SNS 110040000-TR0003-R01

REPORT OF
PULSED POLARIZED NEUTRONS WORKSHOP

FEBRUARY 10-13, 2003
GAITHERSBURG, MARYLAND

Compiled by

Roger Pynn

Date Published: August 2004

Sponsored by:

The U.S. Department of Energy
Office of Science
Basic Energy Sciences

and

The National Science Foundation
Division of Materials Research

SNS is managed by UT-Battelle, LLC, under contract
DE-AC05-00OR22725 for the U.S. Department of Energy.
SNS is a partnership of six national laboratories: Agronne, Brookhaven, Jefferson,
Lawrence Berkeley, Los Alamos, and Oak Ridge.

ACKNOWLEDGEMENTS

The organizers of the Pulsed Polarized Neutrons Workshop thank the U.S. Department of Energy, Office of Science, Basic Energy Sciences and the National Science Foundation, Division of Materials Research (Award Number 0318-589) for cosponsoring this workshop and acknowledge that any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation or the U.S. Department of Energy.

The following people contributed to the completion of this report:

Ian S. Anderson	Spallation Neutron Source
Jeremy Cook	National Institute of Standards and Technology
Gian Felcher	Argonne National Laboratory
Tom Gentile	National Institute of Standards and Technology
Geoffrey Greene	Oak Ridge National Laboratory
Frank Klose	Spallation Neutron Source
Tom Koetzle	Argonne National Laboratory
Eddy Lelievre-Berna	Institut Laue-Langevin
Andre Parizzi	Spallation Neutron Source
Roger Pynn	Los Alamos National Laboratory
Jinkui Zhao	Spallation Neutron Source

TABLE OF CONTENTS

ACRONYMS AND ABBREVIATIONS

ANL	Argonne National Laboratory
ESS	European Spallation Neutron
FFZ	Forschungszentrum Jülich
GPA	generalized polarization analysis
GUI	graphical user interface
HFIR	High Flux Isotope Reactor
HMI	Hahn Meitner Institut
ILL	Institut Laue-Langevin
IPNS	Intense Pulsed Neutron Source
LANL	Los Alamos National Laboratory
LANCSE	Los Alamos Neutron Center
MIEZE	Modulation of Intensity for Zero Effort
MRI	magnetic resonance imaging
Nb	niobium
NCNR	NIST Center for Neutron Research
NIST	National Institute of Standards and Technology
NRSE	neutron resonance spin echo
NSE	neutron spin echo
ORNL	Oak Ridge National Laboratory
PNR	polarized neutron reflectometry
R&D	research and development
Rb	rubidium
Rf	radio frequency
SANS	small-angle neutron scattering
SCANS	Software for Computer Aided Neutron Scattering
SCD	single-crystal diffractometer
SERGIS	Spin Echo Resolved Grazing Incidence Scattering
SESANS	Spin Echo Labeling for Small Angle Scattering
SNS	Spallation Neutron Source
TOF	time of flight
U.S.	United States
YBCO	yttrium, barium, and copper oxide

EXECUTIVE SUMMARY

A Pulsed Polarized Neutrons Workshop was held on February 10–13, 2003, in Gaithersburg, Maryland. The workshop was attended by 61 scientists (47 from the United States) representing work in the United States, Europe, and Japan. The purpose of the workshop was to discuss research with polarized neutrons at pulsed spallation sources and to develop a roadmap for the technology research and development (R&D) required to facilitate this type of work at pulsed neutron sources.

Polarized neutrons provide a powerful tool for research at today's continuous neutron sources, permitting unique information to be obtained from neutron-scattering experiments and in the area of fundamental neutron physics. The information obtained is indispensable to important areas of current research such as magnetism, spin fluctuations in correlated-electron materials, nanoscience, astrophysics, and cosmology.

Unfortunately, the polarized neutron capabilities that already exist at reactor neutron sources, mainly in Europe, cannot be transferred directly to pulsed spallation sources, such as the Spallation Neutron Source (SNS), because many of the relevant devices used at reactors operate only at a single neutron wavelength or with a neutron beam of limited divergence. Both of these restrictions must be overcome for devices to be useful at pulsed spallation sources. This report identifies the significant R&D efforts that will be required to achieve these goals. These efforts must be undertaken now if it is to be useful early in the lifetime of SNS.

Because well-funded efforts in these areas are under way in both Japan and Europe, it makes sense for the United States to collaborate on these activities, as well as to develop its own R&D program. There is ample opportunity within the R&D portfolio outlined in this report for both university-based and national laboratory activities. Synergy between these efforts will contribute to other goals such as the development of a robust program of instrument innovation that will maintain the scientific leadership of SNS in future decades.

1. PRIORITIES FOR DEVELOPING U.S. COMPETENCE

After two days of presentations and debate, workshop participants developed a prioritized list of actions that should be carried out to ensure that the U.S. community develops the knowledge base and instrumentation required to carry out the broad range of science enabled through the use of polarized neutrons. The list of actions is summarized subsequently, with supporting detail provided in the body of the report.

1.1. DEVELOP THE U.S. EXPERIENCE BASE

The U.S. neutron-scattering community has very little experience with the use of polarized neutrons, and although some device development is under way, there are only a few operating polarized neutron instruments in the United States. This is in contrast to the situation in Europe, where the technique has been well developed. To develop the U.S. experience, a number of actions should be undertaken immediately:

- Promote participation by U.S. users of polarized neutrons at European and Japanese facilities.
- Increase beam time usage on existing polarized neutron instruments in the United States.
- Provide test beam lines and support facilities in the United States.
- Provide training and education of new researchers and students.

1.2. SUPPORT DEVELOPMENT OF NEW INSTRUMENT CONCEPTS THAT USE POLARIZED NEUTRONS

The participants emphasized the need to support development of polarized neutron instrumentation, which will require continued commitment from both funding agencies and management of U.S. neutron-scattering facilities. Recommendations are as follows:

- Develop a culture of innovation in instrument design.
- Provide an environment for cross fertilization of R&D activities at universities and facilities.
- Coordinate and enable R&D on polarization devices and components.
- Develop and test new instrument concepts.
- Provide instrument time for testing of new concepts.
- Fund and train new people in the development of instrumentation.

1.3. DEVELOP THE INFRASTRUCTURE AT SNS

The community made an explicit request that the infrastructure required for polarized neutron experiments be developed at the SNS facility:

- Build up on-site capability for the production and use of polarized ^{3}He.
- Make provisions in instrument designs for the use of polarized neutrons.
- Provide necessary sample environments and (low) magnetic background.

2. R&D DIRECTIONS TO SUPPORT CONSENSUS PRIORITIES

The following itemized list summarizes the directions in which workshop participants concluded that R&D should be focused in the coming years to fully enable the use of polarized neutrons at SNS and other neutron facilities. Full descriptions may be found in the relevant sections of the report.

2.1. POLARIZED ^{3}HE

Because of the wide neutron energy-band used in most pulsed source instruments, it is essential to continue the development of polarizers and analyzers based on polarized ^{3}He filters and to provide the infrastructure for their use at SNS. Specific lines of development include the following:

- Cell development–to reach longer relaxation times.
- Development of spectrally narrowed lasers for spin exchange pumping.
- Investigation of pumping of other alkali and mixtures in addition to rubidium.
- Development of a filling station approach to spin exchange pumped cells.
- Development of compact, continuously operating compressors.
- Investigation of the fundamental mechanisms limiting polarization.
- Development of magnetic shielding and transfer methods.

2.2. NEUTRON SPIN FLIPPERS AND SPIN-TURN DEVICES

The broad neutron wavelength band determines the development that will be required to adapt present designs of neutron spin flippers to pulsed sources. A suitable flipper should either function intrinsically over a broad neutron bandwidth or it must be possible to change the flipping conditions as a function of time. Specifically, the priorities for R&D are as follows:

- Development of broad wavelength-band spin flippers and spin-turn devices
  - Push the minimum wavelength to 0.1 Å
  - Increase the angular coverage
  - Minimize sensitivity to external magnetic field environment
  - Reduce “pollution” to magnetic environment
- Development of computational methods
  - Develop codes to calculate beam polarization for a realistic flipper
  - Integrate realistic magnetic field profiles in simulation codes

2.3. NEW METHODS USING POLARIZED NEUTRONS

Novel techniques such as neutron spin echo (NSE) and neutron resonance spin echo (NRSE) have revolutionized neutron instrumentation at continuous neutron sources. Although NSE instruments exist, or are planned, in the United States, new applications have been identified that are high priorities for development. NRSE techniques are not being pursued actively in the United States, though various new applications would require further development. Priorities for

U.S. development are as follows:

- Develop know-how in NRSE techniques through collaboration with European counterparts.
- Develop thin-film precession components for NSE.
- Build and operate test facilities at U.S. neutron sources.
- Develop new instrumentation methods including:
  - MIEZE–allows sub-neV energy resolution
  - SESANS–spin echo labeling for small-angle scattering
  - SERGIS–spin echo–resolved grazing incidence scattering

2.4. DYNAMICALLY POLARIZED TARGETS

This technique is particularly useful in biological samples to distinguish incoherent and coherent scattering and potentially increase diffraction intensity. Limited R&D is required since the technique has matured in Europe; however, the following actions should be undertaken:

- Training and testing through European collaboration.
- Testing of the technique at a U.S. pulsed source.

2.5. COMPUTATIONAL TOOLS

In addition to building and testing new instrument components for polarized neutrons, it is crucial to develop the simulation tools that will allow the performance of components to be predicted and evaluated, especially when new components are to be combined together. Priorities in this area are the following:

- Promote and support existing standard software packages (e.g., McStas, Vitess, Ideas, and NISP).
- Include general descriptions of polarized-neutron propagation in magnetic fields.
- Include the capability of defining complex magnetic-field regions.
- Develop more powerful graphical representation tools for visualization.
- Promote training in the use of standard packages.
- Develop a unified, standardized, simulation package at SNS.

3. THE SCIENTIFIC CASE FOR POLARIZED NEUTRONS IN NEUTRON-SCATTERING EXPERIMENTS

The use of spin-polarized neutrons in neutron-scattering experiments (at either continuous or pulsed neutron sources) provides the capability to study scientific phenomena and/or achieve levels of instrument performance not otherwise accessible.

The first of these advantages is based on the fact that *both* the nuclear *and* magnetic potentials experienced by neutrons interacting with condensed matter depend strongly on the spin polarization of the neutron. This polarization dependence can be exploited to extract quantitative information about spatial and temporal variations of atomic and magnetic densities in condensed matter that cannot be obtained with unpolarized neutrons. Polarized neutrons thus make it possible to study qualitatively different scientific phenomena from those measurable with nonpolarized neutrons.

The second part of the case relies on the fact that manipulations of neutron spins before or after scattering from a sample—for example, Larmor precession of neutron spins in an applied magnetic field—can be used to "label" the velocity or trajectory of each neutron, thereby eliminating the need to define these quantities using conventional collimators or monochromators that cause significant loss of signal intensity. The best-known example of this situation is NSE spectroscopy, a technique that provides the best energy resolution obtainable for neutron inelastic scattering experiments.

It is important to note that the scientific opportunities described here can be realized at either pulsed or continuous neutron sources, provided they are sufficiently powerful. All that is required are technologies for polarizing neutrons and for manipulating them. A principal goal of this workshop was to discuss polarized-neutron technologies appropriate for pulsed spallation neutron sources. These technologies are not yet sufficiently developed to allow pursuit of the scientific agenda described subsequently. We describe each part of the scientific case separately in the following sections, after first digressing to place them in an appropriate historical context.

3.1. HISTORICAL PERSPECTIVE

The first work with polarized neutrons began four years after the 1932 discovery of the neutron by Chadwick[1], with the suggestion by Bloch[2] that polarized neutron beams could be produced by transmission through magnetized iron. In 1939, Halpern and Johnson[3] published an article that has served as the basis for all subsequent theoretical and experimental work.

The construction of nuclear reactors provided more intense neutron sources, and postwar experiments carried out at Argonne and Oak Ridge made possible the production and use of polarized monochromatic beams of neutrons. By the early 1950s, there were three proven methods for producing polarized neutron beams: (1) transmission through magnetized iron, (2) total reflection from magnetized mirrors, and (3) Bragg scattering from ferromagnetic single crystals. The first two-axis polarized beam diffractometers were built at Brookhaven and the Massachusetts Institute of Technology. $Co_{0.92}Fe_{0.08}$ single crystals and resonant flippers were rather quickly adopted at other neutron-scattering centers to measure magnetization distributions.

In the 1960s, the theory of polarized neutrons scattered by various materials was developed by Izyumov and Maleyev,[4] Blume,[5, 6] Izyumov[7], and Schermer and Blume[8]. The theoretical results gave complicated expressions for the total cross section and the final polarization vector in terms of the initial polarization and the nuclear and magnetic scattering amplitudes.

In 1969, Moon, Riste, and Koehler[9] at Oak Ridge studied the various effects that are present in the scattering of polarized neutrons and introduced the four spin-flip and non-spin-flip cross sections that can be deduced by keeping only the neutron spin component parallel to the incident polarization. The fact that the count rates observed by these authors were so low, even at an 85-MW reactor and for "fruit fly" samples, discouraged the use of polarized neutrons for all but the simplest application (i.e., measurement of atomic form factors) for more than a decade. Even though Moon, Riste, and Koehler recognized that their application of a constant magnetic guide field restricted the number of independent magnetic cross sections that could be measured, this point was missed by many and slowed the development of generalized polarization analysis.

In 1971, Mezei[10] demonstrated the spin echo method that allowed very small changes of neutron velocity to be observed independently of the velocity spread in the neutron beam. Mezei and scientists in Russia also invented supermirrors[11] that increased the angular divergence and wavelength range of neutron beams that could be polarized by mirror reflection. With the successful development of supermirrors at the Institute Laue-Langevin (ILL), Schaerpf[12] reconstructed the diffuse-scattering instrument D7 to accommodate polarization analysis. A huge intensity gain was obtained by using 32 detectors equipped with 3200 supermirror analyzers (more such analyzers have been added over the years, and D7 now has more than 6000 supermirrors). Three mutually perpendicular Helmholtz pairs at the sample position allowed the polarization of the incident and scattered neutron beams to be aligned with any of the three directions **x**, **y**, or **z** (three-directional polarization analysis). From the six measured cross sections, one can separate the nuclear, nuclear spin incoherent, and magnetic contributions. This is a generalization of the technique studied previously by Moon, Riste, and Koehler (one-directional polarization analysis).

The 1964 discovery by Brown and Forsyth[13] that the (111) reflection of the Heusler alloy Cu_2MnAl is perfectly polarized eventually led in the early 1980s to the development of polarizing monochromators that could focus polarized neutrons on a sample and provide enough intensity for inelastic neutron-scattering measurements to be made with polarization analysis. The key in this case was careful identification and extraction of single-crystal grains from a Heusler alloy ingot[14] and their deployment in a vertically focusing monochromator. Neutron spin flippers were also improved during this period. The radio-frequency (rf) coils proposed by Shull and used by Moon, Riste, and Koehler were replaced by DC coils developed independently by Mezei[15] and Rekveldt.[16] Tasset proposed and built a third type of flipper called a Cryoflipper, in which two opposite transverse fields are separated by a thin Meissner sheet.

