Final Report for the Office of Science, Dept. of Energy by
Indiana University for project DE-FG02-03ER46093 **entitled**

POLARIZED ^{3}He NEUTRON SPIN FILTERS

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PI: William Snow, Indiana University

W.M. Snow has been a professor of physics at Indiana University since 1993 and was the PI for the DOE grant throughout the entire period of the work.

PI of associated Interagency Agreement with NIST: Tom Gentile

Thomas R. Gentile has been a physicist at NIST since 1993, and the leader of the NIST program in ^{3}He spin filter development since 1996. He lead the activities detailed in the NIST Interagency Agreement closely associated with this work.

Co-PI: Gordon Jones, Hamilton College

Prof. Gordon L. Jones has been a professor at Hamilton College since 2005 active in neutron physics.

Co-PI: Thad Walker, Wisconsin

Prof. Thad Walker has been a professor of physics at Wisconsin since 1997. Prof. Walker is a world expert in spin-exchange optical pumping of noble gases with alkali metal atoms.

The goal of this grant to Indiana University and subcontractors at Hamilton College and Wisconsin and the associated Interagency Agreement with NIST was to extend the technique of polarized neutron scattering by the development and application of polarized ^{3}He-based neutron spin filters. This effort was blessed with long-term support from the DOE Office of Science, which started in 2003 and continued until the end of a final no-cost extension of the last 3-year period of support in 2013. The steady support from the DOE Office of Science for this long-term development project was essential to its eventual success. Further ^{3}He neutron spin filter development is now sited at NIST and ORNL.

The goal of the work summarized in this report was to develop ^{3}He neutron spin filter technology and apply polarized ^{3}He spin-filters to neutron scattering investigations in materials science. Our broad-based program included the basic atomic physics of spin-exchange optical pumping, practical spin filter development, magnetic field design and NMR-based polarization control, ^{3}He and neutron polarimetry, and applications to new instruments and types of scattering techniques. We demonstrated spin filters for wide-angle polarization analysis of importance for many types of neutron spectroscopy. The project was carried out by a collaboration involving scientists at NIST, Indiana University, Hamilton College, and the University of Wisconsin who are experts in ^{3}He polarization techniques, and materials scientists from the IPNS, NIST, ORNL, and LENS who are neutron scattering experts. We have also collaborated very closely with the polarized ^{3}He staff (most of whom we educated) in the new programs at the NIST and SNS to help these efforts continue to grow.

This collaboration involved an uncommon combination of researchers at universities and national labs with backgrounds in neutron physics, atomic physics, and nuclear/particle physics working together for a decade, with an undergraduate institution (Hamilton) playing a key role. NIST brought to bear its neutron facilities and national lab capabilities to test how to integrate polarized ^{3}He onto existing neutron scattering instruments and produce almost 100 neutron spin filter cells using special glasses for neutron beam use and for test measurements. Indiana constructed a polarized ^{3}He gas compression system for some of the early research work and the LENS university-based pulsed neutron source during the course of this work and implemented polarized ^{3}He on the SESAME spin echo development beamline. Wisconsin joined the effort when it became clear that we needed a better understanding of the fundamental atomic physics processes for the technique to succeed.

This project led to the establishment of ^{3}He neutron spin filters as a new user option on many neutron scattering spectrometers at NIST and established the foundation for their (now growing) use on several neutron scattering spectrometers at ORNL. By now it is clear that this effort has produced a major, long-lasting impact on the scientific productivity of neutron scattering, especially in the US. The number of scientific results produced using ^{3}He spin filters at NIST is second only to the ILL**.** This combined R&D/scientific project is one of the few recent examples of a case where an important new neutron optics development, namely ^{3}He polarizers based on spin-exchange optical pumping, was developed in the US before Europe. The SEOP method is now being adopted by the FRM-II source in Munich, JPARC in Japan, and at the new neutron facility at the Chinese Academy of Engineering Physics in Mianyang. The successful development of polarized ^{3}He spin filters is now influencing how neutron scatterers conceive of and design new instruments: in particular, it is an important component of the various types of spin-echo-based small angle neutron scattering spectrometer ideas under development. We performed several studies needed to improve our still-incomplete understanding of subtle atomic physics phenomena in spin-exchange optical pumping (SEOP) which can become more important at higher polarization in an attempt to further increase the ^{3}He polarization and the efficiency of the SEOP process. The improved knowledge of the atomic physics gained in this research has also benefitted other scientific activities in the DOE portfolio, especially nuclear physics research at Jefferson Lab, where polarized ^{3}He nuclei are routinely used as targets in electron scattering experiments to investigate the internal structure of the neutron. ^{3}He spin filters were used in other nuclear physics experiments to search for the neutron-proton weak interaction and to constrain the nuclear few-body force. Finally the extremely long spin relaxation times achieved in these cells has recently been used to set limits on possible exotic spin-dependent interactions of the neutron. I suspect that the DOE would be hard-pressed to identify an individual scientific R&D project with a broader scientific impact: a look at the publications from this project will show that our results are published in 6 different Physical Review journals (PRL, PRA, PRB, PRC, PRD, and PRST-AB). Seven papers associated with this work were published in Physical Review Letters: this is not bad for an activity which was primarily a polarized neutron optics R&D project.

This project also possessed an uncommonly-focused educational impact. A large fraction of the graduate students and postdocs supported in this work have gone on to implement SEOP-based ^{3}He neutron spin filters at neutron user facilities as facility scientists. This is how the project successfully solved the problem of how to smoothly match the R&D activity onto the neutron scattering facility floor. In addition, the relatively small scale of the work lent itself well to undergraduate student involvement. A couple dozen undergraduate students at Hamilton College, a highly-regarded selective undergraduate college in New York state, worked on ^{3}He over the course of this project as part of the required research component of their degree program. I suspect that this project has had one of the largest impacts on undergraduate physics research of any BES-supported scientific research project: in raw numbers of students involved it was not that far from a small-scale REU-type research program.

Indiana University

MEOP Compression System

In the metastability-exchange method, metastable ^{3}He atoms are polarized by optical pumping, and the polarization is transferred to ground-state atoms in metastability exchange collisions. Metastable $2\ ^3S_1$ atoms are produced by an electrodeless rf discharge and optically pumped using the $2\ ^3S_1 \rightarrow 2\ ^3P_0$ transition at 1083 nm. The resultant electronic polarization is transferred to the nuclei by the hyperfine interaction. In a metastability exchange collision, the incoming metastable atom transfers its atomic excitation to the incoming ground state atom, resulting in nuclear polarization of the outgoing ground state atom.

The metastability exchange method can produce highly polarized ^{3}He gas at a rate almost an order of magnitude faster than the spin-exchange method. However, the optical pumping can only be performed at pressures of about 1 mbar, due to the difficulty in maintaining a sufficiently high metastable population at higher pressures. For neutron spin filter applications the gas must be compressed by three to four orders of magnitude, without substantial loss of polarization.

At Indiana University we constructed and operated a large-scale, two-stage piston compressor described below and pictured in Figure 1. The device is located in a large-volume (8 m^3) coil system, which produces a 20 G field with a transverse field gradients below10^{-3} cm^{-1}. The optical pumping takes place in one of four 1 m long cylindrical cells. The cells are interconnected so that we can install the optics needed to optically pump all four volumes simultaneously (so far in our work we have only optically pumped gas in one cell). The compression system is constructed out of Pyrex glass and aluminum. It consists of a two-stage piston compressor with an intermediate storage volume and air-actuated nonmagnetic valves and pistons. The pistons slide on the inside surface of honed aluminum cylinders on Viton quad rings lubricated with a low vapor pressure fluorinated grease. Similar design on a smaller scale applies to the valves. The compression system can achieve a compression ratio of 6000 starting from 1.3 mbar. A LABVIEW program controls the air-actuated compression and recirculation system. The 160 cm^3 cylindrical storage cell is detachable from the system to allow transport to a scattering facility. Glass flow lines connect both the target cell and the intermediate volume back to the optical pumping volume so that the ^{3}He polarization can be measured optically at each step of the compression process. In addition local NMR probes which have been cross-calibrated with optical measurements are used as diagnostics. Hamilton College supplied a convenient NMR electronics box to perform these measurements.

A detailed paper on the performance of the large-scale MEOP piston compressor at Indiana University based in part on neutron measurements on the POSY reflectometer at IPNS was published. During a 2 h fill of a 0.48 L storage cell (Orion) to a pressure of 1.22 bar with a 33% ^{3}He, 67% ^{4}He mixture, we determined that the apparatus preserved 81% of the polarization produced in the optical cell. The storage cell ^{3}He polarization was determined to be 46% based on a neutron-based measurement conducted at IPNS after correction for the transport from Indiana University to IPNS. We determined the optical pumping cell polarization to be 56% by analysis of the circular polarization of the 668 nm light emitted by the discharge. We later decided to focus our proposed developments on spin-exchange optical pumping.

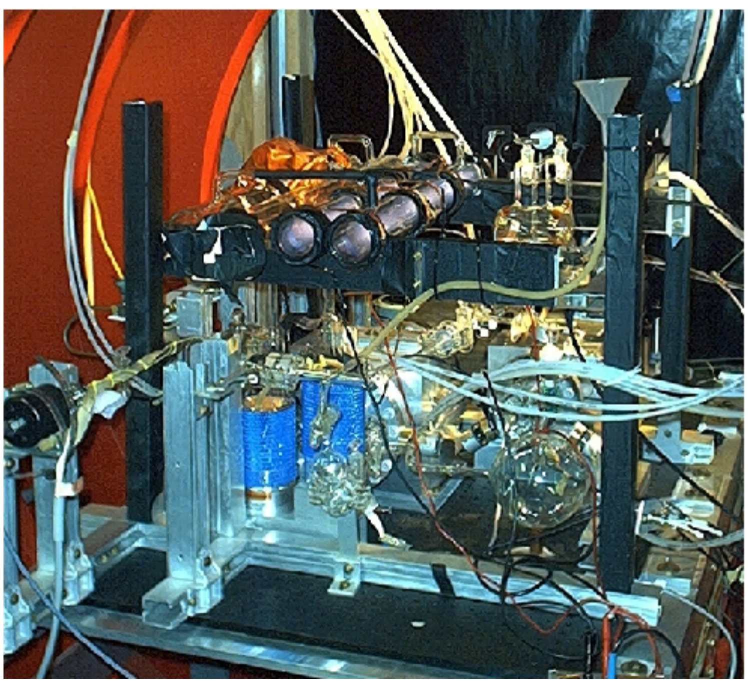

Figure 1. A picture of the polarized ^{3}He compression system in operation at Indiana University. The pink glow from two of the glass cylinders near the center of the picture comes from the electrical discharge needed to create the metastable atoms.

Polarized 3He at ORNL: We collaborated with the SNS polarized 3He group led by Xin Tong on various projects.

HYSPEC: The SNS HYSPEC scattering instrument requires a wide-angle polarized 3He analyzer. The design for this analyzer, shown below, proposes to employ spin exchange optical pumping outside of the instrument combined with mechanical compression of the polarized gas into the analyzer cell. We provided SNS with the details of our design for low-dead volume nonmagnetic air-actuated valves and other details based on our experience with the successful polarized 3He gas compressor tested in the IU metastability-exchange optical pumping system.

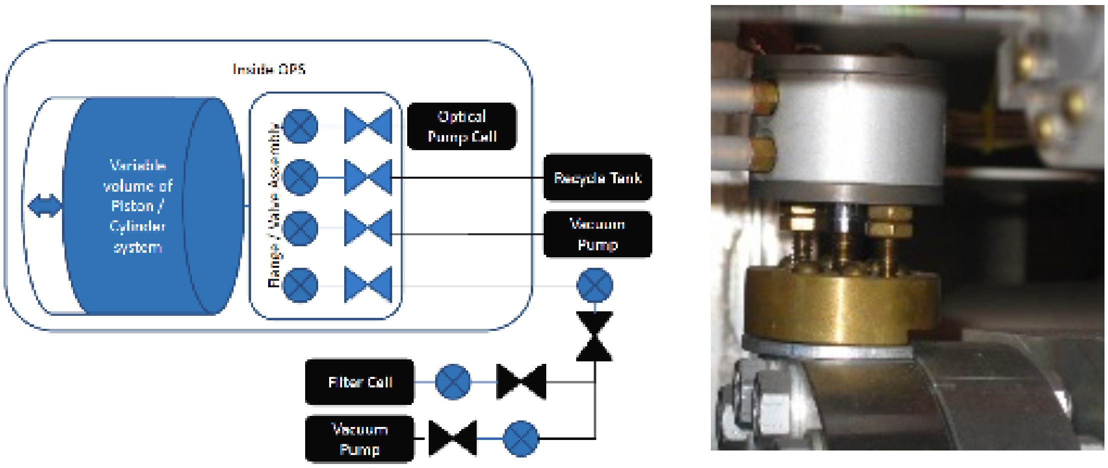

Figure 2: Concept for polarized ^{3}He delivery for the HYSPEC spectrometer at SNS and a valve from the Indiana University MEOP compression system whose design will be used in this system.

