reactor Dosimetry (ISRD13), in May 2008, Akersloot, Netherlands .The neutron fluence specification required by ANSI standards requires new sources at least every 20 months, usually sooner. A new calibration facility is required to meet the demand.

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Neutron Detection Standard

The detection of Special Nuclear Material and other neutron sources is required to prevent nuclear terrorism. NIST has the lead in the development of a new ANSI standard: N42.39 Standard for Performance Criteria for Neutron Detectors for Homeland Security. This will serve as a guide for the development of new detectors and a tool for ensuring consistency in the detection of nuclear materials. Neutron detectors are being developed for Homeland Security. The new standard will provide specific criteria to ensure that new detectors meet DHS needs.

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Active Interrogation Standards

A cargo container test bed with three massive cargo regions as needed for testing under ANSI N42.41 is being set up for use at NIST in Gaithersburg or at other sites

Active interrogation involves directing nuclear radiation into a closed container and measuring secondary radiations to gain information about the contents of the container. Typically, but not always, neutrons are used as the impinging radiation. Active interrogation has a greater potential for detection of small quantities of Special Nuclear Material than by passive detectors. It also holds the promise of detection of non-nuclear materials, such as hazardous chemicals and explosives. NIST has lead the drafting committee that wrote and successfully balloted a new ANSI Standard: ANSI STANDARD N42.41 - Minimum Performance Criteria for Active Interrogation Systems used for Homeland Security. An update of this Standard is now proceeding toward balloting, to improve the statistical analysis aspects of the Standard.

Active interrogation is a highly active area of research and development. The selection of correct techniques for further development, and, ultimately, the selection of appropriate systems, requires a consistent set of standards for comparing the various techniques.

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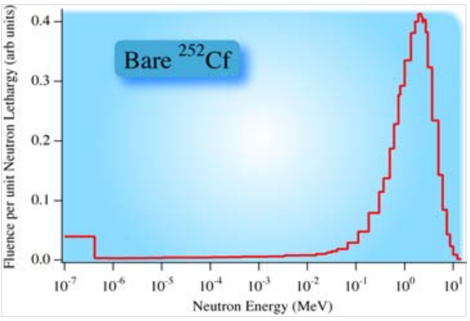
Calibrated Neutron Sources



Energy spectrum of a NIST-calibrated Californium-252 neutron source

ANSI N42.35 requires Cf-252 neutron sources encapsulated in 1 cm of steel with a fluence of 2E4 n/s ±20%. NIST designed a compliant source. NIST acquired, calibrated and delivered several such sources for DOE laboratories, including the Nevada Test Site. They are being used to evaluate potential neutron detectors for Homeland Security. Additional sources are being supplied as needed for new purposes and as old sources decay.

Calibrated sources were delivered for the DOE laboratories to perform equipment testing as required by ANSI standards.

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Neutron Background Reduction

Cosmic ray showers are initiated by high-energy particles entering the earth's atmosphere. A single initiator particle produces a cascade of particles at ground level. Measurements of muon/neutron and neutron/neutron coincidences have shown insufficient density to significantly reduce background through this technique.Our measurements rules out one possibility for reduction of background and false positives in passive detection of Special Nuclear Materials.

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COTS and GOTS Evaluation of Neutron Spectrometers

It is highly desirable to be able to discriminate neutrons emitted from contraband sources from neutrons emitted from legitimate sources and from background. Also, the neutron spectra emitted from contraband will depend on its shielding. A terrorist may attempt to shield a source with various materials in order to escape detection. . The neutron spectrometer Rospec has been calibrated in several NIST neutron fields and has been shown capable of distinguishing a fission-spectrum source such as from special nuclear material from commercial neutron sources such as might be found in moisture density meters. We have determined the ability of current techniques to locate special nuclear material. This material may either be unshielded, in containers, or with shields designed to disguise the nature of the material.

