Report to the
Nuclear Science Advisory Committee

Submitted by the Subcommittee
on Fundamental Physics with Neutrons

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Contents

1. Executive Summary

In February 2003, the Department of Energy (DOE) and the National Science Foundation (NSF) charged the Nuclear Science Advisory Committee (NSAC) to review and evaluate the program in fundamental physics with neutrons and make recommendations for the future program commensurate with projected resources. The charge noted that the recent NSAC Long-Range Plan identified and recommended pursuit of promising new initiatives in fundamental physics with neutrons and requested guidance to implement this recommendation. In response to the charge, NSAC formed a subcommittee to evaluate the scientific opportunities and make recommendations for priorities commensurate with funding constraints.

The subcommittee held meetings at Los Alamos National Laboratory (LANL) and Oak Ridge National Laboratory (ORNL) during April, 2003 to gather information about the ongoing and future plans for this field. The subcommittee was extremely impressed with the present scientific program and future opportunities presented at the two meetings. Following extensive discussion, the subcommittee developed four recommendations for the field which were presented to NSAC in a preliminary report at the end of May, 2003.

At present, two facilities provide beam lines for measurements in fundamental physics with neutrons – the Los Alamos Neutron Science Center (LANSCE) and the National Institute of Standards and Technology (NIST). Two major experiments – UCN-A and $\vec{n} + p \rightarrow d + \gamma$ – are underway at LANSCE using both cold and ultracold neutrons (UCNs). At NIST several smaller experiments are running and others are waiting to run in the near future. For the near term, the subcommittee determined:

! The US has an active program in fundamental physics with neutrons using cold and ultracold neutrons at LANSCE and NIST where measurements of neutron β decay and hadronic parity violation are underway. It is important to successfully complete the commissioning of the two major experiments that are poised to begin operation at LANL. The subcommittee urges the groups in these experiments to focus their efforts on them. The subcommittee strongly recommends that the existing program at NIST continue.

A new experiment to measure the electric dipole moment (EDM) of the neutron is being developed by a collaboration led by a group at LANL. Their goal is to improve the sensitivity for observing a non-zero EDM by a factor of 500 over existing experiments. Several technical issues must be addressed before a proposal can be generated. The subcommittee found the science to be very compelling:

! The EDM experiment has the highest discovery potential of all proposed experiments. The subcommittee strongly supports it. We encourage the collaboration to address the technical issues surrounding this experiment and recommend that R&D funding be provided to accomplish this.

A major construction project – the Spallation Neutron Source (SNS) – is now underway at ORNL. When completed the SNS will be a world-class facility offering the most intense spallation neutron beams available anywhere. A beam line port has been allocated for fundamental physics studies by SNS management but work must start soon to construct the line in order to meet the SNS construction schedule. The subcommittee recognizes this opportunity as key to the future of the field:

! We recommend the construction of the cold beam line at the SNS and the program of measurements in fundamental neutron science that it can support. We further recommend that provision be made for the construction of an ultracold neutron beam line.

The new experimental developments in this field will lead to significant improvement in precision for fundamental properties of the neutron and neutron scattering studies. However, without adequate theoretical support, the program will not reach its full potential. The subcommittee found the present level of theoretical support in the US for this field to be low and recommends:

! Resources should be allocated or redirected to increase the size of the theoretical community associated with fundamental symmetries with effort directed to neutron physics. Such growth could occur through the creation of new senior theory positions at laboratories and at universities where there are strong experimental efforts, faculty bridge positions involving laboratories and universities, and post-doctoral positions in theory groups addressing issues relevant to the fundamental neutron physics program.

The charge to NSAC requested guidance on what future program could be carried out in fundamental nuclear physics with neutrons at a constant level of effort based on the FY04 DOE Nuclear Physics Congressional Request level, and recommend priorities for further investment with additional funds beyond this level. The experiment deemed to have the highest physics impact by the subcommittee, a new measurement of the neutron EDM, simply cannot be done within the baseline budget, even with reasonable (20%) increases. The subcommittee places very high priority on this experiment and urges that new funding should be found outside the core program in fundamental physics with neutrons to construct and operate it. Under the FY04 budget guidelines, a full commitment of DOE capital equipment funds through FY07 for fundamental neutron physics is sufficient to construct the SNS cold beam line, but with little remaining for construction of experiments. ORNL will require funds to operate the beam line thus reducing support available for *research* at a constant level of effort. Thus level funding and no increase in capital equipment monies will severely restrict the future program. Nevertheless, the subcommittee recommends that construction of the SNS beam line must proceed for a viable program in the future.

The impact of constant funding at the FY04 level would be a loss of the EDM experiment, a delay in one of the two major experiments at LANL, no significant construction funds from DOE for experiments at the SNS until FY07, and a loss of support for *research*. In addition to seeking new funds outside the core program for the EDM experiment, the subcommittee urges that DOE increase base funding for the program by 20%. This would allow for an optimal program in fundamental physics with neutrons to be carried out in the future.

2. Introduction

In April 2002 the Nuclear Science Advisory Committee (NSAC) submitted a Long Range Plan (LRP) to the Department of Energy (DOE) and the National Science Foundation (NSF) outlining a program of science for the next decade. Among the initiatives identified in the 2002 LRP was one recommending that the nuclear science community invest in a new beam line for cold and ultracold neutrons at the Spallation Neutron Source (SNS) which is under construction at Oak Ridge National Laboratory (ORNL). In February 2003, Dr. Raymond L. Orbach, Director of the Office of Science of the Department of Energy (DOE), and Dr. John B. Hunt, Acting Assistant Director of the Directorate for Mathematical and Physical Sciences of the National Science Foundation (NSF), charged the Nuclear Science Advisory Committee (NSAC) to review and evaluate the current and proposed scientific capabilities for fundamental nuclear physics with neutrons and make recommendations of priorities consistent with projected resources. In response, NSAC formed a subcommittee to carry out the evaluation.

The subcommittee, chaired by Robert Tribble, consists of seven members of the nuclear physics research community. Six committee members, including an international representative, are experimentalists and one member is a theorist. The committee membership is given in Appendix C. The subcommittee was provided budgetary information by members of the DOE Office of Science (Dennis Kovar, Associate Director for the Office of Nuclear Physics; Gene Henry, Program Manager for Low-Energy Nuclear Physics; Jehanne Simon-Gillo, Program Manager for Facilities and Instrumentation) and the NSF nuclear physics program office (Brad Keister, Program Officer, Nuclear Physics Division). Representatives from DOE and NSF attended the subcommittee meetings. Also the NSAC chair, Richard Casten, served as an ex-officio member of the subcommittee.

The subcommittee made site visits to Los Alamos National Laboratory (LANL) and Oak Ridge National Laboratory (ORNL) in April, 2003. During these visits, the subcommittee heard presentations on the present and future program in fundamental nuclear physics with neutrons that encompassed the ongoing efforts at LANL and the National Institute of Standards and Technology (NIST) and the future programs proposed for these two facilities, plus the program envisaged for a proposed new beam line at the SNS. Two university based initiatives, PULSTAR and LENS also were brought before the committee. The subcommittee held a meeting in early May at the National Science Foundation to discuss the science opportunities and budgetary issues. Following lengthy deliberation, the subcommittee has developed a set of recommendations for the field that are given below in this report.