Polarized neutrons in HB2A: We collaborated with HFIR instrument scientists and the SNS to successfully install and test a ^{3}He polarizer on the powder diffractometer HB2A at HFIR. The measured neutron beam polarization produced by the ^{3}He polarizer was 82%. This polarization was consistent with the ^{3}He polarization inferred from EPR spectroscopy before the cell was placed on the neutron beamline, thereby helping establish the reliability of this technique for neutron scattering applications. Polarized neutrons were then used by a group led by Prof. Mark Meisel (Florida) to explore the magnetization density in a Co-Fe Prussian Blue analog.

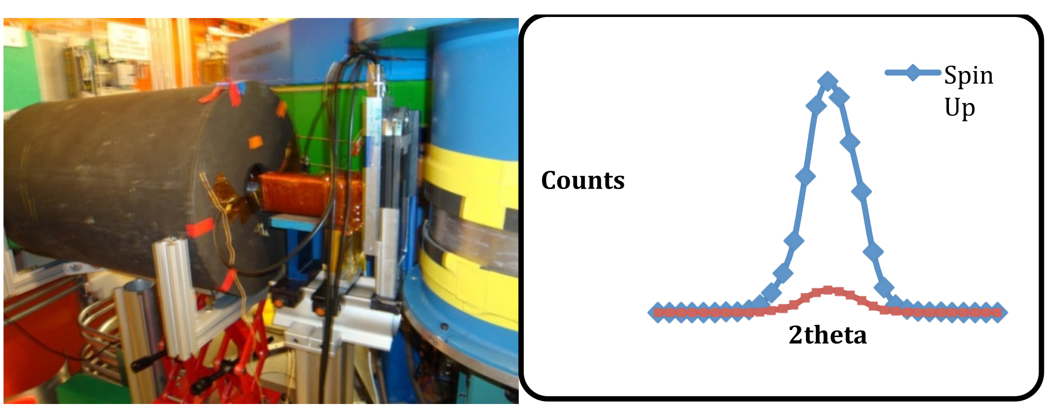

Figure 3: Magnetic shield for the 3He polarizer (left) which produces polarized beam with a neutron polarization of 80% (measured using a Heusler alloy crystal, right) for the first time on the HB2A powder diffractometer at HFIR.

The LENS Neutron Source: The Low Energy Neutron Source (LENS) at the Indiana University Cyclotron Facility (IUCF) is a long-pulsed cold neutron source for neutron research, education, and instrument development now in operation. Figure 4 shows an overview of the target-moderator-reflector and the two existing instruments: a SANS spectrometer and the SESAME spectrometer. The SANS beamline was used to provide neutrons for tests of ^{3}He spin filters for the magnetism reflectometer by the SNS group.

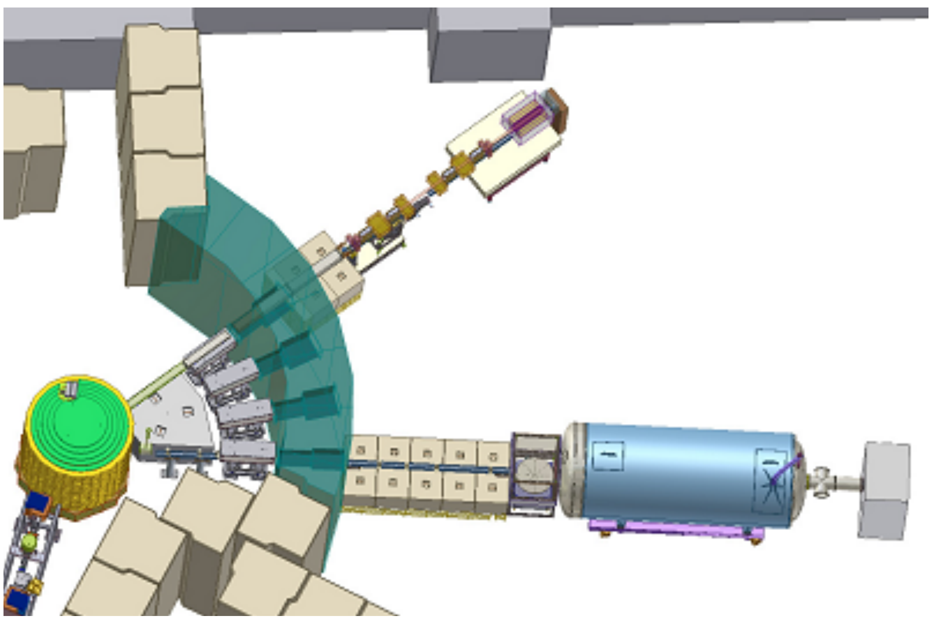

Fig. 4: View of LENS showing the two existing instruments (SANS and SESAME).

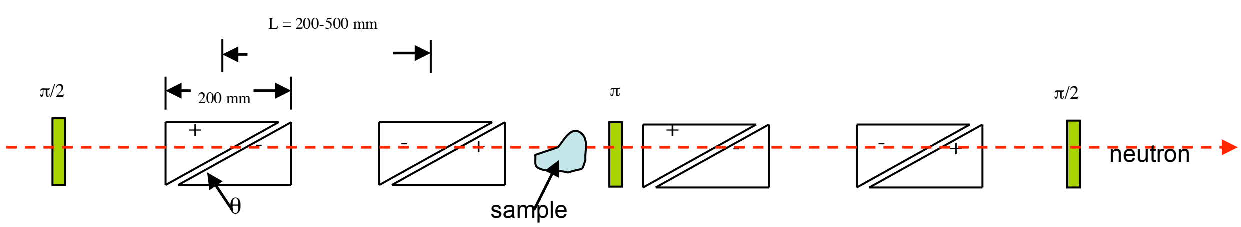

Fig. 5 Conceptual drawing of a SESAME instrument suitable for very small scattering angle measurements

SESAME development at the LENS neutron source: The polarized neutron beam line at LENS supports the development of polarized neutron technology for neutron scattering research. The first example is Spin Echo Scattering Angle Measurement (SESAME) and the application of this technique to a variety of scientific problems. Roger Pynn at Indiana/SNS leads this project.

Figure 5 shows the concept of the instrument. Each of the triangles in the figure represents a solenoid of triangular cross section whose internal magnetic field is either into (-) or out of (+) the plane of the page. This scheme for coherently splitting and recombining a neutron beam using polarized neutron birefringence works for any neutron wavelength and is thus suitable for use at pulsed neutron sources. Because SESAME can use a relatively large wavelength bandwidth, it should be particularly useful at long-pulsed sources such as the planned SNS second target station. The correlation distance probed within the scattering sample, called the spin echo length (Z), is proportional to the field within the triangular solenoids and to the square of the neutron wavelength. Our current generation of water-cooled solenoids is expected to allow us to achieve values of Z well over a micron. At a pulsed source it is often convenient to use the variation of Z with neutron wavelength to measure a range of correlations lengths during a single time-of-flight frame. With a neutron detector that integrates the sample scattering, the measured neutron polarization is a projection of the Patterson correlation function of the scattering sample, measured at a distance equal to the spin echo length.

Figure 6 shows a side view of the beam layout. Extensive test measurements of the spin echo coils and of the reconstruction method for S(Q) from model samples were performed at LANSCE and NIST. The beam is polarized using a curved supermirror polarizing bender and analyzed by either an array of supermirrors or a polarized ^{3}He analyzer, depending on the experiment.

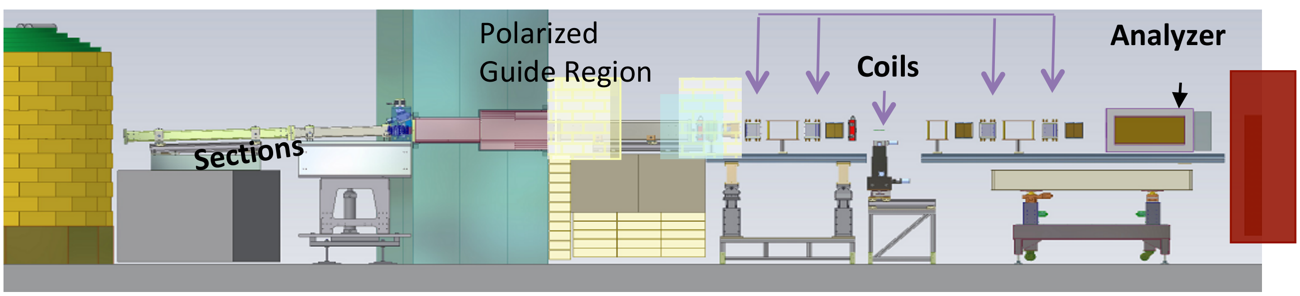

Fig. 6: Side view of the SESAME beamline at LENS. The spin precession regions bracket the sample location. The second precession region pivots in the vertical plane about the sample location to accommodate both SANS and reflectometry modes of operation. All of the components are mounted on optic rails so that they can be translated along the neutron beamline and oriented reproducibly

SESAME development at LENS neutron source

SESAME Cell: SNS established their spin exchange optical pumping cell construction capability, which is an essential process to master for producing a variety of 3He cells for neutron scattering. Peter Jiang worked with SNS to help test and commission this system and in the process produced a hybrid Rb/K optical pumping cell with dimensions and internal 3He pressure optimized for use on the SESAME spectrometer at LENS.

Fig. 7: A 1.1 bar, 7 cm long, 6.5 cm ID Rb/K SEOP cell for the SESAME instrument at LENS.

On-line SEOP for the SESAME spectrometer at LENS

One of the main goals of the Indiana University proposed research was to conduct neutron spin echo measurements on the SESAME spectrometer at the LENS neutron source at IU in collaboration with the group of Roger Pynn. We obtained two 40W fiber-coupled narrowed lasers from Oclaro shown in Fig. 9. The lasers produce narrowed light with 0.24 nm FWHM. Postdoc Haiyang Yan assembled the system and performed EPR measurements to estimate the ^{3}He polarization using a 1.1 bar, 7 cm long, 6.5 cm ID Rb/K SEOP cell made by Peter Jiang. The 3He polarization estimated in off-line tests from EPR measurements is 70%.

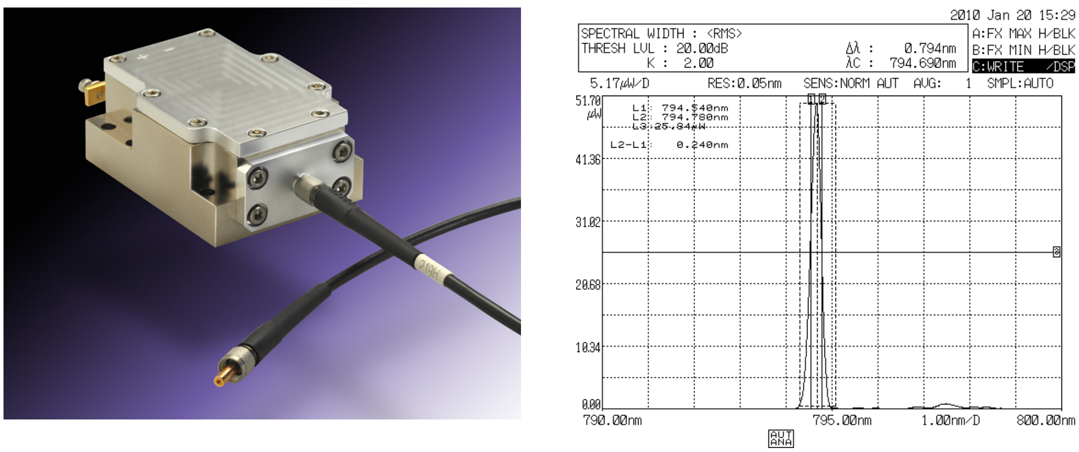

Fig. 8: Narrowed fiber-coupled laser for the ^{3}He SEOP system for the SESAME spectrometer at LENS along with its measured lenewidth.

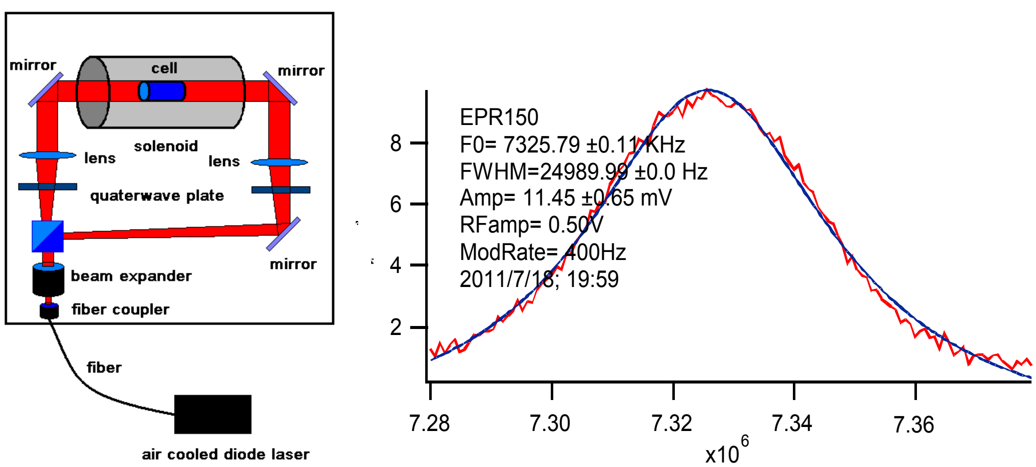

Fig. 9: Schematic of on-line SEOP system for SESAME and EPR signal from the cell.