In the 1980s, several scientists in Europe and Japan developed instrumentation based on the pioneering experiment of Alperin,[17] who had demonstrated that generalized polarization analysis could be realized by connecting two different guide-field directions onto a zero-field sample chamber. The most ambitious of these efforts was undertaken by Tasset[18], who built an apparatus at ILL to determine the direction of the scattered polarization vector for any given incident polarization and any scattering angle. Using his expertise with superconducting screens developed from building the Cryoflipper, he constructed a compact Cryogenic Polarization Analysis Device (Cryopad) that takes advantage of the Meissner shields to define the magnetic field and zero-field regions crossed by the incident and scattered neutron beams. Thanks to this device, all the components of the complicated expression of the final polarization vector can be measured, providing unique information on magnetic structures and nuclear/magnetic interferences occurring in the neutron-scattering process.

Because both mirror and single-crystal neutron polarizers have limitations, alternative methods for polarizing neutron beams have been discussed for many years. The use of gaseous ^3He spin polarizers was first discussed in 1981 at ILL, and some years later, thanks to progress made in gas polarization for other purposes, a group from ILL and Harvard University[19] carried out an experiment of optical pumping of rubidium vapor and Rb-^3He collisions at room temperature. The principle of this filter is based on the enormous difference in the absorption cross sections for neutrons with spin parallel and antiparallel to the spin of a ^3He nucleus first measured in 1966 by Passell and Schermer.[20] In 1996 at ILL, Humblot et al.[21] successfully tested an apparatus constructed at the Mainz University, which includes optical pumping and compression of the ^3He. In this case, the gas was polarized by optical pumping of ^3He atoms excited by an electric discharge at ~1 mbar and collisions of excited ^3He-^3He nuclei. Since then, several experiments have been successfully carried out at ILL, and the second-generation filling station currently under construction has already given impressive results.

From the foregoing discussion, it is obvious that all of the pioneering work with polarized neutrons has been carried out at steady-state neutron sources. Although techniques such as a polarized neutron reflectometry have been transplanted to pulsed sources, many of the methods described previously have not yet made this transition. In this report, we discuss the R&D required to enable polarized neutrons to be fully exploited at pulsed neutron sources.

3.2. SEPARATING COHERENT AND SPIN-INCOHERENT NUCLEAR SCATTERING USING POLARIZED NEUTRONS

The interaction potential of a neutron and an atomic nucleus depends on the spin state of the compound nucleus formed during the interaction. As a result, the scattered neutron intensity separates into two components—called coherent and (nuclear spin) incoherent scattering—which affect neutron polarization differently. *Coherent* scattering results in no change of the neutron polarization during scattering, while the *incoherent* process results in two-thirds of the scattered neutrons having their spins flipped during the scattering process (i.e., the polarization of the scattered neutron beam is –0.33). This difference in behavior immediately provides a way in which coherent and incoherent scattering can be separately identified, at least in nonmagnetic samples. Since coherent nuclear scattering of neutrons measures correlations between the (time-dependent) positions of *distinct* nuclei while incoherent scattering reflects *single-nuclei* correlations, such a separation can be important in identifying the physical processes occurring within the scattering sample. For example, *incoherent* quasielastic neutron scattering provides information about atomic jumps and diffusion, whereas *coherent* inelastic neutron scattering results from correlated movements of separate atomic nuclei, such as those caused by phonon propagation.

3.3. STUDYING MAGNETISM WITH POLARIZED NEUTRONS

Neutrons have a magnetic moment (which is aligned antiparallel with their spin) and are thus sensitive to space- and time-dependent magnetization fluctuations in solid samples. Because of the dipolar nature of this magnetic interaction, only the component, $\vec{M}_{\perp}$, of sample magnetization that is perpendicular to the neutron wavevector transfer $\vec{Q}$ is effective in scattering neutrons. This dependence makes it possible in some cases (notably in isotropic ferromagnets) to separately measure the magnetic neutron scattering by applying a saturating magnetic field to the sample and taking the difference between scattering obtained with the field perpendicular and parallel to $\vec{Q}$. The use of polarized neutrons, however, makes the separation of magnetic and nuclear scattering much easier because scattering by fluctuations in $\vec{M}_{\perp}$ that are parallel to the quantization direction of the neutron spins do not affect the spin direction of the neutron (giving rise to so-called non-spin-flip scattering). On the other hand, fluctuations in $\vec{M}_{\perp}$ that are perpendicular to the neutron quantization direction cause a change in the direction of the neutron's spin (causing so-called spin-flip scattering in simple 1-d polarization analysis experiments). This dependence of magnetic scattering on the initial and final spin states of the neutron has been used in many experiments and probably provides, on its own, a justification for the production and use of polarized neutrons in neutron-scattering experiments. It has been used to deduce the spatial distributions of magnetization as well as the direction of the magnetization vector on an atomic scale in a wide variety of samples, some of which are described subsequently. It has also played a crucial role in supporting the development of new magnetic materials.

3.4. POLARIZED NEUTRON SCATTERING BY MOLECULAR AND ORGANIC MAGNETS

Research in magnetic materials has exploded in recent years because of the development of new molecular and organic magnets, that is, solids that are built up from structurally well-defined clusters containing magnetic ions in a complex environment.[22] Since the discovery of the first ferromagnetic molecular compound (decamethylferrocenium tetracyanoethylenide, T_C = 4.8 K) in 1986, enormous progress has been made in this area. These molecular magnets are typically polynuclear transition metal complexes and they can be termed "single molecule magnets." The unpaired electron responsible for the magnetism sits in a molecular orbital built up from the orbitals of the atoms constituting the molecule. The magnetization tends to be smeared out across the molecule, though perhaps concentrated on certain atoms. Measuring the magnetization distribution across a molecule reveals precious information on the nature of the molecular orbitals responsible for the magnetism and the interactions with neighboring molecules in the solid, as well as the chemical bonding and how the electron spin is spread out and oriented. This allows for testing the underlying theories of molecular bonding and magnetism and for creating new magnetic materials with predicted properties. Molecular magnets can also be viewed as single-domain magnets with a domain size in the nano limit. Thus, they can be used for studies of magnetic phenomena on the nano scale.

A typical example of a molecular magnet is the room-temperature magnet combining a hexacyanometalate $[M(CN)_6]^{q-}$ with a Lewis acid L^{p+} [23] (see Fig. 1). If L and M are transition metal ions, the orbital interactions in the resulting compound can be described by well-understood principles, and it is therefore possible to tune the compound's magnetic properties.

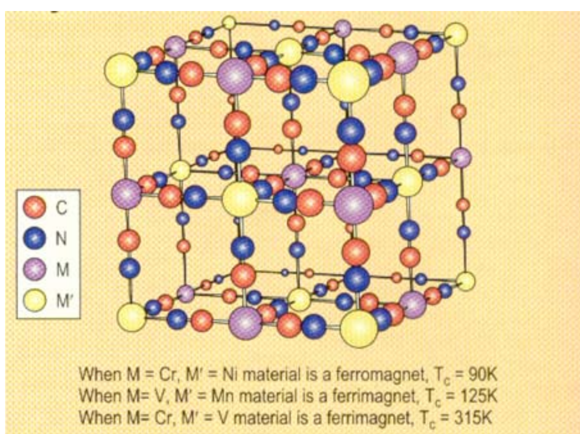

Fig. 1. Nuclear structure of the hexacyanometalate $[M(CN)_6]^{q-}$ with a Lewis acid L^{p+}.

These compounds are of great scientific interest, but a major driving force in this work is the urgent need to find new applications that will exploit their specific properties such as lightness, transparency, solubility, optical properties, and biocompatibility. Molecular magnets with total spin number S =10 also display numerous excited spin states and open the way to a novel class of information storage systems.

Studies of the magnetic properties of such systems aim at understanding both the materials properties (e.g., magnetic coupling mechanisms) and the fundamental chemistry, such as reactivity in coordination complexes and its dependence on electronic structure. An area of research where neutron diffraction has not yet shown its full potential, because of the flux limitations of the present sources, is to combine charge density analyses with magnetic studies in order to obtain an explanation for various magnetic phenomena in terms of electronic structure. An example where this would be useful is the large molecular magnet or "chromium wheel" system, $Cr_8F_8(C_5H_9O_2)_{16}$, containing 272 unique atoms.[24] For this structure, the charge density has been determined from synchrotron X-ray data, and a detailed topological analysis of the electron density has been carried out. Figure 2 shows the experimentally determined electrostatic potential, which is used for predicting the inclusion properties of the molecule. A combination of magnetic neutron-diffraction data and synchrotron X-ray data could provide electronic information on complex molecular systems such as this, which is very difficult to obtain by other methods (e.g., theoretical calculations).

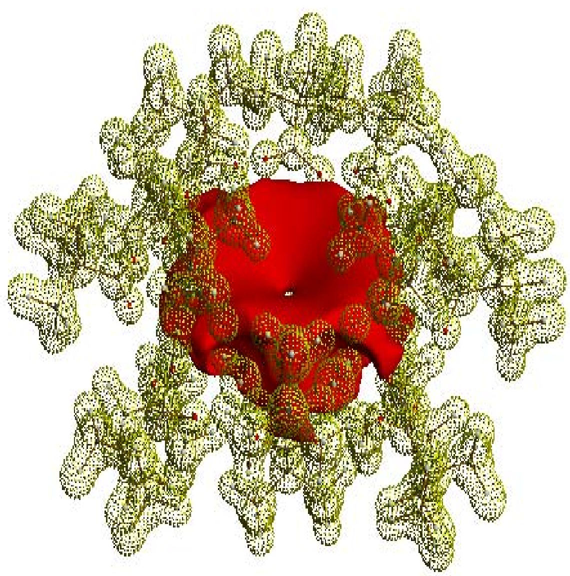

Fig. 2. The experimentally determined electrostatic potential of the "chromium wheel" [Cr8F8(C5H9O2)16]. Surface at -0.54 e Å-1 in red and +0.30 e Å-1 in yellow.

In the area of molecular magnetism, the number of studies of organic radicals has also increased dramatically. Even though radicals are chemically reactive, there are many examples of materials with radicals trapped in the solid phase, such as nitroxides.[25] These materials exhibit many different magnetic phenomena, which to a large extent are determined by the crystal packing and the detailed nature of the intermolecular interactions. Thus, the field of organic radicals will be particularly well suited for research with next-generation neutron sources such as SNS.

As the previous discussion shows, neutron diffraction remains the technique of choice for studying magnetism. It is the classical polarized neutron-diffraction technique that permits investigation of the distribution of the magnetization, which contains essential information on the electronic structure of materials: the nature of the magnetic orbitals, the interactions with neighboring molecules in the solid, and effects such as chemical bonding, spin delocalization, or spin polarization. Up to now, this technique has only been used at continuous neutron sources such as the ILL (using the diffractometer D3) because there has been no device able to simultaneously polarize a beam efficiently at short wavelengths while maintaining the bandwidth. Today, thanks to the progress made in the development of polarizing guides and ^{3}He neutron spin filters (see later sections on techniques), one can envisage applying classical polarized beam diffraction at a pulsed neutron source.

3.5. MAGNETIC MOMENT CONFIGURATIONS DETERMINED BY POLARIZED NEUTRON SCATTERING

The determination of magnetic structures plays a major role in the understanding of phenomena such as low-dimensional systems, phase transitions, and geometric frustrations. This determination is far from trivial, however. Even a “simple” material like elemental neodymium is fascinating. During the past 40 years or so, enormous effort has gone into understanding the electronic and magnetic properties of neodymium, yet the great majority of the antiferromagnetic structures that are stabilized below 20 K under zero or applied field remain unsolved.

In the case of powder diffraction, many Bragg peaks are superimposed in the measured patterns, and Rietveld refinements are rarely able to determine a magnetic configuration unambiguously, except in special cases where there are many extinction rules implying severe constraints.[26] In a single-crystal experiment, the time-of-flight technique provides large Laue maps of reciprocal space, and multidomain/single-*k* structures can be distinguished from multi-*k* ones. As an example of such a study, Fig. 3 illustrates the proposed moment configuration in

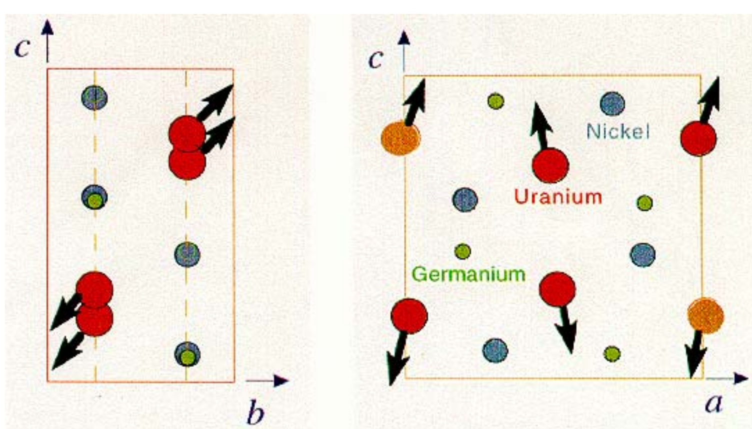

Fig. 3. Moment configuration of one domain in UNiGe shown as projections on the orthorhombic b-c and a-c planes, respectively.27 The moment directions of the second domain are given by the images at the y = ¼ and ¾ mirrors (dashed lines).

UNiGe. For this orthorhombic compound, time-of-flight, single-crystal neutron diffraction revealed a complex configuration of uranium 5f moments, with a single-*k* propagation vector, and the occurrence of two magnetic domains below $T_N = 42$ K[27]. In general, single-crystal neutron diffraction makes it possible to separate the nuclear and magnetic contributions to the Bragg peaks[28] and to distinguish coexisting magnetic phases in a single material.[29] With the presence or absence of key reflections, magnetic configurations of collinear structures are generally determined unambiguously, but for complex antiferromagnets, polarized neutron techniques generally must be employed.

For magnetic structure investigations requiring an applied magnetic field, the transverse components of the neutron polarization are inaccessible, but selection rules can be applied. When the orientation of the single crystal is suitably chosen, relative to the field (or polarization vector) and the scattering vector, one measures spin-flip and non-spin-flip cross sections that reveal some of the information inaccessible from integrated intensity measurements alone. For example, one can determine the component of moments that are transverse to the applied field. This technique was used to confirm the noncollinear magnetic structure of UNiGe shown in Fig. 3.[28]

3.6. THE INTERPLAY BETWEEN CHARGE, MAGNETIC, AND LATTICE FLUCTUATIONS

Since the advent of quantum mechanics, the field of magnetism has attained a special status as an arena in which to develop and test new theories and ideas. The last decade has seen an intensified interest in low-dimensional systems, where quantum fluctuations are germane. The cooperative phenomena of macroscopic quantum ground states and quantum phase transitions, where order is destroyed by quantum fluctuations, have been studied both theoretically and experimentally. Materials where localized magnetic moments are arranged and coupled in specific ways have provided experimental insight into the behavior of many-body quantum systems. In particular, a large group of such model systems have been found in materials with spins from unpaired electrons on metal ions coupled by superexchange interactions through connecting oxygen ions (cupreates, vanadates, nickelates, etc.).