The neutron is the simplest of all unstable nuclei and, consequently, it has been an ideal laboratory for nuclear β-decay studies for many years. The advent of the Standard Model of electroweak interactions has made studying neutrons even more important – neutron properties, neutron decay and neutron scattering offer an excellent means to test the foundations of the model. But progress has been limited over the years due to the lack of sources of slowly moving polarized neutrons. Cold neutrons satisfy this – they are easily polarized and have very low velocities. Ultracold neutrons can also be easily polarized and they provide the added feature that they can be stored in bottles and then used for measurements. For nearly two decades, the US nuclear physics community has recognized the need to develop intense beams of cold and ultracold neutrons in order to carry out precision measurements of the properties of the neutron and its decay, and to study the hadronic component of the weak interaction. The 1989 Long Range Plan for Nuclear Science noted: “A facility judged to be of major importance to [Precision Tests of Fundamental Interactions] is a source of cold and ultracold neutrons. The lack of first-rate sources in the U.S. is limiting basic experiments on parity violation, time-reversal violation, and the lifetime, electric dipole moment, and β-decay angular correlations of the free neutron.” Over the last decade, work at LANL and NIST has advanced significantly our ability to polarize cold neutrons and create and store ultracold neutrons (UCNs). Advances in neutron guide technology have led to reduced losses in transporting cold neutrons and a concomitant increase in flux. These developments, coupled with the advantages of measuring the cold neutron energy from a pulsed cold neutron source, were recognized in the most recent (2002) LRP: “Intense beams of pulsed cold neutrons and beams of ultracold neutrons (UCNs) offer sensitive tools for testing the fundamental symmetries and for elucidating the structure of weak interactions. Experiments are now under way with pulsed cold neutrons at the Los Alamos Neutron Science Center (LANSCE), and in the future, we expect to take similar advantage of the Spallation Neutron Source (SNS), now under construction at Oak Ridge. In a second thrust, great advances have been made in the development of superthermal UCN sources. Such a next-generation high-flux source might be sited at a number of facilities, including the SNS. The opportunities at the SNS represent a very highly leveraged use of nuclear physics funds to carry out world-class experiments with neutrons.”

With any new initiative in nuclear physics, the principal motivation must be the science. The central foci of the science in this field are testing fundamental symmetries of the electroweak interaction via measurements of the intrinsic properties of the neutron, the neutron lifetime and correlation coefficients from the neutron β-decay spectrum and the determination of the strength of the hadronic weak interaction. The emphasis is on precision – improvements in measurements provide ever more sensitive tests of fundamental symmetries and may uncover new physics. Advances in technology are leading to a new generation of measurements that hold the promise for substantial improvements in precision. Consequently there is a compelling science program to be carried out in the future. A discussion of these science opportunities is presented below as part of this report.

The construction of the SNS is proceeding and first beams at full energy are projected to be delivered during 2007. The primary focus of the facility is condensed-matter physics and both the construction and operation funding is being borne by the Office of Basic Energy Sciences at the Department of Energy. Nuclear physics has the opportunity to capitalize on this investment and develop a program in fundamental neutron science at this world-class facility. A beam port has been reserved for a program in fundamental nuclear physics by the SNS management following a review of the science that could be done with cold and ultracold neutron beams by a committee chaired by John Peoples. The new beam line at the SNS would give the US nuclear physics community access to neutrons from a state-of-the-art facility and place us in a more competitive position with our European colleagues who have, for many years, maintained strong programs in fundamental physics with neutrons at the Institut Laue-Langevin (ILL) in France and more recently at the Paul Scherrer Institut (PSI) in Switzerland.

But with a new program comes new costs; nuclear physics must begin construction of the beam line very soon to fit the SNS target area construction profile. The new beam line is only one part of the cost of a future program. In order to utilize the intense beams that will be available at the SNS, there will be additional requirements to fund new experiments and to support operations at the new beam line. Thus funding constraints play a major role in deciding the future direction for this program.

3. Scientific Opportunities

3.1 Overview

Testing the symmetries of the Standard Model (SM) and searching for what may lie beyond it is central to the nuclear physics enterprise. Historically, such tests in nuclei played an important role in establishing the basic structure of the electroweak interaction. Recently, the NSAC Long Range Plan affirmed the on-going importance of this branch of nuclear physics in identifying "What is to be the new Standard Model?" as one of the five key scientific questions driving nuclear physics for the next decade. In this context, studying the properties of the neutron can provide important new clues about the content of the new SM. At the same time, such studies may also yield new insights into unsolved problems within the SM, particularly those involving the delicate interplay of the symmetries of the strong and electroweak interactions.

The SM has been enormously successful in providing a self-consistent phenomenology of the electroweak and strong interactions at the level of radiative corrections. The theory has been stringently tested in a broad array of processes ranging from those involving the lowest energy scales (atomic parity-violation) up to the Z^0 pole and beyond. A particularly important achievement in the history of the SM was the discovery of the top quark. Not only did the SM predict the existence of the top quark, but it also provided expectations for its mass via the m_t-dependence of electroweak radiative corrections to precisely measured electroweak observables. Whatever the *new* SM is to be, it will ultimately have to stand up to the same kind of self-consistency tests that have been applied to the SM. In this respect, precision electroweak measurements, such as those involving neutrons, will provide important input.

Indeed, despite the impressive successes of the SM, there exist a number of fundamental questions in particle physics, nuclear physics, and cosmology which it fails to answer. Among the important questions most relevant to the nuclear and particle physics communities are the following:

What is the character of the neutrino and what is the origin of its mass? Neutrino oscillation experiments have clearly established the existence of a non-vanishing neutrino mass, and, therefore, the existence of right-handed neutrinos. Since right-handed neutrinos are "sterile" with respect to all the interactions of the minimal SM, the origin of the neutrino mass cannot be explained in this framework. At the same time, we do not know whether the neutrino is its own anti-particle, as suggested by many models for massive neutrinos. Both experimental and theoretical studies of hadronic parity violation are important to understand neutrinoless $\beta\beta$ decay so that the mysteries of the neutrino can be revealed.

Why is the Fermi constant such a large number? The Fermi constant, G_F, plays a key role in a variety of processes of interest to nuclear physics, such as β decay, the *pp* reaction in the sun, and the *r*-process. The value of G_F is inversely proportional to the square of the weak scale, M_{WEAK}. The existence of any "new physics" beyond the SM that involves particles heavier than

M_{WEAK} will – via radiative corrections – cause the weak scale to increase and, thus, reduce the value of G_F. From this standpoint, the Fermi constant is a surprisingly large number, and there must have been some additional symmetries in the early universe that have prevented it from being much smaller. By itself, the SM provides no clues as to what these symmetries might be.

Why is there more matter than anti-matter? The observed predominance of matter over anti-matter in the universe – the so-called baryon asymmetry of the universe (BAU) – cannot be explained based on the symmetries of the SM alone. In order to account for it, there must have been additional sources of CP-violation in the evolution of the universe whose effects were not suppressed by the light quark masses and small flavor-mixing angles as is the case for CP-violation in the SM.