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ASTM Committee on Homeland Security

Ionizing Radiation personnel are members of two ASTM Homeland Security subcommittees: Chemical, Biological, Radiological, Nuclear, and Explosive (CBRNE) Sensors & Detectors, and Decontamination. Standards under development include detector requirements for chemical warfare detectors, a method to evaluate biological decontamination agents, procedures to control a contaminated site, and others. Standards will ensure adequacy of response to an incident and ensure that all participants in the response have a common set of expectations.

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New Calibration Service for 14 MeV Neutron Generators

A new calibration service for 14 MeV neutron generators is being developed. The calibrations may be done at NIST or at a customer site, by activation of a standardized aluminum or copper ring, with NaI gamma-ray spectrometry on the activated ring at NIST. We plan to provide a needed calibration service for the many 14 MeV neutron generators now being employed for Homeland Security and industrial applications.

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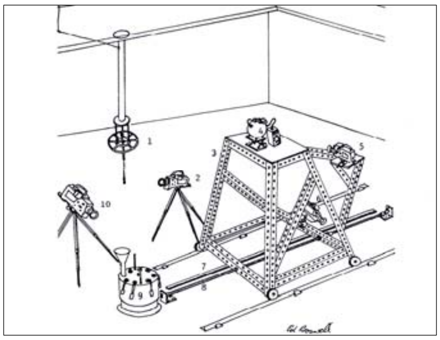
Neutron Calibrations, Detection and Cross Section Standards

Neutron device calibrations



Simplified view of the low scatter neutron calibration facility

NIST provides the national reference for the calibration of neutron radiation detectors and for neutron personnel dosimeters. The reference sources are bare Californium-252 and Californium-252 moderated with a D2O sphere. The spontaneous fission neutron spectrum of bare Cf-252 has been extensively studied and is known well enough to have achieved "benchmark" status. The moderated spectrum, with an abundance of low and intermediate energy neutrons, is more characteristic of reactor working environments and is often preferred for that reason. Some personnel dosimeters are sensitive to neutrons scattered off the person wearing the dosimeter, so that a frequent exposure configuration has dosimeters adjacent to an acrylic phantom. In all exposure geometries, corrections are made for air scatter and room return. NIST periodically compares its standard field to those of other national standards laboratories.

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Californium Neutron Irradiation Facility

NIST provides an exposure facility for high neutron fluence. A Cf-252 source is housed in a large (approximately 15 m x 10 m x 10 m high) room with concrete walls, floor, and ceiling. Inside the concrete is a 5.4 cm thick shell (5.3 m x 5.3 m x 5.9 m high) of anhydrous borax. The anhydrous borax prevents neutrons scattered by the concrete from returning to the source. Typical irradiations include sample activation experiments, electronic damage studies, and other special tests requiring high neutron fluence and a low-room-scatter environment. Interference between successive calibrations through sulfur activation has been identified and eliminated by appropriate scheduling. NIST provides reference high-intensity Cf-252 neutron exposures in support of US nuclear programs.

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Neutron Source Strength Calibrations

Picture of the Mn Bath

We operate a facility to calibrate the neutron emission rate of radioisotope neutron sources. Allowable rates range from 5×10^5 s-1 to 1×10^{10} s-1. They are determined by the manganous sulfate bath method in which the emission rate of the source to be calibrated is compared to the emission rate of NBS–1, the national standard Ra–Be photo-neutron source. Neutron source calibrations typically have a relative expanded uncertainty of about 3.4%, depending on the details of the source encapsulation. During the period 2007-2008, 9 external vendor neutron sources and 1 Department of Homeland Security neutron source were calibrated. In support of these measurements, our own standard neutron sources (NBS–1, BIPM) plus background rates were measured several times. NIST provides a neutron emission rate calibration service in support of US nuclear programs.