It has become clear that several novel phenomena in condensed matter physics, such as high-temperature superconductivity or giant magnetoresistance, require an extension of the localized electronic-moment picture. Common features of these novel phenomena are that a major role is played by the quantum fluctuations, but the understanding of quantum effects in purely magnetic systems must be extended to include orbital effects, charge fluctuations, and lattice distortions, which can be either long-range ordered, correlated on short-length scales, or just dynamic fluctuations. The understanding of these materials involves a competition between charge, spin, and orbital and lattice degrees of freedom both on a static and on a dynamic level. Such a competition should generate “hybrid” correlation functions coupling the various degrees of freedom (charge-lattice, charge-magnetic, spin-lattice, spin-orbit, etc.), which can be accurately measured using powerful inelastic or quasi-elastic polarized neutron-scattering techniques such as generalized polarization analysis. Indeed, by allowing the measurement of the transverse components of polarization, this method gives unique access to the so-called inelastic magnetic-nuclear interference terms. These terms could provide interesting information about the hybrid pair correlation functions, which play a crucial role for the understanding of strongly correlated electron systems.[30]

3.7. NANOMAGNETISM

The world is entering an era in which manipulation of charge and spin offers the possibility to replace present-day semiconductor electronics, just as vacuum tube electronics were supplanted in the past. The term coined to embrace the new wave is “spintronics.” Ultimately, the goal will be to transcend binary logic and move toward quantum computing strategies that can be implemented via electronic or nuclear spin manipulation using quantum-entanglement. Spintronics can converge with the burgeoning field of molecular electronics toward this end. However, there are many challenges ahead. For example, the opportunity to fabricate new systems on length scales that compete with those relevant to magnetism will challenge the fundamental knowledge in magnetism and naïve wisdom that magnetic properties at the nanoscale can be understood in terms of bulk or atomic magnetic properties. In addition, control of magnetism at the nanoscale offers a pathway to create new devices using systematic principles of nanotechnology.

The role of neutron scattering and other techniques in the study of nanostructured magnetic materials has recently been examined in detail in a review article by Fitzsimmons, et al.[31] These authors point out that the key issues in these technologically promising materials is to relate their physical properties (transport, magnetism, mechanical, etc.) to their chemical and physical structure. Success in this endeavor requires detailed quantitative understanding of magnetic structure and properties (which polarized neutrons can often provide), as well as the development of new modeling and simulation capabilities. Progress in applying neutron-scattering methods to samples of ever decreasing size has allowed the technique to be applied to nanostructured materials prepared by thin-film and lithographic techniques. Among the interesting results that have been obtained, Fitzsimmons et al. note: distinguishing between magnetic and chemical boundaries; observing the spatial dependence of the magnetization vector in nonuniform materials; unusual coupling mechanisms across nonmagnetic materials; and unexpected magnetic phase diagrams. These authors anticipate that the extension of elastic neutron scattering to nanostructured arrays and three-dimensional magnetic composites will allow future determination of magnetic structure with unprecedented resolution.

Polarized neutron reflectometry (PNR) has been used very successfully to investigate nanostructured systems composed of thin layers where it has elucidated magnetization profiles close to surfaces and interfaces. Surface sensitivity derives from working in grazing incidence geometry near the angle for total external reflection. PNR is highly sensitive, capable of measuring the absolute magnetization of a monolayer of iron (~10^{-4} emu) with 10% precision and has excellent depth resolution—on the order of a tenth of a nanometer even for films as thick as several hundred nanometers. Polarized neutron reflectometry has enjoyed dramatic growth at both steady-state and pulsed neutron sources during the last decade and has been applied to important problems such as the origin of exchange bias, magnetic reorientation transitions in thin films, enhanced magnetization at surfaces and interfaces, magnetic penetration in superconductors, and the nature and importance of magnetic roughness. Each of these areas, as well as the opportunities for future research involving the use of polarized neutrons, has been examined in detailed by Fitzsimmons et al.[31]

3.8. TIME-DEPENDENT MAGNETIC FLUCTUATIONS IN MATERIALS

Neutron polarization analysis for inelastic scattering experiments was first seriously developed at ILL in the early 1980s by adding polarizing devices such as Heusler alloy monochromators and analyzers, as well as supermirror benders, to classical thermal and cold neutron three-axis spectrometers. The new spectrometers—IN12, IN20, and IN14—proved so successful that they have subsequently been duplicated in North America, Japan, and several European countries. Among early successes at ILL were verification of the Haldane conjecture,[32] determination of the spectral form for spin diffusion in isotropic ferromagnets,[33] identification of new, coupled modes in one-dimensional magnets,[34] and studies of nonlinear, solitary-wave dynamics in both ferro and antiferromagnetic low-dimensional systems.[35] More recently, inelastic scattering with polarization analysis has been applied successfully to the study of the spin-dynamics of high-temperature superconductors[36] and other correlated-electron systems.[37]

3.9. GENERALIZED POLARIZATION ANALYSIS

Until a few years ago almost all neutron-scattering experiments with polarization analysis used only one component of the beam polarization. A polarized beam of neutrons was prepared in which the spins of all neutrons were aligned along an applied magnetic field. Only those spin components of the scattered neutrons that were either parallel (+ direction) or antiparallel (-direction) to the guide field were measured, allowing a total of four different cross sections (++, --, +- and -+) to be measured. Even though this spin-projection method is very powerful, and enables all of the measurements described in previous paragraphs, it does not exhaust all of the information about sample magnetism that can be obtained using polarized neutrons. In general, the magnetic response of a solid to an applied field is described by a second-rank susceptibility tensor that describes how the α Cartesian component of the field affects the β component of the magnetization. By the fluctuation-dissipation theorem, the susceptibility tensor is related to scattering cross sections for neutrons in which the spin directions of incident neutrons also lie along different Cartesian axes. Measuring such cross sections is, however, not straightforward and can only be done if the sample has no macroscopic magnetization and can be placed in a region of zero magnetic field. In such circumstances, generalized polarization analysis (GPA) is possible because the spatial orientation of the spins of both the incident and scattered neutrons can be controlled. GPA (sometimes also known as “spherical polarimetry”) is particularly useful for studying magnetization fluctuations in materials in which atomic moments are noncolinear.

With this technique it has been possible to solve a number of magnetic structure problems that had proven to be intractable when employing other techniques.[38] Very recently, the technique has been applied successfully to the determination of antiferromagnetic densities. When the magnetic and nuclear scatterings occur at the same place in the reciprocal space, this method enables the precise determination of antiferromagnetic form factors, which is not possible by other means. For example, the investigation of the magnetization distribution of Cr_2O_3 has revealed that the Cr^{3+} magnetic moment is reduced by the zero-point spin deviation and by covalent mixing to 2.48 μ_B.[39] These results are consistent with the chromium d electrons being in the trigonally symmetric a_1 and e orbitals derived from the cubic orbitals with t_{2g} symmetry. There is a small but significant magnetization that is not accounted for by these orbitals and which is attributed to covalent overlap. Its symmetry is consistent with the magneto-electric susceptibility. Very recently, V. Fedorov and coworkers have also proposed a new method that takes advantage of GPA, based on the passage of cold neutrons through non-centrosymmetric single crystals in Laue diffraction, to search for the neutron electric dipole moment. The sensitivity of the method relies on the high interplanar electric field in non-centrosymmetric crystals (up to 10^9 V/cm) and on the possibility to increase the time the neutron spends in the crystal by using large Bragg angles.

4. NEUTRON POLARIZATION AS A TOOL TO ENHANCE NEUTRON-SCATTERING INSTRUMENTATION

The second part of the scientific case for polarized neutrons in neutron-scattering experiments involves their use in improving the performance of neutron-scattering spectrometers. In general, spectrometers that use polarized neutrons in this way are not designed to exploit the dependence of neutron-scattering cross sections on neutron polarization but rather make use of the neutron magnetic moment as a spectrometer design element. The most widely used instrument design concept using polarized neutrons is the NSE method invented by Mezei in 1972.[10] In this method, neutron spins undergo Larmor precession in magnetic fields placed before and after a scattering sample. These fields are arranged so that each neutron will experience an equal and opposite number of precessions before and after scattering, whatever the neutron's actual velocity, provided the sample scattering is elastic. At the echo position, all of the precessing neutron spins are in phase, whatever the neutron velocity, and the beam is fully polarized. If the scattering is inelastic, the numbers of neutron spin precessions before and after scattering are not equal, leading to depolarization of the neutron beam. The depolarization turns out to be a direct measure of the difference between the incident and scattered neutron velocities and is independent to the lowest order of the actual neutron velocity. The NSE method thus provides a sensitive measure of neutron velocity changes that occur during scattering, to a large extent independently of the degree of beam monochromatization. For example, a neutron beam with a 10% velocity spread can be used with the NSE method to measure inelastic neutron scattering with an energy resolution that is substantially less than 0.1% of the incident neutron energy. Conventional methods of achieving good energy resolution, which involve defining accurately both the incident and scattered neutron energies, lead to decreases in scattered neutron intensity that usually have to be compensated by a corresponding degradation of resolution. A striking example of this is backscattering, in which huge banks of analyzer crystals are used. Because it breaks the usual relationship between beam monochromatization and energy resolution, the NSE method allows excellent energy resolution and reasonable measured neutron intensity to be achieved simultaneously. Although NSE has been exploited only at steady-state neutron sources since its invention, recent developments at ILL using chopper modulation of the incident neutron beam on the IN15 spectrometer have demonstrated that NSE can be used in time-of-flight mode, paving the way for the use of the technique at pulsed neutron sources.

The NSE technique has proven remarkably useful in the study of polymers and other complex fluids, as well as in determining the slow dynamics associated with glasses.[40] It has even been applied successfully to determine the lifetime of collective excitations in superfluid helium, where it extended by several orders of magnitude the phonon and roton line widths measured by more traditional neutron techniques.

As long ago as 1979, Mezei[41] and Pynn[42] described ways in which NSE could be used to measure the energy widths of collective excitations such as phonons or to improve the angular resolution in diffraction experiments. Because of the difficulty of designing the magnetic field regions needed to implement these ideas, practical applications had to await the development of the so-called NRSE technique that was first demonstrated in Germany by Golub and his collaborators.[43] Although, like NSE, this technique also makes use of Larmor precession of the neutron's spin to code some (vector) component of the neutron velocity, it does so using small coils that produce rf magnetic fields in well-defined regions of the neutron beam line. In this

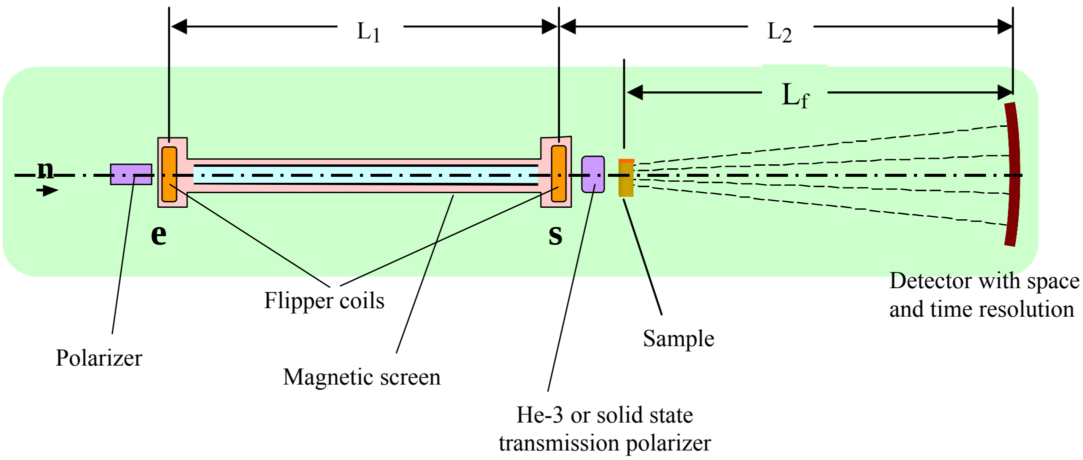

Fig. 4. Schematic of the SANS+MIEZE instrument. The beam is polarized and analyzed using ^{3}He or solid-state supermirror transmission polarizers. The entrance (e) and sample (s) rf coils operate at different frequencies ωe and ωs with a difference ωd of up to 1 MHz to introduce a rapid sinusoidal oscillation of the polarization pattern. This produces an oscillation of intensity. The spin echo signal of a MIEZE instrument is the measured contrast loss of these oscillations. Typical parameters are L1= 9 m, L2= 11.5 m, and Lf= 10 m.

case, it is the rf frequency and the distance between neighboring rf coils that determines the attainable instrumental resolution, rather than the strength and spatial extent of the static magnetic fields applied in the standard NSE method. The NRSE method for measuring lines shapes of dispersive excitations has now been installed on two three-axis spectrometers at steady-state neutron sources in Germany (at HMI and in Munich) and is beginning to produce interesting scientific results.

More recently, an alternative to the NRSE technique for coding the scattering angle for each neutron in a diffraction experiment has been proposed by groups in the Netherlands and the U.S.[44, 45] The new method, which uses thin magnetic films either to define the borders of NSE precession fields or as the precession fields themselves, has been applied both to small angle-scattering and reflectometry. In SANS experiments, it has successfully extended the measurable length scales to several microns.[46]

A promising variation of NRSE can be realized with two flippers driven at different frequencies. This technique has been called "MIEZE," for Modulation of Intensity for Zero Effort-downstream of the sample. Here the intensity at the detector is modulated with a frequency up to several megahertz. Any quasi-elastic scattering at the sample leads to a decrease of contrast of the time pattern at a thin planar detector. If this is operated with microsecond time resolution, sub-nev energy transfers during scattering are expected to be visible.

Although no MIEZE spectrometer has yet been built, the principle has been verified in Munich and a first measurement has been performed in Saclay on the modified NRSE spectrometer MUSES. Technically, it is feasible to adopt MIEZE/SANS to future pulsed sources. The only parameter depending on neutron, velocity is the amplitude of the rf fields. It is proportional to the neutron velocity and can easily be controlled by arbitrary function generators, already in use now at all NRSE machines. It is expected that spectrometers of the MIEZE type will be useful for observing the slow dynamics of materials such as polymers, gels, liquid crystals, and biomolecules, which require not only beam correlation times in the high nanosecond-to-microsecond range but also high lateral beam correlation lengths (10 to100 nm). Such conditions can be met by highly collimated cold neutron beams typically found on small-angle neutron-scattering (SANS) instruments. It therefore seems attractive to insert the spin echo option in an existing long baseline SANS instrument.