These and related issues – such as the origin of electric charge quantization, the reason for parity-violation below M_{WEAK}, or the particle content of cold dark matter – have no resolution within the SM. As we discuss below, studies pertaining to the fundamental properties of neutrons can provide essential information related to each of these unresolved issues. Even within the SM itself, there remain many open questions. Of particular importance to nuclear physics are the symmetries of the strong interaction, such as SU(3) of color for the gauge interactions, chiral symmetry, heavy quark symmetry, and large N_C (number of colors) symmetry. Although these symmetries have been tested and work reasonably well for strong quark-quark interactions, we still do not know the degree of their applicability to *weak* interactions between quarks. For example, the origins of the $\Delta I=1/2$ rule for non-leptonic weak interactions evade an explanation using the symmetries of the strong interaction. Similarly, the non-leptonic weak decays of hyperons strongly violate one's expectations based on these symmetries. Whether these breakdowns of strong interaction symmetries have to do with the presence of strange quarks in the processes under consideration or with more fundamental dynamics that apply equally well for the two lightest flavors is not known. Again, the study of fundamental properties of neutrons may shed new light on this basic question.

While the future of fundamental neutron physics will undoubtedly involve both experimental and theoretical efforts beyond those that we can presently envision, it is nevertheless useful to identify classes of studies that could provide the core of a future program. Here, we outline broadly three such classes of neutron physics and their potential impact on the open questions noted above.

Search for a permanent electric dipole moment

The interaction of a photon with the permanent electric dipole moment (EDM) of the neutron, d_N, violates both parity (P) and time-reversal (T) invariance. Assuming that CPT symmetry is exact, this interaction would also violate CP invariance. The amount of CP-violation in the CKM matrix of the SM would imply a magnitude for d_N of roughly 10^{-32} – 10^{-34} e-cm, whereas the present experimental limits from the Particle Data Group (PDG) imply $|d_N| < 6.3 \times 10^{-26}$ e-cm (90% confidence). As we discuss below, a future experiment operating at the SNS could improve this limit by at least two orders of magnitude. Should an EDM be discovered in this range, it would imply either some new CP violation outside the SM – as needed for the BAU – or a non-zero value for the θ parameter in the QCD Lagrangian. In order to distinguish between these two possibilities, one would require EDM searches on complementary systems. At present, efforts are also underway to improve the sensitivity of electron and atomic EDM measurements by up to two orders of magnitude. Similarly, an experiment is being developed to measure the muon EDM with 10^5 times better precision, while the feasibility of performing a first measurement of the deuteron ion EDM is also being studied. Combining the results of all these classes of EDM measurements is essential to disentangling the various possible mechanisms for CP-violation.

An improvement in the precision of the neutron EDM by two orders of magnitude is significant. Indeed several theoretical predictions have suggested that one might expect a neutron EDM with a magnitude that could be seen in the proposed experiment. Conversely, even the present limits have placed strong constraints on electroweak baryogenesis models. The achievement of more stringent EDM limits would undoubtedly lead to a re-examination of these existing models.

Measurement of β-decay correlation coefficients

A comparison of the Fermi constant characterizing light-quark β decay, G_F^β, with the Fermi constant measured in μ decay, G_F^μ, can provide a window on the physics that may be responsible for stabilizing the weak scale as discussed above. At present, the most precise value for G_F^β is obtained from superallowed, Fermi nuclear β decay. Within the SM, the comparison of G_F^β with G_F^μ yields a value for V_{ud} , the first element of the CKM matrix. The current precision on this number according to the PDG is 1×10^{-3} – just the level needed to probe new physics at the level of radiative corrections. For some time, a combination of this result with those of kaon leptonic decays and *b*-quark decays has implied a 2.2σ deviation from the required unitarity of the SM. If no explanation of this effect can be achieved within the SM, then the implications for various new physics scenarios can be surprisingly strong. For example, supersymmetry (SUSY) is one of the leading candidates for a new symmetry that would stabilize the weak scale and provide a candidate for cold dark matter. However, the implications of standard SUSY-breaking models would not be consistent with the present G_F^β - G_F^μ comparison without sacrificing the viability of SUSY dark matter. Similarly, in the context of left-right symmetric theories, the first row CKM unitarity deviation would be compatible with non-zero mixing between left- and right-handed W bosons. Moreover, the presence (or absence) of such left-right mixing could have significant implications for understanding the origins of neutrino mass, since the sensitivity of neutrinoless ββ-decay experiments to the heavy Majorana neutrino arising in L-R symmetric theories depends strongly on the degree of W_L-W_R mixing. Given such potential implications for various new physics scenarios, then, it is essential to test all possible explanations for the long-standing CKM unitarity deviation.

New measurements of previously un-measured superallowed transitions in both light and heavy nuclei will help test the reliability of theoretical nuclear corrections applied to the extraction of G_F^β from experimental *ft* values. An independent test can be provided by the study of neutron decay, for which one need apply no nuclear theory correction. As discussed below, knowledge of both the neutron lifetime as well as of one primary decay correlation parameter (*a*, *A*, or *B* as defined below) is needed in order to obtain G_F^β. Experiments using ultracold neutrons (UCNs) at LANSCE, when combined with the present neutron lifetime results, are poised to determine G_F^β with a precision comparable to that of the superallowed studies.

Presently, considerable effort is being directed toward both experimental and theoretical re-analyses of kaon leptonic decays to obtain the *s* quark matrix element V_{us} – a recent result suggests that the accepted value for this matrix element may not be correct. Given its importance in CKM unitarity tests, it is extremely important to clarify this situation. But other *s* quark CKM matrix elements are also being addressed by our particle physics colleagues and now a major effort is underway to measure B decays to better determine those CKM matrix elements associated with the *b* quark. Sensitivity to physics beyond the SM varies for the different CKM matrix elements. Indeed CP/T violation is a principal focus of most of the *K* and *B* decay measurements. It is clear that experimental precision will play a major role in all attempts to discover evidence for new physics. For this reason, V_{ud} based unitarity tests will be the benchmark for the foreseeable future. The present precision on V_{ud} already exceeds that for any other diagonal CKM matrix elements, making tests of first row CKM unitarity a promising arena in which to search for the effects of new physics.

Hadronic parity-violation in few-body systems

At present, the study of hadronic parity-violation (PV) provides the only known window on weak interactions between up and down quarks. Indeed, in order to determine whether the apparent breakdown of strong interaction symmetries for hadronic weak interactions is strangeness-dependent, one must study this interaction in the strangeness-conserving sector. Unfortunately, the situation in this respect is clouded by a variety of ambiguities.