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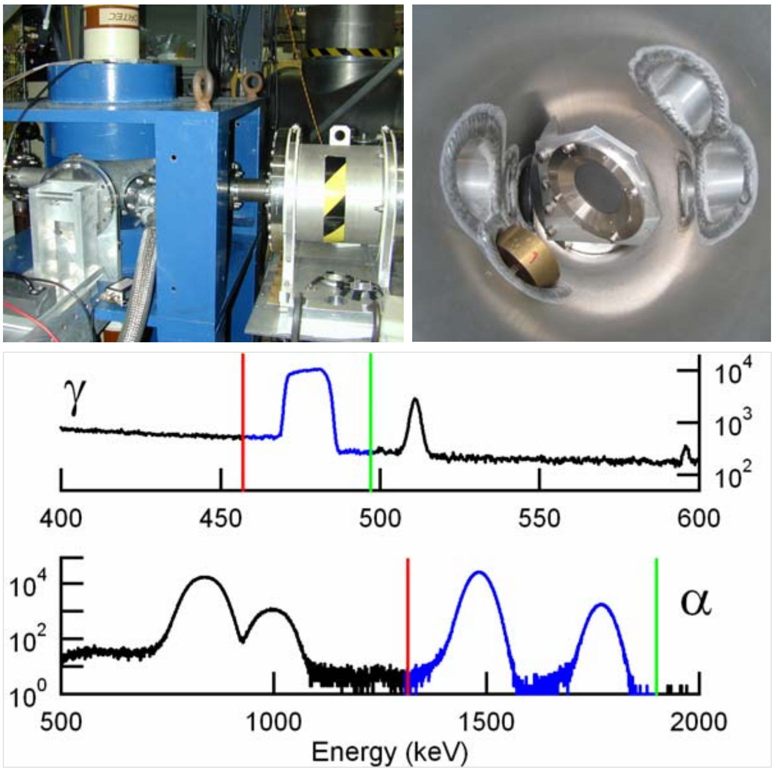
Alpha gamma counting for High Accuracy Fluence Measurement

Neutron fluence is measured by counting gamma-rays from the reaction $n+{}^{10}B \rightarrow {}^{4}He+{}^{7}Li + \gamma$(478KeV) with a calibrated gamma detector. The gamma detector is calibrated in a multi-step procedure that uses a precisely calibrated Pu alpha source (re-calibrated in 2006), an integrated alpha particle detector (the alpha-gamma counter was restored to operation in 2006), a neutron beam, and a thin ^{10}B target. In regular operation, the thin target is replaced with a thick one and the detector operates as a black detector counting the number of neutrons impinging on the target per second. The detector is currently installed on our monochromatic beam line. Recently, thin- and thick-foil data were taken, background rates were measured, and Pu alpha decay particles were counted. Extensive shielding has greatly reduced backgrounds while at the same time tight beam collimation has lead to reasonable signal rates that are little affected by dead time and pileup. The goal of this work is a measurement at the 0.1% level of relative uncertainty. Work is underway to characterize the stability of all the signals. In parallel, a new wavelength-measuring device is being installed upstream of the detector. Absolute knowledge of the beam wavelength (velocity) and fluence will allow us to calibrate thin-foil "*1/v*" neutron detectors, such as the one used in our beam-type neutron lifetime measurement.



Alaph-Gamma detector with the 1/v detector to the right (L). Inside of the chamber showing the alpha detector and the target (R). Typical alpha and gamma spectrum is shown at the bottom.

Impact: This is a new primary calibration method. It will be used to recalibrate the fluence monitor that was used in our beam-type neutron lifetime measurement, thereby simultaneously measuring the ^{6}Li (n,t) and ^{10}B(n,α) thermal neutron cross sections, and to recalibrate the USA national neutron standard NBS-I.

The marked disagreement of a new neutron lifetime experimental result with existing measurements has created serious uncertainty in the value of this important quantity at the 1% level, which is a factor of 10 larger than the relative uncertainty quoted by the Particle Data Group. In ours, the most accurate cold neutron beam determination of the neutron lifetime based on the absolute counting of decay protons, the largest uncertainty was attributed to the uncertainty of the fluence monitor efficiency. The black detector has the potential to reduce the uncertainty in the monitor efficiency by more than a factor of three. This would reduce the uncertainty on our beam-type lifetime measurement by 32% (to 0.25%).