4.1. POLARIZED SAMPLES FOR NEUTRON SCATTERING

Even though polarized neutrons can be used to separate coherent and incoherent scattering, it is sometimes useful to enhance the difference between these two types of scattering processes by polarizing the nuclei of the scattering sample. This method has proven particularly useful in biological samples, which invariably contain large numbers of protons that usually scatter neutrons incoherently. Not only does this incoherent scattering appear as a background in diffraction experiments with biological samples but also the weakness of coherent scattering by protons results in low intensity of the Bragg peaks being measured. Although this problem can sometimes be alleviated by replacing hydrogen with deuterium in the sample, this is often not possible because deuterated versions of many organic (particularly biological) molecules cannot be produced. When hydrogen/deuterium substitution is impossible, dynamical pumping of the proton polarization in the sample can be used to reduce the magnitude of the incoherent scattering and increase the coherent scattering, improving the signal and reducing the noise of a diffraction measurement. Although not necessarily related to the use of polarized neutrons, this polarized sample technology is worth considering in conjunction with polarized neutrons because it provides a way of changing the relative amounts of neutron spin-flip and non-spin-flip scattering from the sample and thus an additional method for separating signals from competing effects within the sample. In the past, the technology has not found widespread use outside of Europe because of the technical overhead involved in its implementation. However, it could make a significant difference to the impact of neutrons in biological problems by allowing neutrons to complement synchrotron radiation and provide information about the all-important hydrogen positions in biological macromolecules. The method also has the potential to enhance the scattering from specific protons by selective pumping.

4.2. POLARIZED PULSED NEUTRONS FOR FUNDAMENTAL NEUTRON PHYSICS

In addition to neutron scattering, essentially all modern, intense neutron sources have had, as a component of their research program, studies in what is now referred to as "Fundamental Neutron Physics." This field, which includes measurements of fundamental constants, precise tests of basic symmetries in particle physics, and measurements of important astrophysical and cosmological quantities, has particularly flourished through the use of intense beams of polarized neutrons from high-flux reactors (see for example[47]).

While the *sine quo non* of modern cold neutron experiments is high flux, intensity alone *does not* ensure a successful experiment. The sensitivity of precision measurements to systematic effects implies that one is often willing to compromise on flux to reduce systematic errors. Selection of the appropriate neutron source for a particular experiment is driven by the need to achieve the optimal balance between systematic and statistical errors. Recently, it has become clear that the pulsed nature of a spallation source offers an important opportunity for the reduction of systematic effects in many of the important fundamental neutron physics experiments (see for example[48]). The high intensities offered by next-generation sources such as the SNS will provide statistical sensitivity at a level that offers outstanding discovery potential. A key to the success of future experiments will be further refinement of the ^{3}He polarization technology.

Most modern polarized cold neutron experiments have used magnetic "supermirror" reflection devices to spin-polarize the neutron beam. These devices are simple to use and can provide quite high polarizations that exceed 99% in optimal situations. However, most fundamental physics experiments require polarization of a large cross-section beam with a broad velocity spectrum and a significant divergence. For such beams, it is has proven difficult to obtain a reliable, high-accuracy measurement of the average neutron polarization to much better than about 1%. This is because the polarization from a supermirror device varies across the beam and depends on both the incident neutron direction and the velocity of the neutron. The problem is exacerbated by the fact that, for decay experiments, the appropriate polarization average must be weighted by the *1/v* to appropriately account for the probability of decay. Most polarization measurements count neutrons with an efficiency that is nearly velocity independent.

A different approach to neutron polarization relies on the use of nuclear spin polarized ^{3}He gas cells as a neutron spin filter. The neutron polarization following transmission through a polarized ^{3}He cell is given by

$$P_n(v) = \tanh\left(P_3 N l \sigma(v)\right) ,$$

where $P_n(v)$ is the neutron polarization, P_3 is the ^{3}He polarization, N is the ^{3}He number density in the cell, l is the Helium cell thickness, and $\sigma(v)$ is the unpolarized capture cross section at neutron velocity v.

Because it is difficult to accurately measure all of the quantities within the previous equation's brackets, an accurate, ab initio determination of the neutron polarization is not feasible. However, by exploiting the simple and well-understood interaction between neutrons and ^{3}He at low energy, the neutron polarization can be determined accurately from the measurement of different, experimentally accessible, quantities.[49, 50] At a pulsed source, the rather long time of flight (TOF) for cold neutrons (tens of milliseconds from source to apparatus at a typical installation) allows high-velocity dispersion, making it possible to relate the neutron polarization to the TOF in a remarkably simple way. We note that the strong dependence of neutron polarization on velocity means that it is much more awkward to determine the polarization of a "white beam" from a reactor.[49] The capture cross section on ^{3}He accurately follows the *"1/v law"* with $\sigma(v) = \sigma(v_0)(v_0/v)$. Substituting into the preceding result for neutron polarization we have the following:

$$P_n = \tanh\left(\frac{P_3 N\sigma(v_0)v_0}{L}t\right) = \tanh(t/\tau) \ ,$$

where L is the distance from the source to the experiment and t is the TOF. In the preceding equation, τ is *the* single instrumental parameter that needs to be determined to extract an accurate polarization. For example, in the neutron-spin/beta-momentum correlation experiment, the measured asymmetry $A_{exp}=AP_n$. Thus the fundamental asymmetry will have the same well-understood parametric dependence on TOF and can be extracted by a single parameter fit to the asymmetry data. In essence, this procedure provides an in situ determination of the polarization of the neutrons that actually undergo decay in the apparatus. We note that the ^{3}He technique provides a number of other highly redundant checks on the polarization that are not available with other schemes.

The ^{3}He technology has another substantial advantage for precision measurements. In all previous cold neutron asymmetry experiments, the neutron spin has been modulated only between “spin-up” and “spin-down.” A pulsed source experiment using ^{3}He thus provides a highly accurate modulation of not only the spin direction but also the magnitude of the polarization during each pulse. This amplitude modulation offers a potentially powerful tool for the identification and elimination of systematic effects that is not possible at a continuous source.

The current level of maturity of the ^{3}He polarization technology makes it useful for the next generation of fundamental physics experiments. Nonetheless, further development will be quite valuable. Like neutron-scattering experiments, fundamental physics experiments would benefit from higher ^{3}He cell polarizations. Because these experiments can often use large cross-section beams, increasing cell size will be quite important.

5. POLARIZED NEUTRON TECHNOLOGY

Realizing the scientific advantages offered by polarized neutrons, both for neutron scattering and for fundamental physics, requires a set of technologies that have been developed over the past several decades and that are continuing to evolve. All of these technologies are now sufficiently mature to allow their use at steady-state neutron sources, albeit sometimes under conditions that are not optimal. On the other hand, these technologies are not all mature at pulsed neutron sources, and few experiments at these sources use polarized neutrons. In fact, there is only one widespread use of polarized neutrons for scattering experiments at pulsed sources: neutron reflectometry.

Two types of component are essential for all polarized neutron experiments:

1. Polarizers (or analyzers) that select a particular neutron spin state (or, equivalently, a particular direction for the neutron magnetic moment).
2. Devices to control the orientation of a neutron spin in a particular spatial direction. The simplest such device is a magnetic guide field that maintains the neutron spin parallel to an applied field. In this class of devices we also include flippers (that invert the direction of the neutron spin), π/2 spin rotators, and more complex configurations (often required for generalized polarization analysis) that allow the neutron spin to nutate to a chosen direction.

At steady-state neutron sources, one finds three different types of neutron polarizers: (1) magnetic mirrors or supermirrors, (2) magnetized crystals, and (3) spin filters. Each of these has its own advantages and disadvantages, and the particular solution chosen depends on the application. Broadly speaking, it is true to say that one or other of these technologies can provide what is needed for almost any polarized neutron experiment at a steady-state neutron source. For pulsed sources, however, the situation is different. First, most spectrometers at pulsed sources rely on TOF rather than monochromatization to determine neutron energies and thus use neutrons with a broad range of energies. For this reason, with very limited exceptions, crystals that prepare (monochromatic) polarized neutron beams by Bragg diffraction are not useful as beam polarizers at pulsed sources.

Supermirrors, on the other hand, have been used successfully to polarize neutron beams at pulsed sources. Used individually they produce polarized beams that are spatially narrow and of limited divergence (especially at short neutron wavelengths). Beams with these properties are suitable for PNR and have allowed this technique to be developed at pulsed neutron sources, perhaps more rapidly than it was at steady-state sources. When supermirrors are incorporated in specially designed neutron guides[51], they can overcome the beam-size and divergence limitations of single mirrors and can, be adequate as polarizers for many applications at pulsed sources that use cold and thermal neutrons. They will not, however, be adequate as polarizers for hot (short-wavelength) neutrons. Such neutrons are produced copiously at pulsed spallation sources and provide a capability that is unique to this type of source.

In addition to using a broad band of neutron wavelengths, pulsed sources achieve much of their impressive performance by collecting neutrons scattered over a large angular range. Analyzing the polarization of such a divergent neutron beam has not yet been solved, although polarized ^{3}He filters are beginning to change this. These filters have the added advantage of being able to polarize neutrons of all wavelengths without the significant practical limitations of beam size. Clearly, the development of this technology will be a key enabler for the use of polarized neutrons at pulsed spallation sources.

The magnetic guide fields used at pulsed sources to maintain neutron polarization are not significantly different from those used at steady-state sources, although somewhat more attention needs to be paid to the magnitude of the fields and the rates at which their orientations change when short wavelength neutrons are used. Spin rotators and spin flippers are, however, a different story. Although several different types of flippers have been tried at pulsed sources, most of them still require further development. Devices that rotate neutron spins through a particular angle (needed for implementation of spin-echo and generalized polarization analysis at pulsed sources) have not yet been developed for pulsed neutron beams with broad wavelength distributions. In any facility where polarized neutrons are to be used it will be important to ensure that the magnetic environment is well understood and controlled.

It is worth pointing out that much of the R&D activity described subsequently will require the use of a neutron beam line that can be easily reconfigured for various tests. It is important that such a beam line be available on short notice.

In the following paragraphs, we summarize the current state of several of these polarized neutron technologies and outline what needs to be done to improve them to the point where they can be used at pulsed neutron sources.

5.1. DEVELOPMENT OF POLARIZED ^{3}HE SPIN FILTERS

The range of scientific questions that can be addressed today with polarized neutrons is restricted by the technical limitations of current neutron polarizers and analyzers. This is especially true at pulsed neutron sources. Both pulsed and continuous neutron sources need polarization analyzers that can accept highly divergent beams. Whereas reactor-based instruments can employ monochromating polarizing crystals such as Heusler alloy, polarization analysis on TOF instruments at pulsed sources often requires broadband polarizers that can operate throughout the cold, thermal, and hot neutron energy ranges. Spin filters based on the large spin dependence of the cross section for absorption of neutrons by ^{3}He gas can address these issues and have additional features. In the field of fundamental neutron physics, ^{3}He spin filters have several advantages, including low background, broadband capability, uniform polarization throughout the neutron beam, and the ability to flip the neutron polarization through spin reversal of ^{3}He spins using the adiabatic fast passage technique. Coupled with the TOF analysis intrinsic to pulsed sources, ^{3}He spin filters can be used to measure polarization with unprecedented accuracy.

For these reasons, polarized ^{3}He spin-filters were identified at the Pulsed Polarized Neutrons Workshop as a key area for development and application. ^{3}He spin-filters have already made an impact on neutron scattering at ILL, and an even larger impact is expected at pulsed sources. In the United States, pilot experiments at the NIST Center for Neutron Research (NCNR) and Intense Pulsed Neutron Source (IPNS) in SANS and reflectometry have been performed using ^{3}He-based neutron spin filters. A spin filter is under development for a fundamental neutron physics experiment at LANSCE also. Both the development and application of ^{3}He spin filters are critical needs to make the largest range of polarized neutron research possible at SNS.

Two optical pumping methods have been employed to polarize the ^{3}He gas for spin filters: (2) spin-exchange (SEOP), in which the gas is polarized directly at high pressure (1-10 bar), and (2) metastable exchange (MEOP), in which the gas is polarized at low pressure (1 mbar) and then compressed. In the MEOP method, metastable atoms produced by an electrical discharge are optically pumped by a laser, while for the SEOP method a laser optically pumps rubidium vapor that is produced by heating the cell. The current maximum ^{3}He polarization achievable for either method is 70% for practical spin filters; 60-70% has been typical for recent applications. A spin filter with 60% ^{3}He polarization will produce 90% neutron polarization with 20% absolute transmission of neutrons. (For 100% ^{3}He polarization, one would obtain 100% neutron polarization and 50% transmission, i.e., all the neutrons of one spin state would be transmitted and all the neutrons of the other spin state absorbed.) Thus for less than 100% ^{3}He polarization, there is a tradeoff between neutron polarization and neutron transmission. The product of the ^{3}He pressure and cell length can be chosen to give priority to either the polarization or the transmission. Because of the wavelength dependence of the absorption cross section, the polarization varies with neutron wavelength. Typical spin filter “thicknesses” are 7-bar-cm of gas for cold neutrons (wavelength of 0.5 nm) or 20-bar-cm of gas for thermal neutrons (wavelength of 0.18 nm).

The maximum value of the polarization attainable with each method is only a small piece of the story in terms of the development needed for successful use of ^{3}He spin filters. There are issues in both methods for actually obtaining and maintaining this polarization in usable spin filters. The best results for the MEOP method have been obtained with large, expensive, complex compressors, resulting in the use of transportable cells that slowly lose polarization on the beam line, rather than continuously operated devices. Compact compressors have been pursued but are not yet competitive. Polarization storage times as long as 200 hours have been obtained, but there are several constraints that are discussed subsequently. Producing high polarization and obtaining long relaxation times for the demanding application of large-volume polarization analyzers remains an issue. In contrast, the SEOP method is compact and can be much more easily operated continuously on a beam line, but long relaxation-time cells and long preparation times before the experiment are still required because of the slow polarizing rate of this method. For transportable cells, optical pumping times of a few days for SEOP and less than one hour for MEOP are required before the experiment to reach the maximum polarization. In addition, large volume cells have significant demands for laser power. The SEOP method can also be used in the MEOP "filling station" approach. Hence, for both of these methods, further development is required to actually make the large variety of spin filters that will be required for SNS instruments. In addition, ^{3}He spin filters require low magnetic field gradients $((1/B_0)(\partial B/\partial r) < 3x10^{-4}\ \text{per cm})$, which is in direct conflict with experiments that require high field superconducting magnets to magnetize a scattering sample, for example. The technology to shield such fields, which typically involves a combination of passive mu-metal and superconducting shields, needs to be developed for several applications at SNS. It may also be worth considering the use of larger holding fields than have been employed to date.

