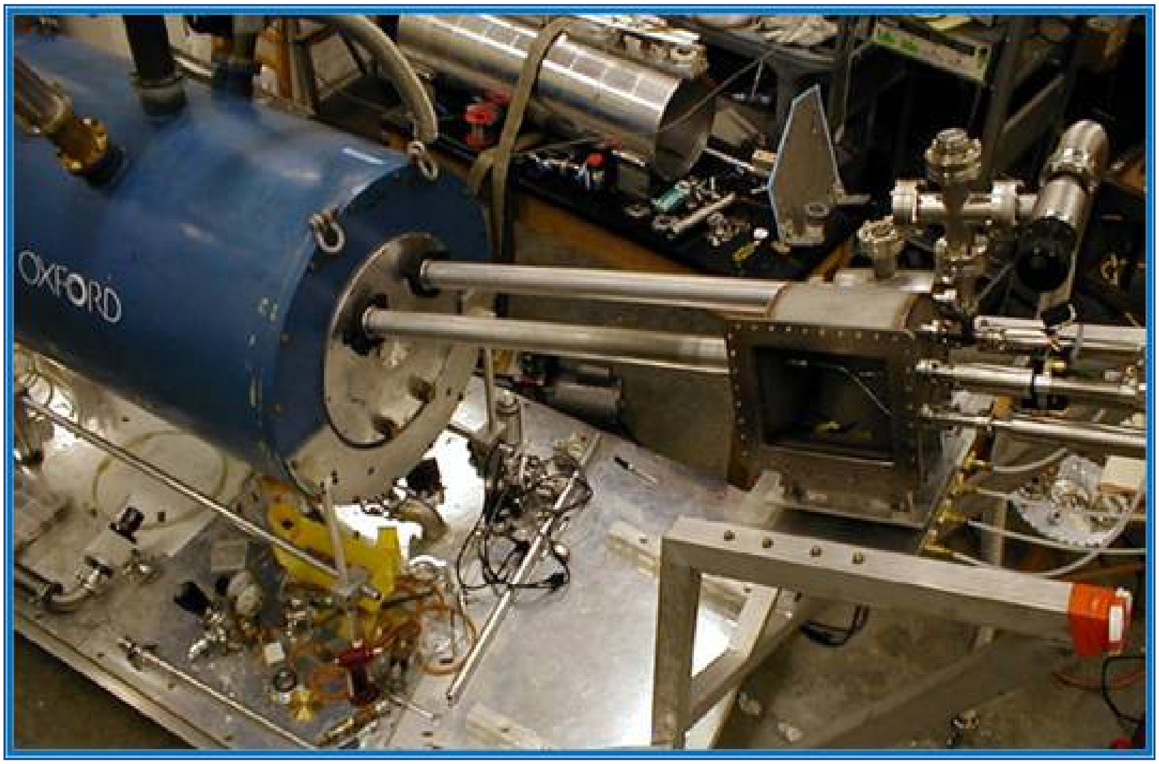
NIST Ionizing Radiation Division Report to the CCRI(III)
2009-2010

Submitted by Lisa Karam (lisa.karam@nist.gov) and M. Scott Dewey (maynard.dewey@nist.gov)

March 2011



The **parity violating neutron spin rotation experiment setup** required this liquid helium cryostat used in a recent successful experiment to study the strong interaction using weak interaction properties of the neutron. In the neutron spin-rotation experiment, a transversely polarized neutron beam experiences a parity non-conserving (PNC) rotation of its polarization vector about its momentum axis in the target due to the weak interaction component of the forward scattering amplitude. Measurement of PNC spin rotation in low ‘A’ nuclei tests the Standard Model descriptions of weak interactions between leptons, leptons and hadrons, and in flavor-changing decays of hadrons. Our experiment has measured the most precise value of the parity violating neutron spin rotation to date.

Ionizing Radiation Division
Radiation Physics Building, Room C229
100 Bureau Drive, Stop 8460
National Institute of Standards and Technology
Gaithersburg, MD 20899-8460, USA
Telephone: +1 301-975-5524
Facsimile: +1 301-869-7682
http://www.nist.gov/pml/div682/

Table of Contents

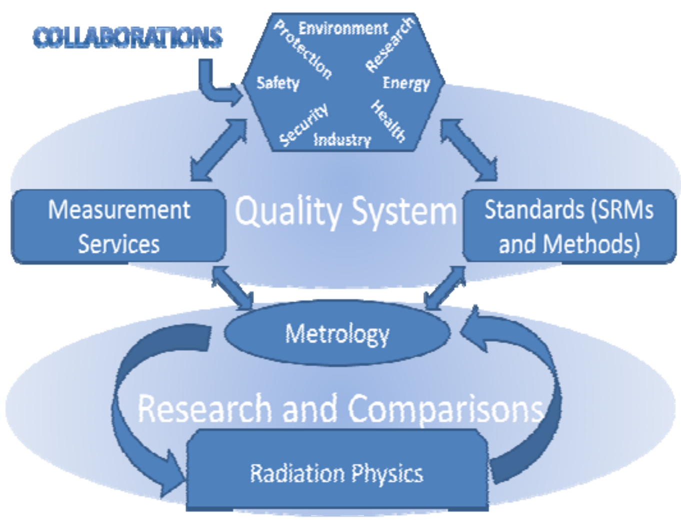
Ionizing Radiation Division

INTRODUCTION

The mission of the Ionizing Radiation Division is to provide the foundation of ionizing radiation measurements for the Nation. The strategy for meeting this goal is to develop, maintain, and disseminate the national standards for ionizing radiation and radioactivity to meet national needs for health care, U.S. industry, and homeland security. This strategy consists of three elements:

- Develop and provide measurement standards in the dosimetry of x rays, gamma rays, and electrons, and engage in research on radiation interactions and effects.
- Develop and provide standards and measurements for neutron dosimetry and neutron sources, and maintain and support fundamental neutron physics user facilities and advance research in fundamental neutron physics.
- Develop and provide measurement standards for radioactivity, and develop and apply radioactivity measurement techniques and engage in related research.

Building from programs ranging from fundamental research in radiation and neutron physics to supporting research in metrology (informed by applied research focused on specific industry sectors), the Division provides critical measurements and standards for all aspects of ionizing radiation in industry, health care, the environment, homeland security, worker protection, energy, defense, and scientific research. Working closely with the user communities in all of these fields enables us to define and prioritize our research and programs in metrology, while an active quality system provides the support needed for confidence in final measurements and high-quality customer service.



The Division, part of NIST's Physical Measurement Laboratory (PML), fulfills its mission through activities in three technical groups: Radiation Interactions and Dosimetry (led by Michael G. Mitch), 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) derived units 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.

Radiation Interactions and Dosimetry (for update on Technical Activities, please refer to report to CCRI Section I): The Radiation Interactions and Dosimetry Group advances the measurement of quantities important in the radiological sciences through programs in the dosimetry of x rays, gamma rays, electrons, and other charged particles. Its mission is to develop, maintain, and disseminate the national measurement standards for these radiations, and to engage in research on radiation interactions and effects to meet requirements for new standards and to address the needs of industry, medicine, and government. These standards are disseminated both directly to the customer and through networks of secondary calibration laboratories by means of calibrations and proficiency testing services provided to maintain measurement-quality assurance and traceability. We maintain the national standards for the *gray*, the Système International (SI) unit for radiation dosimetry, and develop, maintain, and disseminate high-quality data on fundamental radiation interactions.

The Group maintains several electron accelerators, including the Medical Industrial Radiation Facility (MIRF, based on a 32 MeV traveling wave electron linac), and the Medical Electron Accelerator Dosimetry facility (MEAD, built around a Varian Clinac 2100C). The MEAD facility was recently employed in a bilateral comparison between NIST and the Bureau International des Poids et Mesures (BIPM) of absorbed dose to water standards for high-energy accelerator photon beams. Radiation interaction data are used extensively in radiation transport calculations and simulations, employing algorithms and codes often developed by our staff, to solve a wide range of problems in radiation science. A computational model of the Clinac 2100C accelerator was developed, and wall corrections were calculated for a cavity ionization chamber that will allow direct realization of air kerma from megavoltage x-ray beams typically used in cargo inspection systems.

A vacuum double-crystal spectrometer (VDCS) is being used to generate absolute x-ray reference wavelengths from 1.2 nm to 0.1 nm (1 keV to 12 keV), traceable to the definition of the meter, at the femtometer level of accuracy and precision. X-ray wavelength measurements are performed in support of high-accuracy transfer standards needed in fundamental experiments at NIST and around the world.

In 2010, NIST calibrated its 1,000th low energy, low-dose-rate brachytherapy seed using the Wide-Angle Free-Air Chamber (WAFAC). A new laboratory dedicated to establishing a national primary air-kerma rate standard for miniature x-ray sources (< 50 keV) used in brachytherapy was developed. Research in water calorimetry aims to develop primary absorbed dose to water standards that address metrological challenges posed by the dynamic, nonstandard radiation fields with narrow beam cross sections and high dose gradients used in modern 3D conformal radiation therapy. The Group is also pursuing small-field therapy dosimetry studies using alanine pellets and electron paramagnetic resonance (EPR) spectrometry.

With support from the Department of Homeland Security (DHS), the Group facilitates the development of and maintains technical-performance standards for various types of x-ray security-screening systems that are used to detect bulk explosives and other illicit items. NIST provides support to the Domestic Nuclear Detection Office (DNDO) of the DHS for their advanced non-intrusive inspection (NII) initiatives, including radiation dosimetry in and around cargo screening systems and evaluation of the image quality of these systems.

The first comparison of air-kerma standards for mammography x-rays between NIST and the BIPM was recently completed. A bilateral comparison of air-kerma standards from ^{137}Cs and ^{60}Co beams was conducted between NIST and the International Atomic Energy Agency (IAEA) to support international efforts for harmonizing radiation protection measurements around the world, ensuring the safety of radiation workers and the public.

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 has 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, 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 2009-2010, new interferometry experiments to determine the charge distribution of the neutron, and reciprocal space imaging were carried out. We are developing and promoting the applications of efficient neutron spin filters based on laser-polarized ^{3}He. We 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 participating in a Consultative Committee for Ionizing Radiation (CCRI) comparison of thermal neutron fluence rate measurements, characterizing four different beam qualities at the NCNR, and carrying out comparisons of NIST standard neutron sources. We are also 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 2009-2010. 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, and nuclear and particle physics data.

Radioactivity (for update on Technical Activities, please refer to report to CCRI Section II): The Radioactivity Group develops and improves the metrological techniques used for the standardization of radionuclides, and carries out a wide range of programs in low-level standards for environmental measurements and monitoring, standards for nuclear medicine, standards and testing criteria for radiological instrumentation used for security, and radionuclide metrology. Its mission is to develop, maintain, and disseminate radioactivity standards, develop and apply radioactivity measurement techniques, and engage in research to meet the requirements for new standards. Our participation in international comparison exercises has kept us abreast of efforts of other laboratories and helped us to maintain our own capabilities.

We continue to lead the national effort, in collaboration with the Department of Homeland Security, to develop standards and protocols for radiation instrumentation for early and emergency responders. We have developed an accreditation program with National Voluntary Laboratory Accreditation Program (NVLAP) for instrument testing. We are also continuing to spearhead the development of American National Standards Institute (ANSI) standards and testing protocols for spectroscopic portal monitors, neutron detectors, x-ray and high energy gamma-ray interrogation methods, x-ray imaging, data formats for instrumentation data output, and training standards for responders. Significant work has been done on developing tests including radiation detection instruments to be deployed in airports and boat-mounted for maritime applications.

The Group continues to lead an internationally-recognized program for standards in nuclear medicine, providing the national standards for radionuclides used in 13 million diagnostic procedures and 200,000 therapeutic nuclear medicine procedures annually in the US. Secondary standards for the alpha-emitter ^{223}Ra were developed in the form of empirically derived calibration settings for the most commonly used dose calibrators, thereby allowing accurate measurements of this radionuclide to be made in the clinic. This is expected to lead to improved dose estimates to be made of radiopharmaceuticals that incorporate ^{223}Ra, which will lead to increased safety and effectiveness.

During the past two years, a large effort has been focused on the development of standards and measurement methodologies to improve the quantitative capabilities of Positron Emission Tomography-X-ray Computed Tomography (PET-CT) and Single-Photon Emission Computed Tomography (SPECT) imaging. As part of the America Recovery and Reinvestment Act (ARRA), the group was awarded $2.4M to acquire a clinical PET-CT scanner to act as the centerpiece of a new facility being established to support the medical imaging standards program. Renovation of the laboratories and installation of the scanner is expected to be completed by the end of 2010.

The Group's environmental program leads the community in low-level and natural matrix material measurements and standardization, and continues to be heavily involved in the world-wide measurement of environmental-level radionuclide dispersal and contamination through a large number of international intercomparisons and traceability programs and Standard Reference Materials (SRM®s). An extensive program for nuclear forensics methods development, validation and performance evaluation has been established.

Revitalization of our basic metrology capabilities has involved extensive work in many areas. The construction of a second-generation Triple-to-Double Coincidence Ratio (TDCR) system has been constructed and is now in use. The principle method of primary standardization at NIST is live-timed $4\pi\beta$-γ anticoincidence counting. During the past two years, NIST researchers have adapted this method to perform primary measurements on a variety of radionuclides. The Group has participated in a number of international intercomparisons as well as the submittal of samples to the System International Reference (SIR). A new automated ionization chamber has been developed at NIST to measure up to 100 samples with programmable sample queuing, sample handling and measurement parameters.

Interactions with user groups (including the Council on Ionizing Radiation Measurements and Standards, or CIRMS), collaborations with colleagues from other laboratories around the country and world-wide, and input from independent reviews (e.g., National Research Council Panel technical reviews, the NIST Visiting Committee on Advanced Technology, quality system assessments, etc.) are used to identify the most relevant and immediate needs for measurement services to support the breadth of applications where ionizing radiation is used or controlled. Through the optimization of expertise and available resources, the Division leverages its efforts to meet the needs with the greatest potential impact or otherwise indicated by our customers as high priority.

Since self-declaration of conformance in 2006, reassessed early in 2010, the Division has maintained 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®). Details on our quality system, including our various procedures, are available on-line at http://www.nist.gov/pml/div682/qualitysystem.cfm.