The ^{6}Li(n,t) and ^{10}B(n, α) cross sections are important neutron cross section standards. Precise knowledge of these cross sections is essential because they are often used as reference standards for obtaining the neutron fluence in investigations of the properties of neutron-induced reactions and for accurate determinations of neutron cross sections. They are also used for fluence determinations in neutron dosimetry as well as fundamental physics experiments. The recalibration exercise will yield a direct absolute measurement of these cross sections at near-thermal energies.

Finally, the USA national neutron standard NBS-I, a RaBe photoneutron neutron source, is an artifact standard that was most recently calibrated more than 40 years ago. It should be recalibrated using an updated technique. Its current relative uncertainty is 0.85% and this could be reduced using the black detector and a ^{252}Cf transfer standard.

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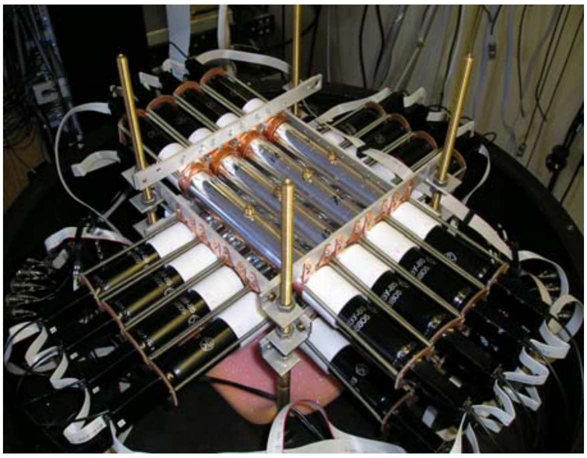
High-Efficiency Neutron Detection and Spectroscopy



16 -channel neutron spectrometer assembly

Precise knowledge of the fast neutron spectrum and fluence is essential for several experimental endeavors requiring the low-background of the underground ground environment. These experiments include some of the most important directions in nuclear and particle physics that are under consideration for the Deep Underground Science and Engineering Laboratory (DUSEL), such as searches for WIMP dark matter, neutrinoless double beta decay, and solar neutrinos. In recent years, the need for sensitive measurements of fast neutron fluences has outpaced the ability to perform such measurements. The current state of fast neutron measurement capability is inadequate to meet the needs of these experiments, and the development of this new technology would greatly advance the ability to characterize the fast neutron backgrounds.

As part of our program in fast neutron technology, we are continuing our work in improving fast neutron detection and spectroscopy. The basic principle involved using a large volume of liquid scintillator to detector fast neutrons through their recoil interaction with protons in the scintillator. The neutrons thermalize and are captured, thus producing a signal indicating that the recoil event was due to a neutron. This capture serves to discriminate against background events. The figure above shows the construction of our 16-channel spectrometer. The size of the 16 segments was chosen so that a fast neutron interacts on average only once in a segment, thus allowing one to correct for the nonlinear light yield, which is the dominant cause of poor energy resolution. We are also working on a large volume detector to use in the underground environment where high efficiency is more important that energy resolution. The prototype will consist of He-3 tubes placed in the interstitial regions of an array of large diameter tubes of liquid scintillator. Upon completion, this detector would be moved to underground laboratories to measure their fast neutron fluxes.

In addition to the application in the underground basic science community, an improved fast neutron detector has obvious application in the area of homeland security where the detection low fluence rates of fast neutrons from fissile material remains an outstanding problem. This innovation will address a critical national need and greatly improve the capability for rapid and accurate monitoring of contraband materials capable of causing catastrophic harm. The field of neutron dosimetry also requires the improved detection of higher energy neutrons. Existing spectrometers fail almost completely for determining neutron fields at medium and high-energy accelerator facilities, requiring multiple measurements with different detectors and complicated unfolding procedures. This need has only grown due to the increased use of 14 MeV neutron generators in interdiction and inspection technologies.