Despite the development needs just noted, a number of applications can be pursued with the current technology of ^{3}He spin filters. Indeed, substantial work has been conducted at ILL, and tests are being conducted by the National Institute of Standards and Technology (NIST) and Indiana University at the NCNR and IPNS. For a variety of reasons, it is important that such experiments be pursued in parallel with future technology development. First, such efforts will establish a base of experience at current neutron facilities that will provide critical guidance for implementation on future SNS instruments. Second, it is important to note that although polarized ^{3}He technology is well developed in other fields such as nuclear physics, there are few materials scientists who have experience with the application of ^{3}He spin filters to neutron scattering. Hence, experiments are required to provide experience for neutron scatterers, as well as to reveal issues in the application of these devices. In particular, the wavelength dependence of ^{3}He spin filters will present new issues that have not been addressed in connection with the use of neutron optical polarizers. In addition, for the cases where it may be difficult to establish a prioi whether ^{3}He spin filters or neutron optical devices are the best path, experience will provide guidance. Finally, necessity is still the mother of invention; hence, the needs of real experiments will result in increased development. A notable example of this is the LANSCE "n-p-d-gamma" experiment, which helped motivate the development of large-area, long-lifetime SEOP cells by the NIST group and the ongoing implementation of these cells by the University of Michigan and others for a reliable, continuously operating spin filter at LANSCE.

Actions to be taken:

With this introduction, we list the following directions for R&D that emerged during the Pulsed Polarized Neutrons Workshop:

1. *Experiments at existing neutron facilities with current neutron spin filters should be pursued.* The priority should be for experiments and instruments in which existing ^{3}He spin filters can

have an immediate impact and can be implemented efficiently. Currently, the only U.S. laboratory with on-site apparatus and personnel for spin filter experiments is the NCNR. [Overseas there is a well-developed program at ILL, and an emerging capability is developing at ISIS, Hahn-Meitner-Institute (HMI), and Forschungszentrum Jülich (FFZ).] A polarizing apparatus that is to be set up at the IPNS is currently under construction at Indiana University. Expertise in polarized ^{3}He exists in the P-23 group at Los Alamos National Laboratory (LANL), but so far there has not been an active program in the application to neutron scattering. There is no activity in polarized ^{3}He at Oak Ridge National Laboratory's (ORNL's) High Flux Isotope Reactor (HFIR). Active programs in the application of the current generation of neutron spin filters need to be cultivated at as many current neutron laboratories as possible. This goal requires not just the polarized gas apparatus and relevant personnel but also an active effort on the part of interested instrument scientists and neutron scatterers to develop applications of the technology.

A brief review of the current status of test experiments at the NCNR and IPNS illustrates the status of applications. Polarization analysis on SANS instruments and polarized neutron reflectometers were chosen for these tests because of both the need for wide-angle analysis, the relatively open access available, and the interest of instrument scientists and neutron scatterers at these laboratories. At the NCNR, a demonstration of the separation of coherent from incoherent scattering was successful, but experiments on separation of magnetic from nuclear scattering have met with mixed success. The origin of the problems with these experiments is unknown, but it is suspected that the wavelength distribution of the beam, coupled with the wavelength dependence of the ^{3}He, may be causing difficulties. The point is that greater attention to the actual issues in using spin filters is as important as the development of these devices. Currently, the attention at the NCNR has shifted to diffuse reflectometry. At the IPNS, one test experiment was performed on the polarized neutron reflectometer; further experiments will be facilitated by an on-site apparatus.

2. *Despite the evolving state of spin filter technology, definition and coordination of the spin filter requirements of SNS, as well as other neutron laboratories, should be initiated.* Because there can be large differences in technical focus depending on the optical pumping method (the choice of on-line operation vs transportable cells, magnetic environment issues, etc.), it is essential that applications provide direction. The emphasis taken in the United States should depend on choosing the approach (or approaches) that will most efficiently address the needs of existing and planned instruments for which ^{3}He spin filters are the most practical.
3. *Whereas individual facilities may focus on one of the two optical pumping methods, development of both methods should continue, not only because of their complementary nature but also because ongoing developments in each make a single choice premature*. To date, essentially all development and application of the SEOP method has been in the United States, as part of past and present application of this method for electron scattering and fundamental neutron physics. In contrast, the European community has almost exclusively focused on the MEOP method and is the leader in this area. The MEOP method has also been developed in the United States in two parallel efforts: (1) construction of a large-scale compression system, similar to the European apparatus, at Indiana University and (2) development of a compact compressor at the NCNR. The Indiana system has not reached the performance level of the European system. The compact NCNR system, which was meant as a test of the concept of a dramatically smaller, simpler, and less expensive compression

method, has shown promise but is not yet competitive with the either the European system or SEOP results.

The question arises as to whether there can be some division between the American and European efforts. In SEOP, the United States is currently the leader, and the Europeans have shown interest in also pursuing this approach. Hence, for this method, the United States should strive to continue its leadership role, while certainly making use of developments that will occur overseas as the method is put into practice there. In MEOP, the Europeans have been the leaders in the large-scale piston compression systems. Aside from the Indiana system, which is based on the European apparatus, there is no other pursuit of such systems in the United States. The priority for the U.S. effort should be to establish capability in MEOP on par with the European effort.

4. *For SEOP, priorities include*:
   a. *Cell development*—Because of the long-time constants for SEOP, cells with polarized gas relaxation times of 100 hours or greater are required so that the highest polarization values can be achieved. In applications in which the gas is polarized off-line and used on the beam line, the longest possible relaxation times are particularly important. To date, such long relaxation times have been obtained with reasonable reproducibility only in carefully prepared blown glass cells made by a few groups. (The theoretical maximum of 800 hours for a cell at a pressure of one bar has been approached.) The rubidium that is introduced for optical pumping also plays a key role in suppressing wall relaxation. For future applications, flat-windowed cells (which cannot be completely blown) will be desirable for uniform thickness spin filters. Experience with such cells is even more limited, with the only development for neutron applications being pursued at NCNR and ILL. Both the achievable relaxation times and the reproducibility of obtaining these times are inferior in these cells. Studies of different processing methods and/or coatings are needed. In addition, there can be sheer construction issues with the range of cell geometries and sizes that will be needed in the future. For this latter issue, direction should be established by the needs of instruments that can profitably use ^{3}He spin filter technology.

      Whereas alkali-coated glass is currently the best material for cells and thus should be the first line of further development, other options should be investigated. For example, work is currently being done at the University of Virginia with cells that are first coated with sol-gel before the alkali is introduced. Sapphire has desirable neutron properties, but there are issues with construction of large-scale cells and with birefringence. At ILL, cells have made from single crystal silicon. Although certain pure metals, such as titanium or aluminum, can exhibit long relaxation times, no one has actually constructed cells from such materials. Recently it has also been observed that cells can become magnetized in strong magnetic fields and exhibit magnetic hysteresis. Even cells that have never been in strong fields can show induced and remnant magnetization that leads to a dependence of relaxation time of magnetic field direction (or equivalently cell orientation in a given field), field magnitude, and magnetic history. These effects need to be better understood.
   b. *Spectrally narrowed laser development*—Large cells require substantial amounts of laser power. A scheme has recently been developed at the University of Wisconsin to spectrally narrow the broadband commercial diode bars typically used for SEOP. However, these lasers do not have the convenience of commercial fiber-coupled lasers.

Further investigation is required to fully explore the utility of spectrally narrowed lasers and make them more convenient for on-line spin filter applications.

c. *Investigation of a filling station approach*—Although a major advantage of the SEOP method is the capability to continuously optically pump on a neutron beam line, for some applications a "filling station" approach may be desirable. In this approach, one decouples the optical pumping requirements from the spin filter requirements. For example, SEOP is more efficient for small, high-pressure cells that have a favorable geometry for optical access, whereas spin filter cells may be large, low-pressure cells with special shapes for large solid-angle polarization analysis. In this case, an SEOP filling station could provide the technical simplicity of the SEOP method along with the capability to fill a large range of cells, which is currently practiced at ILL using the MEOP method.
d. *Investigation of optical pumping of other alkalis and alkali mixtures*—It has recently been shown by collaboration between the University of Wisconsin and Amersham Health that optical pumping of a rubidium-potassium mixture can increase the polarizing rate of SEOP. This approach could increase the range of cell relaxation times that are acceptable and thus also increase the range of tolerable magnetic field gradients. In addition, it would increase the convenience and versatility of the SEOP method by shortening the time required to polarize a cell.
e. *Investigation of the fundamental mechanisms limiting the polarization*—It has recently been discovered at the University of Wisconsin that the polarization achievable by the SEOP method is limited to about 75% by an unknown form of relaxation that scales with the rubidium density. If this relaxation could be identified and eliminated, ^{3}He polarizations approaching 100% could be possible.

5. *For MEOP, priorities include*:
   a. *Establishing in the United States a state-of-the-art compression apparatus comparable in performance to those at ILL and Mainz, Germany.*
   b. *Cell development*—Long relaxation times are important for the MEOP method, but for somewhat different reasons than those for the SEOP method. The MEOP method has a higher polarizing rate, which lessens the need for long relaxation time cells to reach high polarizations. However, the physical scale of current compressors requires a filling station approach; hence, cells are not optically pumped on the beam line. The issues for MEOP cells are similar to SEOP cells but with a few differences. MEOP cells are valved rather than sealed, which introduces additional issues in maintaining cleanliness. MEOP cells can be made of fused silica, while SEOP cell use GE180 (a boron-free aluminosilicate glass) because of excessive permeation of ^{3}He at high temperatures for fused silica.
   c. *Investigation of improved compact, continuously operating compressors*—Although some work has been done in this area in both the United States and Europe, a more substantial effort will be required to determine whether the highest polarizations are possible with a compact system. This is a more risky endeavor relative to either the SEOP method or the already-developed large-scale compressors. However, success would allow for both the rate available from the MEOP method in a system that could operate continuously on a beam line.
   d. *Investigation of the fundamental mechanisms limiting the polarization*—In the newest ILL system, there is almost no loss of polarization during compression, which now turns

attention to a more precise understanding of the limits of the polarization that can be produced by MEOP. We note that there is essentially no activity in the United States in fundamental studies of MEOP. Increased attention to these issues from the Atomic, Molecular, and Optical physics community would be ideal, but if not, we should make use of developments overseas.

e. *Polarized gas transfer methods*—In some instruments, it may be difficult to access the ^{3}He cell. In such cases, it might be desirable to have a cell fixed in the instrument that is filled through a gas line.

6. *Development of magnetic shielding methods*—In this area, no single approach is appropriate to address all issues. The solution needs to be matched to the application, which implies that more specific knowledge of the desired applications must lead the way. For relatively modest stray fields, passive magnetic shields will be adequate. A more formidable stray field will require a combination of mu-metal and Meissner shields. In this area, ILL is clearly the leader, and efforts in the United States should make use of that capability. Recently, it has been shown that glass spin filter cells can become magnetized in strong fields, resulting in decreased relaxation time.
7. *Development of accurate neutron polarimetry using ^{3}He spin filters*—This area is of most importance for fundamental studies of the weak interaction with neutrons. Measurements of correlation coefficient in neutron beta-decay require knowledge of the neutron polarization at the 0.1% level. This is possible using ^{3}He spin filters because the polarization can be determined by neutron transmission measurements and because the dependence of the absorption cross section on neutron energy is well known. Development of this method would facilitate a class of experiments on the SNS fundamental physics beam line.
8. *Commercial ^{3}He gas polarizers*—These polarizers are being developed for polarized gas magnetic resonance imaging. These devices cannot be used directly as neutron spin filters because the technical needs for magnetic resonance imaging (MRI) imaging are different from those of spin filters. However, some of the R&D for the polarized gas MRI is likely to be useful for spin filters. The neutron community should make use of the relevant technology from the polarized gas MRI enterprise.

It is important to note that such development will require input from a broad range of researchers, including neutron scatterers, nuclear and atomic physicists, and engineers, as well as cross-disciplinary collaboration. Fostering such interaction should be a priority in this program.

5.2. NEUTRON SPIN FLIPPERS

All instruments that will use polarized neutrons at SNS will need one or more neutron spin-flippers. To be suitable for a spallation neutron source, the flipper either needs to function intrinsically over a broad neutron bandwidth (example: cryo flipper) or it must be possible to change the flipping conditions according to a dynamic TOF mode (e.g., Mezei flipper with ramped currents). The kind of spin-flipper that is best suited to a particular application depends on the wavelength range to be handled, magnetic environment, beam size/angular coverage, space restrictions, and/or other particularities.

From our discussions at the workshop, we agreed on the following priorities:

a. Development of broad wavelength-band spin-flippers

- push λ_{min} to shorter wavelength (a suitable goal might be 0.4 Å for diffraction instruments, 0.1 Å for high-energy inelastic spectrometers)
- develop spin flippers that provide substantial angular coverage
- develop spin flippers that are insensitive to magnetic field environments
- develop spin flippers that do not pollute the magnetic environment (the latter applies particularly to RF flippers)

b. Development of computational methods
- calculate neutron beam polarization for realistic flipper/magnetic field environments
- integrate realistic magnetic field profiles in Monte Carlo simulation programs

We present in the following different types of neutron spin-flipper concepts to be evaluated, adapted, and refined for the applications that will be available at SNS. For each spin-flipper, some comments are made about the current state of the art and what advances will be necessary to ensure stable and reliable operation of these devices in the instruments. As a conclusion, in each section, we specify the actions we judge necessary to achieve these advances.

5.2.1. Drabkin Non-Adiabatic Flipper

This design uses a static magnetic guide field configuration. At the flipper entrance, the field is parallel to the momentum of the neutron. This longitudinal field, which defines the quantization axis for the neutron spin, reverses its direction over a very short distance at the midpoint of the flipper (an appropriate field configuration can be achieved by mounting two dc coils with opposite polarity coaxially along the neutron beam). The neutron spin cannot follow this fast field change and is therefore reversed relative to the guide field direction at the exit of the flipper.

This is a relatively simple solution that requires almost no further development and adaptation. In particular, there are no special requirements for magnetic field homogeneity and stability. This kind of flipper works well for epithermal and thermal wavelengths but is usually less efficient for cold neutrons. The upper bound is typically around 10 Å, but magnetic stray fields could lower this value. Efficiencies of >99.5% have been demonstrated for a beam diameter less than 30 mm. This configuration is currently operating in spallation sources (e.g., POSY I at IPNS). This setup requires space on the order of 500 mm (length) along a beam line. The design does not require having material in the beam, which has the advantage that a neutron guide may run through the flipper. This design could be turned into a $\pi/2$ flipper by adding one more field component in the transition region, although its performance might not be satisfactory.

A variant of this spin reversal system was set up at Los Alamos. An additional transverse magnetic field is used to control the spin direction at the end of the spin flipper. In the transverse field-on state, the spin adiabatically follows the field direction and the spin direction is reversed. In the transverse field-off state, the spin passes rapidly through the region where the solenoidal field reverses the sign and the spin direction is not reversed. With this design, the spins of an 8-cm-diameter beam of longitudinally polarized neutrons can be reversed with efficiency greater than 88% over a range of neutron energies of more than four orders of magnitude.

Actions to be taken:

1. Identification of opportunities for the use of this flipper, in particular, SNS instruments. The decision would be mostly determined by the energy and wavelength band and the required spin-flip efficiency. A realistic performance evaluation comparison can be quickly made by sharing available data (e.g., from POSY I, Los Alamos.).
2. Evaluation of the performance of its modified version as a $\pi/2$ flipper.