The Division continues to be involved in international efforts, and several members are active participants in the three sections of the Consultative Committee on Ionizing Radiation (CCRI) as well as in our Regional Metrological Organization, the Sistema Interamericano de Metrología (SIM). We participate in comparisons of our national standards with those of other National Measurement Institutes (NMIs) to assure the quality of our measurement services and to satisfy the requirement that the U.S. standards are consistent with those of other NMIs and with the SI within stated uncertainties. Special priority is given to comparisons conducted under the auspices of the International Committee on Weights and Measures (CIPM) in support of the CIPM Mutual Recognition Arrangement; a listing of the over 100 ionizing radiation comparisons NIST has been involved in (more than 20 during the last 5 years) can be found at http://kcdb.bipm.org/AppendixB/KCDB_ApB_search.asp (search "ionizing radiation" for metrology area and "United States" for country). Through collaborations, interactions, and comparisons with our colleagues throughout the world, we are able to ensure customers that NIST calibrations are the best available and will be recognized outside the U.S. borders and provide the technical basis in the radiation sciences for international trade, commerce and regulatory affairs.

Lisa R. Karam
Gaithersburg, MD
December 2010

TECHNICAL ACTIVITIES

The research activities of the Ionizing Radiation Division can be broken out into three general categories:

- Radiation and neutron physics (including facilities, neutron characteristics, and decay physics)
- Research in metrology (neutron science, radionuclide metrology, and dosimetry; and research supporting international comparisons)
- Applied research (to support health care and medical physics, energy and environment, industry and manufacture, and safety and security)

Research results are distributed to the larger community through a variety of mechanisms including publications, presentations, and measurement services (including calibrations and SRM®s). Listings of calibrations services (http://www.nist.gov/ts/msd/calibrations/ionizing-rad_index.cfm) and SRM®s [http://www.nist.gov/ts/msd/srm/ (key word: radioactive)] are available on-line.

Radiation and Neutron Physics: *providing the tools for radiation sciences*

Research in Nuclear Physics

Precision Measurement of Radiative Neutron Decay Branching Ratio and Energy Spectrum

Figure 1: Photon detection is done by twelve BGO crystals viewed by avalanche photodiodes forming and annular ring around the neutron beam. Photograph by: NI&D group

*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 near the bottom. (*Photograph by: NI&D group)

Although neutron decay is typically considered as a three-body process, in the radiative correction it is always accompanied by inner-bremsstrahlung (IB) soft photons, $n \rightarrow e^- + p + \nu_e + \gamma$. While IB has been measured in nuclear beta decay and electron capture decays, it has only recently been observed in free neutron beta decay. 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 upgraded 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 operated by detecting an electron in prompt coincidence with a photon followed by a delayed proton. The requirement that there be a triple coincidence provided a powerful suppression of background events. This was critical because the very low rate of these events was insufficient to make it measurable above the large rate of random coincidences. A beam of cold neutrons passed through the bore of a superconducting solenoid. Decay electrons and protons were guided out of the beam by the magnetic field and detected by a silicon detector. The primary improvement was increasing the solid angle of photon detection by constructing a 12-element annular BGO detector that surrounded the decay region of the cold neutron beam (*figure 1*). The new detector allowed us to upgrade the apparatus (*figure 2)* completing its data acquisition in November of 2009. The photon detector performed very well as did a second detector consisting of bare photodiodes. This detector allowed us to lower the energy detection threshold to about 200 eV, significantly lower than the 15 keV from the first run.

In this second run of the experiment, we expect to measure the radiative decay branching ratio to a 1 % total uncertainty. The analysis of the data is in progress. We have completed an initial analysis of all the data and have not encountered any significant problems with the data set. We are currently in the process of refining the analysis and beginning to study the systematic effects. Statistically speaking, we should be able to reach our goal of approximately 1 % and are optimistic that we will be able to quantify the systematics at a similar level of uncertainty. This experiment represents an important exploration to future precision radiative decay experiments below 1 % uncertainty.

Primary Contact(s):

Jeffrey S. Nico	Thomas R. Gentile	Maynard S. Dewey	Hans P. Mumm
301-975-4663	301-975-5431	301-975-4843	301-975-8355
jeffrey.nico@nist.gov	thomas.gentile@nist.gov	maynard.dewey@nist.gov	hans.mumm@nist.gov

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 angle, 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. The challenge was to distinguish small parity-violating rotations from rotations that arise from residual magnetic fields.

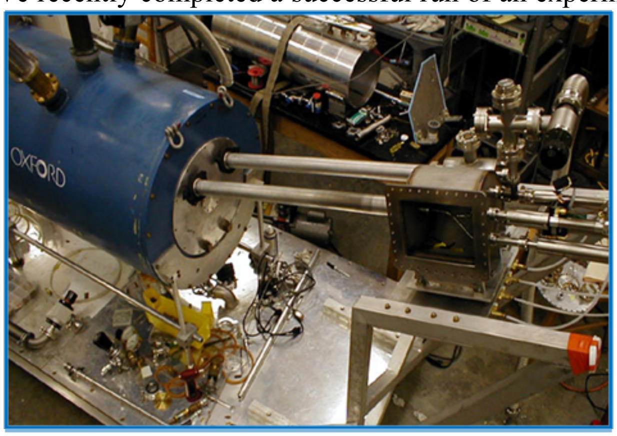


Figure 1 Photograph of the apparatus on the NG-6 beam line. The neutron beam exits after traversing the LHe targets and the polarization is analyzed in with the supermirror and ^{3}He ion chamber. **(Photograph by: NL&D group.)**

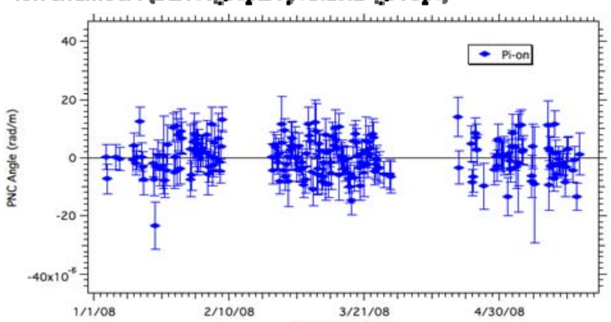


Figure 2: Results of the pi-coil on runs for the neutron spin rotation experiment. The rotation angle from each run is plotted as function of the time of the run throughout the entire experiment. The result of this experiment produced the best limit on the party-nonconserving neutron spin rotation in liquid helium.

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 a neutron spin flipper, input and output guides made from float-glass, magnetic shielding, cryogenic targets, a data acquisition system, and a segmented ^{3}He ion chamber. It is shown in *Figure 1* assembled on the NG-6 beamline. The target was divided into four quadrants, front and back and side to side. This allowed 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 was changed by pumping the liquid helium using a non-magnetic centrifugal pump. Data were acquired in three pi-coil states: off, +180 degree rotation, and -180 degree rotation.

We acquired three reactor cycles (about 18 weeks) of data and recently completed both the statistical and systematic analysis of the data. We calculated rotation angles for each of the pi-coil and target states. *Figure 2* shows the PNC angle with the pi-coil on (i.e., when it is sensitive to party-nonconserving influences) as a function of the run. The result from the final analysis for the rotation angle is (+1.7 +/-9.2) rad/m, which is the best limit on spin rotation in liquid helium. The uncertainty is dominated by counting statistics, and hence, an improved experiment is being considered for the new high flux NG-C beamline.

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

Primary Contact(s):

Jeffrey S. Nico
301-975-4663
jeffrey.nico@nist.gov

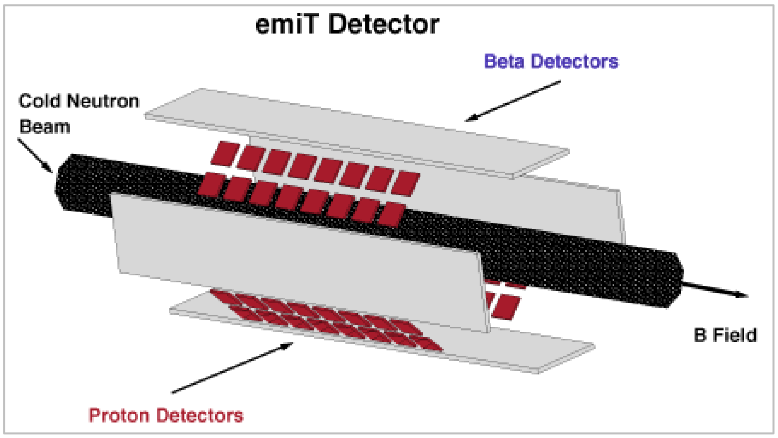
Hans P. Mumm
301-975-8355
hans.mumm@nist.gov

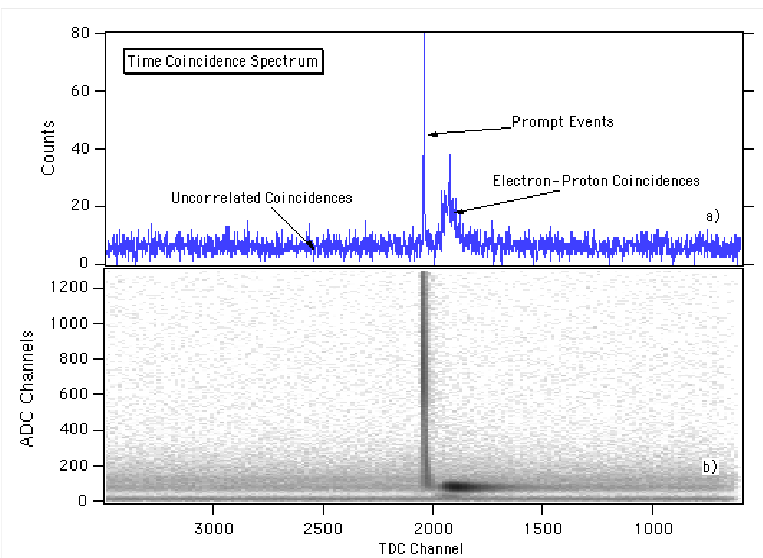
William M. Snow
Indiana University
snow@iucf.indiana.edu

Erik Swanson
University of Washington
swanson@npl.washington.edu

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.





(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 coincidence events. The peak is due to neutron decay.

The performance of the detector during the 2003 run was 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.

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 finalizing a systematic error budget. 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 exceedingly well. We are completing an assessment of the sole remaining systematic correction and stand poised to un-blind the data.

In all, the new data set is approximately 25 times larger than the 1997 run. We anticipate the completion of data analysis in early FY11 with a value that is a factor of nearly 4 better than the current limit. This result will 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.

Primary Contact(s):

Hans P. Mumm	Jeffrey S. Nico	John F. Wilkerson	Timothy E. Chupp
301-975-8355	301-975-4663	University of North Carolina	University of Michigan
hans.mumm@nist.go	jeffrey.nico@nist.gov	jfw@email.unc.edu	chupp@umich.edu

Precision Measurement of the Neutron-^{3}He Incoherent Scattering Length

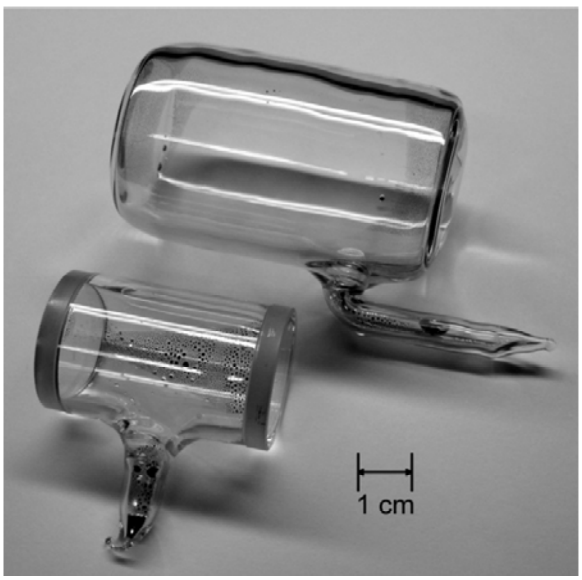


Figure 1: The smaller ^{3}He cell was used as a sample inside the interferometer. The larger cell was used in polarization analysis. (Photograph by: NI&D group.)

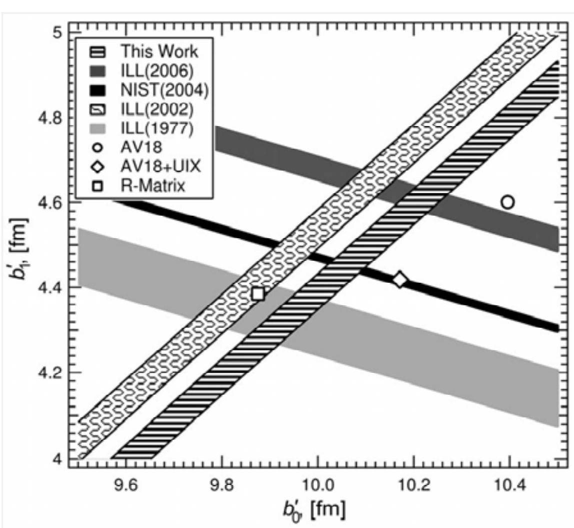


Figure 2: This work compared to previous experimental measurements on the n-^{3}He system. Theoretical predictions are shown as single point.

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 EFT's 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. 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 (*figure 1*) placed in one path of the interferometer. 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 = (-2.429 ± 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. *Figure 2* shows this the current state of the n-^{3}He system. 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 experimental and theoretical work.

Primary Contact(s):

Michael G. Huber	Thomas R. Gentile	Frederick E. Wietfeldt	Timothy C. Black
301-975-5641	301-975-5431	Tulane University	UNC-Wilmington
huberm@nist.gov	thomas.gentile@nist.gov	few@tulane.edu	blackt@uncW.edu

Measurements of the Neutron Magnetic Dipole Moment (MDM) Using Schwinger Scattering

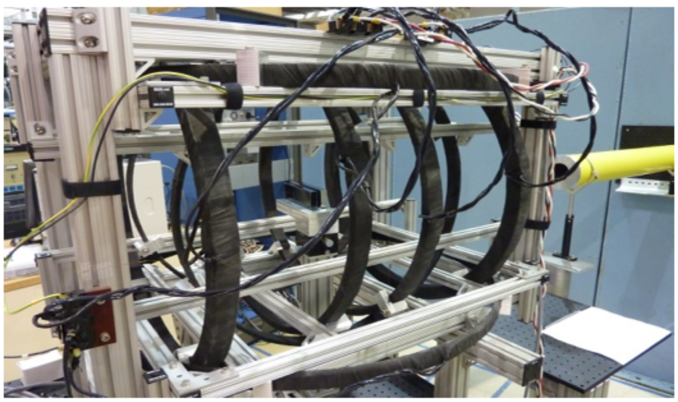


Figure 1: The crystal for the MDM experiment. Neutrons are reflected down the slot. (Photograph by: NI&D group.)