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A Novel Optical Technique for Rapid Detection of Neutrons

Almost every instrument at the NCNR and other neutron scattering facilities depends on ^{3}He proportional tubes because of their high efficiency, good background rejection, and reliability. New research results [1] may lead to a new detector for thermal and cold neutrons: the Lyman Alpha Neutron Detector (LAND). This detector, based on the same fundamental nuclear reaction as ^{3}He proportional tubes, measures ultraviolet light of 122 nm wavelength produced by the reaction instead of amplifying and collecting charge. This new technique may be able to circumvent limitations of ^{3}He proportional tubes while preserving their advantages over other techniques. The fundamental nuclear reaction that is the basis of the LAND is n + ^{3}He → t + p, where n is a thermal or cold neutron, ^{3}He is the nucleus of an isotope of helium, and t and p are a tritium nucleus and a proton, respectively. The reaction releases 763 keV of energy that is shared between t and p. The velocities of the ^{3}He atomic electrons and the outgoing t have similar magnitude, which makes it possible to have a reaction product that is a tritium atom (T) instead of a bare tritium nucleus. This tritium atom is likely to be formed in an excited state that quickly decays to its ground state, emitting one or more photons in the process. The decay from the first excited state of hydrogen to the ground state emits a characteristic photon at 121.6 nm, the "Lyman Alpha Line" (Lα). Because the energy needed to produce Lα light is 10.2 eV, there is enough energy available between the t and p to produce tens of thousands of photons.

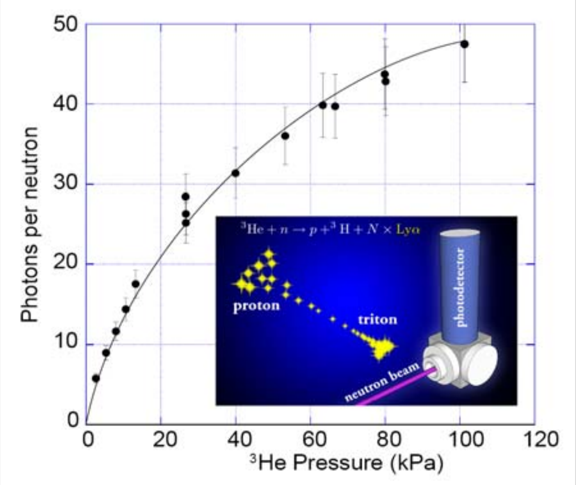
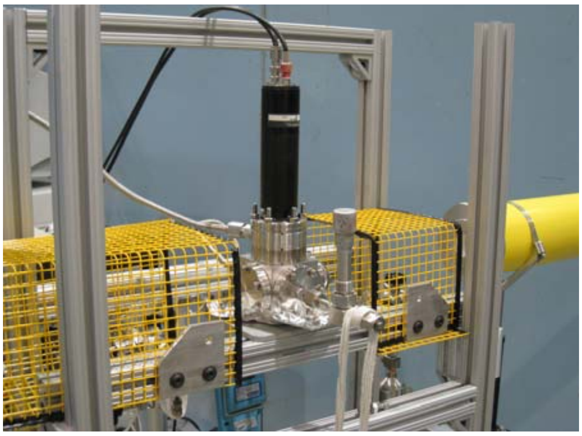


Figure 1: Lyman alpha photon yield per reacted neutron as a function of 3He pressure. The inset states the nuclear reaction and the cartoon indicates photon production and the experimental setup.