Experimentally, measurements have been performed in both few-body systems, such as the *pp* and $p\alpha$ systems, and in nuclei ranging from the *p*-shell nuclei like ^{18}F to heavy nuclei such as cesium. Theoretically, the interpretation of these measurements has relied on a meson-exchange model that contains seven phenomenological meson-nucleon couplings. At present, one cannot obtain a self-consistent set of values for these couplings from the existing measurements. A particular quandary involves the parity-violating πNN coupling, h_π. In units of $g_\pi = 3.8 \times 10^{-8}$ that are appropriate for hadronic weak interactions, naturalness arguments derived from QCD symmetries imply h_π should be of order 10. The analysis of parity-violating *pp* scattering and the cesium anapole moment are consistent with these expectations. In contrast, the parity-violating γ decays suggest a value for h_π that is an order of magnitude smaller. With these and similar discrepancies, the origin may lie in approximations used to compute effects in nuclei, in the use of a meson-exchange model as the basic framework, in one or more of the experiments, or some combination.

In order to arrive at an unambiguous window on the weak, $\Delta S=0$ quark-quark interaction, it is necessary to obtain a set of numbers that are free from the uncertainties associated with many-body nuclear physics and that do not require a meson-exchange model for interpretation. Recently, a theoretical framework for such a program has been developed using the ideas of effective field theory (EFT). As experimental input, one requires a minimum of seven independent few-body experiments. At present, only two have been carried out. The remaining five could be completed through a combined program at LANSCE, NIST, and the SNS, where inclusion of the latter would be essential. The results would be interpreted theoretically in an unambiguous way, since EFT provides one with a systematic, model-independent framework for treating few-body nuclear physics and since there exists well-tested theoretical machinery for carrying out *ab initio* few-body calculations.

The results of such a program would have implications in two directions. First, one would have in hand a set of unambiguous numbers that could be compared with the expectations based on QCD symmetries. Any significant discrepancies would suggest that something beyond the strange quark is responsible for the breakdown of QCD symmetries in hadronic weak processes. Second, one could re-analyze the nuclear parity-violating observables using the experimentally constrained few-body EFT as input. Doing so would allow one to determine whether there exists a reasonable truncation of an EFT for weak processes in nuclei involving only the lowest-order operators. The results of such a study would have important implications for the analysis of other weak processes in nuclei, such as neutrinoless ββ decay. Indeed, the nuclear theory ambiguities involving 0νββ decay have been a notoriously challenging problem. If the new physics responsible for lepton-number violation needed to generate 0νββ decay is heavy, then EFT could in principle be applied to the study of this process, leading to considerable simplifications in the nuclear theory. In this respect, the study of hadronic PV in few- and many-body systems would provide an important laboratory for studying the viability of such an approach and contribute toward our understanding of the character of the neutrino.

3.2 T-violation and the Neutron EDM

The violation of time-reversal symmetry, and the closely related CP symmetry, is among the most fundamental issues in physics. In 1964, CP violation was observed in the neutral kaon system. Since then, the CP symmetry has been the focus of an intense research effort which continues today. As discussed above the violation of CP-symmetry is believed to be necessary to explain the fact that the Universe is dominated by matter over anti-matter. Assuming CPT symmetry holds – and all experiments so far support this assumption – CP violation then implies T violation. Recently, both the KTeV collaboration at the Fermi National Accelerator Facility and the CPLEAR collaboration at CERN have reported evidence for direct T violation in the neutral kaon system. The KTeV collaboration finds that the average angle between pions and leptons in semi-leptonic neutral K decay differs from 0, the value expected in the absence of T violation, by more than 3σ. From measurements of oscillations between particle and antiparticle states, the CERN group reports a result that shows T violation at the 4σ level. Both results can be incorporated into the SM by a complex phase in the CKM matrix. But the solution is not natural and the new results could be a hint of physics beyond the SM. Meanwhile, two on-going experimental groups, the BaBar collaboration at the Stanford Linear Accelerator Center and the Belle collaboration at the Japanese KEK facility, have recently observed similar CP violation in the neutral B-meson system.

To date, the observed CP violation effects are consistent with the SM. Furthermore, the size of the CP violation in both the kaon and B-meson systems is too small to explain the observed BAU. This leads to the expectation that there are sources of CP-violation besides those put into the SM. Extensions to the SM such as SUSY, Multi-Higgs models, and Left-Right Symmetric models all predict a relatively large neutron EDM – one that would be accessible to the next generation of EDM-search experiments. Thus the neutron EDM provides an outstanding opportunity to discover new physics beyond the SM.

Searches for a neutron EDM have spanned more than five decades. In addition, much effort has been devoted to measuring a non-zero EDM in diamagnetic atoms and the electron. But to date all searches have generated null results. Already, limits on EDMs have ruled out classes of models that attempt to extend the SM. And as noted above, the next generation of neutron EDM searches will provide sufficient sensitivity to probe many of the existing favored SM extensions.

Thus far, the most sensitive neutron EDM searches have been performed at the ILL. New experiments are planned for the ILL facility and for PSI as well as a US based experiment that, as presented, would be initiated at LANSCE and then move to the SNS. A summary of these new experiments is given in Table 3.1. Although there are a number of technical issues that must be answered, the experiment planned for LANSCE/SNS could have the greatest reach of all the new generation experiments. The results for the LANSCE/SNS experiment are expected after the LHC at CERN has become operational. It is important to emphasize that even if experiments at the LHC confirm, through direct searches for new particles, a new physics model, the neutron EDM search will still be extremely important since it will provide information on the parameters of the new model that are not easily determined in LHC experiments.

The most promising scheme to substantially improve the sensitivity of the neutron EDM measurement involves the trapping of 0.89 nm neutrons in superfluid helium. A US-based experiment using this approach proposes to initially make use of a neutron beam line at LANSCE that is modified to produce 0.89 nm neutrons and, ultimately, the UCN beam line at the SNS. This technique is believed to give a large neutron density, a long coherence time and permit the use of a high electric field (50 kV/cm). The experiment will also use a ^{3}He co-magnetometer to compensate for low-level magnetic field noise. There are a number of technical issues that must be addressed before a proposal becomes viable. The EDM collaboration has submitted a request to DOE to fund the necessary feasibility tests. The collaboration must address the issues of UCN wall losses, particle identification, maximum electric field, and ^{3}He relaxation time in the UCN volume. The group has developed a detailed plan to deal with each of these issues and anticipates that within approximately one year, the feasibility tests will be completed at a sufficient level to develop a full proposal. Based on preliminary design work, capital equipment costs for the experiment are expected to be about $14 M, including contingency and escalation.

A similar plan that makes use of trapping neutrons in superfluid helium will be used in a new experiment at the ILL by a European collaboration. At present, the main difference between the US and European schemes is that the US experiment involves a ^{3}He co-magnetometer. Co-magnetometers have been found to be essential in previous experiments. Thus, it is likely that the US scheme could attain the best sensitivity, as shown in Table 3.1. A full review of the US EDM proposal, when it becomes available, must carefully assess the relative merits of the two approaches. Presently, the plan calls for developing the EDM experiment at LANSCE, performing a measurement to the 6-27 x 10^{-28} e-cm level in the 2008-10 time frame, and then moving the experiment to the SNS for the ultimate sensitivity of 3-12 x 10^{-29} e-cm during 2010-12, as summarized in the Table. The present ILL experiment is in operation and is expected to reach an ultimate sensitivity of 8-20 x 10^{-27} e-cm by the end of 2006.