Figure 2: Four vertical coils provide a smooth magnetic field around the crystal region. (Photograph by: NI&D group.)

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.

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 π/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 small but measurable 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 slot wall. A constant magnetic field is provided by four coils. Additional pairs of cancel any external magnetic fields. Schwinger interaction will rotate the neutron polarization creating measured neutron polarization along beam direction. The 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.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.

Primary Contact(s):

Murray Peshkin	Thomas A. Dombeck	Muhammad Arif	Donald Koetke
Argonne National Laboratory	University of Hawaii	301-975-6303	Valparaiso University

peshkin@anl.gov dombeck@hawaii.edu muhammad.arif@nist.gov donald.koetke@valpo.edu

Facilities and Methods

Advanced Neutron Imaging Facility

Photo of the NIST neutron imaging facility.
(Photograph by: Robert Rathe.)

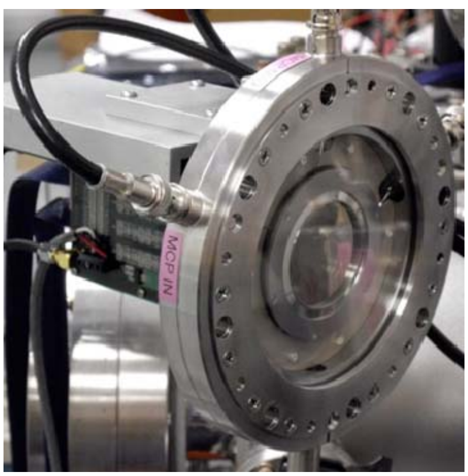


Photo of the new 10 micrometer detector.
(Photograph by: NI&D group.)

The NIST Neutron Imaging Facility (NNIF) at the NIST Center for Neutron Research (see first *figure)* 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; in 2009 there were users from 21 individual institutions and in 2010 there were users from 14 individual institutions. These groups compete for beam time through a competitive external peer review process. 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, Batteries, Biology, Geology, 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, assist 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, and there have been some recent facility updates that are notable improvements and accomplishments. These include the development of a 10 micrometer resolution detector (see second *figure)* as a standard capability for imaging fuel cells, and electro-impedance spectroscopy. An ongoing partnership and collaboration between General Motors and NIST has resulted in an exciting use of neutron imaging to visualize the operation of fuel cells and lithium-ion batteries for automotive vehicle applications. Neutron imaging is an ideal method for visualizing both hydrogen and lithium, the fuel of electric vehicles engines. With a newly developed 10 micrometer spatial resolution detector, studies of the transport phenomena from the anode to the cathode in fuel cells and batteries have been conducted. These unique, fundamental measurements, provide valuable material characterizations that will help improve the performance, increase the reliability, and reduce the time to market introduction of the next generation electric car engines.

Primary Contact(s):

David L. Jacobson
301-975-6207
david.jacobson@nist.gov

Daniel S. Hussey
301-975-6465
daniel.hussey@nist.gov

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.

Photograph of Cf irradiation facility.
(Photograph by: NI&D group.)

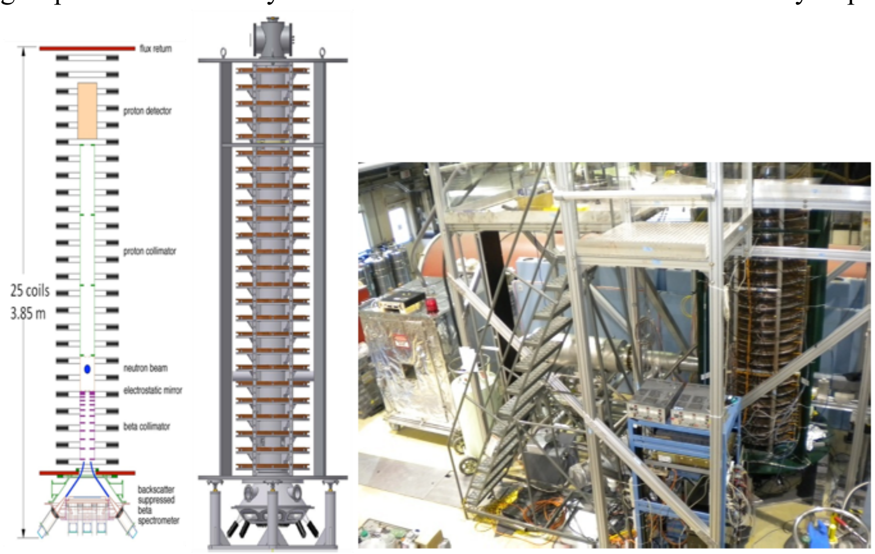
NIST provides reference high-intensity Cf-252 neutron exposures in support of US nuclear programs.

Primary Contact(s):

David M. Gilliam	Craig R. Heimbach	Jeffrey S. Nico	Alan K. Thompson
301-975-6206	301-975-8874	301-975-4663	301-975-4666
david.gilliam@nist.gov	craig.heimbach@nist.gov	jeffrey.nico@nist.gov	alan.thompson@nist.gov

Measurement of the Electron-Antineutrino Correlation in Neutron Decay

The angular correlation between the beta electron and antineutrino in nuclear beta decay, *a*, is the least well-known of the group of neutron decay observables that has been studied intensely experimentally. A more precise value for it can be used to test the validity and self consistency of the Electroweak Standard Model. We are carrying out an experiment using a new method that promises reduced systematic uncertainties, and consequently a factor of five improvement in precision of *a* compared with previous measurements of this quantity. This new method relies on constructing an asymmetry that directly yields *a* without requiring precise proton spectroscopy. An important advantage of measuring *a* compared with other correlation coefficients is the fact that there is no need for neutron polarimetry.



Two schematic diagrams of the apparatus is show on the left. The apparatus installed at our NG-6 beam position. **(Photograph by: NI&D group.)**

The figure shows a schematic of the apparatus as well as a photograph of it on our beamline. The neutron beam passes through a long vertically oriented solenoid. A proton detector atop the solenoid detects protons originating from neutron decays that occur inside the apparatus while an electron detector at the bottom detects beta electrons in coincidence. In order to conserve momentum, the unobserved electron antineutrinos must travel either upward or downward. This leads to two groups of protons for many beta energies: a fast moving group and a slow moving group. These two groups can be distinguished using the time of flight between electron and proton. The asymmetry in counts between the fast and slow groups is proportional to *a*. In the experiment this asymmetry is measured as a function of beta energy and a value for *a* is extracted. The use of two-fold coincidences leads to a significant reduction in interfering background events. The goal of the experiment is an overall relative uncertainty on *a* between 0.5 % and 1 %.

During 2009, the entire apparatus, except for the beta detector, was constructed, assembled and tested without neutrons at Indiana University. In parallel, the beta detector was tested at NIST using an electron beam as well as several radioactive electron sources. In late 2009, the apparatus was shipped to NIST and installed on our beamline NG-6. Since January 2010, the apparatus has been undergoing commissioning. Recently, the first time of flight versus electron energy scatter plot was obtained. The quality of the data indicates that all of the major systems (magnetic field, high voltage, grids, and detector systems) are functioning. Data collection will continue until the long shutdown which is currently scheduled for April 2011.

Primary Contact(s):

Maynard S. Dewey	Jeffrey S. Nico
301-975-4843	301-975-4663
mdewey@nist.gov	jeffrey.nico@nist.gov

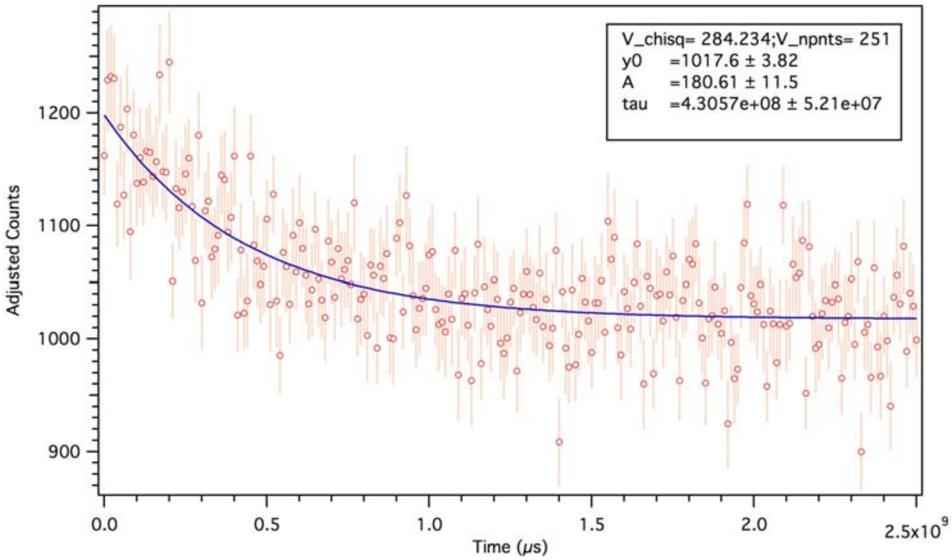
Magnetically Trapped Neutron Lifetime Experiment

This program is a collaborative effort between NIST and NC State. 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 anti-parallel to the magnetic field, they will seek to minimize their potential energy by moving towards low field regions. By cooling the trap 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 non-imaging 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.

Photograph of the operating apparatus.
(Photograph by: NI&D group.)

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.



Data from initial test runs at 50 %, showing the decay curve associated with the trap 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. We have also 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 of other experiments in the field.

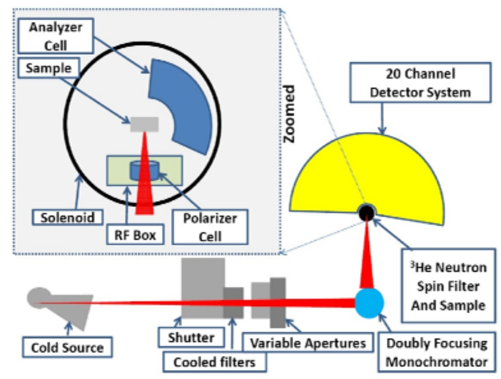
We have now completed the extensively upgraded apparatus. All systems have been independently tested and perform according to expectations. We are currently taking data using conservative field strength of 50 %. We expect to begin production data collection beginning next reactor cycle. Estimates of background and increased counts rates indicate that we should reach a sensitivity of 2-3 s with approximately three cycles of data collection.

Primary Contact(s):

Hans P. Mumm	Alan K. Thompson	Paul R. Huffman	Karl Schelhammer
301-975-8355	301-975-4666	North Carolina State Univ	North Carolina State Univ.
hans.mumm@nist.gov	alan.thompson@nist.gov	paul_huffman@ncsu.edu	Schelhammer@nist.gov

Wide-Angle Neutron Polarization Analysis

The capabilities of many neutron scattering instruments would be greatly enhanced by neutron polarization analyzers that can cover a wide angular range. We have tested a polarizer-analyzer-spin flipper system based solely on ^{3}He spin filters on the Multi-Axis Crystal Spectrometer (MACS) at the NIST Center for Neutron Research. The compact system is housed by a 36 cm diameter, vertical solenoid. 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. The polarization of neutrons scattered into a wide angular range are analyzed by a second ^{3}He spin filter cell. The system has been demonstrated on MACS and the first physics experiment is scheduled for Nov. 2010.



(Top) Apparatus for wide-angle polarization analysis. (Bottom) Photograph of a analyzer cell constructed from three sections of resized fused quartz tubing. (Photograph by: NI&D group.)

The top figure shows a top view of the MACS instrument, with an enlarged view of the spin filter system: the neutron beam (red) passes through the neutron-compatible solenoid and is polarized by a ^{3}He spin filter. After being scattered from a sample (located in a cryostat that is lowered into the solenoid), one or two curved ^{3}He cells analyze the polarization of the widely scattered neutrons.

The development of the analyzer cells has revealed a new phenomenon in the relaxation of ^{3}He. Whereas our ^{3}He cells are normally constructed from a boron-free aluminosilicate glass, the curved wide-angle (120 deg) cells were fabricated from fused quartz. Despite the long relaxation times we achieved, the polarization was lower than expected due to temperature dependence for the ^{3}He relaxation. For upcoming experiments we will employ aluminosilicate cells with reduced angular range (about 30 deg), which will meet the experimental needs. We will develop a solution for full angular coverage.

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.

Primary Contact(s):

Thomas R. Gentile
301-975-5431
thomas.gentile@nist.gov

Neutron Interferometry with Polarized Neutrons as an Additional Degree of Freedom

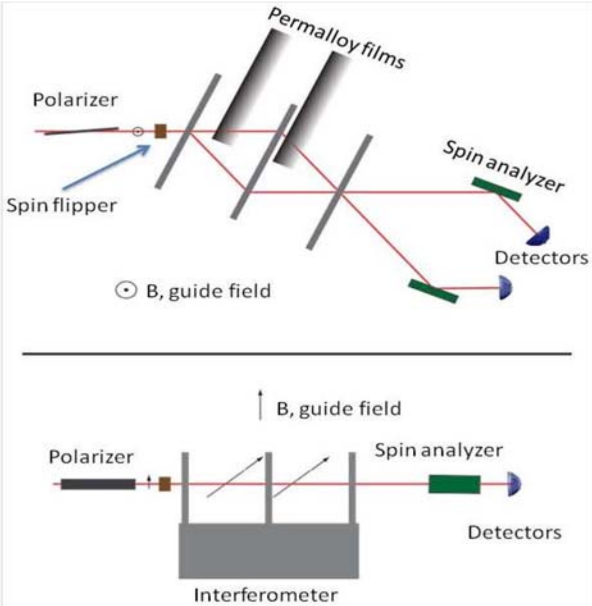


Figure 1: Schematic views of the experimental setup.

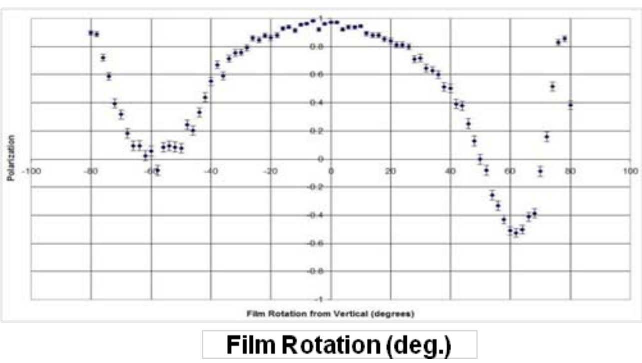


Figure 2: Polarization vs. single 10 micron permalloy film tilt.