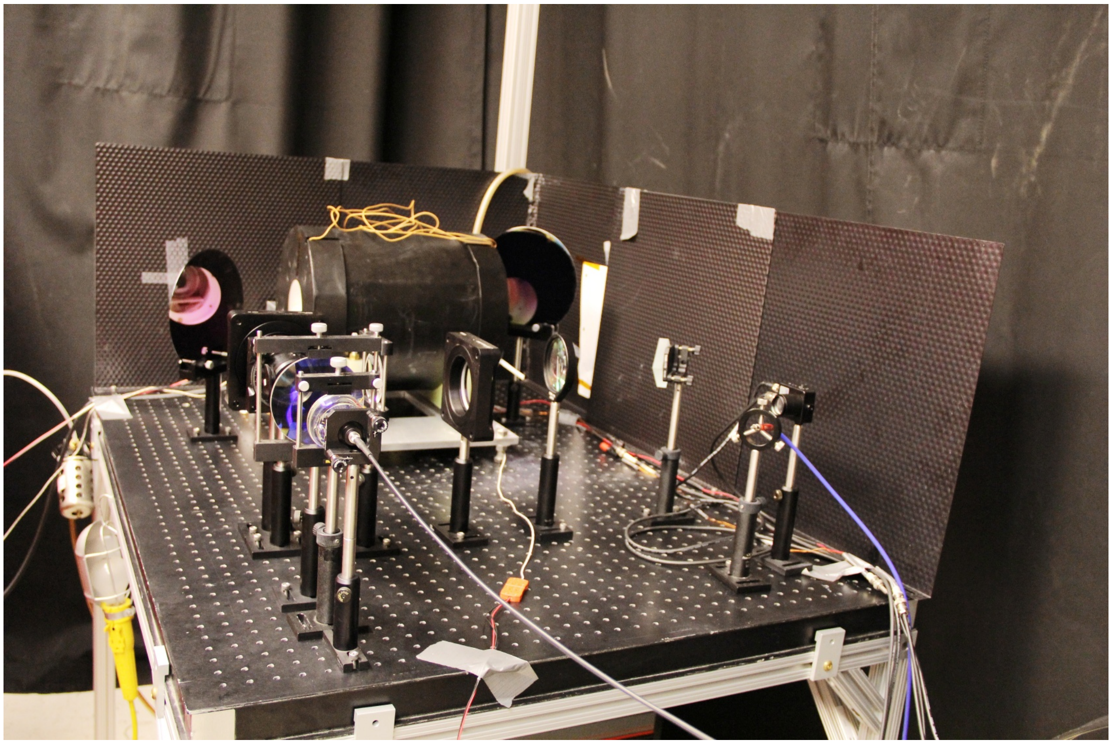

Fig. 10: Picture of on-line SEOP system for SESAME before transfer to the instrument.

Our polarized ^{3}He system achieves a ^{3}He polarization of 75%, consistent with off-line tests from EPR measurements.

First SESAME Spin Echo Measurements using a Polarized ^{3}He Analyzer

The picture below in Figure 11 shows the SESAME spin echo instrument at LENS with the polarized ^{3}He analyzer installed on the beamline. The beam is polarized by a supermirror bender-polarizer located inside the shielding. The magnetic prism elements in the foreground of the picture have been thoroughly tested in measurements at NIST and LANSCE. We replaced the supermirror polarization analyzer on SESAME with our 3He spin-exchange optical pumping (SEOP) system.

We conducted a series of measurements to characterize the interference contrast of the SESAME spin echo instrument as a function of the beam size. The flat-windowed, 6 cm diameter polarized 3He analyzer provided by NIST allowed us to perform this exploration, which is expected to be one of the advantages of the SESAME spin echo technique. Figure 12 shows the preliminary results for the interference contrast fringes. From this data it is clear that we will be able to use beams as large as 2.5 cm x 2.5 cm for SESAME spin echo measurements.

We also conducted a measurement of the one-dimensional projection of the pair correlation function (the Patterson function G(z)) for a sample of anodic aluminum which has been measured previously on ASTERIX. Figure 3 shows the preliminary data. The agreement is good for small correlation lengths z but there is a discrepancy in the intensity of the peak near 100 nm.

We showed later that this discrepancy was due to the narrower phase space acceptance of the supermirror-based polarization analyzer on ASTERIX and that the use of polarized 3He with SESAME is important for an accurate measurement of G(z).

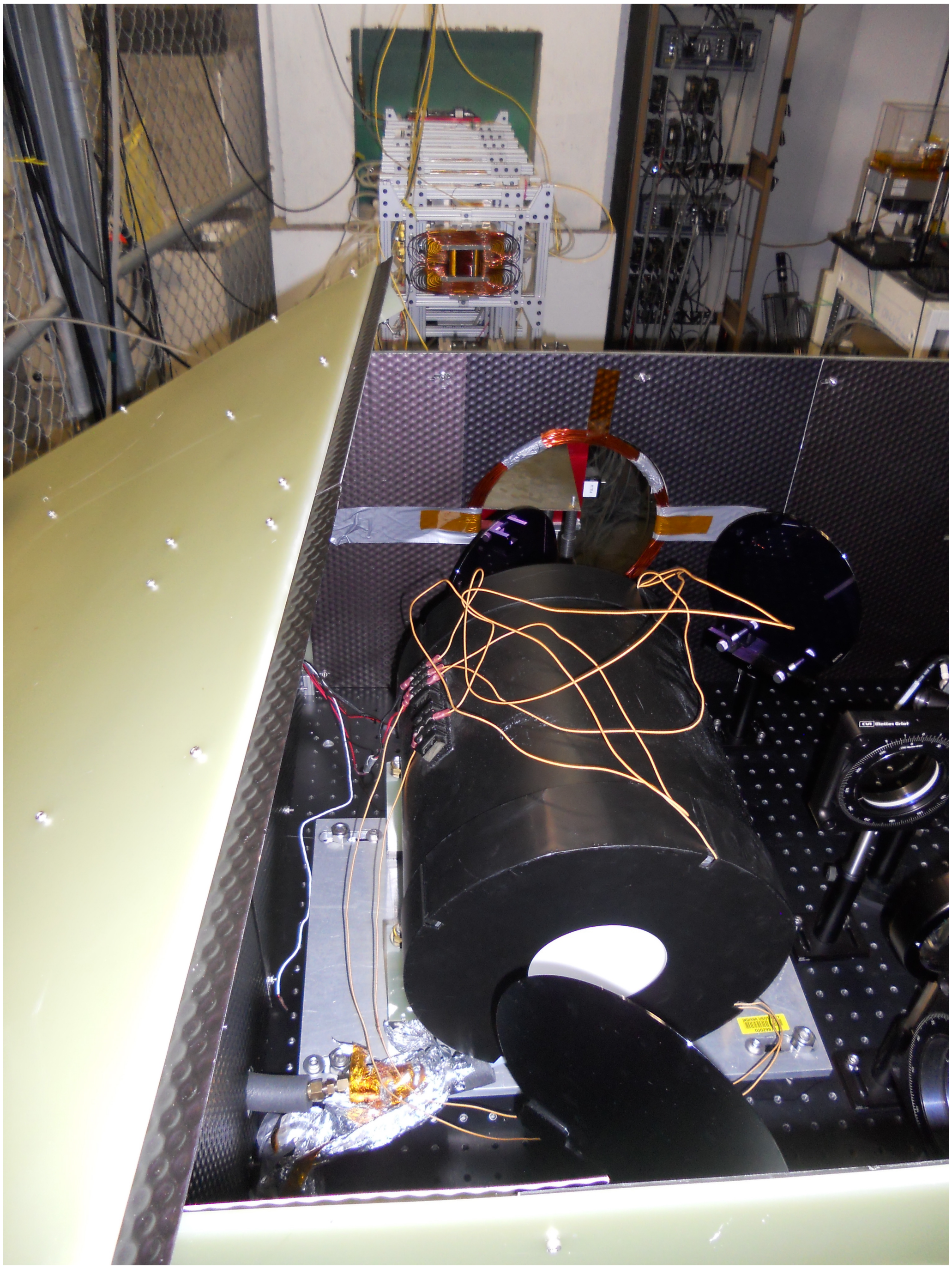

Fig. 11: Polarized ^{3}He analyzer on the SESAME spin echo spectrometer at LENS

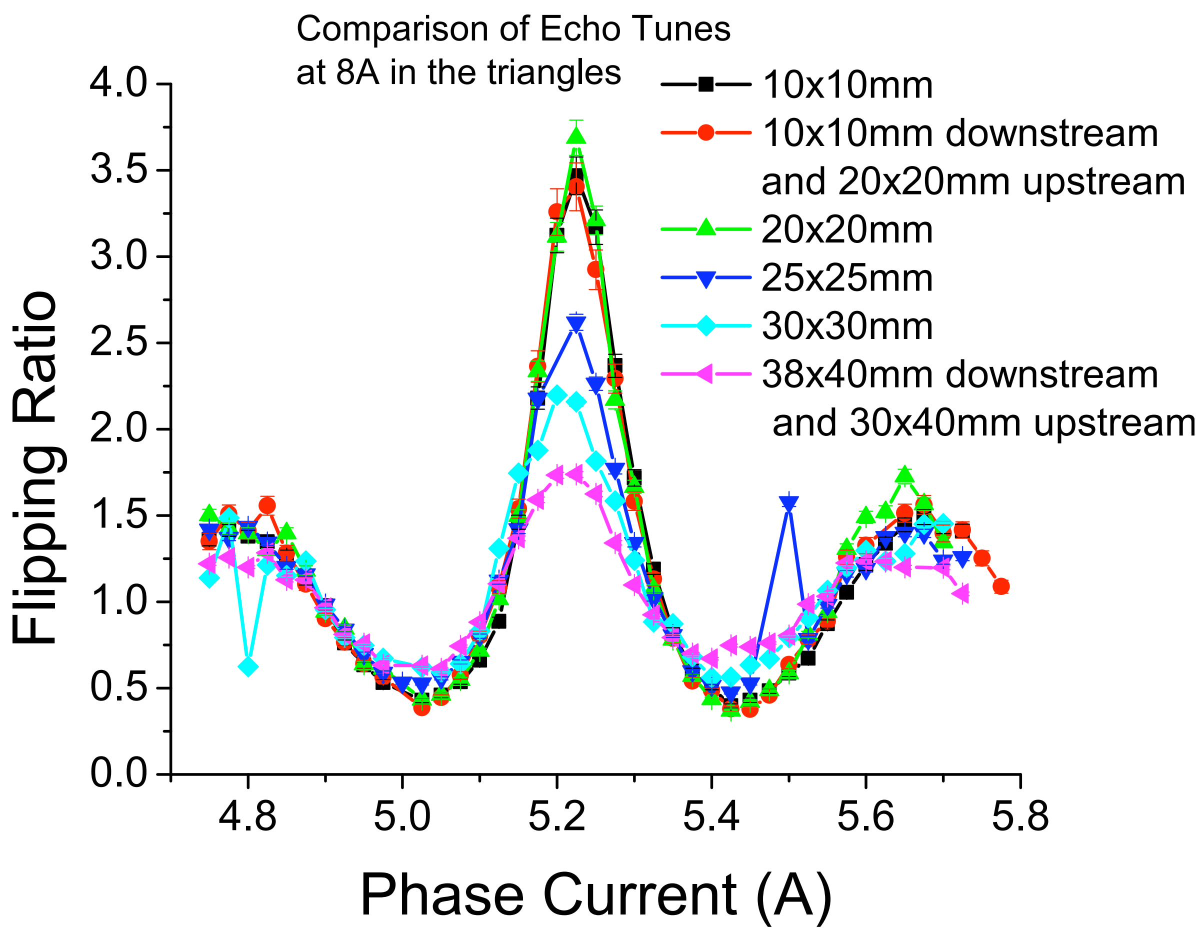

Fig. 12: Data on SESAME spin echo interference contrast as a function of beam phase space. This data demonstrates that SESAME can work with large beam cross sectional areas.