TABLE 3.1: Status of neutron EDM experiments. Limits are given for 95% CL. The values quoted as limits for future experiments are from proposals or pre-proposals.

Facility	**Limit (e-cm)**	**Date**	**Technique**	**Status**
ILL (ILL-99)	7.5×10^{-26}	1999	20-ℓ cell Hg magnetometer	Latest publication
ILL	3.4×10^{-26}	2003	20-ℓ cell Hg magnetometer	(ILL-99) Now running
ILL	$8\text{-}20 \times 10^{-27}$	2004-6	20-ℓ cells Hg magnetometer	(ILL-99) Possible continuation
PSI	2×10^{-27}	2006-8	Eight 3-ℓ cells neutron/Cs magnetometer	New proposal under review
ILL	$1\text{-}20 \times 10^{-28}$	2006-9	Superfluid He trap, neutron magnetometer	New proposal under review
LANSCE (1st stage)	$6\text{-}27 \times 10^{-28}$	2008-10	Superfluid He trap, ^{3}He magnetometer	Pre-proposal stage
SNS (2nd stage)	$3\text{-}12 \times 10^{-29}$	2010-12	Superfluid He trap, ^{3}He magnetometer	Pre-proposal stage

Complementary approaches to the search for non-SM CP-violation are also possible through measurements of semi-leptonic decays of time-reversal violating observables. Non-zero T-violating, parity-violating observables could arise from scalar or tensor couplings in models beyond the SM. Limits have been obtained from nuclear β decay, but not yet for the decay of free neutrons, although potential future experiments are being considered. T-violating parity-conserving (TvPc) observables probe new sources of parity-conserving C-violation (and, thus, CP-violation) under scenarios where C is broken at a scale below that of left-right symmetry breaking. Measurements sensitive to TvPc effects have been carried out in neutron and nuclear β decay. Neutron decay offers the best opportunity to observe T violation since final state effects, which ultimately limit the sensitivity of these experiments, are small. The emiT collaboration is carrying out an experiment at NIST to measure the TvPc *D* correlation coefficient (see section 3.3) for neutron β decay. Results from a first measurement yielded the value $D = -0.6 \pm 1.3 \times 10^{-3}$. The experiment is presently scheduled to run through fall 2003. At that time, the collaboration expects to achieve a sensitivity for *D* of $\sim 2 \times 10^{-4}$. Theoretical estimates suggest that final state effects which mimic a non-zero *D* coefficient should enter at the 10^{-5} level in neutron decay. With the anticipated results from emiT, new efforts to improve the reliability of the theoretical calculations of these final state effects are warranted. A future experiment with improved statistics could approach the level of sensitivity of the final state effects.

From a theoretical perspective, there exist several open problems that must be addressed in tandem with experimental probes of CP and T violation. A particularly challenging issue involves delineating clearly the implications of EDM and other T-violation measurements for the BAU and vice versa. At present, there exist a number of baryogenesis scenarios, only some of which provide for fairly direct connections between EDM's and the baryon asymmetry. Even in weak scale baryogenesis scenarios, for which the relationship may be the most direct, a number of model approximations have been invoked in the existing calculations.

In the broader context involving systems whose EDM's must be compared with that of the neutron as discussed above, there exists considerable need for new theoretical input. For example, only one computation of the deuteron EDM has been performed to date. Similarly, various corrections to the so-called "Schiff moment" that gives rise to an atomic EDM have yet to be fully characterized. Again, any meaningful comparison of neutron, atomic, and leptonic EDM's will depend on addressing these open, theoretical problems.

3.3 Lifetime and Correlations Measurements

The neutron is the simplest of all nuclear β decays. Its decay spectrum, averaged over electron spin, is given by

$$\frac{dW}{dE_e d\Omega_e d\Omega_\nu} \propto p_e E_e (E_0 - E_e)^2 \left[1 + a \frac{\vec{p}_e}{E_e} \bullet \widehat{p}_\nu + b \frac{m_e}{E_e} + A \vec{\sigma} \bullet \frac{\vec{p}_e}{E_e} + B \vec{\sigma} \bullet \hat{p}_\nu + D \vec{\sigma} \bullet \frac{\vec{p}_e \times \hat{p}_\nu}{E_e} \right]$$

where $p_{e(\nu)}$ is the electron (neutrino) momentum, $E_{e(0)}$ is the electron energy (end point energy) and σ is the neutron spin. The correlation coefficients *a, b, A, B* and *D* all have definite predictions in the SM. Four of the coefficients (*a*, *A*, *B*, *D*) depend on the parameter λ, the ratio of axial vector to vector coupling constants (g_A/g_v). The Fierz interference term, *b*, is predicted to be 0. Thus precise measurements of low-energy neutron β-decay observables allow stringent tests of the SM and offer potential sensitivity to the discovery of new physics beyond it. In particular, the measurement of the neutron lifetime, when combined with precise measurements of parity-violating correlations in neutron β decay, provides a determination of the vector and axial vector weak coupling constants g_A and g_V and thus G_F^β . Using this information one can calculate the quark mixing matrix element V_{ud} in a manner independent of nuclear structure effects. This result can then be combined with other measurements to test the unitarity of the CKM quark mixing matrix. Furthermore, by carefully measuring the coefficients of the allowed angular correlations (electron-neutrino (a), neutron spin-electron (A), neutron spin-neutrino (B)) one can search for the presence of right-handed currents, the effects of supersymmetric particles, and scalar and tensor terms in the weak interaction. Finally, the weak coupling constants as well as the value of the neutron lifetime play a significant role in our understanding of big bang nucleosynthesis and precision cosmology. Hence improved measurements of both the neutron lifetime and the correlation coefficients can have an important impact on our understanding of both nuclear physics and astrophysics.

The availability of enhanced sources of cold and ultracold neutrons, along with the future high intensity pulsed cold neutrons from the SNS, provides the opportunity to make significant strides in reducing the uncertainties on both the neutron lifetime and the allowed correlation coefficients.

The neutron lifetime

The advent of neutron lifetime experiments based on the storage of UCNs, coupled with improved decay in-flight beam measurements, has resulted in the uncertainty on the neutron lifetime being significantly reduced in recent years. The current PDG value for the neutron mean life determined from the five most recent experiments gives $\tau_n = 885.7 \pm 0.8$ s. To make further significant improvements on this number will almost certainly require a major advance in the techniques and technologies used to perform such measurements.

The most recent lifetime result, $\tau_n = 886.8 \pm 3.4$ s, is from the NIST Penning-trap lifetime experiment, which used an in-beam technique. Ancillary absolute flux measurements that are currently underway at NIST may reduce the final uncertainty to approximately two seconds. However, it is likely that this may be the final experiment undertaken using the decay in-beam technique. A program to reduce the uncertainty from the UCN storage-bottle based neutron lifetime experiment at the ILL is continuing, but it is unlikely that this technique can do much better than 0.5 s uncertainty.