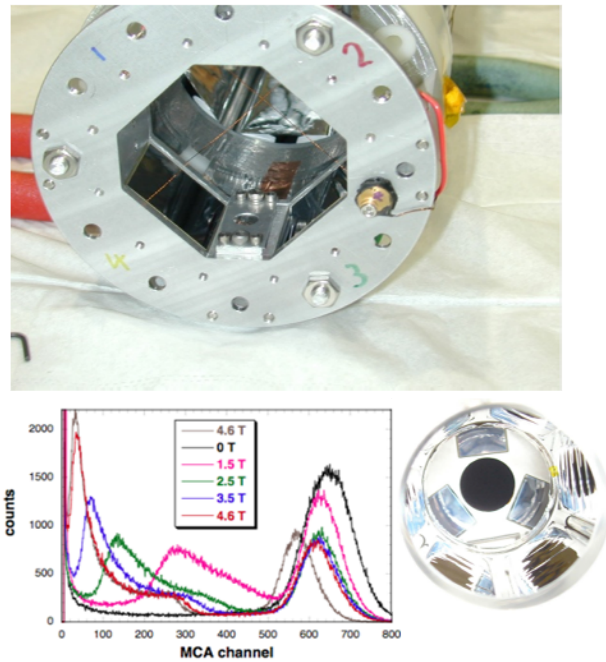
Our goal is to apply Quantum Information Processing techniques to improve neutron interferometry contrast by making our final measurement insensitive to crystal imperfections. One approach to achieve this is to employ the Power of One Qubit protocol initially outlined by Knill and Laflamme. This protocol enables us to detect the neutron phase via the neutron spin degree of freedom, which is insensitive to surface defects and blade imperfections. Thus, by entangling the path and spin degrees of freedom, we propose to measure the path-dependent phase difference using the neutron spin. The key step is to introduce an entangling gate that is independent of the blades and dependent on the magnetic properties of a material placed in one path of the neutron interferometer. This is accomplished by rotating the neutron spin in one beam path away from the polarization direction, allowing its magnetization to process about a material's internal magnetization, and then rotating it back to the polarization direction. As a proof of principle experiment, we can equivalently measure the phase accrual from the precession about the vertical guide field rather than a material. Our experimental setup is outlined in *Figure 1* A transmission supermirror spin polarizer selectively transmits one neutron spin orientation to the interferometer and reflects the other away *from the apparatus*. An aluminum DC coil spin flipper with efficiency >99% enables us to select the incident spin state. Spin rotation inside the interferometer is accomplished using 10 micron thin film permalloy deposited onto a silicon substrate. These films offer the advantage that they are magnetized without requiring an active current supply, which would introduce heating near the interferometer and cause temperature gradients that are destructive to the measurement. When placed in an ambient magnetic field of greater than 6 gauss, the films are magnetized to 1 Tesla in-plane. By tilting the films with respect to the neutron beam, a mutual angle is created between the spin polarization direction and the permalloy magnetization, and Larmor precession occurs. By tuning the tilt angle based on film thickness, the neutron can exit the film having achieved a particular desired rotation (e.g. 90 degrees). Saturated Heusler crystals serve as spin analyzers that are used downstream of the interferometer to again select one spin orientation. Detection is achieved using ^{3}He detectors of >99% efficiency. Experimental data for neutron polarization vs. film tilt angle for a single 10 micron film are shown in *Figure 2.* As the film is titled, the mutual angle between it and the neutron spin orientation grows and the neutron experiences progressively larger rotations. At 50 degree tilt, a 90 degree spin rotation is induced. As the tilt grows to near 60 degrees, the vertical size of the neutron beam exceeds the vertical projection of the film, and thus rotation of the full beam is not accomplished. Thus, we observe dephasing of the neutron beam. The results correspond well with our calculations and are important enabling steps for accomplishing our experiment. The permalloy films are good replacements for the bulky and hot DC coil flippers, which achieve exceptional efficiencies but cannot be applied to the space and heating requirements of the interferometer. We also expect that as we characterize these film rotators further, they may prove useful to other types of neutron experiments as well.

Primary Contact(s):

Dmitry A. Pushin	Mohamed Abutaleb	David G. Cory	Michael G. Huber
U. Waterloo	MIT	U. Waterloo	301-975-5641
mitja@mit.edu	abutaleb@mit.edu	dcory@mit.edu	huberm@nist.gov

X-Ray Detection with Large Area Avalanche Photodiodes for the Neutron Radiative Decay Experiment

Operation of the second neutron radiative decay experiment has been completed. In this experiment, we observed the emission of photons that accompany neutron beta decay. The primary photon detector was a 12-element array of scintillating crystals coupled to avalanche photodiodes (APDs) which operated between 10 and 700 keV. The overall energy range for the experiment was extended with a three-element array of large area APDs to directly detect X-rays with energies between 0.3 and 20 keV. X-ray detection with APDs for our operating conditions (cryogenic temperatures (77 K) along with high magnetic fields) had never been presented in the published literature. In the development and application of this detector, we observed previously undocumented and unexpected magnetic field effects on APDs, in particular for the case in which the APD electric field is perpendicular to an applied magnetic field. Studies of the temperature (77 - 300 K) and magnetic field (0 - 5 T) dependence of the APD response were performed in this configuration and a paper published on this topic. The key result is that the magnetic field effects are not present at room temperature, and are associated with X-rays that are absorbed in the drift region of the APD.



On the top is shown the first version of the X-ray detector, in which the magnetic field was perpendicular to the APD electric field. These effect of the field on the response of the APD to 6 keV X-rays are shown in the bottom left plot. On the bottom right is shown the three-APD detector used for the radiative decay experiment, looking through the scintillator detector. **(Photograph by: NI&D group.)**

For the radiative decay experiment, we operated with the electric field parallel to the magnetic field, in which field effects were minor. However, the responses of APDs at the low end of our energy range (below 1.5 keV) have not previously been investigated. In measurements at the NIST Synchrotron Radiation Facility, we found a complex response function in this regime that we will study in further experiments with monochromatic X-ray beams at the National Synchrotron Light Source at Brookhaven National Laboratory.

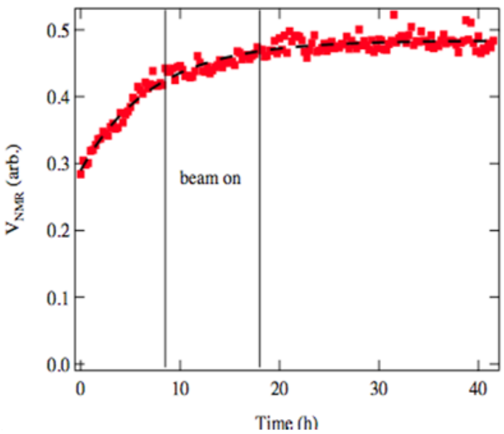
These studies will provide the understanding of APD response required for analysis of the low energy part of the radiative decay experiment, and provide information for other users of APDs on their characteristics in unique regimes.

Primary Contact(s):

Thomas R. Gentile
301-975-5431
thomas.gentile@nist.gov

Continuous Spin-Exchange Optical Pumping in High Flux Neutron Beams

We collaborated on tests at the Insitut Laue Langevin (ILL) to study the effects of high flux neutron beams on spin-exchange optical pumping (SEOP). The key result of this published work was the finding that the alkali spin relaxation induced by the beam, which increases the laser power demand, scales as the square root of the neutron flux. However, this work opened new questions as the data suggested a possible dependence on the nitrogen pressure in the cells. Nitrogen is required to suppress radiative emission of alkali atoms in SEOP cells. In addition, both fast and slow (~300 s) components of the beam-induced relaxation were observed. In a second set of experiments at the ILL, we collaborated on further investigations. We found that the slow component appears to be associated with nitrogen. However, interpreting the results has proven to be remarkably complicated for several reasons, such as the shortening of stopping lengths for charged particles for higher nitrogen densities. The experiments provided new data, but again opened new questions for further study.



On the top is shown a small double cell that was tested in the high neutron flux beam at the ILL. As shown in the plot on the bottom, the rise in polarization as the cell was polarized by SEOP was unaffected when the cell was exposed to the neutron beam. (Photograph by: NI&D group.)

In parallel, we are developing and testing "double cells," which can potentially bypass this issue by separating the optical pumping volume from the spin filter volume. We tested a small double cell in the high flux ILL beam and the data indicate that it was insensitive to the neutron beam. Such cells have other advantages for continuous pumping, but also present greater demands on the laser power required for maximum polarization. To test a large double cell, we employed an electrically heated oven in a solenoid for SEOP. Although a 150 h relaxation time was observed for this cell, the polarization was lower than expectations. This discrepancy will be investigated further.

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.

Primary Contact(s):

Thomas R. Gentile
301-975-5431
thomas.gentile@nist.gov

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 new 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.

We made a five blade single crystal interferometer that incorporates both the MZ and DF geometries in one single perfect silicon crystal. By removing or adding neutron absorbing cadmium beamblocks we can choose either the MZ or DF equivalent (*figure 1*). This allows us to compare the MZ and DF under the same conditions.

Calculations show that the DF configuration is much less sensitive to low frequency vibrations. For the DF configuration the contrast does eventually fall off at high frequencies, which can be easily damped with small, commercially available systems. The decrease in sensitivity to vibrations in the DF case is due to the fact that any change in momentum caused by vibrating blades in the first loop is compensated by the same change in the second loop. In the MZ case this is not true. *Figure 2* shows interferograms for the two cases. For the MZ case the fringe visibility becomes zero at only 8Hz while at the same frequency the DF still has optimal visibility.

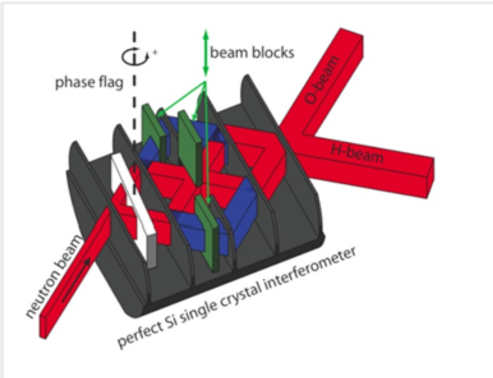


Figure 1: A schematic diagram of the5-blade neutron interferometer. By changing the location of Cd beam blocks we can switch from a MZ and DF type interferometer without having to use completely different interferometer crystals.

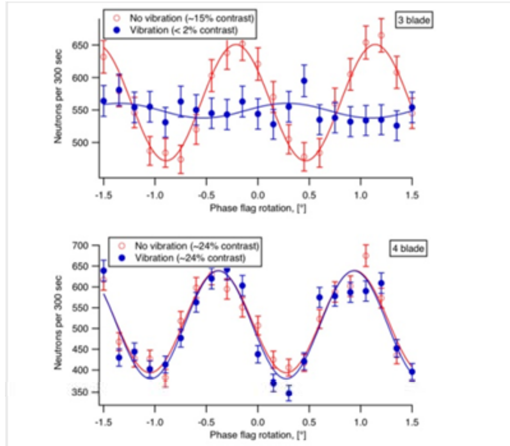


Figure 2: The fringe visibility for the MZ (top) and DF (bottom) type geometries. The DF type is insenitive to vibrations while the MZ is clearly not.

These results demonstrate a concrete example of how quantum information theory can control the effects of noise on useful macroscopic quantum devices. They validate our expectations that a quantum code can improve coherent control in neutron interferometry. The DF interferometer's insensitivity to vibration will enable it to be placed closer to the guide, thereby recovering neutron intensity by having a larger solid angle reach the detector. We anticipate relying on this and related quantum information theory approaches to construct a new series of compact neutron interferometer setups tailored to specific applications.

Primary Contact(s):

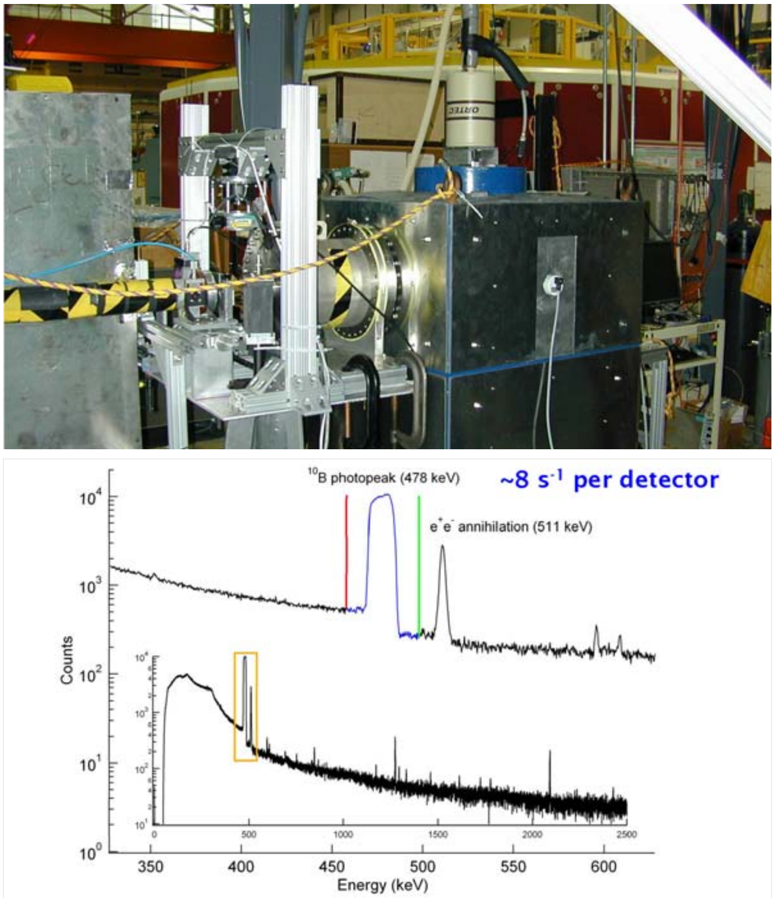
Dmitri A. Pushin	Mohamed Abutaleb	David G. Cory	Michael G. Huber
U. Waterloo	MIT	U. Waterloo	NIST
mitja@mit.edu	abutaleb@mit.edu	dcory@mit.edu	huberm@nist.gov

Metrology: *from the laboratory to quantitative measurements*

Metrology Research

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 beamline. The apparatus is functioning and the observed relative statistical precision of the gamma detector calibration is less than 0.1 %. Several systematic effects are being characterized at present including the effects of beam size, dead time, and neutron scattering. It is believed that the combined final uncertainties on these effects will be less than 0.1 %. In order to use this device to calibrate a thin foil "1/v" neutron detector, such as the one used in our beam-type neutron lifetime measurement, it is necessary to know additionally the wavelength of the beam. A wavelength measuring device was installed upstream of the detector and several wavelength measurements made during the past two years exhibit a relative statistical precision at the sub 0.1 % level. We are close to our goal of having a black neutron detector capable of counting a beam of neutrons with an absolute relative uncertainty of 0.1 %.