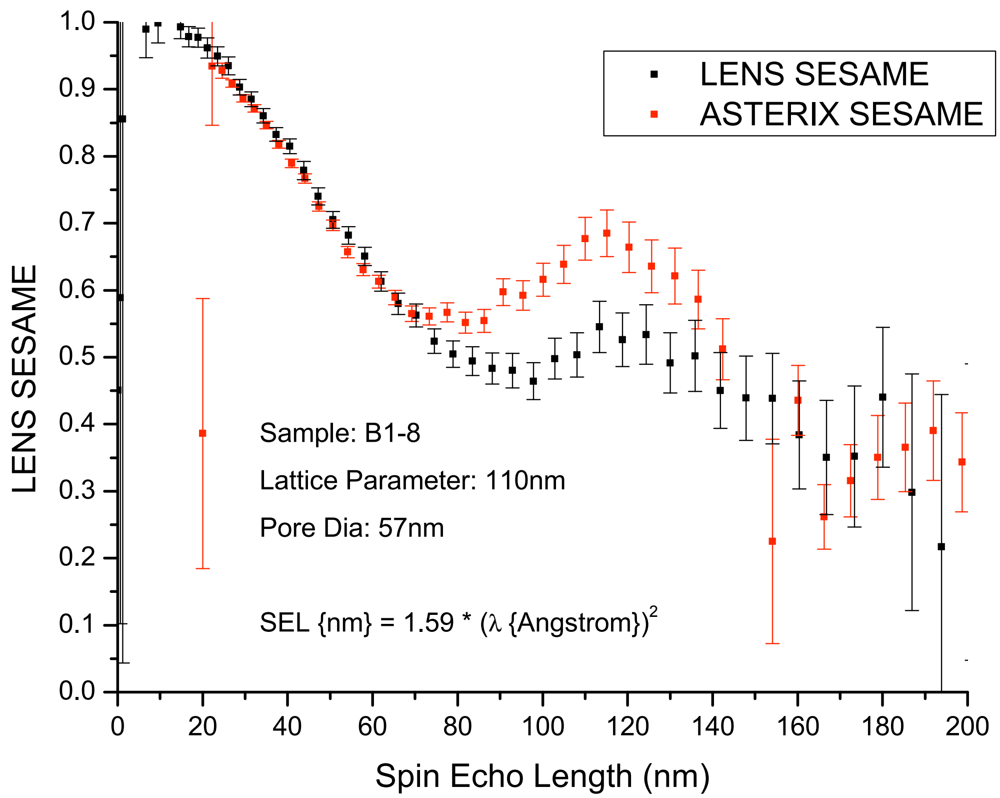

Fig. 13: Data on G(z) for anodic aluminum measured on SESAME compared to the same sample measured on ASTERIX. This discrepancy showed us that the uniform, borad phase space acceptance of ^{3}He neutron spin filters is important for a quantitiave extraction of G(z).

We completed an experiment on LENS in collaboration with Roger Pynn's group using a polarized ^{3}He analyzer to attempt to measure (a) G(z) for a collection of suspended spheres of known density low enough to predict G(z) using the Percus-Yevcik theory, and (b) the performance of a superconducting neutron spin rotator for polarized neutron scattering instrumentation.

The idea of the first experiment was to test the use of the polarized ^{3}He analyzer to see if the measured G(z) agrees with the a known shape that can be calculated from theory. The sample to test the Percus-Yevick theory was silica spheres surrounded in D2O. The spheres were previously measured by dynamic light scattering and a diameter of 294nm prepared using the Stober method. Figures 13 and 14 show this data.

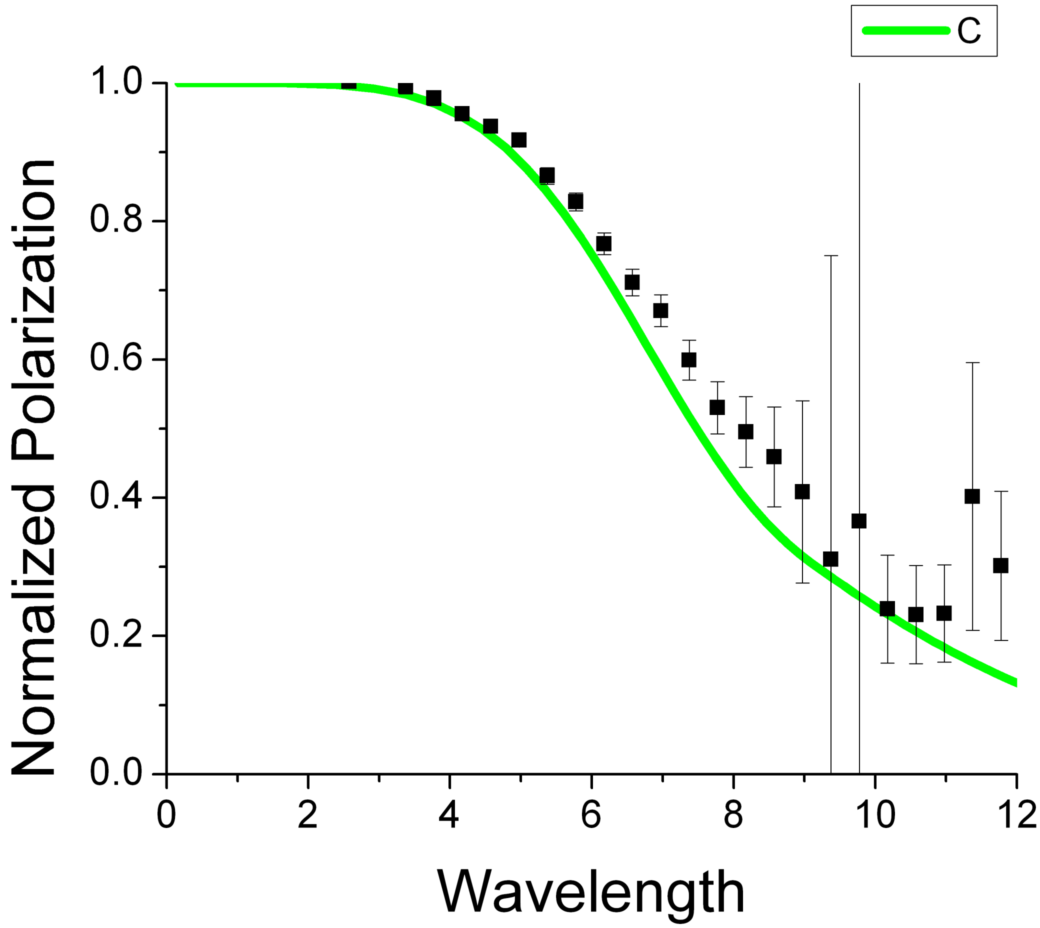

Fig. 14: G(z) of silica spheres measured on SESAME at LENS using a polarized 3He analyzer compared to the theoretical expectation from a calculation using Percus-Yevick theory with a size distribution measured from light scattering. The x axis is neutron wavelength (not yet converted into spin echo length).

The polarized ^{3}He analyzer was also used to test a superconducting "Cryocup" for neutron polarization manipulation in a project funded by NSF DMR. This device, shown in Figure 15, is designed to precess the neutron spin through a predetermined angle. It consists of two high-Tc films mounted perpendicular to the neutron beam, separated by a distance of about 15 mm, with a field between them generated by a rectangular-cross-section Helmholtz coil wound with high-Tc superconducting tape. This device is intended to be one part of an inexpensive spherical neutron polarimeter which will have most of the functional specifications of the Cryopad device available at several European neutron centers. It is being designed as part of an NSF project to develop neutron spin manipulation devices for implementation at U.S. neutron scattering centers. As shown in the figure, the device produces a neutron spin rotation that is proportional to the energizing current, as required.

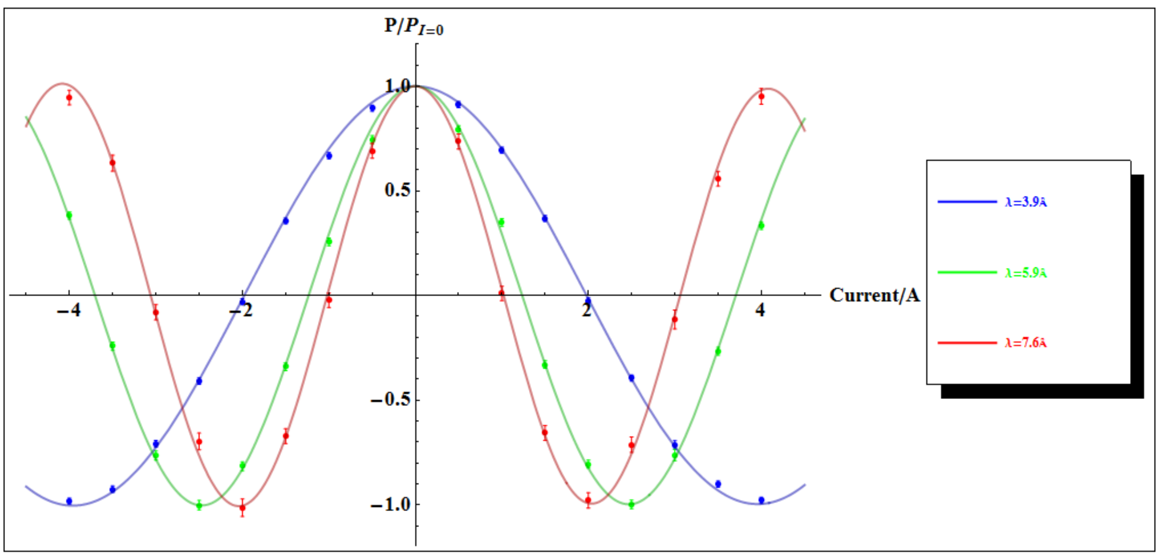

Fig. 15: (top) Picture of cryostat for the superconducting neutron spin rotator. (bottom) Neutron polarization as a function of current in the coil for different neutron wavelengths.

LANL Experiment

Indiana, Hamilton, and NIST collaborated with Michigan, New Hampshire, University of Dayton, and the NPDGamma collaboration at LANSCE to install and operate a polarized ^{3}He neutron spin filter in summer 2005 for several weeks of continuous operation on the new FP12 neutron beamline. Figure 16 below shows the ^{3}He spin filter in blue, which takes up only a small length along the beamline. Although this is not a neutron scattering application of ^{3}He we mention this activity because its success has important implications for long-term continuous on-line operation of polarized ^{3}He for neutron scattering. This application emphasized long-term operation using laser light that was coupled by fiber optics into the cell and a large (11 cm diameter) cell which was blown and filled at NIST. This ^{3}He system produced polarized beam on Flight Path 12 at LANSCE over nearly a year of continuous operation. This successful long-term operation bodes well for continuous operation of polarized ^{3}He neutron spin filters on neutron scattering instruments.

At the beginning of the run the ^{3}He polarization was 58%; although we have produced 75% in similar cells using spectrally narrowed laser light, the NPDGamma experiment employs only 50 W of broadband laser light, which limits the polarization.

Fig. 16: Polarized ^{3}He neutron spin filter for the NPDGamma experiment at LANSCE. This polarizer worked on-line for this experiment over almost a year of continuous operation.

Hamilton College

In-situ optical pumping at IPNS: Hamilton focused on developing neutron polarizers in which the ^{3}He is optically pumped in the neutron beam. Our tests were run at the Single Crystal Diffractometer (SCD) at the Intense Pulsed Neutron Source (IPNS) at Argonne National Lab using cells made at NIST. The SCD beam made an ideal test case due to the small size of the neutron beam and the enthusiasm of our neutron scattering colleagues Christina Hoffmann, Art Schultz, and Hal Lee. The small size of the neutron beam allowed us to focus on the practical complications of putting an optical pumping apparatus into a space-constrained neutron beam while using small inexpensive components. Figure 17 shows a picture of this device on the SCD instrument at IPNS.

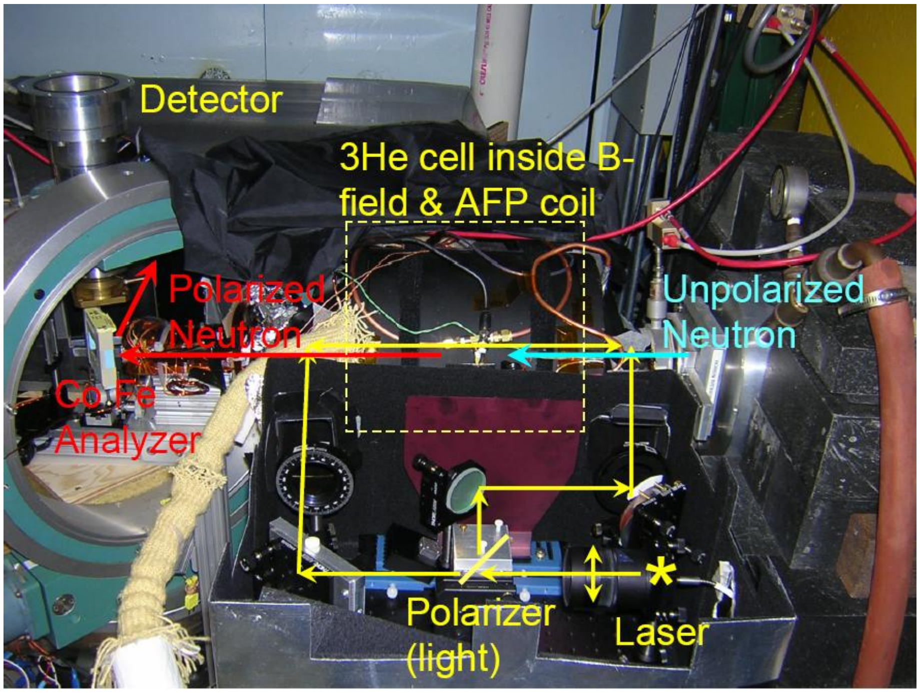

Fig. 17: Picture of the in-situ ^{3}He spin filter from Hamilton used at the IPNS SCD instrument in 2006 and 2007 for polarized neutron diffraction measurements.