A promising new method that is being investigated at NIST is a measurement of the neutron lifetime using magnetically trapped UCNs. The collaboration carrying out this experiment has demonstrated magnetic trapping of UCNs in superfluid ^{4}He and has upgraded the apparatus to include a deeper trap, a more efficient detection system, and a first of its kind 0.89 nm neutron monochromator. A lifetime measurement with about 1 s accuracy is feasible in its current configuration. The experiment plans an additional upgrade using a magnet recently borrowed from KEK. It also would benefit from moving to the UCN line that is planned at SNS. Ultimately it may be possible to gain an order of magnitude over the current uncertainty value.

Correlations Measurements

Four recent measurements of the neutron spin-electron (A) coefficient have been carried out on cold neutron beams at reactors. Although each experiment quotes a combined statistical and systematic uncertainty of about 1%, the agreement between the four measurements is poor and the current PDG value of $A = -0.1162 \pm 0.0013$ reflects these inconsistencies. These results, when combined with the neutron lifetime, are also in disagreement with the superallowed $0^+ \rightarrow 0^+$ nuclear β-decay results as well as with the CKM unitarity expectations.

Currently there are two groups preparing to make new measurements of the *A* coefficient. A Heidelberg group plans to largely reuse their PERKEO II apparatus and perform a measurement on the new high-flux PF1 beam at the ILL. The uncertainty on the previous PERKEO II result was limited by backgrounds and on the knowledge of the neutron polarization. It is not clear if a major improvement on *A* can be achieved continuing this beam-line based technique. But the use of neutron time of flight to determine neutron polarization provides a capability at a spallation neutron source that is not available to reactor experiments. At Los Alamos, the UCN-A collaboration is developing a radically different approach that will utilize UCNs to measure *A*. This technique offers significant advantages over reactor beam experiments since UCNs can be transported away from potential background sources and because they can be transported into the measurement region with essentially 100% polarization. The collaboration expects to initially determine *A* to the level of 0.2%, and with possible increases in the UCN source intensity and a better understanding of systematic effects, they ultimately expect to be able to improve the accuracy beyond that of existing experiments by an order of magnitude or better. If this measurement proves successful, the group plans to upgrade the spectrometer, replacing plastic scintillator β detectors with Si counters and recoil proton detection, in order to measure the other allowed angular correlation coefficients (*a* and *B*). The upgrade also will allow them to investigate recoil order effects such as weak magnetism and to search for the Fierz interference term *b* by measuring the energy dependence of the decay.

In terms of future efforts, there are several groups preparing proposals for new measurements of the neutron beta decay correlation coefficients. Two groups are proposing new measurements of the electron-neutrino *a* coefficient, which was last measured in 1978 with an uncertainty of 5%. The advantage of measuring this coefficient as opposed to the neutron spin-electron *A* coefficient is that the resulting determination of λ is completely independent of neutron polarization measurements. At the Technical University Munich a group is building a spectrometer called "*a*spect" to measure this coefficient with the goal of reaching 0.5% precision. A US/Russian collaboration is proposing a new technique that bypasses the need in previous experiments of measuring the proton energy, and expects to achieve an initial measurement of 1% uncertainty at NIST. This is a modest sized proposal that would require about $250 k of construction funds from US sources.

There are also at least two additional groups pursing global determination of the allowed angular correlations coefficients (*a*, *A*, and *B*). A Heidelberg group has stated that they intend to utilize the ILL PF1 beam, which is currently the world's most intense cold neutron beam, to make improved measurements of all the correlation coefficients. A US collaboration known as *abBA* is preparing a proposal that would utilize pulsed cold neutrons to measure the correlation coefficients (*a*, *A*, and *B*) as well as search for the Fierz interference term (*b*) which is expected to be zero in the SM. The experiment proposes to initially run at LANSCE on the FP12 beam line, but will ultimately be designed to run on the cold beam line at the SNS. The aim is to achieve statistical uncertainties for each coefficient on the order of about 1×10^{-4}. There are still some remaining technical and manpower issues, and final estimates on systematic uncertainties were not presented. This experiment has the nice feature that it would be able to determine λ in a totally redundant manner. The initial capital equipment cost estimate for the experiment is approximately $4 M. Given the importance of high-precision tests beyond the SM, it is likely that a large next-generation correlation coefficient experiment will be mounted at the SNS. But the exact final nature of this experiment will strongly depend on the outcome of the current UCN-A LANSCE experiment.

The neutron lifetime and λ from correlation coefficient measurements must be combined to obtain V_{ud}. As was noted above, the best value for V_{ud} at present comes from superallowed Fermi nuclear β decay. The PDG value for V_{ud} from superallowed decays has an uncertainty of 0.1%, which is double the uncertainty quoted by standard analyses in nuclear physics. The inflation factor invoked by the PDG is due to uncertainties arising from quark-level contributions and it may disappear in the future as this issue is resolved. The present uncertainty in the neutron lifetime leads to a 0.05% contribution to the uncertainty in V_{ud}. This is comparable to the precision for V_{ud} from superallowed decays without the inflation factor. In order to achieve a result from neutron decay that is comparable to that for superallowed decays, it will be necessary to reduce the uncertainties in the both the lifetime and correlation coefficient to a level below 0.05%. In the near term, a factor of two improvement in the lifetime would be more than adequate for a V_{ud} determination at 0.05%. Reducing the uncertainty in λ (corresponding to a measurement of *A* to about 0.2%) so that it contributes less than 0.05% to the uncertainty in V_{ud} is the major challenge.

More reliable determinations of the neutron lifetime and correlation coefficients will address one potential culprit in the CKM unitarity puzzle – possible nuclear theory errors in the analysis of superallowed β decays. Both the neutron and nuclear decays, however, share an additional source of uncertainty that cannot be addressed through measurement alone. This uncertainty involves hadronic contributions to the higher-order, electroweak radiative corrections to the leading-order decay amplitude. This problem has been known since the time of Sirlin’s benchmark calculation in the 1970’s, yet the intervening decades have seen little theoretical headway. Estimates of the theoretical uncertainty associated with these hadronic effects, though performed using entirely reasonable arguments, remain model-dependent and *ad hoc*.

Recent advances in lattice QCD methods and their application to baryon properties is opening a new avenue for progress on this problem. Addressing it will require a concerted theoretical effort, likely involving theorists with expertise in non-perturbative QCD, EFT, and low-energy weak interactions. At present, however, the number of theorists with both the necessary expertise and interest is sub-critical. Nevertheless, as illustrated by the recent experience with theoretical, hadronic ambiguities in the muon anomalous magnetic moment, it is important to address these kinds of hadronic uncertainties in a serious way if the results of precision, low-energy measurements such as neutron β decay are to have a meaningful impact.

3.4 Hadronic Parity-Violation

A study of PV in the NN system provides a window on the strangeness-conserving weak interaction between quarks. The understanding of this interaction is complicated by the presence of non-perturbative strong interactions, and in the $\Delta S=1$ sector, the symmetries present in purely strong quark-quark interactions appear not to apply in the presence of weak interactions. By studying PV in the $\Delta S=0$ sector, one can in principle determine whether this symmetry breakdown for $\Delta S=1$ processes is a consequence of the presence of strange quarks or is a more general phenomenon. At the same time, were one to have in hand a set of the leading-order parity-violating NN operators, one could also re-analyze previously measured parity-violating observables in nuclear systems and learn whether there exists a reasonable truncation of the EFT for weak processes in nuclei. The results of such a study could have important implications for our understanding of other processes, such as $0\nu\beta\beta$ decay and the origins of lepton-number violation.