(Top) Photograph of Alapha-Gamma detector setup with the 1/v detector shown to the left. (Bottom) A typical alpha and gamma spectrum. (Photograph by: NI&D group.)

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 new neutron lifetime experimental results with previous 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.

Primary Contact(s):

Maynard S. Dewey	Jeffrey S. Nico	David M. Gilliam	Geoffrey L. Greene
301-975-4843	301-975-4663	301-975-6206	University of Tennessee
maynard.dewey@nist.gov	jeffrey.nico@nist.gov	david.gilliam@nist.gov	ggreene@utk.edu

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 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.

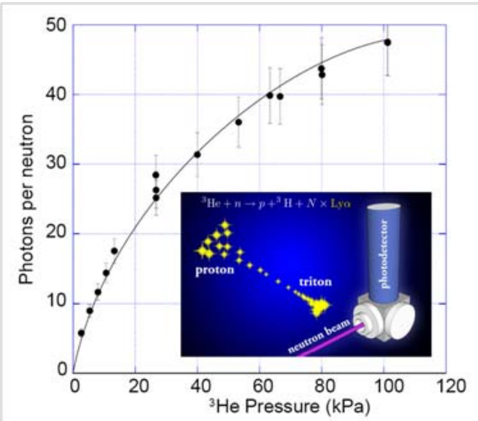


Figure 1: Lyman alpha photon yield per reacted neutron as a function of 3He pressure. The inset states the nuclear reaction and the cartoon indicates photon production and the experimental setup.

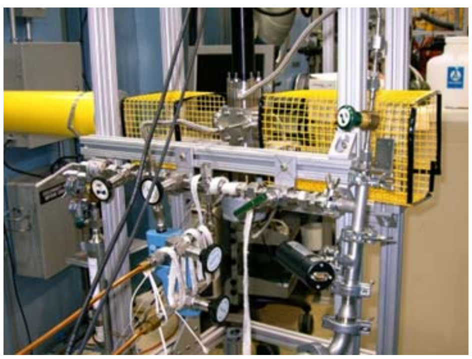


Figure 2: The 'LND' detector taking data at NG6-A beam-line in the guide hall. (Photograph by: NI&D group.)

The fundamental nuclear reaction that is the basis of the LAND is n + ^{3}He $\rightarrow$ 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. Our initial hypothesis was that the tritium atom was likely to be formed in an excited state that would quickly decay 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.

The experimental apparatus (*figure 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 ^{4}He, 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 2* shows the Lyα photon yield per reacted neutron. If the photon production were a result of the n + ^{3}He $\rightarrow$ 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.

Given that the signal in pure ^{3}He seemed to be coming from spectator atoms, we initiated a program to determine whether mixing the ^{3}He with other gases could increase the light yield from the neutron reaction. Rough spectral measurements from some noble gases (Xe, Kr, and Ar) are consistent with the source of the light being emission from the decay of noble-gas excimers genarated by the proton and triton; the fact that essentially no signal was seen from Ne, which has an excimer emission outside of the spectral range which can be directly observed by our detector. The efficiency of the Xe, Kr, and Ar mixtures with ^{3}He was high: the nuclear reaction energy is converted to far-ultraviolet radiation with efficiencies of up to 30 %, equivalent to tens of thousands of photons per absorbed neutron, as shown in Figure 41.

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. Further research on mixtures of ^{3}He and other noble gases show that the light signal can be easily amplified by factors of 1000 and more. We are now seeking to extend this research to use nuclear reactions other than with ^{3}He.

Primary Contact(s):

Alan K. Thompson	Charles W. Clark	Michael A. Coplan	Muhammad Arif
301-975-4666	301-975-3709	University of Maryland	301-975-6303
alan.thompson@nist.gov	charles.clark@nist.gov	coplan@umd.edu	muhammad.arif@nist.gov

High-Efficiency Neutron Detection and Spectroscopy

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, neutrino-less 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.

Figure 1.: Final assembly of the 16-channel neutron spectrometer. The detector was recently assembled and tested in the CNIF. (Photograph by: NI&D group.)

Figure 2: Photograph of the enclosure containing the prototype fast neutron detector at the Kimballton Underground Research Facility (KURF). (Photograph by: NI&D group.)

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. *Figure 1* shows the final assembly of a 16-channel spectrometer constructed in collaboration with Russian researchers at the Institute for Nuclear Research. 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. The detector was constructed in Russia and recently sent to NIST for testing. The detector was filled with liquid scintillator and tested with neutrons in the CNIF facility.

We are also working on a large volume detector to use in the underground environment where high efficiency is more important than energy resolution. A construction of a prototype detector was recently completed and assembled at Kimballton Underground Research Facility near Blacksburg, VA, as seen in *Figure 2*. It consists of six He-3 tubes placed between two large blocks of plastic scintillator. It has been taking data on the fast neutron flux continuously since July of 2010. Using knowledge gained from this detector, we will design and construct the larger-volume detector that will have a greater sensitivity to the fast neutron flux. Upon completion, the detector would be moved to other 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.

Primary Contact(s)

Jeffrey S. Nico	Herbert Breuer	Elizabeth J. Beise	Craig R. Heimbach
301-975-4663	University of Maryland	University of Maryland	301-975-8874
jeffrey.nico@nist.gov	hbreuer@umd.edu	beise@umd.edu	craig.heimbach@nist.gov

Probing Artificial Muscles with Neutrons

Ionic polymer metal composites (IPMCs) are a class of materials that exhibit actuation due to electrical stimulation with similarities to biological muscles, and are often referred to as artificial muscles. Although IPMCs have been studied for more than 10 years, the exact actuation mechanism is still not well understood. IPMCs are based on a solid polymer electrolyte, which is plated on both surfaces by dense layers of metal nanoparticles (e.g., platinum or gold) to serve as conductive electrodes, which resembles the membrane electrode assemblies used in fuel cells. Under the stimulus of a relatively low electric field (2 V – 3 V), IPMCs are capable of undergoing significant mechanical bending motion; an example of this is shown in *Figure 1.*

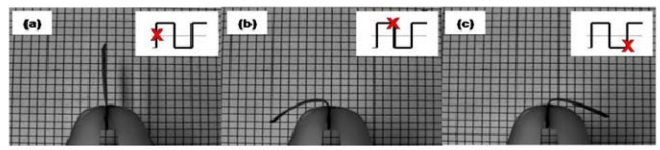


Figure 1: IPMC actuation under applied electrical voltage. Each image was captured at the position of X on the excitation square wave

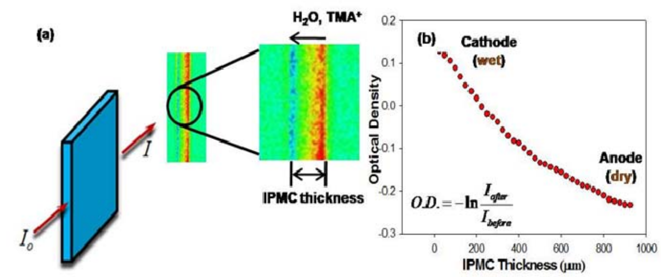


Figure 2: (a) Colorized images showing water/counterion -depleted zones represented by red pixels and water/counterion -rich areas represented by blue pixels. IPMC was subjected to 3 VDC. (b) Relative neutron optical density due to water/counterion gradient profile across the IPMC thickness.

One proposed mechanism for IPMC actuation that has commonly been discussed in the literature is an electrophoresis-like counterion and water redistribution within the nanostructured ionomer membrane. Since the ionic polymer is negatively charged with protons or alkali-metal cations as the counterions, these mobile cations in the hydrated membrane readily redistribute in response to an applied electric field to create cation-rich and cation-poor boundary layers near the electrode/membrane interfacial regions**.** As cations migrate toward the cathode, they drag along water molecules. This hydraulic action results in swelling near the cathode and contraction near the anode that gives rise to the bending force that curves the IPMC towards the anode.

The results of the neutron imaging are shown in *Figure 2*. Here the IPMC was oriented to allow neutrons to travel parallel to the anode and cathode surfaces. The resulting neutron transmission allows the mapping of water distributed through the plane of the IPMC from anode to cathode. In the figure, the image of the unstimulated state is compared to the state after an electrical stimulus of 3 V was applied for 30 s. The resulting change in neutron attenuation showed a rapid redistribution of water/conterions in the IPMC when the electrical stimulus was applied. When the polarization of the applied electric field is reversed the corresponding water/counterion distribution is also rapidly reversed, in direct support of the hydraulic model for the deformation of the IPMC due to the applied electric potential. Additional measurements were made using D_2O swollen IPMCs neutralized to contain sodium and tetramethylammonium counterions were also studied to separate the cation motion from the hydraulic motion. These results showed that both the cations and water migrate under electrical stimulation.

Primary Contact(s):

Robert B. Moore	David L. Jacobson	Daniel S. Hussey
Virginia Polytechnic Institute and State University	301-975-6207	301-975-6465
rbmoore3@vt.edu	david.jacobson@nist.gov	daniel.hussey@nist.gov

Calibrations and Standards *("Measurement Services")*

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 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. A summary of the new NIST capabilities was presented at the 21st International Conference on the Application of Acclelerators in Research and Industry. A survey of techniques was done to investigate providing calibration services for 2.5 MeV neutrons, but no NIST capability is currently in place. These generators, using the deuterium-deuterium reaction, are of some interest as they allow facilities access to neutrons without special nuclear material or tritium. They also produce no neutrons when turned off, as opposed to isotopic sources.

Primary Contact(s):

Craig R. Heimbach	Maynard S. Dewey	David M. Gilliam
301-975-8874	301-975-4843	301-975-6206
craig.heimbach@nist.gov	maynard.dewey@nist.gov	david.gilliam@nist.gov

Calibrated Neutron Sources

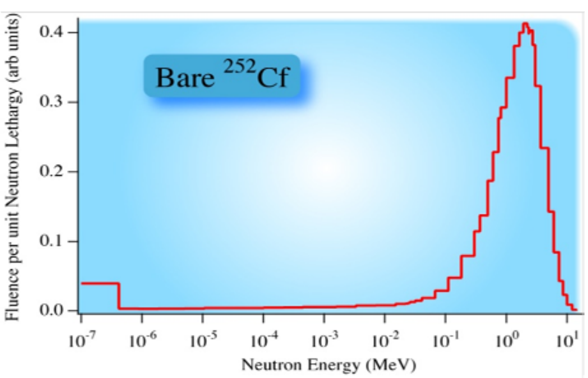


Figure 1: Energy spectrum of a ^{252}Cf *neutron source.*

ANSI N42.35 requires ^{252}Cf neutron sources encapsulated in 1 cm of steel with a fluence of 2x10^4 n/s ±20%. NIST designed a compliant source. NIST acquired, calibrated and delivered several such sources for DOE laboratories, including the Nevada Test Site, and for the U.S. Navy. 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. *Figure 1* shows a reprentative energy spectrum from such sources.
During the last several years, NIST has responded to the national need of calibrated neutron sources. Calibrated sources were delivered to the Navy and DOE laboratories to perform equipment testing as required by DoD and ANSI standards.

Primary Contact(s):

David M. Gilliam	Alan K. Thompson	Maynard S. Dewey
301-975-6206	301-975-4666	301-975-4843
david.gilliam@nist.gov	alan.thompson@nist.gov	maynard.dewey@nist.gov

Neutron Device Calibrations

NIST provides the national reference for the calibration of neutron radiation detectors and for neutron personnel dosimeters. The reference sources are unmoderated ^{252}Cf and ^{252}Cf moderated with a D_2O sphere. The spontaneous fission neutron spectrum of unmoderated ^{252}Cf 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.

Primary Contact(s):

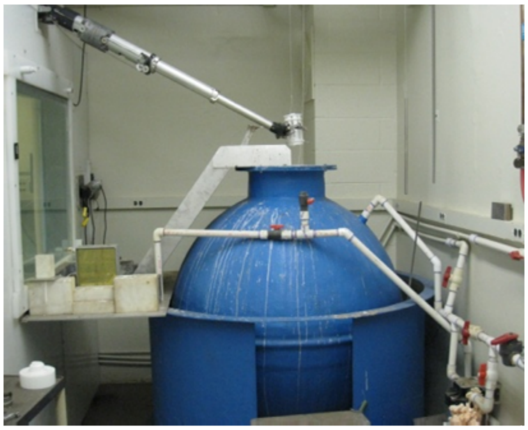
Alan K. Thompson
301-975-4666
alan.thompson@nist.gov

David M. Gilliam
301-975-6206
david.gilliam@nist.gov

Jeffrey S. Nico
301-975-4663
jeffrey.nico@nist.gov

Neutron Source Strength Calibrations

The neutron source calibration facility operated by NIST is a world-class calibration laboratory providing neutron source calibration services for radioisotopic sources with neutron emission rates ranging from 5×10^{5} to $10^{10}\ s^{-1}$. Calibrations are performed using the manganous sulfate bath technique 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 2.5 %, depending on the details of the source encapsulation.



Photograph of the Mn bath. (Photograph by: NI&D group.)

The principal customers for this service are commercial vendors of radioisotopic neutron sources, manufacturers of instruments and devices that monitor radiation exposure and dose, secondary calibration laboratories that service the aforementioned radiation monitoring instrumentation, nuclear electric generating stations, nuclear fuel fabrication facilities, US Department of Defense establishments, and government and private research and development laboratories. In addition to its external customers, the neutron source calibration facility also provides important contributions to other neutron irradiation and calibration services provided by NIST, as well as to intramural research programs in neutron metrology and fundamental neutron physics.

During the period 2009-2010, 8 external vendor neutron sources were calibrated. In support of these measurements, our own standard neutron sources (NBS–1, BIPM) and the background rates were measured several times. NIST provides a neutron emission rate calibration service in support of US nuclear programs.