5.2.2. Mezei Flipper

This is a flipper where two coils with perpendicular windings create a sharp change from a transversal guide field direction to a transversal perpendicular field direction in a well-defined region in space. The neutron spin enters and exits the coils non-adiabatically (i.e., without changing its direction). The outer coil is used to cancel the guide field that is present at the flipper location. Inside the inner coil (which provides a transverse flip field perpendicular to the guide field), the polarization components precess around the resulting field axis. This flipper is widely used in reactors. To make it work in spallation source instruments requires the flip coil to be operated in a pulsed current mode (i.e., with a certain waveform and with the source frequency). The Mezei flipper might be the best option for instruments with tight space restrictions (typical Mezei flippers are about 5 mm thick). This flipper can also work as a $\pi/2$ flipper.

Disadvantages of this kind of flipper include that it requires the guide field compensation coil to be finely retuned whenever residual magnetic fields change at the location of the flipper (e.g., when switching on a sample magnet) and that the procedure of determining the appropriate flip current/wavelength relationship initially could be time consuming. Also, the Mezei flipper requires having material in the beam (the wires of the coils). This could cause additional scattering effects that could lead to a significant additional background signal in the detectors. Several groups are working on designs that would minimize this effect.

Tests of a prototype Mezei flipper operated in TOF mode were carried out several years ago by Fitzsimmons at LANL and more recently by SNS staff at IPNS in collaboration with Suzanne Te Velthius (MSD-ANL). The electronics required to operate such a flipper in a spallation source are readily available. Good performance has been achieved by flipping the spin of neutrons with wavelengths up to 10 Å (measurement was intensity limited). At IN15 in TOF mode, neutrons of 18 Å wavelength have been flipped with high efficiency using a Mezei flipper.

Actions to be taken:

1. Preliminary calculations should be continued to determine the cause of performance loss from imperfect non-adiabatic transitions and influences of the external magnetic environment.
2. The results of the calculations in item 1 should be shared with instrument scientists who can provide feedback about the possibilities of using such flippers.
3. If the results achieved in items 1 and 2 are satisfactory, prototypes can be built and tested, working as π and $\pi/2$ flippers, to confirm the expected performance at spallation sources operating at 60 Hz.

4. Magnetic shielding designs should be developed.

5.2.3. Current Sheet and Superconducting Sheet Flippers

The operation of a current sheet flipper (also called a Dabbs foil flipper) is based on a non-adiabatic magnetic field transition created by a current crossing a foil. It typically operates at cryogenic temperatures to achieve higher currents and, consequently, a stronger field magnitude. A similar non-adiabatic transition between fields on both sides of the flipper foil can be achieved by using the Meissner screening effect of superconducting sheets. Niobium sheets have been in operation at ILL for many years. Recently, Fitzsimmons (LANL) also used high T_C films for this purpose.

Sheet flippers may be good options for several instruments. We know that these types of flippers are in operation at ILL (France) and that the ILL staff is willing to exchange information about their features and performance.

- Advantages: works well for white neutron beam; very stable; no tuning.
- Disadvantages: Material in the beam, could be sensitive to external magnetic fields (e.g., from a sample magnet in the case of current sheets); arrangement of the guide field before and after the flipper might not be not trivial for current sheets; will require some space along the beam line.

Actions to be taken:

1. By exchanging information with the ILL staff, we should identify the requirements to operate such flippers (usage of helium, acceptable stray fields, materials, etc). These requirements should be taken into account when deciding whether a cryogenic flipper is really the best option for a particular instrument. Mike Fitzsimmons should be contacted regarding his experience with the yttrium, barium, and copper oxide (YBCO) sheet flipper.
2. Calculate the performance of these flippers in the magnetic environment expected for the instruments for which the instrument scientists see such flippers as a good option (code to perform these calculations is already available at SNS).
3. If the results achieved in items 1 and 2 are satisfactory, a further decision should be made about buying flippers from a supplier (this information should be available at ILL) or about building a prototype if a supplier is not available.

5.2.4. RF-Gradient Flipper

This is an adiabatic neutron spin-flipper and works with two basic magnetic fields: (1) a constant guide field with a spatial gradient and (2) an RF oscillating field. This design flips all neutrons with wavelengths larger than a certain minimum wavelength for which it is designed. There is no need for a pulsed current to be synchronized with the source. It can also be designed to work well in a variable field environment, without the need of compensation (we believe that Cryogenic flippers could be designed to work this way as well). Another advantage of this flipper is that it does not require placing material in the neutron beam. For these reasons, the RF-gradient flipper may be the preferred flipper for most applications, if a noise free and stable set of electronics is available for the RF field. Different solutions for the RF electronics have been used in several places in Russia, at HMI/FRM2 (Germany), and at LANSCE (Los Alamos), and the exchange of information between key people in these places would help in finding a single solution that could be the standard electronics for this type of flipper at SNS (in this case, one optimized design would likely serve any RF-gradient flipper at SNS).

Actions to be taken:

1. Create a list of people who could provide information about their experience with the electronics issues (e.g., Thomas Keller and Mike Fitzsimmons) and promote a brainstorm on the subject to achieve a good solution for the electronics. To extend the wavelength range of this flipper to λ <1 Å, the involvement of an RF specialist would probably be of great help.
2. Calculate the performance of these flippers for various magnetic environments expected for the instruments (code to perform these calculations is already available at SNS). A designated group of people (e.g., A. Parizzi and other) could give support for the magnetic and polarization calculations.
3. Construct and test prototypes in suitable polarized beam lines (preferably with strong magnetic fields available) to cross check the results obtained in calculations. Fitzsimmons's beam line is ideally suited for further development of the RF flipper since he also has a high-field magnet available (12 Tesla).
4. Provide feedback of the results to the instrument scientists.

5.2.5. Flippers with Multiple Current Foils (Drabkin Spatial Spin Resonance)

A Drabkin spin-resonance flipper functions somewhat similarly to an RF flipper. The difference is that the adiabatic spin rotation is accomplished by passing the neutron beam through an arrangement of current sheets that create a *spatially* oscillating magnetic field instead of an RF field. For TOF operation, the guide field coils and the current sheets need to be operated with ramped currents. Depending on the number of current sheets, the flipper can be made to be wavelength selective ($\Delta E/E$ <1%). According to calculations, it should allow dynamic energy filtering at spallation neutron sources. The corresponding set up would consist of a wavelength-selective magnetic resonator (the actual flipper) and a supermirror polarizer/analyzer system. SNS is currently developing a prototype system that should be operational by July 2003.

Actions to be taken:

1. Wait and see how the SNS prototype performs. Share the results with the community. (Japanese scientists are currently working on a similar device).

5.2.6. Options for $\pi/2$ Flippers

For some applications, like spin-echo spectroscopy and three-dimensional polarization analysis instruments, $\pi/2$ flippers are needed. Mezei flippers have been successfully used for this purpose, but there are also other solutions (some of which were discussed previously). Recently, magnetic thin films have been used as $\pi/2$ flippers[45], and one can imagine ways in which their use could be extended to pulsed sources by changing the direction of the magnetic field applied to the film during each neutron pulse. Japanese scientists report successful construction of a π/2 flipper based on a combination of a current sheet and Helmholtz coils.

5.2.7. Remanent Supermirrors

Recently, so called “remanent polarizing supermirrors” were developed. These can be operated as spin-selecting devices and could make spin-flippers dispensable for some applications. These supermirrors are designed such that spin “up” neutrons are reflected if the magnetic coating is magnetized parallel to the guide field direction. Magnetic hysteresis allows the coatings to maintain their magnetization direction even if a small field is applied in the opposite direction (reverse fields of approximately 20 Gauss are possible). In this state, the mirror reflects spin “down” neutrons.

5.3. NEUTRON SPIN ECHO DEVELOPMENTS

It is clear that, for the foreseeable future, research using polarized neutrons at pulsed sources will rely heavily on ^{3}He spin filters. The properties of these systems are very different from their optical counterparts, and some thought is needed to determine how best to use them for neutron-scattering experiments. What, for example, is the implication for various experimental techniques of the rather low neutron polarization currently available with neutron high transmission spin filters? While such low polarization is probably quite adequate for separating roughly equal signals, the situation is quite different when the signal in one channel is an order of magnitude (or more) different from that in the other channel. The optimum polarization and transmission of the spin filters will need to be established for each potential application, as will the effect of the wavelength dependence of both of these quantities.

As detailed elsewhere in this report, there are a number of instrumental methods that involve more than a straightforward assembly of the polarizer and flipper components described previously. All of these methods involve controlling Larmor precession of the neutron spin in some manner. Traditional neutron spin echo uses large volume electromagnets designed so that the precession angle of a neutron spin depends only on the neutron velocity and not (in lowest order) on divergence or position within the neutron beam. NSE methods to code the angular trajectory of a neutron, on the other hand, require fields whose boundaries are inclined to the neutron beam. MIEZE and NRSE methods use both homogeneous static magnetic fields and RF fields. Finally, generalized polarization analysis uses precession of neutron spins to arrange for the spins of neutrons incident on and scattered from a sample to be aligned along well-defined spatial directions.

Traditional NSE has been in use at continuous neutron sources for more than two decades, although experience with the method in the United States is limited to a recently constructed spectrometer at NIST. This method has recently been tested in TOF mode using the IN15 spectrometer at ILL and is likely the easiest of the Larmor precession techniques to transfer to SNS, once some of the problems with polarizers and flippers (including π/2 rotators) described previously have been adapted to the particular requirements (wavelength range, time structure, divergence, etc.) of pulsed neutron sources. The (energy-resolving) NRSE method has not been attempted in TOF mode, but the development necessary to ensure that this can be done is relatively straightforward since it involves only the ramping of magnetic fields during each neutron pulse. It is possible that the same solution could be applied to implementing generalized polarization analysis at pulsed sources. Alternatively, it might be worth exploiting the broad wavelength band available at pulsed sources to simultaneously probe different components of the susceptibility tensor (just as one uses this bandwidth, for example, to simultaneously probe different lattice spacings in a diffraction experiment). R&D will be needed to determine the optimal solution.

Finally, there are several instrumental techniques that are either new or still under development at continuous sources and that hold the promise of enhancing the resolution and sensitivity of neutron scattering. One such technique is NRSE applied to the measurement of line widths of collective excitations or to measurement of very small scattering angles. In the context of surface studies, the latter has been dubbed SERGIS (spin echo coding of grazing incidence scattering); while for scattering from bulk samples, it is known as SESANS. Although the NRSE-based SERGIS and SESANS techniques can likely be implemented at a pulsed source with about the same level of difficulty as the standard energy-resolving NRSE method, it is less obvious how measurement of phonon line shapes would be implemented using TOF methods. Significant R&D will be needed. Similarly, new techniques that use magnetic thin films for SERGIS and SESANS[44, 45] will need to be explored at both continuous and pulsed sources before they can become part of the standard arsenal of neutron-scattering methods.

Actions to be taken:

1. Develop SERGIS and SESANS at existing reactor-based sources to assess their potential for obtaining unique scientific information.
2. Develop the technology required (such as wavelength independent $\pi/2$ rotators) to test SERGIS at existing pulsed sources.
3. Construct a prototype SERGIS spectrometer at an existing pulsed source. The ASTERIX spectrometer at LANSCE could provide an appropriate base for such an instrument.
4. Continue to actively involve the neutron community both in the United States and abroad to determine whether results achieved in prototype tests warrant construction of a dedicated instrument.

Design concepts for a MEIZE spectrometer have been developed and presented in several forums including a workshop on Neutron Spin Echo Techniques at Pulsed Sources held at ANL in July 2002. Because MIEZE is considered technically feasible for adapting to a pulsed source, it is appropriate to begin exploring the practicalities of such a spectrometer.

Actions to be taken:

1. Assess the fast detector electronics that will be needed for MIEZE.
2. Calculate the performance of MIEZE based on the performance of individual components operating in TOF mode.
3. Construct a prototype including polarizers and spin flippers and perform tests to assess the accuracy of calculations. The existing SAD Small-Angle Scattering beam line at IPNS could be used for this purpose.
4. Continue to actively involve the neutron community both in the United States and abroad to determine whether results achieved in prototype tests warrant construction of a dedicated instrument.

5.4. DEVELOPMENTS IN POLARIZED-NEUTRON OPTICS

Many experiments in neutron scattering are limited by flux and sample size. Optical elements have been developed that enhance the neutron flux on the sample with little or no compromise to the overall instrument resolution. Two types of scattering experiments in which these limitations are particularly severe are small-angle scattering, where the samples are often large but weakly scattering, and single-crystal diffraction, where the samples are often quite small. There are possible solutions to this problem that will work for polarized beams both for SANS and diffraction. Hexapole lenses are a suitable polarization-sensitive flux-gathering optic for SANS, and Kumakov lenses are suitable for small crystals on single-crystal instruments.

5.4.1. Hexapole Lens

A magnetic hexapole field acts as a lens for neutron beams, convergent for one spin component of the beam while divergent for the opposite. This device has already been demonstrated in steady-state monochromatic operation at the JRR-3 reactor in Japan by the neutron optics and detector group at RIKEN. Efforts are under way to develop a version of the device based on superconducting electromagnets. This would give the device a large enough open area to be practical as a polarization-dependent, flux-gathering optic for small-angle scattering, while at the same time allowing the field strength to be controlled in a time-dependent fashion to maintain a fixed focal length over a broad range of wavelengths for use on TOF instruments such as those at SNS.

Actions to be taken:

1. Calculate the control parameters for a pulsed, superconducting hexapole lens for operation in the second and higher frames of SNS. Develop and test the control electronics.
2. Explore the possibility of using wavelength-compensating material lenses in conjunction with the superconducting lens to extend its wavelength range.
3. Design and construct a prototype lens element to test performance in pulsed-beam operation. These tests will require a polarized beam, a high-resolution area detector, and polarization analysis capability. Small-angle scattering beam lines at either IPNS or LANSCE could be used for these tests
4. Provide feedback on the results to instrument scientists.

5.4.2. Magnetic Kumakov Lens

In the past decade, the Kumakov (focusing capillary, lobster-eye) lens has been demonstrated to be an effective means for boosting flux on a very small sample area. This device is a monolithic assembly of confocal tapered waveguides. These devices show great promise in the field of single-crystal diffraction. To date, all such devices have been constructed of silica and hence do not influence the polarization of the neutron beam. Thus, they can be used in conjunction with spin filters for studies of the magnetic scattering from small single crystals. However, another interesting possibility exists: the lenses themselves can be manufactured from a magnetically birefringent material (a cobalt-iron alloy, for example) so that they selectively focus one spin state of the incident beam and produce a polarized beam on the sample.

Actions to be taken:

1. Determine suitable materials for fabricating a polarizing Kumakov lens both from a neutron-optical and from a fabrication standpoint.
2. If suitable materials can be found, design and construct a prototype lens element and test its focusing and polarization efficiencies. The SCD single-crystal diffractometer beamlines at IPNS or LANSCE could be used for these tests.
3. Provide feedback on the results to instrument scientists.

5.5. SOFTWARE FOR POLARIZED NEUTRON INSTRUMENTATION DESIGN

Workshop participants identified several areas of importance to the development of simulation software that advances polarized neutron instrumentation and techniques. Reliable and powerful simulation software and advanced neutron instrumentation development are now inseparable commodities.