At present, results for only two parity-violating observables in few-body systems have been reported – the longitudinal analyzing power in $\vec{p}p$ and $\vec{p}\alpha$ scattering. The remaining results have been obtained using nuclei and include the directional asymmetry in the decay of polarized nuclei, the photon polarization in the decay of un-polarized nuclei, the longitudinal analyzing power in the transmission of epithermal neutrons through heavy nuclei, and the nuclear anapole moment of cesium. Because the theoretical interpretation of such observables requires reliance on nuclear model calculations and their attendant approximations, one cannot obtain from them a pristine determination of the underlying weak NN interaction.

Carrying out a program of hadronic PV measurements with neutrons will allow one to arrive at a complete determination of the leading-order parity-violating operators in a way that is independent of nuclear model approximations. The key ingredients in this project include a set of seven measurements in few-body systems and the corresponding few-body calculations. Since the theoretical technology exists for performing reliable *ab initio* few-body computations, the missing ingredient is experimental.

For the sake of illustration, if one neglects the presence of π-exchange, then the leading-order effects are parameterized by five quantities: λ^{PP}, λ^{PN}, λ^{NN}, λ_T, and ρ_T. A minimum set of few-body measurements needed to determine these quantities could include the longitudinal analyzing power, A_L, in $\vec{p}p$ and $\vec{p}\alpha$ scattering; the circular polarization, P_γ, and photon asymmetry, A_γ, in radiative neutron capture; and the angle of rotation, $\phi^{N\alpha}$, of the spin of a polarized neutron passing through helium. In terms of these observables, the five parity-violating quantities are given approximately as

$m_N\,\lambda^{PP} = -1.22\,A_L(\vec{p}p)$,
$m_N\,\rho_T = -9.35\,A_L(\vec{n}p \to d\gamma)$,
$m_N\,\lambda^{PN} = 1.6\,A_L(\vec{p}p) - 3.7\,A_L(\vec{p}\alpha) + 37\,A_\gamma\,(\vec{n}p \to d\gamma) - 2\,P_\gamma\,(\vec{n}p \to d\gamma)$,
$m_N\,\lambda_T = 0.4\,A_L(\vec{p}p) - 0.7\,A_L(\vec{p}\alpha) + 7\,A_\gamma\,(\vec{n}p \to d\gamma) + P_\gamma\,(\vec{n}p \to d\gamma)$,
$m_N\,\lambda^{NN} = 0.83\,d\phi^{N\alpha}/dz - 0.69\,A_L(\vec{p}p) + 1.18\,A_L(\vec{p}\alpha) - 33.3\,A_\gamma\,(\vec{n}p \to d\gamma)$
$-\ 1.08\,P_\gamma\,(\vec{n}p \to d\gamma)$.

The leading effects of parity-violating π–exchange are contained in the parameter ρ_T. In order to separate the π–exchange contribution from short-distance effects one would require measurement of two additional parity-violating observables. The effects of π–exchange appear both in the PV potential, where they are parameterized by the parity-violating πNN coupling, h_π, and in a new meson-exchange current with a presently unknown coefficient, $\overline{C}_\pi$. The possibilities for the required two additional measurements include the photon asymmetry in radiative $\vec{n}d$ capture and neutron spin rotation on hydrogen.

At present, a measurement of $d\phi^{N\alpha}/dz$ at NIST has been completed and the results are being analyzed. This measurement represents a first generation experiment and in order to obtain the precision needed for a meaningful separation of the seven PV parameters, a more precise, follow-up measurement will be necessary. Such a measurement could be carried out in two stages, the first being at NIST and the second occurring at the SNS.

Similarly, a measurement of $A_L(\vec{n}+p\to d+\gamma)$ is underway at LANSCE. To the extent that ρ_T is dominated by the long-range, π–exchange contribution, the LANSCE measurement would provide a value for the parity-violating πNN coupling, h_π. Although "naturalness" arguments imply that the π–exchange contribution should be considerably larger than the short-distance contributions, the results of parity-violating γ decay of ^{18}F imply that the value of h_π is suppressed. Thus, it remains unclear to what extent the pion plays an important role in the parity-violating NN interaction. As noted above, one would need the sixth and seventh PV measurements in order to separate the short-range and π–exchange contributions and address this issue. Moreover, the precision now expected for the present $A_L(\vec{n}+p\to d+\gamma)$ measurement is a factor of three worse than originally proposed, owing to a number of factors discussed elsewhere in this report. Thus, a clear separation of short-range and pion effects may likely require a follow-up $A_L(\vec{n}+p\to d+\gamma)$ measurement. Such an experiment would benefit from the high flux at the SNS cold neutron beam line.

Beyond the second generation follow-up measurements to the current $d\phi^{N\alpha}/dz$ and $A_L(\vec{n}+p\to d+\gamma)$ experiments, a complete program would require three additional measurements. The latter could include A_γ in radiative $\vec{n}d$ capture, the spin rotation for polarized neutrons through hydrogen $d\phi^{Np}/dz$, and a measurement of the photon helicity in polarized neutron capture on hydrogen $P_\gamma(\vec{n}+p\to d+\gamma)$. Given the difficulties of measuring photon helicity, the $P_\gamma(\vec{n}+p\to d+\gamma)$ measurement would represent a formidable challenge. An alternative possibility would be to measure $A_L(\vec{\gamma}+d\to n+p)$ using the HIGS facility at Duke, where it would require achievement of the highest possible photon flux. The remaining two possibilities, $A_L(\vec{n}+d\to t+\gamma)$ and $d\phi^{NP}/dz$ would require use of the SNS cold neutron beam line. The first stage of the radiative $\vec{n}d$ capture experiment could be carried out at NIST and later moved to the SNS to acquire the needed statistics.

In short, a complete program of parity-violating few-body studies would require five additional measurements beyond those already completed or currently underway. Of these, four would likely be carried out at the SNS. Collaborations interested in pursuing these measurements at the SNS and NIST have been formed although no proposals for new experiments have been prepared. In contrast to the situations for the neutron EDM and neutron β decay, there exist no other plans elsewhere in the world to complete these experiments. Thus, the program of hadronic PV studies with cold neutrons at the SNS presents US nuclear physics with an opportunity to make a unique contribution.