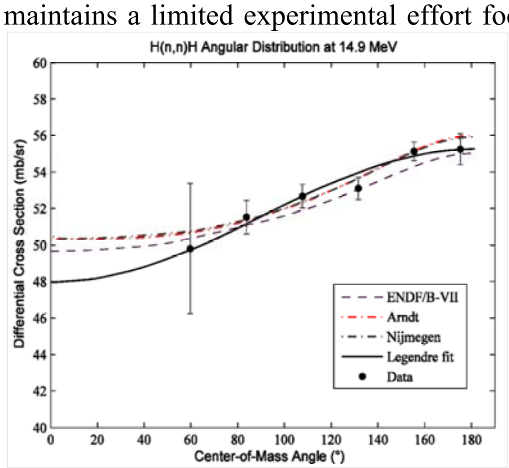
Primary Contact(s):

Maynard S. Dewey
301-975-4843
maynard.dewey@nist.gov

David M. Gilliam
301-975-6206
david.gilliam@nist.gov

Neutron Cross Section Standards

NIST continues to be deeply involved with measurements and evaluations of neutron cross section standards. NIST maintains a limited experimental effort focused on improvements to the database of the standards. 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. This work was initiated as a result of problems that became apparent in evaluations of this cross section. The work has been published in Phys. Rev. C82 014001 (2010). These data were obtained by detecting the scattered protons from scattering of neutrons on hydrogen. The large uncertainty for our point near 60 degrees in the CMS is a result of significant background at smaller angles using the proton detection method. A new experiment is now underway in which the scattered neutrons are being detected. With this method measurements can be made at smaller CMS angles with smaller uncertainties. Only one experiment has been done (in 1967) at small CMS angles and that experiment indicates higher cross sections near zero degrees in the CMS. Also some improvements to measurements at 10 MeV by this collaboration



Comparison of new measurements of the hydrogen scattering cross section with the ENDF/B-VII evaluation and the Arndt and Nijmegen calculations.

were published in Phys. Rev. C82 039901 (2010). 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.

Data from a number of NIST collaborations focused on other applications have produced measurements useful for the standards program. This includes measurements made at NG6 of the spin-dependent portion of the coherent neutron scattering length for ^{3}He that were recently completed. These data can be used in R-matrix analyses to improve the ^{3}He(n,p) standard cross section. Also measurements are underway now of the ^{6}Li(n,t) cross sections at sub-thermal energy. Following the completion of that work, measurements will be made of the ^{10}B(n,α) cross sections at that energy. These will be the first absolute measurements of these cross sections in this energy region. These two cross sections are very important standards in the low energy region.

A major effort was the recently completed 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 more than 100 page detailed journal paper on this work was published in Nuclear Data Sheets 110 3215 (2009). 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. These standards were accepted for use in the ENDF/B-VII.0 evaluation. In an effort to continually update the standards so they will be current for use by data libraries, 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 second Consultants' Meeting of this project, chaired by the NIST representative, was held in Vienna in October 2010. At the meeting the cross section database was discussed and updated; further work was done to help decide what inelastic scattering cross section should be used as a reference cross section; an investigation was continued on an additional energy region where gold capture could be a reference cross section; and 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 with the objective of reducing uncertainties at the highest and lowest energies.

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 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 which provided covariances in the regions not included in our evaluation, so now the very well defined covariances obtained from the standards evaluation process are included in the new ENDF/B-VII mod, ENDF/B-VII.1.

Impact: 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.

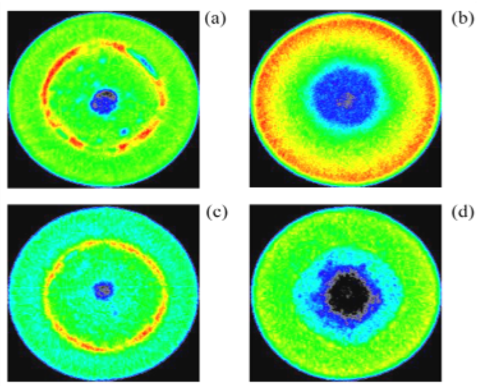
Primary Contact(s):

Allan D. Carlson	Alan K. Thompson	David M. Gilliam
301-975-5570	301-975-4666	301-975-6206
allan.carlson@nist.gov	alan.thompson@nist.gov	david.gilliam@nist.gov

Applied Research: *from the laboratory to the customer*

Energy and the Environment

Neutron Imaging of Lithium and Alkaline Batteries



Comparison of the changes in an alkaline AA cell after operation at two different constant currents, where black is low neutron attenuation, red is high neutron attenuation. (a) Fresh cell before operation at 50 mA, (b) discharged cell after operation at 50 mA for 52.5 h, (c) fresh cell before operation at a constant 1 A, (d) discharged cell after operation at 1 A for about 70 min. The electrolyte has an initially uniform distribution (green) in the anode (interior) and in the cathode (exterior), and the separator (red/yellow) is clearly visible in (a) and (c).

A common topic in energy systems is the need for *in situ* measurement of the mass transport of light ion species such as hydrogen or lithium. Neutron imaging has played a critical role in the understanding of water transport in proton exchange membrane fuel cells (PEMFCs). This is due to the high sensitivity of neutrons to hydrogen, while having relatively small sensitivity to many common materials of construction such as aluminum and carbon. Neutron imaging can play a similar role in advanced battery development by providing *in situ* measurements of hydrogen or lithium distributions at different states of charge of the battery. The intense, highly collimated, thermal neutron beam has high penetration lengths through battery chemistries of interest, with sufficient sensitivity to measure changes in the ion distribution; by using high resolution imaging detectors, it is possible to resolve features down to 10 µm.

In alkaline primary cells, the neutron attenuation is dominated by the aqueous electrolyte. Tomograms (three-dimensional images) of two AA alkaline cells were acquired before and after discharge to a cell potential of 0 V. Shown in the figure are tomographic slices through two different AA batteries after the end of life achieved by two different current draw conditions, 50 mA and 1 A. In the initial state, the distribution of electrolyte is homogenous in the anode and the cathode. Also, the separator, which is composed of a porous hydrogenous material such as rayon where the pores are filled with electrolyte solution, is clearly visible and is highly attenuating to neutrons. The distribution of the electrolyte after the cell potential has fallen to 0 V clearly depends on the discharge rate. By optimizing particle size to reduce the removal of electrolyte from the anode, it is possible to increase the cell capacity. In more recent experiments, two-dimensional neutron imaging has been used to study a wound prismatic lithium-ion battery. By using high resolution neutron imaging, the thermal expansion of the battery on charge and discharge could be directly measured.

Primary Contact(s):

Daniel Hussey	David L. Jacobson	Anna G. Stefanopoulou
(301)975-6465	301-975-6207	University of Michigan
daniel.hussey@nist.gov	david.jacobson@nist.gov	annastef@umich.edu

Neutron Tomography of Hydrogen Storage Bed

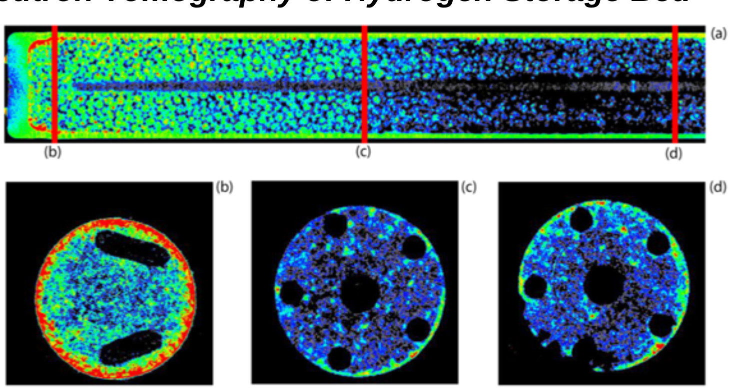


Figure 1. (a) Slice along the length of the storage bed, (b)-(d) axial slices from the locations denoted in (a).

Future hydrogen fuel cell vehicles will require hydrogen storage vessels that efficiently store and quickly release the hydrogen fuel. The hydrogen uptake in most storage materials strongly depends on the thermal environment, thus optimizing the fuel tank will require understanding the coupled heat and mass transport system. While many techniques exist to measure the volume average of the hydrogen uptake, to date no method exists that can measure the full three-dimensional hydrogen distribution within the storage vessel. In order to address this shortcoming, a prototype hydrogen storage bed has been studied using neutron tomography and radiography.

The prototype metal hydride bed consisted of a ≈90 % porous aluminum foam filled with $LaNi_{4.78}Sn_{0.22}$ powder. The foam provided structural integrity and enhanced the thermal conductivity of the system. A heater rod with four turns ran the length of the bed and was in contact with the aluminum foam to heat the metal hydride during hydrogen desorption. Hydrogen gas was introduced into and removed from the bed via a hollow stainless steel filter tube in the center. One aspect of this study involved acquiring two tomograms of the hydrogen storage bed: the first was after the bed was heated to 100 °C and evacuated to a pressure below 10^{-6} mbar; the second was after the bed was charged with about 12 standard liters of hydrogen. In *figure 1* slices through the 3-D image of a hydrogen storage bed after the addition of 12 standard liters of H_2 are shown. Red indicates higher concentration of hydrogen, black the absence of hydrogen. (a) Slice along the length of the storage bed, (b)-(d) axial slices from the locations denoted in (a). Hydrogen absorption is an exothermic process, and the hydrogen uptake decreases with increasing temperature. This is why hydrogen is seen to preferentially absorb along the outer circumference in (a), and accumulate towards the end of the storage bed. This is a result of the absorption of hydrogen by $LaNi_{4.78}Sn_{0.22}$ being exothermic coupled with reduced hydrogen uptake at higher temperatures. From neutron imaging an accurate picture of the hydrogen distribution in a storage bed can be obtained and compared with models of heat and mass transfer in order to optimize the storage and transport of hydrogen in the bed.

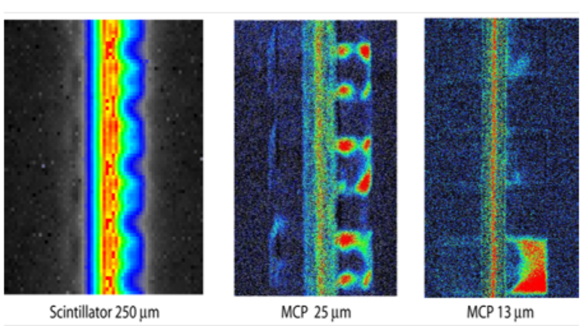
Primary Contact(s):

Daniel S. Hussey	David L. Jacobson	Robert Bowman
(301)975-6465	(301)975-6207	Department of Energy
daniel.hussey@nist.gov	david.jacobson@nist.gov	Robert.Bowman@ee.doe.gov

Industrial Applications

Evolution of Image Spatial Resolution

Measuring the through-plane water content in a hydrogen fuel cell is critical to understanding this complicated heat and mass transport environment, where the waste heat produces temperature gradients, the inlet and outlet gases are a two phase flow phenomenon, and the porous media has a wide range of both pore diameters and wettabilities. Neutron imaging has yielded valuable insight into the water content of fuel cells, since minimal changes to a test section are needed. A limit of neutron imaging is the achievable spatial resolution, which is primarily dominated by the detector. This effect is clearly demonstrated in, where the water content in a fuel cell was measured by three separate detectors at nominally the same operating conditions. With the new "10 micron" detector, researchers using the NIST neutron imaging facility are able to directly measure the water content and distribution in the porous media with unprecedented details that have been never achieved before.



Progression of improved spatial resolution in the measured through plane direction of a hydrogen fuel cell.

The approach at NIST is to define critical technical parameters of detectors, collaborate scientifically, and provide support to academic and industrial partners in the development of such detectors. This collaborative effort resulted in the development of high resolution detectors based on Micro-Channel Plates (MCPs) with sub-ten micrometer channel diameters and readout electronics capable of neutron count rates of greater than1 MHz; this represents a 20-fold improvement in the spatial resolution and factor of 1000 increase in neutron count rate over 4 years and is the current state-of-the-art in neutron detection. While the range of the charged particles in the MCPs limits the current resolution of this technology to about 10 µm, there is still development work in progress to increase the field of view for wider use of the enhanced imaging capability. Since there is a very significant interest in the studies of water transport, content, and mapping in catalysts layers and membranes, there is also ongoing exploration of other means to further improve the spatial resolution of neutron imaging.

Primary Contact(s):

Daniel S. Hussey
(301)975-6465
daniel.hussey@nist.gov

David L. Jacobson
(301)975-6207
david.jacobson@nist.gov

Characterization of Porous Transport Media for Hydrogen Fuel Cells

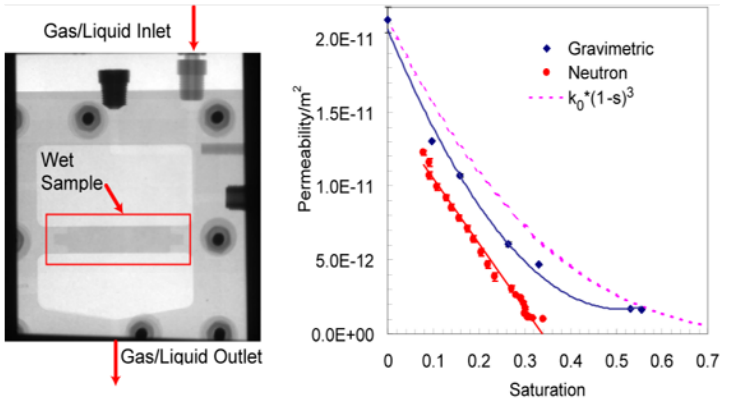


Figure 1: Left is a neutron image of the liquid and gas permeability measurement device. Right shows a comparison of the air permeability as measured by neutron radiography and gravimetrically, as well as a common functional form for the permeability as a function of saturation.

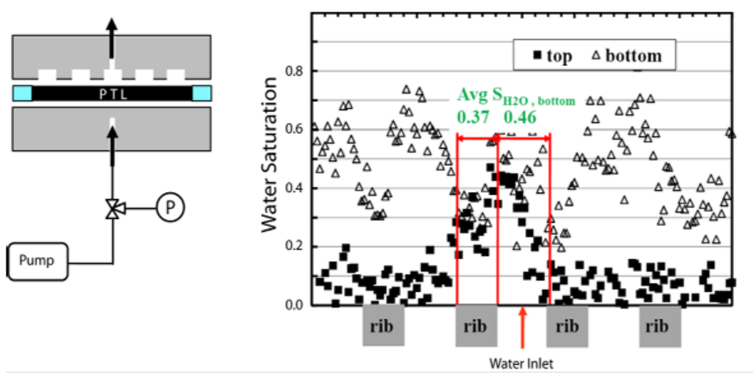


Figure 2: Left is the measurement device used in the experiment to mimic the compression of the PTL in a real fuel cell with channels and ribs. Right shows the measured water saturation as a function of position.