The experimental apparatus (inset, Fig. 1) consisted of a gas cell with a neutron-transparent window, a gas-handling system to allow evacuating and filling the cell with ^{3}He, ^{4}He, or a mixture of the two, and a high-efficiency Lyα sensitive photodetector (a Hamamatsu R6835 "solar-blind" photomultiplier, which detects light only between 120 nm and 180 nm). The detector was installed on the 4.96 Å NG6M neutron beam line. We measured photon detection rates with the gas cell evacuated, at various pressures of 4He, and at various pressures of ^{3}He. The ^{4}He has essentially no interaction with neutrons, and provides a check that we were not seeing signals produced by beam-related non-neutron radiation. A series of measurements both with and without a narrow band-pass filter demonstrated that the signal was within the filter bandwidth (8.7 nm bandwidth at 119.2 nm), and thus almost certainly Lyα light. Figure 1 shows the Lyα photon yield per reacted neutron. If the photon production were a result of the n + ^{3}He → t + p reaction alone, their number per reacted neutron should be constant, independent of ^{3}He pressure. Instead, the data fall on a curve. We take this as strong evidence that Lyα photons are produced in atomic interactions with "spectator" ^{3}He atoms occurring after the primary nuclear reaction. Preliminary theoretical calculations suggest that most of the radiation we observe comes from excitation of neutral atoms of H and T after they have been slowed to below 1 keV. At 93 kPa (700 Torr), 46 photons are produced for every neutron reacting with ^{3}He. This high yield of photons is the main result of this investigation. One way in which the LAND can improve upon current technology is in significantly reducing the time signal per detection event. Observed pulses were in the nanosecond range, compared to microseconds for typical ^{3}He proportional tubes. Moreover, charge collection along a high-voltage anode wire requires a cylindrical geometry that has variable efficiency. The LAND would not be constrained to this geometry.



The 'LND' detector taking data at NG6-A beam-line in the guide hall

In sum, carefully calibrated experiments on a new type of neutron detector, LAND, using a ^{3}He gas detector near atmospheric pressure, showed that tens of Lyα photons were generated per neutron absorbed. In recognition of its promise for a transformational approach to neutron detection, this result has garnered a 2008 R&D 100 award for LAND as one of the most significant technologies developed during the previous year.

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Neutron Cross Section Standards

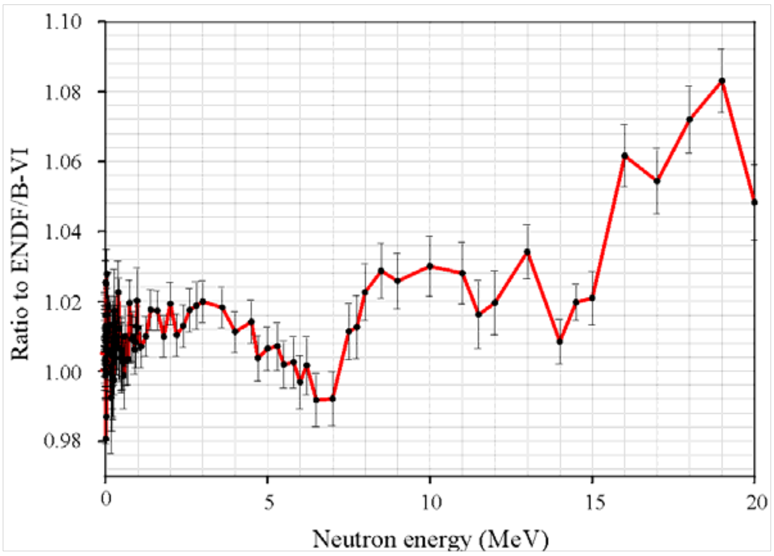

Figure 1: Comparison of the ^{239}Pu(n,f) dosimetry cross section derived from the international standards evaluation with that from ENDF/B-VI.