NIST/Hamilton-Influenced Polarizer System at the SNS: As the polarized ^{3}He program at the SNS grew, it made sense to ship our most recent polarizer to the SNS so that Hal Lee could start the scaling-up process with a working system. Hamilton played a strong role in the design and development of the 3He polarization analyzer for the SNS magnetism reflectometer, which was successfully tested in May 2009 using a ^{3}He cell provided by NIST. This test was the first polarized ^{3}He spin filter operated on a neutron beamline at the SNS and was a direct outgrowth of the IPNS work.

AFP Polarization Flipper: Flipping the ^{3}He polarization using adiabatic fast passage (AFP) NMR is useful for any polarizer with space constraints. Hamilton students produced two transverse sine coils and user-friendly code to flip the polarization in the NIST solenoids. In modeling these coils, we found that eddy currents in the winding form for the main (static field) solenoid have a large effect on the size of the RF field and on the inductance of the RF coil, but have a relatively small effect on the uniformity of the RF field. The eddy current effect is even more important in a case like the MACS instrument at NIST, where the analyzer cell must be shielded from the RF field that flips the polarizer polarization. Strong RF is required to produce efficient flips in the polarizer, but any leakage of the RF could cause losses in the nearby analyzer cell. A Hamilton student developed a three-coil design with two of the RF coils providing a yoke or flux return for the main RF coil. The design provides a higher RF field, better shielding, and is more easily matched to standard RF amplifiers than a single coil.

Electron Paramagnetic Resonance (EPR): NMR provides a very convenient relative measure of ^{3}He polarization, but it is difficult to use NMR to make an absolute measurement. Neutron transmission provides an absolute measurement of the ^{3}He polarization, but neutron measurements are inconvenient and are not always available. The Wisconsin group has been using electron paramagnetic resonance (EPR) for absolute ^{3}He polarimetry without neutrons. Hamilton developed a simple, user-friendly EPR system that is almost as convenient as NMR. The ability to make convenient absolute measurements was especially important for the SNS due to the lack of a development beam line. In the summer of 2008, a student trained at Hamilton brought EPR capability to the SNS.

Free Induction Decay NMR (FID): Free induction decay (FID) NMR is the most convenient way to get a relative measure of the ^{3}He polarization. It can be performed using simple coil taped crudely to a cell making it portable. At the request of Hal Lee, we have simplified the electronics as well making our FID system extremely portable. A function generator and lock-in amplifier have been replaced with software and a National Instruments data acquisition board. The new system requires a coil, a laptop, and a small electronics box. This is particularly convenient at the SNS due to the stairs between Hal's lab and the beamlines, and trips to HIFR and LENS to find test beamlines.

Updating NMR/EPR code for SNS and NIST

The SNS and NIST use NMR and EPR systems based on code written at Hamilton years ago. Over the years these systems have been adapted locally to the specific needs of each group. For instance, NIST runs two polarizers for transportable cells by switching components with relays. NIST also runs in-situ diagnostics from a cart carrying the computer and standard electronics necessary for FID NMR. As each local group has tuned their NMR systems and code to their specific needs, Hamilton has continued to improve on the basic system using a more flexible interface with more channels, and replacing standard function generators and lock-in amplifiers with faster DAQ systems and flexible computer code. Hamilton students updated these systems at SNS and NIST continuously throughout the project.

Field mapping Robot: Hamilton brought an automated two axis positioning system to NIST for use in mapping magnetic fields. The robot helped with building so-called "magic boxes" made out of sheets of mu metal, and more complicated coil geometries required for in-situ optical pumping.

X-Factor Measurement Apparatus: One of the difficulties in studying the temperature dependent ^{3}He relaxation mechanism (x-factor) is the time required to measure 'x' for each new cell. Leonard Teng, '12, and Lucas Kang, '13 completed a system that allowed us to test cells at Hamilton, thereby freeing up apparatus at Wisconsin and NIST for other measurements. There is a growing body of data on the larger cells used by NIST on neutron beams, but systematically measuring x in smaller cells may shed light on the origin of the relaxation and on whether the additional relaxation is indeed dependent on surface to volume ratio.

Wisconsin

SEOP Wall Relaxation rates: We studied the limits of attainable polarization in Rb-^{3}He cells through a painstaking experimental characterization of the excess temperature-dependent wall relaxation rates. We found that the wall relaxation rate has a temperature dependence that closely mirrors the Rb vapor pressure, with the combination of effects producing a maximum ^{3}He polarization of 75-80% for the best cells at the time. These measurements illustrate the importance of this collaborative effort, in that complementary measurements of these effects were made at Wisconsin and NIST. Attaining similar results using different methods at the two locations was very important. For the first time, we were able to quantitatively correlate wall relaxation with surface-to-volume ratio. Figure 18 shows the data.

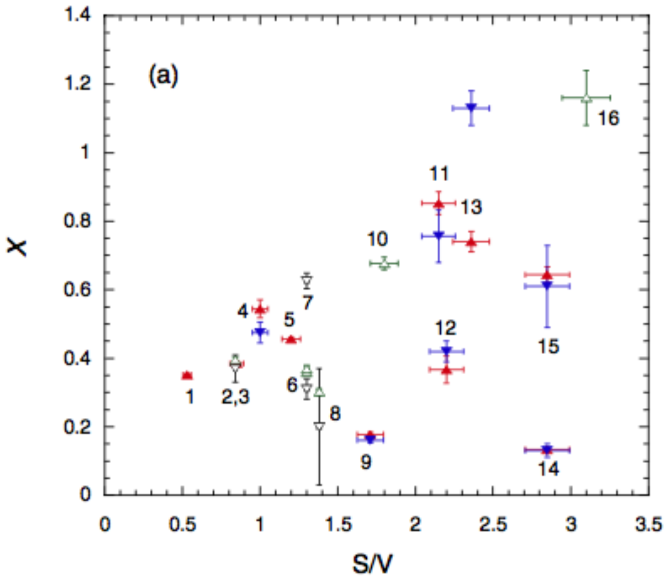

Fig. 18: Measured ^{3}He excess wall spin-relaxation rates for a variety of cells.

Hybrid Spin-Exchange Optical Pumping: The basic idea of hybrid spin-exchange optical pumping is to take advantage of the superior collisional properties of K as compared to Rb, and the convenience of using Rb for the actual light absorbing agent, by combining the two elements in the same cell with a higher K density as compared to Rb density. The spin-exchange process then becomes: 1) Rb atoms are spin-polarized by absorption of circularly polarized laser light, 2) the K atoms are polarized by rapid, high efficiency spin-exchange collisions with Rb atoms, and 3) the ^{3}He atoms are polarized by spin-exchange collisions with primarily K atoms. We demonstrated hybrid spin-exchange optical pumping. With the NIST group we published an extensive analysis of hybrid spin-exchange in the context of practical targets and analyzers and concluded that substantial performance gains in laser power demand and polarization rate are realizable. These gains have been realized in practical polarizers and analyzers in the U.S. and abroad. As an illustration of the broader impact of this work, the hybrid technology has now become the standard at the Thomas Jefferson National Accelerator Facility (J-Lab) Hall A polarized target, where the figure of merit has been dramatically improved using hybrid spin-exchange, as illustrated in Figure 19. We note that the use of spectrally narrowed diode lasers, also developed initially in our group, is making a significant contribution to the improved performance. Hybrid spin-exchange improves the polarization rate, while the spectrally narrow lasers give the higher polarization.

To illustrate the gains for hybrid pumping, Figure 20 shows the spin-exchange rates attainable for various types of cells. The three hybrid cells can maintain high alkali polarization (and therefore high ^{3}He polarization) at substantially higher spin-exchange rates than the pure alkali cells.

Neutron-induced Alkali Relaxation: We devoted much effort to understand the effects of intense neutron beams on the alkali polarization in spin-exchange optically pumped neutron polarizers. Although these effects are negligible for most of the applications foreseen in neutron scattering, which are dominated by the lower neutron fluxes usually encountered in polarization analysis after scattering from a sample, the existence of these effects was not clearly anticipated and they could impact some polarizer applications. Original observations of this phenomenon in the NPDGamma nuclear physics experiment at LANSCE motivated subsequent experiments led by Earl Babcock (a former Wisconsin student trained under this grant), which showed unexpectedly large increases in alkali spin-relaxation rates when illuminated by the high flux beam at ILL. We predicted that the spin-relaxation rates would scale as the square root of the neutron beam intensity, which was found to be the case experimentally and was a key part of the PRL reporting this result shown in Figure 21. The extremely high spin-relaxation rates result in reduced alkali polarization, which in turn reduces the ^{3}He polarization. These rates are generally significantly higher than expected on the basis of comparisons with earlier measurements of α-induced depolarization, though the arguments for this depend on the details of interpretations of the two experiments. Further studies led by Babcock with active participation of NIST, Hamilton, and Wisconsin showed that the relaxation has a very peculiar time dependence; when the cell is first subjected to the neutrons the relaxation quickly increases to a moderately high value, then over the course of a few hundred seconds increases further to the final high value.

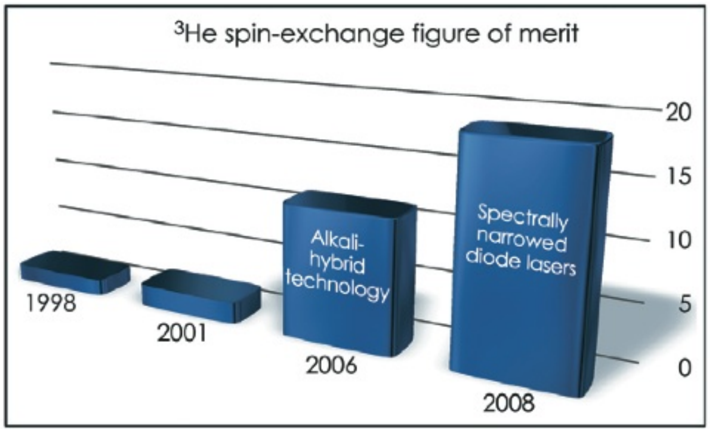

Fig. 19: Figure of merit for the Jefferson Lab polarized ^{3}He target program. Figure courtesy of Prof. Gordon Cates of University of Virginia, from the Nuclear Physics Highlights report to the DOE Office of Nuclear Physics.

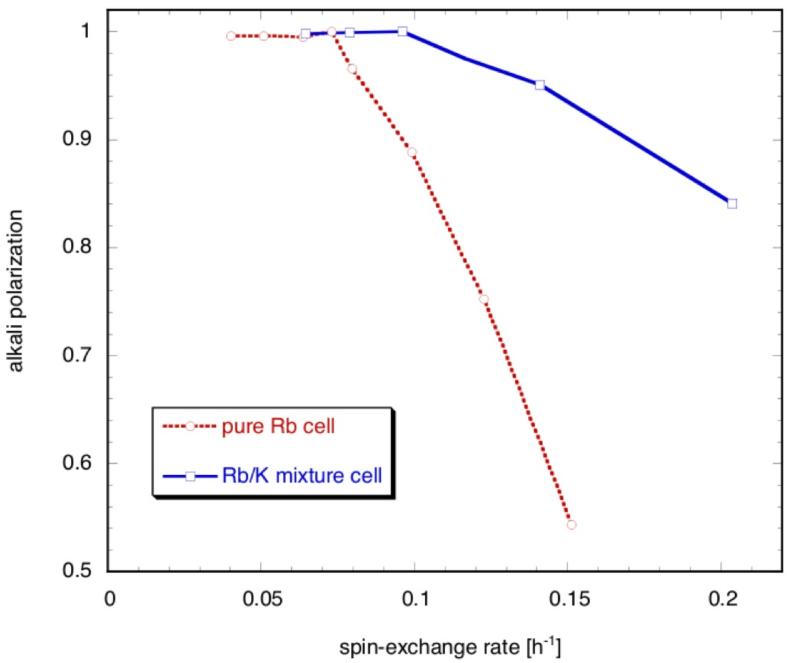

Fig. 20: Comparisons of hybrid cells with pure alkali cells. The moderate K/Rb density ratio (D) cells retain high alkali polarization at much higher spin-exchange rate than the pure or nearly pure alkali cells.