Efficiently managing water transport in proton exchange membrane fuel cells (PEMFCs) is critical to the performance, cost, and durability in order for this technology to become the next automobile engine. Accurate, *in situ* characterization of the physical properties of a porous transport layer (PTL) – porosity distribution, liquid saturation as a function of pressure, liquid and gas permeability, thermal conductivity – is critical to improving the understanding, and hence manipulation, of the water transport in PEMFCs. In collaboration with the University of Kansas, neutron imaging has been used to perform measurements of the liquid and gas permeability and the liquid saturation as a function of pressure of PTLs. Shown in Figure 1 on the left is a neutron image of the device that was developed to measure both the liquid and gas permeability of PTL's.

On the right in *Figure 1* is a comparison of the in-plane permeability of air through the porous transport layer as a function of saturation as measured by neutron radiography and gravimetrically, as well as a common functional form for the permeability as a function of saturation. Since the gravimetric method requires disassembly, it is possible for the saturation in the porous transport layer to change during the measurement; this change can be directly observed by neutron radiography. An advantage of neutron imaging to traditional gravimetric methods is that the water mass measurement is performed *in situ* without disassembling the device. Also, the measurement can be made in a manner that is consistent with how the porous transport layer is used in an actual fuel cell; thus the liquid water content and distribution during the measurement is known and one can use the locally resolved data, for instance to understand the effects of non-uniform compression.

Such a measurement is shown in *Figure 2*, which shows a device designed to mimic the compression experienced by a PTL in a real fuel cell with channels and ribs. The ribs compress the PTL, altering the pore size distribution and is seen to reduce the saturation at the top of the PTL after the applied pressure is sufficient for the liquid water to breakthrough to the top of the PTL. The ability to resolve the variation in saturation is critical to accurately model and control the water transport in hydrogen fuel cells.

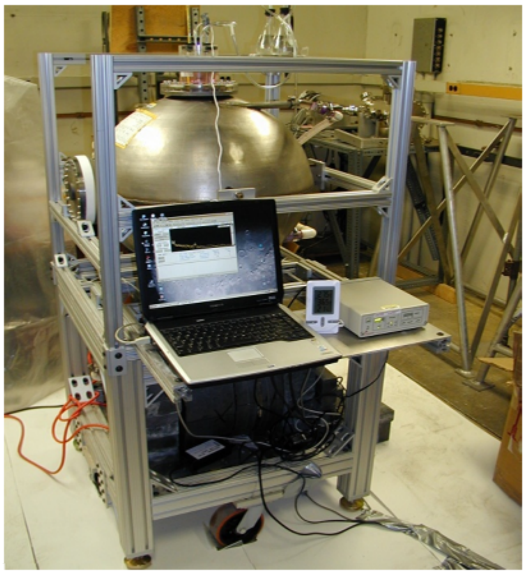
Primary Contact(s):

Trung Van Nguyen   Daniel S Hussey   David L. Jacobson

University of Kansas | (301)975-6465 | (301)975-6207
email: cptvn@ku.edu | daniel.hussey@nist.gov | david.jacobson@nist.gov

Homeland Security

New Manganese Sulfate Bath



A new reduced-volume manganese bath permits calibration of low-intensity neutron sources as required for DHS applications. (Photograph by: NI&D group.)

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 reduced-volume bath so that a greater fraction of the manganese is close to the source and therefore induces higher manganese activity per unit volume. 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. A 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. The new calibration facility is required to meet the demand. The reduced-volume bath has been running continuously for more than two years now. Several test-sources have been calibrated for DHS customers. The bath has so far been completely free of the usual leakage problems of manganese sulfate systems, and the water-vapor-barrier vent has kept the bath volume very nearly constant.

Primary Contact(s):

David M. Gilliam | Maynard S. Dewey | Craig R. Heimbach | Alan K. Thompson
301-975-6206 | 301-975-4843 | 301-975-8874 | 301-975-4666
david.gilliam@nist.gov | maynard.dewey@nist.gov | craig.heimbach@nist.gov | alan.thompson@nist.gov

Active Interrogation Standards

Active interrogation involves directing nuclear radiation into a closed container and measuring secondary radiations to gain information about the contents of the container.

An ISO Standard Cargo Container has been outfitted with the four cargo regions specified in N42.41. The section filled with hollow steel cubes can be seen. Part of each cargo region is on tracks to permit access to the central rack for threat specimens or stimulants. (Photograph by: NI&D group.)

Typically neutrons or high-energy photons are used as the impinging radiation. Active interrogation has a greater potential for detection of small quantities of Special Nuclear Material than passive detectors. It also holds the promise of detection and identification of non-nuclear materials, such as hazardous chemicals and explosives, including Vehicle-Borne Improvised Explosive Devices (VBIED). NIST has lead the drafting committee that wrote and successfully balloted 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.

Primary Contact(s):

David M. Gilliam	Alan K. Thompson
301-975-6206	301-975-4666
david.gilliam@nist.gov	alan.thompson@nist.gov

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.

Primary Contact(s):

Alan K. Thompson	David M. Gilliam
301-975-4666	301-975-6206
alan.thompson@nist.gov	david.gilliam@nist.gov

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.

Primary Contact(s):

Craig R. Heimbach	David M. Gilliam
301-975-8874	301-975-6206
craig.heimbach@nist.gov	david.gilliam@nist.gov

PUBLICATIONS

Babcock, E., Boag, S., Becker, M., Chen, W.C., Chupp, T.E., Gentile, T.R., Jones, G.L., Petukhov, A.K., Soldner, T.,and Walker, T.G., "Effects of High Flux Neutron Beams on He-3 Cells Polarized In-Situ with Spin-Exchange Optical Pumping," Phys. Rev. A **80**, 033414 (2009).

Borgmeyer, B., Wilson, C., Winholtz, R.A., Ma, H., Jacobson, D.L., and Hussey, D.S., “Heat Transport Capability and Fluid Flow Neutron Radiography of Three-Dimensional Oscillating Heat Pipes,” J. of Heat Transfer-Transactions of the ASME, **132**, 061502 (2010).

Boukharouba, N., Bateman, F.B., Carlson, A.D., Brient, C.E., Grimes, S.M., Massey, T.N., Haight, R.C., and Carter, D.E., “Measurement of the *n-p* Elastic Scattering Angular Distribution at E_n = 14.9 MeV,” Phys. Rev. C **82**, 014001 (2010).

Chen, W.C., Erwin, R., McIver III, J.W., Watson, S., Fu, C.B., Gentile, T.R., Borchers, J.A., Lynn, J.W., and Jones, G.L., “Applications of He-3 Neutron Spin Filters at the NCNR," Physica B **404**, 2663-2666 (2009).

Cooper, R., Bass, C.D., Beise, E., Breuer, H., Byrne, J., Chupp, T.E., Coakley, K.J., Dewey, M.S., Fisher, B., Fu, C., Gentile, T.R., McGonagle, M., Mumm, H.P., Nico, J.S., Thompson, A.K., and Wietfeldt, F.E., “An Experiment for the Precision Measurement of the Radiative Decay Mode of the Neutron,” Nucl. Instrum. Meth., 219-223 (2009).

Cooper, R., Chupp, T.E., Dewey, M.S., Gentile, T.R., Mumm, H.P., Nico, J.S., Thompson, A.K., Fisher, B., Kremsky, I., Wietfeldt, F.E., Beise, E., Breuer, H., Kiriluk, K.G., Bryne, J., Coakley, K.J., and Fu, C., “Radiative Beta Decay of the Free Neutron,” Phys. Rev. C, 23-40, (2009).

Dewey, M.S., "Measuring 6Li(n,t) and 10B(n,alpha) Cross Sections using the NIST Alpha-Gamma Device,” *Proc. 13th ASTM-EWGRD Reactor Dosimetry Symposium,* Akersloot, Netherlands, World Scientific Publishing Co., Hackensack, New Jersey, (2009).

Dewey, M.S., Coakley, K., Gilliam, D., Greene, G., Laptev, A., Nico, J.S., Snow, W., Wietfeldt, F., and Yue, A., "Prospects for a New Cold Neutron Beam Measurement of the Neutron Lifetime,” Nucl. Instrum. Meth A. **611**, 189-193 (2009).

Fu, C.B., Gentile, T.R., and Snow, W.M., "Constraints On Monopole-Dipole Interactions Of Wisps From Polarized Gas Relaxation Time," in *Proc. of the Fifth Meeting on CPT and Lorenz Symmetry,”* Bloomington, Indiana, (in press).

Fu, C.B., Gentile, T.R., Jones, G.L., Chen, W.C., Erwin, R., Watson, S., Broholm, C., Rodriguez-Rivera, J. A., and Scherschligt, J. "A Wide-Angle Neutron Spin Filter System Using Polarized He-3," Physica B; doi:10.1016/j.physb.2010.10.002. (in press).

Gentile, T.R., Bass, C.D., Nico, J.S., Breuer, H., and Farrell, R., "Magnetic Field Effects on Large Area Avalanche Photodiodes at Cryogenic Temperatures," Nucl. Instr. and Meth. A; doi:10.1016/j.nima.2010.08.061(in press).

Gentile, T.R., Brown, S.W., Lykke, K.R., Shaw, P.S., and Woodward III, J.T., “Internal Quantum Efficiency Modeling of Silicon Photodiodes." Appl. Optics **49**, 1859-1864 (2010).

Gericke, M., Page, S. Ramsay, D., Alarcon, R., Balascuta, S., Barron, L., Bowman, J.D., Carlini, R.D., Chen, W., Chupp, T.E., Crawford, C., Covig, S., Dabaghyan, M., Freedman, S.J., Gentile, T.R., Gillis, R.C., Greene, G.L., Hersman, F.W., Ino, T., Jones, G.L., Lauss, B., Leuschner, M., Losowki, B., Mahurin, R., Masuda, Y., Mei, J., Mitchell, G.S., Muto, S., Nann, H., Penttila, S.I., Salas-Bacci, S., Santra, S., Seo, P.-N., Sharapov, E., Sharma, M., Smith, T., Snow, W.M., Wilburn, W.S., an Yuan, V, "Parity Violation in Neutron-Proton Capture: the NPD Gamma Experiment," Nucl. Instrum. and Meth. A **611**, 239-243 (2009).

Hickner, M. A., Siegel, N. P., Chen, K. S., Hussey, D. S., and Jacobson, D. L., "Observations of Transient Flooding in a Proton Exchange Membrane Fuel Cell Using Time-Resolved Neutron Radiography," J. of Electrochemical Soc., **157**, B32-B38 (2010).

Hickner, M. A., and Hussey, D. S., "Neutron Radioscopy: Industrial and Scientific Applications," Wiley Encyclopedia of Analytical Chemistry, R.A. Meyers (ed.), Chapter A 9069 (2010).

Huber, M.G., Wietfeldt, F.E., Gentile, T.R., Chen, W.C., Arif, M., Pushin, D.A., Yang, L., and Black, T., "Precision Measurement of the Neutron He-3 Spin-Dependent Scattering Length Using Neutron Interferometry," Nucl. Instrum. Meth. A 611, 235-238 (2009).

Hussey, D. S., Jacobson, D. L., Arif, M., Coakley, K. J., and Vecchia, D. F., "In Situ Fuel Cell Water Metrology at the NIST Neutron Imaging Facility," J. Fuel Cell Science Tech., **7**, 021024 (2010).

Jacobson, D.L., Hussey, D.S., Baltic, E., Udovic, T.J., Rush, J.J., and Bowman, Jr., R.C., "Neutron Imaging Studies of Metal-Hydride Storage Beds," Int. J. of Hydrogen Energy, 35, 12837 - 12845 (2010).

Jacobson, D.L.,and Hussey, D.S., "High Resolution Neutron Radiography Analysis of Proton Exchange Membrane Fuel Cells," Modern Aspects of Electrochemistry, Vol. **49**, ed. by, Pasaogullari, Ugur, Wang, Chao-Yang (2010).

Krycka, K.L., Booth, R.A., Hogg, C.R., Ijiri, Y., Borchers, J.A., Chen, W.C., Watson, S.M., Laver, M., Gentile, T.R., Dedon, L.R., Harris, S., Rhyne, J.J., and Majetich, S.A., "Core-shell Magnetic Morphology of Structurally Uniform Magnetite Nanoparticles," Phys. Rev. Lett. **104**, 207203 (2010).

Krycka, K.L., Borchers, J.A., Booth, R., Hogg, C.R., Ijiri, Y., Chen, W.C., Watson, S.M., Laver, M., Gentile, T.R., Harris, S., Dedon, L.R., Rhyne, J.J., and Majetich, S.A., "Internal Magnetic Structure of Magnetite Nanoparticles at Low Temperature," J. Appl. Phys. **107**, 09B525 (2010).

Krycka, L., Booth, R., Borchers, J.A., Chen, W.C., Conlon, C., Gentile, T.R., Hogg, C., Ijiri Y., Laver, M., Maranville, B.B., Majetich, S.A., Rhyne, J., and Watson, S.M., "Resolving 3D Magnetism in Nanoparticles Using Polarization Analyzed SANS," J. Physica B, **404**, 2561-2564 (2009).

Lee, S.W., Hussey, D.S., and Jacobson, D.L., "Development of the Grating Phase Neutron Interferometer at a Monochromatic Beam Line," NIMA, **605**, 16-20 (2009).

Nico, J.S., "Neutron Beta Decay", J. Physica G., **36**, 104001 (2009).

Park, J.K., Jones, P.J., Sahagun, C., Page, K., Hussey, D.S., Jacobson, D.L., Morgan, S.E., and Moore, R.B., "Electrically–Stimulated Gradients in Water and Counterion Concentrations within Electroactive Polymer Actuators," Soft Matter, **6**, 1444-1452 (2010).

Quan, P., Lai, M.C., Jacobson, D.L., Hussey, D.S., Kumar, A., and Hirano, S., "Time-Resolved Water Measurement in a PEM Fuel Cell Using High-Resolution Neutron Imaging Technique," J. Cell Science Technol., **7**, 051009 (2010).

Trabold, T.A., Owejan, J.P., Gagliardo, J.J., Jacobson, D.L., Hussey, D.S., and Arif, M., "Use of Neutron Imaging for Proton Exchange Membrane Fuel Cell (PEMFC) Performance Analysis and Design," Handbook of Fuel Cells, Volume 5, Chapter 44, (2009).

Invited Talks

Arif, M., "QIP - Enhance Neutron Interferometry," NIST Quantum Based Measurements and Future Initiatives, Breckenridge, Colorado, November 2010.

Arif, M., "Neutron Interferometry: The Vision Superman Should Have Had," American Conference on Neutron Scattering (ACNS) 2010, Ottawa, Canada, June 2010.