5.5.1. Existing Software Packages Available to the Public

Examples of well-documented, "whole instrument" simulation software include the Monte Carlo packages recently summarized in *Neutron News*, Vol. 13, Issue 4. These include VITESS,[52] maintained by HMI, Germany, despite the recent demise of the European Spallation Source (ESS) project. VITESS incorporates modules for supermirror polarizers and benders, ^{3}He polarizers, simple flipper coils, precessions in inhomogeneous fields, and precessions in rotating fields (useful for RF spin flippers). Compound devices such as polarizing cavities or beam-splitter polarizers could be constructed using the available modules. Expressed future development goals for VITESS include comprehensive simulation capabilities for NSE spectrometers, including TOF NSE. VITESS has some development cross-links with MCSTAS[53], supported by Risø National Laboratory, Denmark, and ILL, France. MCSTAS appears to have limited polarized neutron capability apart from ^{3}He polarizers in its current form. RESTRAX[54] was developed jointly at the Nuclear Physics Institute, Czech Republic, and ILL. Oriented towards triple-axis instruments, RESTRAX has some capability for simulating other instrument architectures and offers the possibility to model supermirror benders.

Packages developed in the United States include NISP (LANSCE/LANL)[55] and IDEAS (SNS/ORNL).[56] NISP is at an advanced level of development and offers spin-dependent transport calculations and superposition of magnetic fields within arbitrarily chosen regions. Both spin state and spin precession are accounted for. NISP offers a well-established input data format (MCNP), a web-based graphical user interface (GUI) for geometry building, file format conversion, and 3-D instrument visualization utilities. However, NISP still lacks "plug and play" modules for specific polarization devices and is actively encouraging contributions from the user community. IDEAS is an evolving package whose polarized neutron components currently include various types of polarizers and spin flippers. It has a standardized module interface that offers flexibility for user-contributed modules but is currently single platform (Windows). User-contributed modules are incorporated into the library subject to their proven test results and availability of documentation.

5.5.2. Development of Existing Software

Multi-platform packages such as VITESS and NISP and the (currently) single-platform IDEAS have well thought out program structures where the possibility of distinguishing neutron polarization states has been integrated from the outset. Such programs feature modular structure; standardized module interfaces; ease of use; GUI-assisted, geometry-building tools; evolving libraries of modules for common “standard” optical elements and samples; and the possibility for entry of numerical data (e.g., most packages model supermirror polarizers by allowing input of both a spin up and a spin down reflectivity curve). These features and good documentation make them ideal candidates for module development for polarized neutron devices.

These packages are not restricted to instrument design and optimization problems but also provide powerful tools for correcting and/or analyzing experimental data from existing instruments and a learning tool where simulated experiments can be performed using appropriate sample scattering models. The Monte Carlo technique is particularly powerful because quantities can be tallied that are otherwise experimentally inaccessible. However, apart from perhaps NISP, input of spin-dependent, sample-scattering laws for simulating polarization analysis experiments with magnetized samples appears to be an area where some work is needed. Other areas of need appear to include accounting for adiabaticity or non-adiabaticity of spin rotators and guide fields, assessment of polarization homogeneity at arbitrary positions in a neutron beam, and the possibility for defining complex field maps within specific regions. Such field maps can be generated by sophisticated, commercially available simulation software. There is also a ubiquitous need for more powerful graphical tools for representing geometries and simulation results. The possibility to export data into the more commonly available commercial graphics packages could be a useful first step in this area.

5.5.3. Standardization of Packages

It seems neither reasonable nor straightforward to enforce a standardized input for packages that are already at an advanced stage of development. For example, NISP is heavily founded on the MCNP format. However, module interfaces should be standardized within a given package and possibly a standard should be agreed upon for future developments. Also, input conversion utilities that allow certain problems to be run using several packages with a minimum of learning effort or setup time might be feasible.

The European organization SCANS (Software for Computer Aided Neutron Scattering[57]) has the following expressed mission statement: “*software development that enables more cost effective and scientifically productive use of existing neutron scattering facilities in Europe.*” This should also be our objective in the United States.

5.5.4. Benchmarking, Quality Assurance, and Version Control

Libraries of realistic and efficient models for optical elements are essential for making reliable predictions of complex instrument behavior. These models cannot be tested without suitable experimental data. This inevitably requires cooperation from existing neutron sources with respect to ensuring availability of test beam facilities and allocation of adequate beam time for these apparently mundane purposes. Furthermore, measured data are used as the model in some simulations.

User-submitted modules must be subject to quality control and approval by the authors of packages before they are integrated into libraries. Release of source code is useful for understanding algorithms that cannot be fully documented. However, a release of unauthorized versions of the source code by individuals is often an undesirable consequence. This practice should be strongly discouraged by providing easy and rapid processing mechanisms for code (and accompanying documentation) submitted privately to package administrators and/or by facilitating temporary plug-ins of user-customized modules, where the user assumes responsibility for the reliability of the results. These concerns seem to be well addressed for some of the projects cited previously.

5.5.5. Publicity and User Education

An important step in discouraging both duplication of effort and distribution of software of dubious reliability lies in continual publicity of available simulation packages and provision of education tools (on-line tutorials, workshops etc.). These constitute some of the activities of the European group SCANS, cited in Section 3. The authors of VITESS are to be commended on making available demo simulation problems that greatly accelerate the software learning process.

5.5.6. Attracting Software Developers

A point of concern is that of attracting motivated professional software developers to work on these important projects. Poorer long-term career prospects and remuneration compared to the software industry norms appear to be partially responsible. Often, research scientists assume these roles in addition to their other responsibilities.

5.5.7. Long-Term Strategy in the United States

Clearly, several of the software packages reviewed in this report have already been used in the design of neutron-scattering instrumentation at SNS. In view of its anticipated position of dominance in U.S. neutron-scattering research within a decade, we envision SNS assuming the role of the U.S. center for advanced neutron instrumentation software development over the next few years. Software must continually evolve to receive the maximum benefit from the astonishingly rapid progress in computing technology and must incorporate the latest component models issuing from an increasing knowledge base of component performance. In the short term, activities might include maintaining existing software packages such as IDEAS (and/or possibly NISP in light of the questionable guarantee of future developments by LANL). SNS activities might also include supporting mirror sites for European packages such as VITESS and MCSTAS while they are being officially maintained or else collaborating in their development. In the long term, one might envision a comprehensive, unified, and standardized package whose upkeep is guaranteed by SNS.

6. DEVELOPMENT OF THE U.S. COMMUNITY

Although U.S. scientists participated in and sometimes led the early development of polarized neutron techniques (see section on historical background), the past three decades have seen a marked shift towards European dominance in this field. If polarized neutron techniques are to be implemented at U.S. neutron sources such as the SNS it is imperative that the local community rapidly reach a forefront level of expertise. While this may not be too difficult in some areas (such as polarized ^{3}He) where there are already established programs in this country, there are other areas (such as generalized polarization analysis) where the U.S. community has no experience whatsoever. There are also broad areas (such as experience with building and operating polarized neutron spectrometers or designing experiments with polarized neutrons) populated only by a very few U.S. experts. Most of these individuals have little or no opportunity to pass on their knowledge to others in the current environment. Furthermore, the number of spectrometers equipped to use polarized neutrons is very low in this country (there are only two such instruments at pulsed sources in the U.S.) and there are almost no facilities available for testing polarizers and other essential hardware elements.

Solutions to these problems are easily devised and a list of relevant steps (see below) was produced at the workshop. The impediment to implementing these solutions is more one of political will and financial means rather than one of designing suitable solutions. Ideas that emerged at the workshop were:

- Promote participation by U.S. users of polarized neutrons at EU and Japanese facilities. These facilities already include sophisticated spectrometers that use polarized neutrons. They produce some of the most far-reaching scientific results in the field. Although U.S. scientists are often not able to participate in experiments at these facilities under the same conditions enjoyed by scientists from the facilities' member countries, there are no rules that prevent U.S. scientists from joining and participating in existing collaborations. In most cases, U.S. scientists bring other benefits to such groups so they are welcome members. Another route to participation in experiments at foreign facilities is to station U.S.-funded post docs at them. Several U.S.-funded post docs have already been welcomed at foreign facilities and the workshop attendees suggested that this program be specifically extended to provide U.S. post docs with experience in the use of polarized neutrons.
- Increase beam time usage on existing polarized neutron instruments in the U.S. to the extent that this is feasible. Since these instruments generally operate full time in polarized mode, the only real way to increase beam time is to add operating time.
- Provide test beam lines and support facilities in the U.S. In spite of suggestions that have been made for such facilities in the past, little has been done to provide them. While everyone acknowledges that little publishable science will come from such installations, the world's best neutron facilities have recognized that they can only stay at the forefront by providing neutron beams for technique development. Managers of these facilities have taken the necessary steps, sometimes in the face of criticism from users who saw that these beam-lines could be used full-time for neutron scattering investigations.
- Provide training and education of new researchers and students. There is almost no formal training in the use of polarized neutrons in the U.S. The subject is not taught through lecture courses nor is there any opportunity to learn it in practice, except through participation in scheduled user experiments, which are often so hectic that little knowledge transfer can take

place. The short training program being offered at NIST in connection with the 2004 PNCMI conference is a small attempt to make progress in educating users, but more needs to be done. An introductory course on polarized neutrons should be incorporated in one or more of the neutron schools held (often annually) at various U.S. neutron facilities.

REFERENCES

1 J. Chadwick, Proc. Roy. Soc. (London) **136**, p. 692, (1932)
2 F. Bloch, Phys. Rev. **50**, p. 259, (1936)
3 O. Halpern and M. Johnson, Phys. Rev. **55**, p. 898, (1939)
4 Y. Izyumov and S. Maleyev, Soviet Phys. - JETP **14**, p. 1668, (1962)
5 M. Blume, Phys. Rev. **130**, p. 1670, (1963)
6 M. Blume, Phys. Rev. **133**, p. A1366, (1964)
7 Y. Izyumov, Soviet Phys. - Usp. **16**, p. 359, (1963)
8 R. Schermer and M. Blume, Phys. Rev. **166**, p. 554, (1968)
9 R. Moon, T. Riste, and W. Koehler, Phys. Rev. **181**, p. 920, (1969)
10 F. Mezei, Z. Phys., **255**, 146 (1972)
11 F. Mezei and P. A. Dagleish, Commun. Phys **2**, 41 (1977)
12 O. Schaerpf, Physica B **156-157**, 639 (1989)
13 P. Brown and J. Forsyth, Br. J. Phys. 1529, p. 15, (1964)
14 A. Freund, R. Pynn, W. G. Stirling and C. M. E. Zeyen, Physica **120B**, 86 (1983)
15 F. Mezei, Physica **86-88**, 1049 (1977)
16 M. T. Rekveldt and Z. Phyzik, **259**, 391 (1973)
17 H. Alperin, International Conference on Magnetism, Moscow, ed., Proc. ICM-73, (1973)
18 F. Tasset, Physica **B 157-157**, p. 627, (1989)
19 F. Tasset, T. Chupp, J. Pique, A. Steinhof, A. Thompson, E. Wasserman, and M. Ziade, Physica **B 180 & 181**, p. 896, (1992)
20 L. Passell and R. I. Schermer, Phys. Rev., **146**, 150 (1966)
21 H. Humblot, W. Heil, E. Lelièvre-Berna, and F. Tasset, Neutron News Vol. 13/No. 1, G. Lander, ed., p. 27, Taylor & Francis Inc., (1997)
22 J. Schwizer and E. Ressouche, *Magnetism: Molecules to Materials*, J. S. Miller and M. Drillon, Eds., Wiley – VCH, p235 (2001)
23 S. Ferlay, T. Mallah, R. Ouahès, P. Veillet, and M. Verdaguer, Nature **378**, p. 701, (1995)
24 Overgaard, J., Iversen, B. B., Palii, S. P., Timco, G. A., Gerbeleu, N. V., Singerean, L., and Larsen, F. K., *Chem. Eur. J.*, **8**, 2775-2786 (2002)
25 Pillet, S., Souhassou, M., Pontillon, Y., Caneschi, A., Gatteschi, D., and Lecomte, C. *New J. Chem.*, **25**, 131-143 (2001)
26 Déportes, J., Lemaire, R., Ouladdiaf, R., Roudaut, E., and Sayetat, F., Antiferromagnetism of the Hexagonal Laves Phases $ThMn_2$. *J. Magn. Magn. Mater*., **70**, 191-193 (1987)
27 Purwanto, A., Sechovsky, V., Havela, L., Robinson, R. A., Nakotte, H., Larson, A. C., Prokes, K., Bruck, E., and deBoer, F. R., *Phys. Rev. B*, **53**, 758-765, (1996)
28 Nakotte, H., Dilley, N. R., Torikachvili, M. S., Bordallo, H. N., Maple, M. B., Chang, S., Christianson, A., Schultz, A. J., Majkrzak, C. F., and Shirane, G., *Physica B*, **261**, 280-282 (1999)
29 Radaelli, P. G., Ibberson, R. M., Argyriou, D. N., Casalta, H., Andersen, K. H., Cheong, S. W., and Mitchell, J. F., *Phys. Rev. B*, **63**, 172419 (2001)
30 S. Maleyev, Physica **B 297**, p. 67, (2001)
31 M. R. Fitzsimmons, S. D. Bader, J. A. Borchers, G. P. Felcher, J. K. Furdyna, A. Hoffmann, J. B. Kortright, I. K. Schuller, T. C. Schultthess, S. K. Sinha, M. F. Toney, D. Weller, S. Wolf, J. Mag. and Mag. Materials (to be published)