Photon Budget: The systematic theoretical underestimate of photon demand by simulations that include all the known effects in spin-exchange optical pumping was a longstanding problem in spin-exchange optical pumping which was largely solved in the course of this project. This discrepancy was reduced with the advent of frequency-narrowed lasers, which produced alkali polarizations much closer to unity than achieved with broadband pumping. Still, practical polarizers consistently required about a factor of 5 more light than is believed necessary, which raised concerns that some crucial SEOP physics may still be missing in the models. This is illustrated in Figure 8. We pointed out that a slight breakdown in atomic selection rules, presumably through excited-state collisions with He, would if present be greatly amplified in optically thick vapor cells used for SEOP. The point is that if a fully polarized atom continues to absorb light, even at a small rate, that corresponds to a very strong relaxation mechanism and greatly increases the photon usage.

The importance of our study of the photon budget for SEOP was underscored during our hybrid spin-exchange studies, where we made the first measurements of photon efficiencies for spin-exchange optical pumping. We measured the number of polarized nuclei produced per absorbed photon shown in Figure 8. We thought (and later confirmed) that the likely culprit for the lower-than-expected efficiency lies in the purity of light absorption by the Rb atoms themselves, and imperfections arising from either pressure broadening and fine-structure mixing due to the ^{3}He buffer gas.

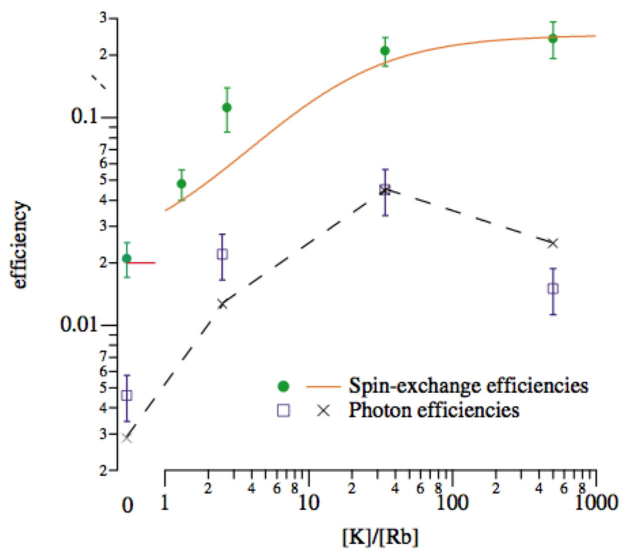

Fig. 21: Measured spin-exchange and photon efficiencies. The order-of-magnitude discrepancy between these two numbers is a key focus of this proposed work.

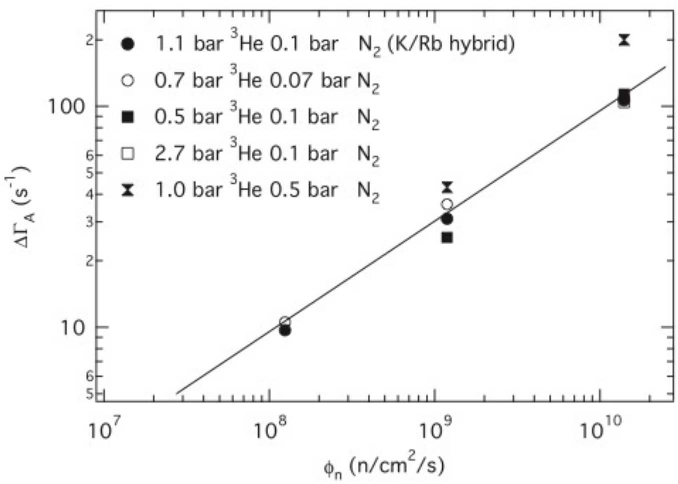

Fig. 22: Alkali spin-relaxation rate as a function of neutron flux.

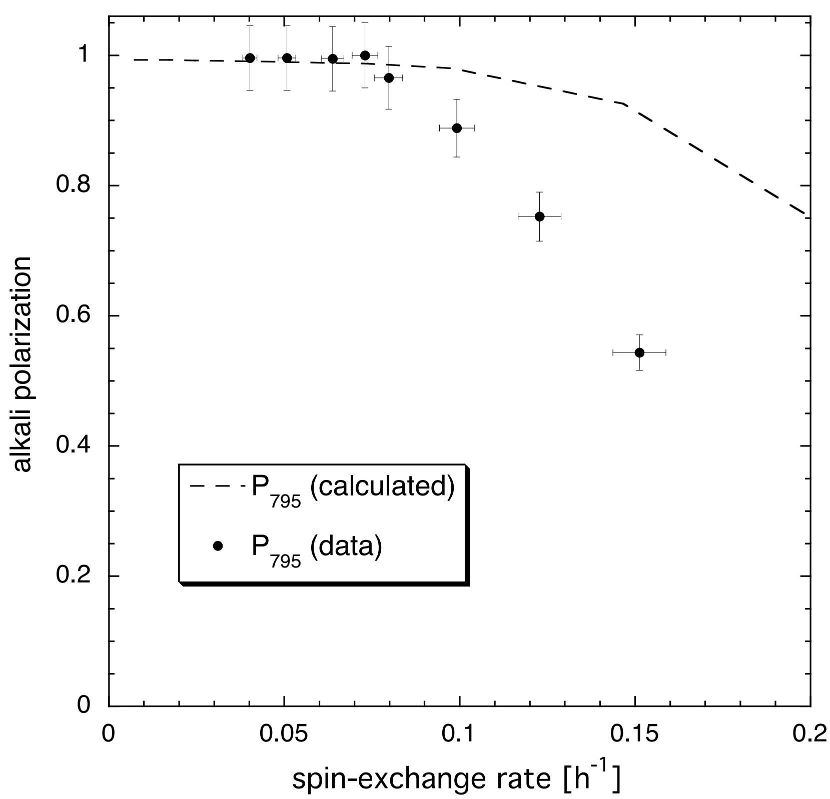

Fig. 23: Theoretically-modeled and experimentally measured spin-exchange rates. For unknown reasons, the alkali polarization begins to drop at lower spin-exchange rates than the model

predicts.

We measured the absorption of circularly polarized light of different helicities by spin-polarized atoms. This is a challenging experiment. In order to make a quantitative measurement, we have to accurately measure 1-P_A, the difference between the alkali polarization and 1. This requires much better precision than a measurement of P_A Results shown in Figure 24 suggested that this effect is not present over the ± 100 GHz region that frequency narrowed lasers primarily access, but shows that at 150 GHz and greater detunings that are strongly pumped by unnarrowed lasers the dichroism is a major effect. A by-product of this experiment is that we have greatly improved our understanding of the quantitative interpretation of alkali polarization using EPR spectroscopy. We have found that simplest EPR spectroscopy method, detecting the EPR resonance with a change in pump laser intensity or Faraday rotation of a co-propagating probe, tends to overestimate the alkali polarization. This effect turns out to be small for polarimetry, but very significant when trying to get an accurate value of 1-P_A.

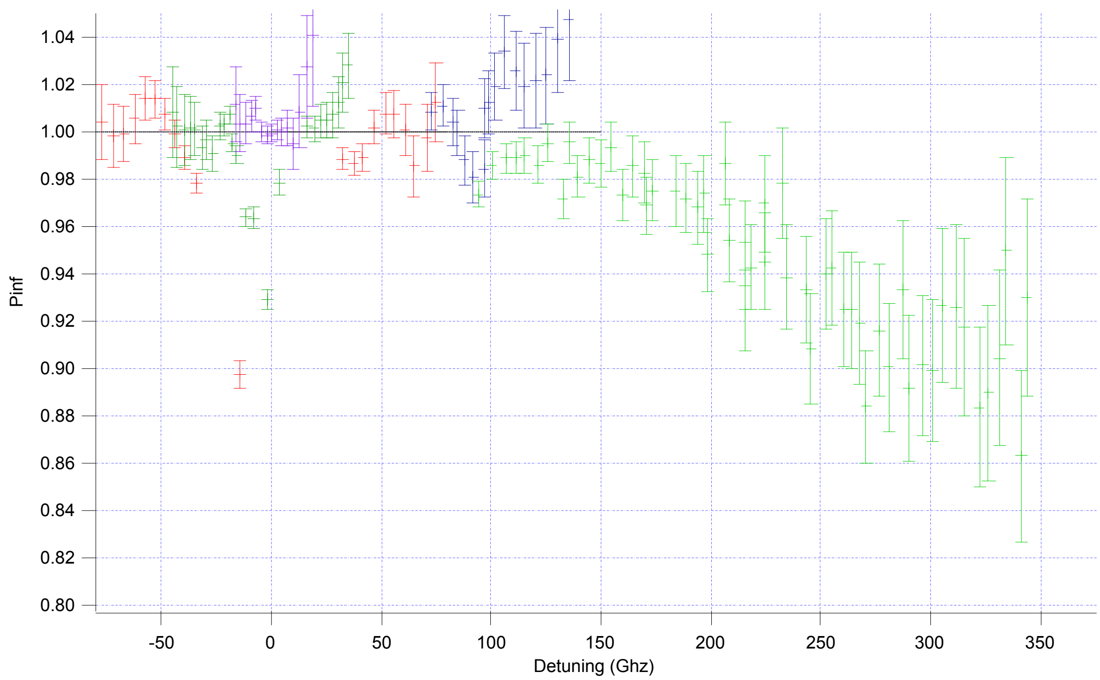

Fig. 24: Circular dichroism measurements, taken by UW graduate students Brian Lancor and Bob Wyllie, near resonance in a spin-exchange cell. The ideal value for spin-exchange optical pumping is 1. These data suggest no deviations from ideal dichroism in the critical ±100 GHz line center region accessed by frequency-narrowed lasers. The reduction in dichroism at larger detunings is likely the origin of the low polarizations obtained when using unnarrowed lasers. We note that in the vast literature on line broadening of alkali vapors this is the first experiment we know of that probes the spin-dependence.

The initial motivation for using frequency narrowed lasers was to improve the efficiency of spin-exchange optical pumping. Since spin filters operate at low pressure (compared to electron scattering targets or MRI applications), there was particular concern about pumping with broad lasers because there is so little pressure broadening. The excellent results obtained using narrowed lasers were not completely understood. The dichroism results go a long way towards explaining why narrowed lasers are important. Off-resonant pumping from a broad laser degrades the optical pumping due to the imperfect circular dichroism. Even if one pressure broadens the alkali absorption lines to better match the laser spectral profile, the gains are marginal because of the poor off resonant pumping characteristics. Thus, these results not only provide an explanation of a key, long standing mystery, but provide important guidance for comparing different laser sources for SEOP.

Wisconsin conducted a theoretical study of nuclear spin-relaxation in the excited state, along with a simple model of radiation trapping. Both of these effects are very sensitive to nitrogen pressure, a topic that has become particularly relevant to neutron spin filters due to the neutron – induced relaxation processes appearing to be less of an issue at low nitrogen pressures. This paper allowed researchers to quantitatively estimate the minimum nitrogen pressures needed for their spin-exchange optical pumping experiments.

Wisconsin studied the feasibility of measuring for the first time the cross-section for anisotropic spin-exchange. This is the only known process that fundamentally limits the polarization attainable by spin-exchange optical pumping. Wisconsin set an upper limit on its value and contributed to a detailed paper on the observations of neutron-induced spin relaxation made at the ILL.

The book Optically Pumped Atoms, by W. Happer, Y-Y Jau, and T. G. Walker, was published in April 2010 by Wiley-VCH. It presents a new approach to practical computation and modeling of optical pumping phenomena, include spin-exchange optical pumping.

X-factor measurements for quartz cells

In collaboration with T. Gentile (NIST) Wisconsin made independent measurements of the X-factor for the large quartz cell Jekyl and were able to confirm the NIST results. The very large X=0.85 values obtained were consistent with the observed maximum polarizations measured at NIST. The X-factor is still an important and perplexing problem for spin-polarized neutron filters. The data are shown in Figure 25.

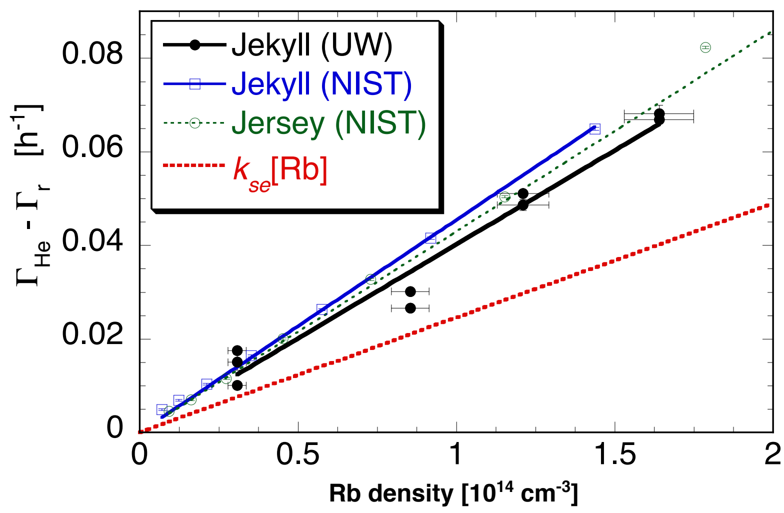

Fig. 4. $\Gamma_{He} - \Gamma_r$ for measurements of the temperature dependence of relaxation for the quartz cells Jekyll (Univ. of Wisconsin and NIST data shown by solid black circles and open blue squares, respectively) and Jersey (NIST data shown by open green circles). Values for [Rb] were determined as discussed in the text. Error bars not visible are smaller than the size of the points. The solid lines show linear fits to the data for each cell with the intercepts fixed at zero. The dotted red line show the Rb spin-exchange rate k_{se}[Rb].