Arif, M., "Neutron Physics Research at NIST," American Physical Society Division of Nuclear Physics (APS-DNP) Meeting, Waikoloa, Hawaii, October 2009.

Arif, M., "The NIST Center for Neutron Research (NCNR) Expansion and the Impact on Research," "The Fundamental Neutron Physics Program at NIST," and "Applied Neutron Research at the Physics Laboratory at NIST," The First Special Summer Lecture on Neutron Physics, Optics, and Precision Measurements, Korea Atomic Energy Research Institute (KAERI), Daejon, South Korea, August 2009.

Dewey, M. Scott, "Fundamental Properties on the Neutron," NIST 2009 Summer School on Fundamental Physics, Gaithersburg, Maryland, June 2009.

Huber, M.G., "Measuring the Neutron's Mean Square Charge Radius Using Neutron Interferometry," Department of Physics, Univ. of Maryland, College Park, Maryland, November 2010.

Hussey, D.S., "Water Content Measurement of Gas Diffusion Media and Membranes by Neutron Radiography," 218th Electrochemical Society (ECS) Meeting, Las Vegas, Nevada, October 2010.

Hussey, D.S., "Neutron Imaging and the Study of Electrochemical Energy Sources," Department of Electrical and Computer Engineering Seminar, Howard Univ., Washington, D.C., September 2010.

Hussey, D.S., "Neutron Imaging of Water," Los Alamos National Laboratory (LANL)/Advanced Industrial Science & Technology (AIST)/New Energy & Industrial Technology Organization (NEDO) Fuel Cell Workshop, Honolulu, Hawaii, August 2010.

Hussey, D.S., "The Developments in High Resolution Neutron Radiography at NIST," Los Alamos National Laboratory (LANL)/Advanced Industrial Science & Technology (AIST)/New Energy & Industrial Technology Organization (NEDO) Fuel Cell Workshop, Palm Springs, California, November 2009.

Hussey, D.S., "Neutron Imaging and the Study of Electrochemical Energy Sources," Department of Chemical Engineering Seminar, Univ. of Maryland, College Park, Maryland, November 2009.

Hussey, D.S. "Two Phase Flow Visualization with Real-Time Neutron Radiography," American Society of Mechanical Engineers (ASME) Heat Transport Conference, San Francisco, California, July 2009.

Hussey, D.S., "Feasibility of Vapor-liquid Contactor Studies via Neutron Tomography," The 2009 Annual American Nuclear Society Meeting, Atlanta, Georgia, June 2009.

Hussey, D.S., "Principles of Neutron Imaging," Neutron Scattering Society of America (NSSA) International Conference on Neutron Scattering (ICNS) 2009, Knoxville, Tennessee, May, 2009.

Jacobson, D.L., "Neutron Radiography and Tomography for In Situ Imaging of Hydrogen and Lithium," Materials Research Society (MRS) Fall Meeting, Boston, Massachusetts, November 2010.

Jacobson, D.L., “Neutron Radiography and Tomography for In Situ Imaging of Hydrogen and Lithium,” The United States Army Tank Automotive Research, Development and Engineering Center (TARDEC), Warren, Michigan, November 2010.

Jacobson, D.L., “Neutron Imaging Study of the Water Transport in Operating Fuel Cells, “ The United Stated Council for Automotive Research (USCARS) Fuel Cell Tech Team Review, Detroit, Michigan, August 2010.

Jacobson, D.L., “Neutron Imaging Study of the Water Transport in Operating Fuel Cells,” The Department of Energy Merit Review, Washington D.C., June 2010.

Jacobson, D.L., “Understanding the Water Transport in Hydrogen Fuel Cells Using Neutron Radiography,” Neutron Scattering Society of America (NSSA) International Conference on Neutron Scattering (ICNS) 2009, Knoxville, Tennessee, May 2009.

Jacobson, D.L., “Using Neutron Imaging to Study Hydrogen Fuel Cells and Hydrogen Storage,” Hydrogen Symposium 2009, Purdue Univ., West Lafayette, Indiana, April 2009.

Jacobson, D.L., “Freeze Testing Fuel Cells at NIST Using Neutron Radiography,” Nuvera Freeze Workshop, Nuvera Fuel Cells, Inc., Billerica, Massachusetts, January 2009.

Nico, J.S., “Measuring the Neutron Lifetime,” American Physical Society Spring Meeting 2010, Washington, D. C., February 2010.

Nico, J.S., “Physics with Neutron Decay,” Department of Physics Colloquium, North Carolina State Univ., Raleigh, North Carolina, April 2009.

Scientific and Technical Staff Vitae

ARIF, MUHAMMAD, PHYSICS, B.Sc., Dacca Univ., Bangladesh, 76; M.Sc., Ohio Univ., 80; Ph.D., Univ. of Missouri, 86; Univ. of Missouri; Postdoctoral Fellow, 86-88; Physicist, NIST, 88-03; Group Leader, 03-present. Res: Neutron and X-ray scattering, neutron interferometry, neutron imaging. Member: American Physical Society.

BALTIC, ELIAS M., AERONAUTICAL SCIENCE, B.Sc., Embry Riddle Aeronautical Univ., 01-05. NIST, 05-present. Engineering Technician, Res: Proton exchange membrane fuel cells, neutron radiography, and tomography

BASS, CHRISTOPHER D., PHYSICS, B.Sc., Indiana Univ., 99; M.Sc., Indiana Univ., 01; Ph.D., Indiana Univ., 08; National Research Council Postdoctoral Fellow, Neutron Interactions and Dosimetry Group, Physicist, NIST, 08-10.. Res: Precision measurements of parity-violating hadronic weak interactions, measurement of the neutron radiative decay, fast neutron spectroscopy. Member: APS, NSSA

DEWEY, MAYNARD S., PHYSICS, B.Sc., State Univ. of New York at Stony Brook, 78; Ph.D., Princeton Univ., 84; Research Assoc., Princeton Univ., 86; Physicist, NIST, 86-present. Res: Neutron beta decay studies, neutron fluence measurements, neutron source strength measurements. Member: American Physical Society.

GENTILE, THOMAS R., PHYSICS. B.Sc., State Univ. of New York at Stony Brook, 79; Ph.D., Massachusetts Institute of Technology, 90; Research Fellow, California Institute of Technology, 90-92; Physicist, NIST, 93-present.. Res: Neutron polarization based on polarized He-3, fundamental neutron physics. Member: Fellow of the American Physical Society

HUBER, MICHAEL G., PHYSICS, B.A., Kalamazoo College 01; Ph.D., Tulane Univ., 09; National Research Council Postdoctoral Fellow, Neutron Interactions and Dosimetry Group, NIST, 09- present. Res: Neutron interferometry, neutron lifetime, neutron scattering. Member: American Physical Society.

HUGHES, PATRICK, PHYSICS. B.Sc., Univ. of Maryland, 01; Ph.D., Univ. of Maryland, 07; Postdoctoral Research Assoc., Univ. of Maryland, 07-08; National Research Council Postdoctoral Fellow, NIST, 08-10. Res: Neutron detection, photon generation from neutron interactions with He-3. Member: AGU.

HUSSEY, DANIEL S., PHYSICS, B.Sc., Univ. of New Hampshire, 95; M.Sc., Indiana Univ., 01; Ph.D., Indiana Univ., 03; National Research Council Postdoctoral Fellow, NIST, 04-06; Physicist, NIST, 2006-present. Res: Neutron imaging, neutron optics, neutron interferometry, proton exchange membrane fuel cells. Member: The Electrochemical Society, American Physical Society.

JACOBSON, DAVID L., PHYSICS, B.A., Westminster College, 90; Ph.D., Univ. of Missouri, 96; Doctoral Fellow, Univ. of Missouri, 96; National Research Council Postdoctoral Fellow, NIST, 96-98; Physicist, NIST, 98-present. Res: Neutron imaging, polymer electrolyte membrane fuel cells, hydrogen storage, neutron magnetic dipole moment, neutron optics, and neutron interferometry. Member: American Physical Society, Sigma Xi.

MUMM, HANS PIETER, PHYSICS, B.Sc., Univ. of California, 95; Ph.D., Univ. of Washington, 04; National Research Council Postdoctoral Fellow, Neutron Interactions and Dosimetry Group, NIST, 04-06; Univ. of Maryland Postdoctoral Research Assoc., 06-08; Physicist, NIST, 08-present. Res: Fundamental symmetries, weak interactions. Member: American Physical Society.

NICO, JEFFREY S., PHYSICS, B.Sc., Michigan State Univ., 83; M.Sc., Univ. of Michigan, 90; Ph.D., Univ. of Michigan, 91; Postdoctoral Fellow, Univ. of Michigan, 91; Postdoctoral Fellow, Los Alamos National Laboratory, 91-94; Physicist, NIST, 94-present. Res: Absolute neutron reaction rate measurements, weak interactions, neutron dosimetry. Member: Fellow of the American Physical Society.

SHANKLE, ROBERT L., Frederick High School, Machining 1, 2 & 3, 83-86; Welding 1,2 & 3, 83-86; Frederick Community College, Machine Shop 1, 01. Engineering Technician, NIST, 06-present.

THOMPSON, ALAN K., PHYSICS, B.A., Rice Univ., 86; Ph.D., Massachusetts Institute of Technology, 91; Research Assoc., Harvard Univ., 91-93; Physicist, NIST, 93-present, Res: He-3 polarization, neutron polarization, tests of fundamental symmetries, structure of the neutron, weak interactions, neutron dosimetry. Member: American Physical Society, Health Physics Society.

NIST ASSOCIATES

NAMES	SPONSORS	PROJECT
	Division Office	
Caswell, Randall	Self	Radiation transport calculations
	Neutron Interactions and Dosimetry Group	
Abdurashitov, Dzhonrid	Russian Academy of Sciences Moscow, Russia	Fundamental Physics
Abutaleb, Mohamed	Massachusetts Institute of Technology Boston, MA	Neutron Interferometry
Beise, Elizabeth	Univ. of Maryland College Park, MD	Fundamental Physics
Breuer, Herbert	Univ. of Maryland College Park, MD	Fundamental Physics
Black, Timothy C.	Univ. of North Carolina Wilmington, NC	Neutron Interferometry
Carlson, Allan D.	Self	Neutron Cross Section Standards
Darius, Guillaume	Tulane Univ. New Orleans, LA	Fundamental Physics
Cory, David	Massachusetts Institute of Technology Boston, MA	Neutron Interferometry
Fu, Changbo	Indiana Univ. Bloomington, IN	He-3 Polarization
Gagliardo, Jeffery	General Motors Honeyoe Falls, NY	Neutron Imaging
Gilliam, David	Self	Dosimetry & Homeland Security
Grundl, James A.	Self	Neutron Measurements

Hassan, Md. Taufique	Tulane Univ. New Orleans, LA	Fundamental Physics
Heimbach, Craig	Self	Neutron Measurements
Huffer, Craig	North Carolina State Univ. Chapel Hill, NC	Ultra Cold Neutrons
Hughes, Patrick	Univ. of Maryland College Park, MD	Fundamental Physics
Huffman, Paul	North Carolina State Univ. Chapel Hill, NC	Ultra Cold Neutrons
Komvies, Alexander	DePauw Univ. Greencastle, IN	Fundamental Physics
Jones, Gordon	Hamilton College Clinton, NY	Fundamental Physics
Langford, Thomas	Univ. of Maryland College Park, MD	Fundamental Physics
Noid, George	Tulane Univ. New Orleans, LA	Fundamental Physics
Mustafin, Marat	Russian Academy of Sciences Moscow, Russia	Fundamental Physics
Opper, Allena	George Washington Univ. Washington, DC	Fundamental Physics
O'Neill, Benjamin	Arizona Univ. Tempe. AZ	Neutron Radiative Decay
O'Shaughnessy, Christopher	North Carolina State Univ. Chapel Hill, NC	Ultra Cold Neutrons
Owejan, Jon	General Motors Honeyoe Falls, NY	Neutron Imaging
Pushin, Dmitry	Institute for Quantum Computing Univ. of Waterloo Ontario, Canada	Neutron Interferometry
Schelhammer, Karl	North Carolina State Univ. Chapel Hill, NC	Ultra Cold Neutrons
Schrack, Roald A.	Self	Neutron Cross Section Standards

Shahi, Chandra	Tulane Univ. New Orleans, LA	Fundamental Physics
Snow, Michael	Indiana Univ. Bloomington, IN	Fundamental Physics
Steinbach, Tracy	Indiana Univ. Bloomington, IN	Fundamental Physics
Trabold, Thomas	Rochester Institute of Technology Rochester, NY	Neutron Imaging
Werner, Samuel	Self	Neutron Interferometry
Wietfeldt, Fred	Tulane Univ. New Orleans, LA.	Fundamental Physics
Winogradoff, David	Univ. of Maryland College Park, MD	Fundamental Physics
Yue, Andrew	Univ. of Tennessee Knoxville, TN	Neutron Radiometry

IONIZING RADIATION DIVISION (682)

IONIZING RADIATION DIVISION, 682.00

Lisa R. Karam, Chief
Wanda Lease, Secretary

RADIATION INTERACTIONS AND DOSIMETRY, 682.02

Michael G. Mitch, Group Leader
Diana Copeland, Secretary

Fred B. Bateman
Paul M. Bergstrom
Marc F. Desrosiers
David F. Eardley
Larry T. Hudson
Melvin R. McClelland
Ronaldo Minniti
C. Michelle O'Brien
James M. Puhl
Ronald E. Tosh
Jason S. Walia

NEUTRON INTERACTIONS AND DOSIMETRY, 682.03

Muhammad Arif, Group Leader
Martha Neviaser, Secretary

Elias M. Baltic
M. Scott Dewey
Thomas R. Gentile
Michael G. Huber
Daniel S. Hussey
David L. Jacobson
Hanns P. Mumm
Jeffrey S. Nico
Robert Shankle
Alan K. Thompson

RADIOACTIVITY, 682.04

Michael P. Unterweger, Group Leader
Cecelia Huestis-Beshai, Secretary

Douglas Alderson
Denis E. Bergeron
Jeffrey T. Cessna
H. Heather Chen-Mayer
Ronald Collé
Evan B. Crawford
Lonnie T. Cumberland
Ryan P. Fitzgerald
Anne Marie Forney
Michelle Hammond
Kenneth G.W. Inn
Lynne E. King
Jerome J. La Rosa
Lizbeth Laureano-Pérez
Larry Lucas
Payam Motabar
Bruce Norman
Leticia Pibida
Janet Stann
Peter Volkovitsky
Brian E. Zimmerman