NIST continues to be deeply involved with evaluations and measurements of neutron cross section standards. A major effort was the completion of the international evaluation of the neutron cross section standards. This evaluation was supported in part by an International Atomic Energy Agency (IAEA) Coordinated Research Project, a Nuclear Energy Agency Nuclear Science Committee Subgroup and a U.S. Cross Section Evaluation Working Group Task Force. NIST played a major leadership role in each of these activities. A detailed report on this work was recently published and is available at http://www-pub.iaea.org/MTCD/publications/PDF/Pub1291_web.pdf. A journal publication is being written now. Contributors to the evaluation were from Austria, Belgium, China, Germany, Japan, Russia, South Korea, and the U.S.A. The cross sections for the H(n,n), ^{6}Li(n,t), ^{10}B(n,α), ^{10}B(n,$\alpha_1\gamma$), Au(n,γ), ^{235}U(n,f), and ^{238}U(n,f) standards were obtained from this evaluation. The cross sections were used in the new ENDF/B-VII library. Also an ENDF/B-VII standards sublibrary, at http://www.nndc.bnl.gov/exfor/endf00.htm , and an ENDF/A library, at http://www.nndc.bnl.gov/exfor7/4web/ENDF-A/partial-evaluations/ have been established. These two special libraries contain the entire numerical output of the evaluation process with full covariances, including cross-material covariances. There had been some concerns expressed about the small uncertainties (variances) obtained in parts of the evaluation and their impact on practical calculations. We have stressed that it is essential to consider the covariances, not just the variances, in such applications. The evaluation process leads to a redistribution of the uncertainties between variances and off-diagonal covariances of the uncertainty matrix with a reduction of the variances. As a result, the uncertainties are reduced but the uncertainty of the integral quantities sensitive to the evaluated data in a wide energy region is conserved in general.

Many of the standards are used directly in neutron dosimetry for fluence determination. Also, almost all measurements of other dosimetry cross sections have been made relative to neutron cross section standards. The effect of the new evaluation of the standards on fluence determinations was investigated. In Figure 1, a comparison is given between the ^{239}Pu (n,f) dosimetry cross section derived from the international evaluation of the neutron cross section standards and that of ENDF/B-VI. Changes as large as 8 % occur. The dosimetry community requires covariances for the full energy range from 10^{-5} eV to 20 MeV for their evaluations. Since the standards evaluation does not cover that entire region, it at first appeared that our evaluation would not be used by them. This led to additional work to provide covariances in the regions not included in our evaluation, so it is expected they will now be able to use the very well defined covariances obtained from the standards evaluation process.

NIST worked with the IAEA to form a nuclear data development project, “maintenance of the neutron cross section standards.” This development project provides some resources for continually improving and updating the standards. Also codes used for the evaluation process will be maintained. The first Consultants' Meeting of this project was held in Vienna in October 2008. At the meeting the cross section database was updated, a number of inelastic scattering cross sections were considered for standards, an additional energy region was established where gold capture is a reference cross section, database improvements for updates to evaluations of the ^{252}Cf spontaneous fission neutron spectrum and the ^{235}U thermal neutron-induced fission neutron spectrum were investigated, and a procedure was established for improving the smoothing process for evaluations of the Au(n,γ) and ^{238}U(n,γ) cross sections.

In addition to the evaluation work, NIST maintains a limited experimental effort focused on improvements to the database of the standards. Data from a number of NIST collaborations focused on other applications have produced measurements useful for the standards program. These include measurements made at NG6 of the spin-dependent portion of the coherent neutron scattering length for ^{3}He that were recently completed and ongoing measurements of the ^{6}Li(n,t) and ^{10}B(n,α) cross sections at sub-thermal energy. Also measurements have been completed at Ohio University of the important hydrogen scattering angular distribution standard at 14.9 MeV neutron energy in an NIST-Ohio University-LANL collaborative experiment. These data were obtained by detecting the scattered proton from scattering of neutrons on hydrogen. A new experiment has been designed in which the scattered neutrons will be detected. This method will allow measurements to be made at much smaller angles. Also plans have been made to measure this cross section using a Time Projection Chamber which will provide higher counting rates than are possible with other methods.

Improved values for the standard neutron cross sections lead to similar improvements both in fundamental measurements such as absolute determination of neutron fluence and in applications using neutrons including neutron shielding for personnel protection, design of new detectors for nuclear monitoring and homeland security, and design of next-generation nuclear reactors and isotope production facilities.

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