Fig. 25: Density dependence of the spin relaxation rate in a quartz cell.

Spin-exchange modeling:

1) Measurement of optical wavefront velocities. A key goal of the Wisconsin research was to produce a comprehensive model of spin-exchange optical pumping of ^{3}He that incorporates all we know about the processes involved. They realized that more sensitive tests of the model can be made by measuring the temporal dynamics of the polarization wavefronts, which give sensitive information about pumping rates as a function of position and time inside the optical pumping cell. Wisconsin have developed a method to measure these velocities as a function of space/time after application of the pumping light by applying a sinusoidal magnetic field instead of a DC bias field in SEOP. As the field sweeps through zero, the Rb atoms are rapidly depolarized. Then the optical pumping begins to polarize the atoms and the vapor becomes more and more transparent, as measured by Faraday rotation of a longitudinal probe beam. The slope of the signal gives the wavefront velocity, typically 10s of meters/sec as shown in Figure 26.

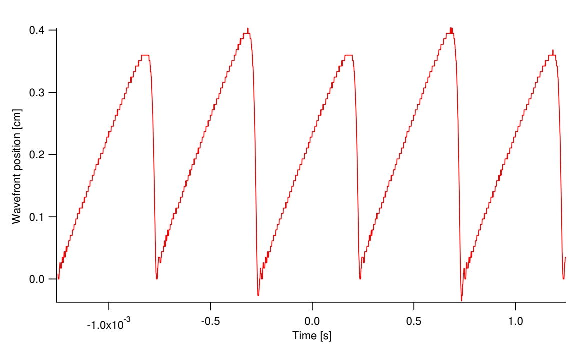

Fig. 26: Polarization wavefront velocities measured in a spin-exchange optical pumping cell.

2) Reconfiguration of the existing spin-exchange model.

Based on this work Wisconsin realized that we need to reconfigure the spin-exchange model to allow for quantitative comparison to experiment. The steady-state properties of ^{3}He spin-exchange cells are of greatest relevance to experimenters wanting to design neutron spin-filters. The basic equations that determine this steady state are first order in the time-derivate of the polarization and the spatial derivative of the spectral flux. We have traditionally first found the steady-state polarization for given spectral flux, then propagated the spectral flux across the cell to find the steady-state solution for the full problem. However, we realized that if we instead find the spectral flux spatial distribution, then integrate the polarization equation with time, we have exactly what we need to deduce the wavefront velocities as shown in Figure 27.

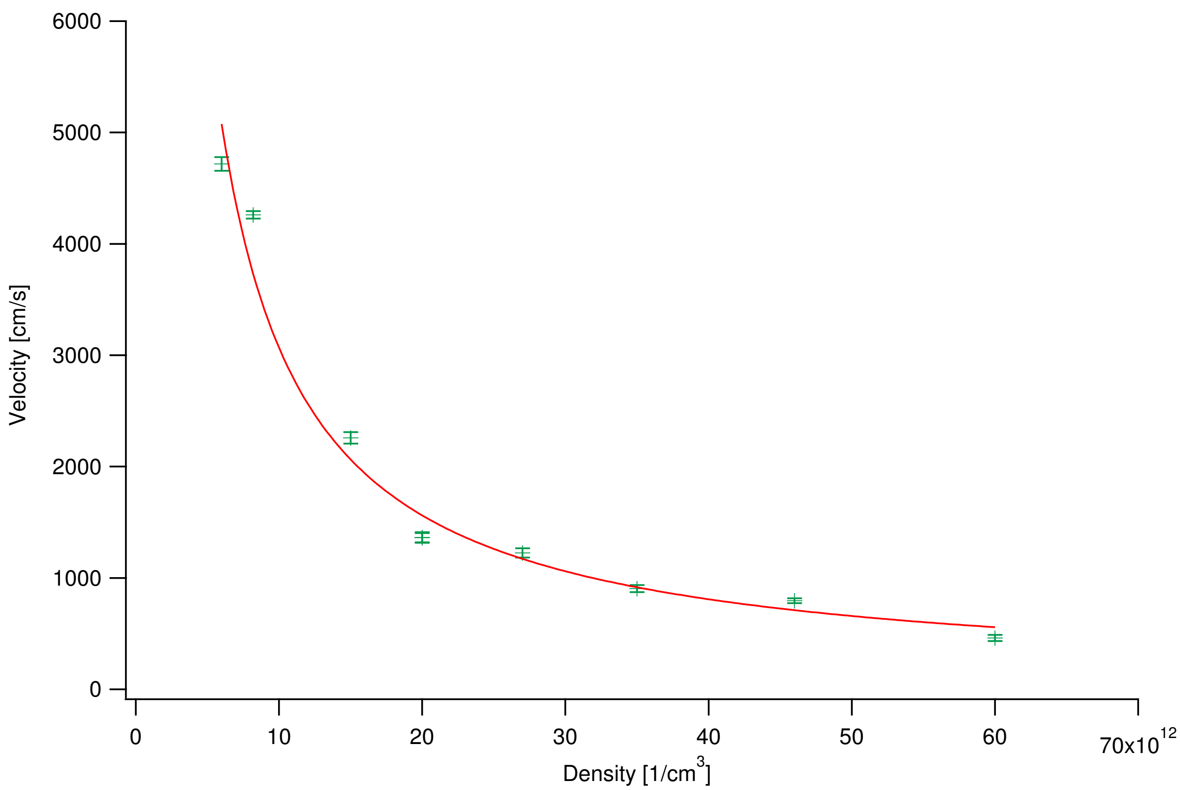

Fig. 27: Measurements of the wavefront velocity as a function of density.

Production of a documented, public access model for SEOP

Armed with a well-tested model, we produced a web-based version accessible to and run by scientific users. Spin-exchange researchers are able to give details of the cell composition and geometry, and the laser power and spectral characteristics, and the model outputs the spatial and temporal dependence of the polarization and light intensity.

Personnel

Changbo Fu worked as a postdoc at NIST with T.R. Gentile from 2007-2010, went to IU where he continued some involvement in polarized ^{3}He work until 2011. He later became an assistant professor of physics at Shanghai Jiaotong University. Peter Jiang finished his PhD thesis at IU, did a postdoc at SNS, and is now employed in the SNS polarized neutron group. Alan Ye became a postdoc located at NIST and supported through ORNL to work on polarized ^{3}He. He is now a member of the NIST polarized ^{3}He group. Haiyang Yan did a PhD and later a postdoc at Indiana and later became a staff member at the Chinese Academy of Engineering physics responsible for setting up a polarized ^{3}He group for their neutron scattering facility. Brian Lancor received his PhD from Wisconsin in August 2011 and is a lecturer at a small college. Zach DeLand worked on ^{3}He and biomagnetism in the Wisconsin group. Ke Li worked on the SESAME ^{3}He measurements at LENS and is writing his PhD thesis.

Publications, Talks, and Education

The appendix lists our research publications, talks, seminars, and service activities in the neutron physics and scattering community over the grant period, and also documents our record of education of undergraduate and graduate students and postdocs. The NIST/Indiana/Hamilton/Wisconsin collaborators contributed to 52 refereed papers (6 in Phys. Rev. Letters), wrote one book, delivered more than 32 invited talks, and co-organized one 3-month neutron physics workshop program, one week-long neutron summer school, one session at the APS DAMOP meeting and at the APS April meeting on polarized ^{3}He. The longer-term impact of our research and development efforts on the education of neutron scientists is also starting to become visible. Among the former graduate students and postdocs in our ^{3}He group are one associate and one full professor (each active in neutron physics), two research scientists at the NIST Center for Neutron Research, one postdoc in polarized ^{3}He at Juelich (sited at the FRM-2 reactor in Munich), and one postdoc at the SNS. In addition a number of undergraduate students have obtained their first real experience in scientific research in one of our labs. Of the more than 27 undergraduate students we have involved in ^{3}He-related research over the project, 22 are from Hamilton College, 12 have written senior theses at Hamilton involving ^{3}He, and at least 11 have gone on to graduate school in science or engineering

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B. Lancor, E. Babcock, R. Wyllie, T. G. Walker, **Circular Dichroism of RbHe and RbN_2 Molecules,** Phys. Rev. A. **82**, 043435 (2010).

B. Lancor, T. G. Walker, **Effects of Nitrogen Quenching Gas on Spin-Exchange Optical Pumping of 3He,** Phys. Rev. A. **82**, 043417 (2010).

T. G. Walker, **Fundamentals of Spin-Exchange Optical Pumping**, 2011 J. Phys.: Conf. Ser. **294,** 012001 (2011).

E. Babcock, S. Boag, C. Beecham, T. E. Chupp, T. R. Gentile, G. L. Jones, A. K. Petukhov and T. G. Walker, **Effects of high intensity neutron flux on in-situ spin-exchange optical pumping of ^{3}He,** J. Phys.: Conf. Ser. **294**, 012011 (2011).

B. Lancor and T. G. Walker, **Polarization limits in K-Rb spin-exchange mixtures**, Phys. Rev. A **83**, 065401 (2011).

N. Brahms, T. Tscherbul, P Zhang, J. Klos, R. Forrey, Y. Au, H. R. Sadeghpour, A. Dalgarno, J. Doyle, and T. G. Walker, **Formation and dynamics of van der Waals molecules in buffer-gas traps,** Phys. Chem and Chem. Phys., DOI: 10.1039/c1cp21317b (2011).

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C. Fu, T. R. Gentile, and W. M. Snow, **Limits on Possible New Monopole-Dipole Interactions from the Spin Relaxation Rate of Polarized ^{3}He Gas**, Phys. Rev. D83, 031504(R) (2011).

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W. M. Snow, **Exotic Physics with Slow Neutrons**, Physics Today **66**, 50 (2013).

P.-H. Chu, A. Dennis, C. B. Fu, H. Gao, R. Khatiwada, G. Laskaris, K. Li, E. Smith, W. M. Snow, H. Yan, and W. Zheng, **Laboratory Search for Spin-dependent Short-range Force from Axion-Like-Particles using Optically Polarized ^{3}He Gas**, Phys. Rev. D **87**, 011105(R) (2013).

Q. Ye, T. R. Gentile, J. Anderson, C. Broholm, W. C. Chen, Z. DeLand, R. W. Erwin, C. B. Fu, J. Fuller, A. Kirchhoff, J. A. Rodriguez-Rivera, V. Thampy, T. G. Walker, and S. Watson, **Wide**

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W. C. Chen, T. R. Gentile, Q. Ye, T. G. Walker, E. Babcock, **On the limits of spin-exchange optical pumping of ^{3}He**, J. Appl. Phys. **116**, 014903 (2014).

M. G. Huber, M. Arif, W. C. Chen, T. R. Gentile, D. S. Hussey, T. C. Black, D. A. Pushin, C. B. Shahi, F. E. Wietfeldt, and L. Yang, **Neutron interferometric measurement of the scattering length difference between the triplet and singlet states of n-^{3}He** , Phys. Rev. C. **90**, 064004 (2014).

H. Yan, K. Li, R. Khatiwada, E. Smith, W. M. Snow, C. B. Fu, P.-H. Chu, H. Gao, and W. Zheng, **A Mean Frequency Determination Method for Digitized NMR Signals**, Communications in Computational Physics **15**, 1343 (2014).

S. R. Parnell, A. L. Washington, K. Li, H. Yan, P. Stonaha, F. Li, T. Wang, A. Walsh, W. C. Chen, A. J. Parnell, J. P. A. Fairclough, D. V. Baxter, W. M. Snow, and R. Pynn, **Spin Echo Small Angle Neutron Scattering (SESANS) using a continuously pumped 3He neutron polarization analyser**, Rev. Sci. Inst. **86**, 023902 (2015).

Invited Talks/Seminars/Colloquia

"Polarized ^{3}He Spin Filters", Invited talk, T.R. Gentile, Spallation Neutron Source, Oak Ridge, Tennessee, Nov. 12, 2003.

"Polarized ^{3}He Neutron Spin Filters", T.R. Gentile, Invited talk, Amersham Health, July 22, 2003.

"Precision Polarimetry and Spin Manipulation of Polarized Low Energy Neutron Beams", W. M. Snow, invited talk at the Pulsed Polarized Neutron Workshop, Gaithersburg, MD, Feb. 10, 2003.

The LENS Neutron Source, W. M. Snow, seminar, Instituto Nazionale di Fisica Nucleare, Laboratori Nazionale di Leganro, Padova, Italy, Jan. 10, 2003.