32 M Steiner, K. Katurai, J. K. Kjems, D. Petitgrand, and R. Pynn, J. Appl. Phys., **61**, 3953-3955 (1987)
33 P. W. Mitchell, R. A. Cowley and R. Pynn, J. Phys. **C17**, L875 (1984)
34 K. Kakurai, R. Pynn, M. Steiner, and B. Dorner, Phys. Rev. Lett., **59**, 708 (1987)
35 M. Steiner, K. Kakurai, W. Knop, R. Pynn and J. K. Kjems, Solid State Commun., **41**, 329 (1982), J. P. Boucher, L. P. Regnault, R. Pynn, J. Bouillot and R. P. Renard: Europhys. Lett., **1**, 415 (1986)
36 P. Bourges, B. Keimer, L. P. Regnault, Y. Sidis, Journal of Sperconductivity, **13**(5), 735 (2000)
37 D. N. Argyriou, T. M. Kelley, J. F. Mitchell, R. A. Robinson, R. Osborn, S. Rozenkranz, and J. D. Jorgensen, J. Appl. Phys., **83**, 6374 (1998)
38 P. Brown Physica **B 297**, p. 198, (2001)
39 P. Brown, J. Forsyth, E. Lelièvre-Berna, and F. Tasset, J. Phys, Cond. Matter **14**, p. 1, (2002)
40 See, for example, *Neutron Spin Echo Spectroscopy – Basics, Trends and Applications*, F. Mezei, C. Pappas, and T. Gutberlet, (Eds), Springer-Verlag, (2003)
41 F. Mezei, *Neutron Inelastic Scattering* (IAEA, Vienna, 1978), p. 125
42 R. Pynn, *Neutron Spin Echo, Lecture Notes in Physics*, edited by F. Mezei (Springer, Berlin, 1980), Vol. 128, p. 159
43 T. Keller, R. Gaehler, H. Kune, and R. Golub, Neutron News 6, no. 3 (1995)
44 M. T. Rekveldt, NIM **B 114**, 366 (1996)
45 R. Pynn, M. R. Fitzsimmons, M. T. Rekveldt, J. Major, H. Fritzsche, D. Weller and E. C. Johns, Rev. Sci. Instrum., **73**, 2948 (2002)
46 T. Krouglov, W. H. Kraan, J. Plomp, M. T. Rekveldt, and W. G. Bouwmann, J. Appl. Cryst., **36**, 816 (2003)
47 O. Zimmer, et al NIM A440, No. 3 (2000)
48 C. R. Gould, G. L. Greene, F. Plasil, W. M. Snow, *Fundamental Physics with Pulsed Neutron Beams*, World Scientific (2001)
49 G. L. Greene, A.K. Thompson, and M.S. Dewey, Nucl. Instrum Methods **A 356**, 177 (1994)
50 D. R. Rich, et al., NIM **A 440**, 772 (2000)
51 K. Al Usta, R. Gaehler, P. Boni, P. Hank, R. Kahn, M. Koppe, A. Menelle, and W. Petry, Physica **B241**, 77-78 (1997)
52 http://www.hmi.de/projects/ess/vitess/
53 http://neutron.risoe.dk/mcstas/
54 http://neutron.risoe.dk/mcstas/
55 http://strider.lansce.lanl.gov/NISP/Welcome.html
56 http://www.sns.anl.gov/pdfs/montecarlo/NN_v13n4_pgs30-34.pdf
57 http://www.studsvik.uu.se/software/scans/scans.htm-Projects

APPENDIX A

PULSED POLARIZED NEUTRON WORKSHOP AGENDA

Pulsed Polarized Neutron Workshop

Marriott Washingtonian Hotel
Ballroom A-C
Gaithersburg, Maryland

February 10-12, 2003

Monday, February 10

7:00 - 8:00	Continental breakfast and registration	
8:00 - 8:30	Welcome and Goals for the Workshop	Ian Anderson
8:30 - 9:15	Projects and new visions for polarized neutrons: 3d-polarization analysis; bunching of cold beams; and Wanderfeld focusing for Time-of-Flight	Roland Gahler
9:15 - 10:00	Carrying out research using polarized ^{3}He gas: ILL current capabilities and European perspectives	Eddy Lelièvre-Berna
10:00 - 10:30	Polarized ^{3}He-based neutron spin filter development at NIST and Indiana University	Tom Gentile
10:30 - 11:00	Break	
11:00 - 11:30	Neutron spin filter development at Mainz University	Stefan Baessler
11:30 - 12:00	Do we really need collimators? Prospects for SERGIS - Spin Echo Resolved Grazing Incidence Scattering -- and other applications	Roger Pynn
12:00 - 12:30	Neutron Resonance Spin Echo - basic principles and applications	Thomas Keller
12:30 - 14:00	Lunch	
14:00- 14:30	Precision Polarimetry and Spin Manipulation of Polarized Low Energy Neutron Beams	Mike Snow
14:30 - 15:00	Measuring the spin-dependent n-d scattering length and nuclear spin diffusion using targets of polarized protons and deuterons	Oliver Zimmer
15:00 - 15:30	Neutron diffraction from dynamically polarized biological samples	J. K. Zhao
15:30 - 16:00	Break	
16:00 - 16:30	Developments in Polarized Mirrors and Heusler Crystals	Ian Anderson

16:30 - 17:30	Open discussion of the day's presentations	
18:30	Dinner (Ballroom C and D)	

Tuesday, February 11

7:30 - 8:30	Continental breakfast	
8:30 - 9:15	Polarized Neutron R&D in Japan	
	Introduction	Michi Furusaka
	The polarized neutron reflectometer PORE at KENS	Masayasu Takeda
	Spin Exchange ^{3}He polarization R&D at KEK	Takashi Ino
	Development of spin control devices for the pulsed neutron source at J-PARC	Kazuhiko Soyama
	Overview of the development of Neutron OPtical (NOP) devices	Hiro Shimizu
	Development of Magnetic Refractive Devices	Takayuki Oku Jun-ichi Suzuki
9:15 - 9:45	Milestones and Goals of the proposed European R&D network on polarized neutron techniques	Alexander Ioffe
10:00 - 13:00	Discussion Group 1 "The Providers" chaired by Geoff Greene	
	Discussion Group 2 "The Users" chaired by Kent Crawford	
13:00 - 14:30	Lunch	
14:30 - 17:30	Discussion Group 3 Chaired by Ian Anderson	
	Discussion Group 4 Chaired by Roger Pynn	

Wednesday, February 12

7:00 - 8:00	Continental Breakfast	
8:00 - 8:30	Presentation of results from Discussion Group 2	Kent Crawford
8:30 - 9:00	Presentation of results from Discussion Group 1	Geoff Greene

9:00 - 9:30	Presentation of results from Discussion Group 3	Ian Anderson
9:30 - 10:00	Presentation of results from Discussion Group 4	Roger Pynn
10:00 - 10:30	Break	
10:30 - 12:30	Development of a consensus roadmap: Discussion led by Ian Anderson	
12:30	Adjourn	
13:30 – 15:40	Tour on the NIST Center for Neutron Research	Tom Gentile

APPENDIX B

WORKSHOP ATTENDEES LIST

Workshop Attendees List

Adachi, Tomohiro	RIKEN	tadachi@riken.go.jp
Agamallian, Michael	ANL	magamalian@anl.gov
Anderson, Ian	SNS	andersonian@sns.gov
Ankner, John	ANL	jankner@anl.gov
Baessler, Stefan	Mainz	Stefan.Baessler@uni-mainz.de
Borchers, Julie	NIST	julie.borchers@nist.gov
Bowman, David	LANL	bowman@lanl.gov
Chen, Wangchun	NIST	wcchen@nist.gov
Chupp, Tim	University of Michigan	chupp@umich.edu
Cook, Jeremy	NIST	jeremy.cook@nist.gov
Crawford, Kent	ANL	rkcrawford@anl.gov
Dzhosyuk, Sergei	Harvard Univ/Nist	sergei.dzhosyuk@nist.gov
Eccleston Roger	ISIS	R.S.Eccleston@rl.ac.uk
Felcher, Gian	ANL	felcher@anl.gov
Fitzsimmons, Mike	LANL	fitz@lanl.gov
Furusaka, Michi	KEK	michihiro.furusaka@kek.jp
Gahler, Roland	ILL	gahler@ill.fr
Gentile, Tom	NIST	thomas.gentile@nist.gov
Ghosh, Vinita	BNL	ghoshvj@bnl.gov
Glinka, Charlie	NIST	charles.glinka@nist.gov
Greene, Geoff	University of Tennessee/ORNL	greenegl@ornl.gov
Hoffmann, Christina	ANL	choffmann@anl.gov
Huffman, Paul	NIST	paul.huffman@nist.gov
Ikeda, Kazuaki	RIKEN	kazuaki@riken.go.jp
Ino, Takashi	KEK	takashi.Ino@kek.jp
Ioffe, Alexander	Julich	a.ioffe@fz-juelich.de
Jones, Gordon	Hamilton College	gjones@hamilton.edu
Keller, Thomas	HMI	Thomas_Keller@ph.tum.de
Kerch, Helen	DOE	Helen.Kerch@science.doe.gov
Klose, Frank	ORNL	klosefr@ornl.gov
Koetzle, Tom	ANL	tkoetzle@anl.gov
Lal, Jyotsana	ANL	jlal@anl.gov
Lee, Hal	ANL	hlee@anl.gov
Lelievre, Eddy	ILL	lelievre@ill.fr
Littrell, Ken	ANL	klittrell@anl.gov
Lynn, Jeff	NIST	jeffrey.lynn@nist.gov
Majkrzak, Chuck	NIST	charles.majkrzak@nist.gov
Masayasu Takeda	JAERI	takeda@neutrons.tokai.jaeri.go.jp
Mildner, david	NIST	david.mildner@nist.gov
Morishima, Takahiro	RIKEN	moris@riken.go.jp
Neumann, Dan	NIST	dan.neumann@nist.gov
Odonovan, Kevin	NIST	kevin.odonovan@nist.gov
Oku, Takayuki	JAERI	oku@riken.go.jp
Parizzi, Andre	ANL	aparizzi@anl.gov
Passell, Larry	BNL	passell@bnl.gov
Pentilla, Seppo	LANL	pentilla@lanl.gov
Pynn, Roger	LANL/UCSB	pynn@lanl.gov
Rehm, Christine	SNS/ANL	crehm@anl.gov
Sato, Hiromi	RIKEN	hsato@riken.go.jp

Schoen, Keary	NIST	keary.schoen@nist.gov
Schroder, Ivan	NIST	ivan.schroder@nist.gov
Shi, Huong-Tao	W. Virginia University	
Shimizu, Hiro	RIKEN	shimizu@riken.jp
Snow, Mike	Indiana Univiversity	snow@iucf.indiana.edu
Soyama, Kazuhiko	JAERI	soyama@popsvr.tokai.jaeri.go.jp
Suzuki, Jun-ichi	JAERI	suzuki@neutrons.tokai.jaeri.go.jp
Van Horn, Hugh	NSF	hvanhorn@nsf.gov
Wilburn, Scott	LANL	wilburn@lanl.gov
Yang, Liang	Harvard Univ/Nist	liang.yang@nist.gov
Zhao, J. K.	ORNL	zhaoj@ornl.gov
Zimmer, Oliver	TU Munich	Zimmer@E18.Physik.TU-Muenchen.de

DISTRIBUTION

Adachi, Tomohiro	RIKEN	tadachi@riken.go.jp
Agamallian, Michael	ANL	magamalian@anl.gov
Anderson, Ian	SNS	andersonian@sns.gov
Ankner, John	ANL	jankner@anl.gov
Baessler, Stefan	Mainz	Stefan.Baessler@uni-mainz.de
Bennett, Kristin	DOE/SC	kristin.bennett@science.doe.gov)
Borchers, Julie	NIST	julie.borchers@nist.gov
Bowman, David	LANL	bowman@lanl.gov
Chen, Wangchun	NIST	wcchen@nist.gov
Chupp, Tim	University of Michigan	chupp@umich.edu
Cook, Jeremy	NIST	jeremy.cook@nist.gov
Crawford, Kent	ANL	rkcrawford@anl.gov
Dehmer, Patricia	DOE/SC	PATRICIA.DEHMER@science.doe.gov
Dzhosyuk, Sergei	Harvard Univ/Nist	sergei.dzhosyuk@nist.gov
Eccleston Roger	ISIS	R.S.Eccleston@rl.ac.uk
Felcher, Gian	ANL	felcher@anl.gov
Fitzsimmons, Mike	LANL	fitz@lanl.gov
Furusaka, Michi	KEK	michihiro.furusaka@kek.jp
Gahler, Roland	ILL	gahler@ill.fr
Gallagher, Pat	NIST	patrick.gallagher@nist.gov
Gentile, Tom	NIST	thomas.gentile@nist.gov
Ghosh, Vinita	BNL	ghoshvj@bnl.gov
Glinka, Charlie	NIST	charles.glinka@nist.gov
Greene, Geoff	University of Tennessee/ORNL	greenegl@ornl.gov
Hoffmann, Christina	ANL	choffmann@anl.gov
Huffman, Paul	NIST	paul.huffman@nist.gov
Hurd, Alan	LANL	ajhurd@lanl.gov
Ikeda, Kazuaki	RIKEN	kazuaki@riken.go.jp
Ino, Takashi	KEK	takashi.Ino@kek.jp
Ioffe, Alexander	Julich	a.ioffe@fz-juelich.de
Jones, Gordon	Hamilton College	gjones@hamilton.edu
Keller, Thomas	HMI	Thomas_Keller@ph.tum.de
Kerch, Helen	DOE	Helen.Kerch@science.doe.gov
Klose, Frank	ORNL	klosefr@ornl.gov
Koetzle, Tom	ANL	tkoetzle@anl.gov
Lal, Jyotsana	ANL	jlal@anl.gov
Lee, Hal	ANL	hlee@anl.gov
Lelievre, Eddy	ILL	lelievre@ill.fr
Lisowski, Paul	LANL	lisowski@lanl.gov
Littrell, Ken	ANL	klittrell@anl.gov
Lynn, Jeff	NIST	jeffrey.lynn@nist.gov
Majkrzak, Chuck	NIST	charles.majkrzak@nist.gov
Masayasu Takeda	JAERI	takeda@neutrons.tokai.jaeri.go.jp
Mason, Thom	ORNL	masont@sns.gov
Mildner, david	NIST	david.mildner@nist.gov
Mook, Herb	ORNL	pedro.montano@science.doe.gov
Montano, Pedro	DOE/SC	mookhajr@ornl.gov
Morishima, Takahiro	RIKEN	moris@riken.go.jp
Nagler, Steve	ORNL	naglerse@ornl.gov
Neumann, Dan	NIST	dan.neumann@nist.gov

Odonovan, Kevin	NIST	kevin.odonovan@nist.gov
Oku, Takayuki	JAERI	oku@riken.go.jp
Oosterhuis, Bill	DOE/SC	W.OOSTERHUIS@science.doe.gov
Parizzi, Andre	ANL	aparizzi@anl.gov
Passell, Larry	BNL	passell@bnl.gov
Pentilla, Seppo	LANL	pentilla@lanl.gov
Pynn, Roger	LANL/UCSB	pynn@lanl.gov
Rehm, Christine	SNS/ANL	crehm@anl.gov
Richardson, Jim	ANL	jwrichardson@anl.gov
Root, John	National Res. Council/CA	John.Root@nrc.ca
Rowe, Mike	NIST	j.rowe@nist.gov
Sato, Hiromi	RIKEN	hsato@riken.go.jp
Schoen, Keary	NIST	keary.schoen@nist.gov
Schroder, Ivan	NIST	ivan.schroder@nist.gov
Shi, Huong-Tao	W. Virginia University	
Shimizu, Hiro	RIKEN	shimizu@riken.jp
Smith, Greg	ORNL	smithgs1@ornl.gov
Snow, Mike	Indiana Univiversity	snow@iucf.indiana.edu
Soyama, Kazuhiko	JAERI	soyama@popsvr.tokai.jaeri.go.jp
Suzuki, Jun-ichi	JAERI	suzuki@neutrons.tokai.jaeri.go.jp
Teller, Ray	ANL	rteller@anl.gov
Van Horn, Hugh	NSF	hvanhorn@nsf.gov
Wilburn, Scott	LANL	wilburn@lanl.gov
Yang, Liang	Harvard Univ/Nist	liang.yang@nist.gov
Zhao, J. K.	ORNL	zhaoj@ornl.gov
Zimmer, Oliver	TU Munich	Zimmer@E18.Physik.TU-Muenchen.de