LENS, A University-Based Pulsed Cold Neutron Source for Education and Research, W. M. Snow, condensed matter physics seminar, Brookhaven National Lab, July 21, 2003.

The LENS Neutron Source, W. M. Snow, seminar, California Institute of Technology, May 23, 2003

``Spin-Exchange Optical Pumping with Alkali-Metal Vapors", Earl Babcock, invited talk at the ILL, Grenoble, France, summer 2004.

``Spin-Exchange Optical Pumping with Alkali-Metal Vapors", Earl Babcock, invited talk at FRM Juelich, Germany, summer 2004.

“Polarized ^{3}He Neutron Spin Filters”, T.R. Gentile, Invited talk, Condensed Matter Physics seminar, Brookhaven National Laboratory, Upton, New York, Oct. 22, 2004.

“Polarized ^{3}He - A Gas For All Seasons But Still Mysterious”, T.R. Gentile, special Colloquium, Arizona State University, Tempe, Arizona, Oct. 8, 2004.

“Polarized neutron reflectometry with ^{3}He spin filters“, T.R. Gentile, Invited talk, 8th International Conference on Surface X-Ray and Neutron Scattering, Bad Honnef, Germany, June 28 - July 2, 2004.

“Polarized ^{3}He-based Neutron Spin Filters“, T.R. Gentile, Invited talk, International Workshop on Polarized Neutrons in Condensed Matter Investigations 2004, Washington, DC, June 1-4, 2004.

“Polarized ^{3}He Neutron Spin Filters”, T.R. Gentile, Invited talk, Univ. of Wisconsin, Atomic Physics seminar, May 11, 2004.

“Polarized ^{3}He Neutron Spin Filters for Slow Neutron Physics”, T.R. Gentile, Invited talk, International Conference on Precision Measurements with Slow Neutrons, NIST, Gaithersburg, Maryland, April 5-7, 2004.

“Polarized ^{3}He Neutron Spin Filters”, Invited talk, T.R. Gentile, Intense Pulsed Neutron Source, Argonne National Laboratory, seminar, March 2004.

“Neutron Polarizers based on Polarized 3He”, W. M. Snow, invited talk at the International Conference on Polarized Neutrons in Condensed Matter Investigations, Washington, DC, June 4, 2004 (part of a one-day polarized neutron school held at the conference).

“Turning photons into polarized nuclei”, Thad Walker, Physics Colloquium, University of Central Michigan, April 15, 2004.

“Polarized ^{3}He - A Gas For All Seasons But Still Mysterious”, T.R. Gentile, Colloquium, George Mason University, Fairfax, Virginia, Nov. 4, 2005.

“Polarized ^{3}He - A Gas For All Seasons But Still Mysterious”,, T.R. Gentile, Colloquium, Bucknell University, Lewisburg, Pennsylvania, April 12, 2005.

“Polarized ^{3}He - A Gas For All Seasons But Still Mysterious”, T.R. Gentile, Colloquium, Hamilton College, Clinton, New York, April 11, 2005.

T.R. Gentile, **"Polarized 3He Spin Filter Development in the U.S.",** Polarized Inelastic Neutron Scattering conference, Brookhaven National Lab, April 6, 2006.

W. M. Snow**, The LENS Neutron Source**, invited talk at Japan Proton Accelerator Research Complex (J-PARC), Tokai, Japan, Dec. 19, 2006.

W. M. Snow**, Slow Neutrons: Cold, Very Cold, and Ultracold**, invited talk at the meeting of the International Collaboration on Advanced Neutron Sources, ICANS XVIII, Dongguan, China, April 26, 2007.

T. G. Walker, **"Turning photons into polarized nuclei",** Physics Colloquium, College of William and Mary, Dec. 7, 2007.

T.R. Gentile, **"The NIST-Indiana-Hamilton-Wisconsin and NCNR spin filter programs",** Meeting of the Joint Research Activity in Neutron Spin Filters, European Union Integrated Infrastructure Initiative in Neutron Scattering and Muon Spectroscopy, Institut-Laue-Langevin, Grenoble, France, April 16-17, 2007.

T. R. Gentile, "**Science Applications of Polarized ^{3}He Spin Filters in the USA**" and "**Development of Polarized ^{3}He Spin Filters in the USA",** International Workshop on Polarized Neutron Scattering at ANSTO, Australian Nuclear Science and Technology Organization, Lucas Heights, New South Wales, Australia, November 28-29, 2007.

T. R. Gentile, "**Polarized ^{3}He-based neutron spin filters for materials science**", Council on Ionizing Radiation Measurements and Standards meeting (Industrial Applications and Materials Effects Breakout Session), NIST, Gaithersburg, Maryland, Oct. 7, 2008.

W. M. Snow**, Larmour Precession in Quantum Mechanics,** discussion forum at the Bhabha Atomic Research Centre, Mumbai, India, Dec. 19, 2008.

W. M. Snow**, Slow Neutrons,** colloquium at the Bhabha Atomic Research Centre, Mumbai, India, Dec. 15, 2008.

Spin Echo Small Angle Neutron Scattering, W. M. Snow, seminar, Chinese Academy of Engineering Physics, Mianyang, China, August 11, 2015.

Polarized ^{3}He Neutron Spin Filters, W. M. Snow, seminar, Chinese Academy of Engineering Physics, Mianyang, China, August 10, 2015.

Former ^{3}He PhD Students: present location

B. R. Lancor, "**Studies of the Efficiency of Spin Exchange Optical Pumping**", PhD thesis, University of Wisconsin (2011). Present position: lecturer, Edgewood College.

Peter Jiang, "**Polarized ^{3}He Filter Development for Neutron Scattering"**, PhD thesis, Indiana University (2010). Present position: staff, polarized neutron group, Oak Ridge National Laboratory.

Haiyang Yan, "**Applications of Polarized ^{3}He Filters in Neutron Scattering"**, PhD thesis, Indiana University (2008). Present position: staff scientist, research reactor facility, Chinese Academy of Engineering Physics, Mianyang, China.

Xin Tong, "**Development of Neutron Polarizers Based on Polarized ^{3}He Filters and Application in Polarized Neutron Diffractometry",** PhD thesis, Indiana University (2007). Present position: staff, polarized neutron group, Oak Ridge National Laboratory.

Earl Babcock**, "Spin-Exchange Optical Pumping with Alkali-Metal Vapors"**, Ph.D. thesis, University of Wisconsin-Madison (2005). Present position: scientific staff, FRM/Juelich, based at the FRM-2 research reactor, Munich, Germany.

Dan Hussey, "**Coherent Effects in Xray and Neutron Reflectometry** ", PhD thesis, Indiana University (2003) Present position: staff scientist in neutron imaging and interferometry, NIST Center for Neutron Research, Gaithersburg, MD

Bien Chann, "**Studies of spin-exchange optical pumping",** PhD thesis, University of Wisconsin-Madison (2003). Present Position: Quantum Electronics Group, MIT Lincoln Labs

Former ^{3}He Postdocs: present location

Wangchun Chen, Indiana/NIST postdoc 2001-2006, NIST staff scientist 2006-present.

Changbo Fu, Indiana/NIST postdoc 2007-2010, now assistant professor of physics Shanghai Jiaotong University

Former ^{3}He undergraduates:

Hamilton College senior theses: (class year, thesis title, post-Hamilton location)

Jessica Smith '09, **"EPR absolute** ^{3}He **polarization measurement",** Hamilton College

Ruth Duggan '08, **"Shielded AFP coil for MACS instrument at NIST"**, financial consulting

Jordan Barone '08, **"Transverse AFP coil for neutron polarizers"** Ph.D student, Rutgers University

Jonathan "Wex" Wexler '08, **"NMR code for polarized ^{3}He",** Ph.D. student, UMass. Amherst

Dan Tomb '08, **"Magnetic modeling calculations for RF coils"**

Kosta Popovic, '06, **"Magnet sample environment design SCD polarizer,"** Ph.D. student, Univ. of Virginia

John Steinberg, '06, **"NMR system for compact neutron polarizer,"** Seattle, WA

Roberto Andrade, '05,**"Making cells for spin exchange optical pumping,"** teaching capioera
M. Freddie Dias, '05, **"Novel compact neutron polarzer",** robotics tech., Carnegie Mellon
Jim Baker, '04, **"*In-situ* pumped compact neutron polarizer",** physics graduate school, Ph.D. student, Univ. Of Rochester

Other Hamilton research students: (class year, research description, present location)

Julia McDougal, '09 **"Magnetic modeling for a compact solenoid,"** Hamilton College
Greg Fullman, '09 **"Magnetic modeling for a compact solenoid,"** Hamilton College
Dan Campbell,'08 **"Shielded RF coil for MACS Polarizer,"** Goldwater Scholar, Ph.D. student, University of Maryland
Josh Newman, '06 **"Magnetic mapping for aCORN expt. and compact polarizer"**
Andrew Yue, '03 **"Magnetic mapping,"** physics Ph.D student, U. Tennessee

NIST summer undergraduates (year of research, school, present location)

Greg Armstrong (2005) Hamilton College

IUCF Research Experiences for Undergraduates program

Gavin Hall (2003), undergraduate REU summer student, University of Oregon.

Service in Neutron Science

T. Gentile, **DoE Cost and Schedule Review Panel for SNS Fundamental Physics Beam Line**, Nov. 2003. committee member

T. Gentile, **Pulsed Polarized Neutrons workshop**, Gaithersburg, MD, Feb. 2004. author for ^{3}He spin filter section of report.

T. R. Gentile and W. C. Chen, **Polarized Neutron School**, lecture and demonstration on 3He spin filters, (sponsored by NSF-DMR, ORAU, BoE-BES and SNS, held at the NCNR June 4-5, 2004).

W. M. Snow**, Polarized Neutrons in Condensed Matter Investigations**, Gaithersburg, MD, May 30, 2004, program committee.

W. M. Snow**, Neutron Physics**, series of 5 lectures at the 16th National Summer School in Nuclear Physics, Bar Harbor, Maine, June 13-18, 2004.

W. M. Snow, **NSF Division of Materials Research Instrumentation for Materials Research-Major Instrumentation Program (IMR-MIP) Reverse Site Visit**, NSF panel for review of proposals for the new NSF DMR IMR-MIP program, May 25-26, 2004.

W. M. Snow**, International Collaboration on Advanced Neutron Sources**, LENS contact, 2004.

T. R. Gentile and W. M. Snow: **^{3}He Neutron Spin Filter JRA, NMI3, European Union Framework Programme 6.** observers

W. M. Snow**, Probing Complex-Fluid Membranes and Films with Neutron Spin Echo**, Bloomington, Indiana, August 14-17, 2005, organizing committee.

T. Gentile, **International Conference on Precision Measurements with Slow Neutrons,** NIST, Gaithersburg, Maryland, April 5-7, 2004. local organizing committee member and guest editor for conference proceedings published in J. Res. Natl. Inst. Std. Technol., 2005.

W. M. Snow**, The 8th International Conference on Quasielastic Neutron Scattering (QENS2006)**, Bloomington, Indiana, June 14-17, 2005, organizing committee

W. M. Snow**, International Collaboration on Advanced Neutron Sources: ICANS-XVII**, April 24-29, 2005, international advisory committee.

W. M. Snow**, SNS/SHUG Users Group Executive Committee**, elected member (2005-present).

W. M. Snow, **LANSCE Users Group Executive Committee**, elected member (2005-present).

T. R. Gentile, **International Conference on Precision Measurements with Slow Neutrons,** NIST, Gaithersburg, Maryland, April 5-7, 2004. local organizing committee member and guest editor for conference proceedings published in J. Res. Natl. Inst. Std. Technol., 2005.

W. M. Snow**, Neutron Summer School,** University of Tennessee, June 4-10, 2006, co-organizer.

T. R. Gentile, NCNR Expansion Workshop panel **"Instrumentation: Polarized Beam Methods and Optical Devices"**, July17-19. 2006.

W. M. Snow**, Fundamental Neutron Physics**, program at the National Institute for Nuclear Theory, Seattle. WA, March 12-June 1, 2007, co-organizer.

W. M. Snow**, International Collaboration on Advanced Neutron Sources XVIII**, Dongguan, China, international advisory committee (2007).

W. M. Snow**, American Conference on Neutron Scattering, ACNS2008,** program committee.

T. R. Gentile, **Organizer, polarized gas session and informal satellite workshop on polarized** ^{3}He, Division of Atomic, Molecular, and Optical Physics 2009, Charlottesville, VA, May 20-23, 2009.

W. M. Snow**, Neutron Summer School,** NIST, June 22-26, 2009, co-organizer.

W. M. Snow, **DOE Graduate Research Fellowship Program,** reviewer, February 2010.

W. M. Snow, **American Conference in Neutron Scattering 2010,** chair, symposium program committee on Neutron Physics.

W. M. Snow, **Scoping Workshop for Second Guide Hall at OPAL**, 16-18 April 2012, Sydney, Australia, discussant.

W. M. Snow, **Topical Group on Precision Measurements and Fundamental Constants (GPMFC),** At-Large Member, Executive Committee, April 2013-present.