As with the other areas of study described in this report, realizing the unique opportunities for solving the hadronic PV problem will require additional theoretical as well as experimental effort. The theoretical effort should be directed along a number of lines. First, new few-body computations of hadronic parity-violating observables – using the EFT framework –

must be carried out. While the technology exists for performing such computations, the task is far from trivial. For example, the medium-range component of the parity-violating NN potential – generated by 2π exchange – also has associated with it a corresponding electromagnetic current operator. This two-body current must be included in order to carry out a gauge-invariant calculation of processes involving photons, such as the $\vec{n}+p\rightarrow d+\gamma$ reaction. Such a calculation will require the focused effort of at least two collaborating theorists (in order to provide for cross-checks) for a substantial period of time. Similarly, a variety of *nuclear* parity-violating observables must be re-computed if the results of the few-body hadronic PV program are to be used in testing the applicability of the lowest-order EFT to nuclei. Finally, understanding the dynamical origin of the seven, leading-order, parity-violating low-energy constants that would be determined by experiment is an open – and formidable – theoretical task. It must be undertaken, however, if one is to derive new insight into the issue of QCD symmetries and hadronic weak interactions from the experimental program outlined above.

3.5 Baryon Number Conservation

The conservation of B-L, baryon - lepton number, is an accidental symmetry of the SM which need not persist in SM extensions. Indeed, simple extensions of the SM often include new B-L violating interactions. Experiments provide constraints on some, but not all, of these so-called B-L violating effects. Among the most stringent is the search for proton decay. From a theoretical standpoint, the search for B violation is motivated by various grand unified theories, wherein B-violation occurs through the exchange of massive ($M >> M_{WEAK}$) particles. In addition, some scenarios for this baryon asymmetry provide for B violation indirectly through the presence of a Majorana neutrino, whose L violating properties may generate B violation in B-L conserving models.

Apart from the search for proton decay, there exists another way to look for B violation that is of interest to nuclear physics – a measurement of $n-\bar{n}$ oscillations. The existence of such oscillations requires $\Delta B = 2$. In B-L nonconserving theories such as left-right symmetric models, the existence of Majorana neutrinos, whose interactions involve $\Delta L = 2$, could be linked to the occurrence of $\Delta B = 2$ processes. Observation of neutrino oscillations, thus, strengthens the motivation for carrying out $n-\bar{n}$ searches. The present limit on $n-\bar{n}$ transitions is slightly over 10^8 s. With the advent of new cold and UCN beams, a new search could improve this limit by several orders of magnitude, making it commensurate with proton decay limits. No specific $n-\bar{n}$ oscillation experiments were proposed to the subcommittee although an interest was expressed in developing a new oscillation experiment at PULSTAR.

4. Facilities

Today the US program in fundamental physics with neutrons has access to cold neutron beams at LANSCE, a spallation neutron source that is built around an 800 MeV proton linac, and both cold and ultracold neutron beams at the NIST research reactor. The two neutron sources are complementary, offering somewhat different capabilities. At LANSCE, the time structure of the primary beam is often used to measure neutron energy by time of flight. This capability comes at the expense of reduced flux compared to that available at the NIST reactor. Additionally a new UCN source is about to be commissioned at LANL using an 800 MeV proton beam on a new target station. A new spallation neutron source, the SNS, is now under construction at ORNL with construction funding provided by Basic Energy Sciences of DOE. The SNS will provide pulsed neutron beams similar to LANSCE but with a neutron flux approaching that of a large research reactor. Initial operation of the SNS accelerator is scheduled for 2006 and neutron beam operations are to begin in 2007. The High Flux Isotope Reactor (HFIR) at ORNL is being upgraded and should be operating in 2004. It has not been used for fundamental neutron physics studies in the past but it does offer the potential for a high intensity cold neutron beam. Table 4.1 provides the characteristics for these four sources and two European based facilities – the ILL and PSI. The PSI facility does not operate in a true pulsed mode, but rather it has a repetition rate of about 50 Hz where the ratio of the peak-to-trough neutron yield is about 2:1. Thus, the PSI facility, although a spallation source, is listed under continuous sources.

Proposals for two university-based initiatives in neutron science – LENS and PULSTAR – have been submitted to NSF. In July, 2003, the LENS proposal, which is based at Indiana University, was approved by the Materials Science Division of NSF. Research at LENS would focus on neutron scattering studies for materials science and biology. The facility could provide a possible test source for developing new cold neutron moderators. The PULSTAR proposal is to construct a university based UCN facility using neutrons from a small research reactor at North Carolina State University (NCSU). In addition to educating both graduate and undergraduate students in UCN technology, it would provide a source for developing new techniques to produce UCNs.

4.1 LANSCE

The LANSCE facility includes the 800 MeV proton linac that previously provided beams for LAMPF, a proton storage ring and target stations at the Lujan Neutron Scattering Center, the Weapons Neutron Research (WNR) area and the new UCN source in Area B. The proton linear accelerator at LANSCE accelerates H^- ions to 800 MeV. Beams are then transported to Area B for ultracold neutron production and to Line D, which feeds the WNR/Lujan complex. A recently installed fast kicker magnet will allow the two facilities to run simultaneously.

Funding for LANSCE operations is shared by the BES and NNSA offices of DOE. The number of hours of linac operation has increased during the past few years with about 2500

Table 4.1: Comparison of Facilities. HFIR, as noted in the text, is not being used for fundamental neutron physics but it does provide a high flux of cold neutrons.

Facility	**Status**	**Op days per year** Note 1	**Guide Area (cm^2)**	$\begin{pmatrix}\textbf{Guide}\\ \textbf{m}\end{pmatrix}^2$ Note 2	**Cold source Brightness at ~4Å** **(10^{10} n/cm^2/s/sr/Å)**	**Relative Brightness *Area*Year** Note 3	**Relative Yearly Fluence** Note 3
Pulsed Sources							
Lujan (FP12)	Op	104 85%	90	9	2.5	1	1
SNS (FP13)	*Prop*	*208*	*120*	*12*	*71*	*76*	*101*
Continuous Sources							
NIST (NG6)	Op	266 100%	36 Note 4	1.4	150	61	10
HFIR (HB4)	*Prop*	*261* *93%*	*22* Note 5	*4*	*450*	*110*	*50* Note 5
PSI	Op	245	120	9	60	75	75
ILL (PF1b)	Op	200	120	4	450	460	205

Note 1 – Based on recent operations or projected operations for proposed facilities. The % number represents actual to projected days of operation. See the OSTP *Report on the Status and Needs of Major Neutron Scattering Facilities and Instruments in the United States,* June 2002 for a more detailed and compete comparison.

Note 2 – "Guide m" is a term related to how effective the guide tube internally reflects and delivers neutrons to the end of the guide. It is essentially the cold guide's reflectivity $\theta/\theta_{critical}$.

Note 3 – The Fluence is Brightness * Guide Area * "Guide m" term. An experiment's ability to fully utilize the fluence is very geometry dependent. Experiments using collimated beams will not see significant enhancement for larger "Guide m" values. Hence for relative comparsions one should compare both the last two columns.

Note 4 – NIST is currently using less than half of the available NG-6 guide area (90 cm^2).

Note 5 - The HFIR cold guides cross section has an aspect ratio that is not optimal and an additional "shape-changing/area-conserving" guide would be needed to reach this fluence. Without such a device, the useful fluence at HFIR may be reduced by as much as a factor of ~2-3.

hours of beam delivered to the Lujan Center in 2002. Future estimates are for 8 months of linac operation with the primary limitation being the cost for electrical power. Problems with reliability in the linac which have resulted in unscheduled maintenance in the past are now being addressed by LANSCE management with the expectation for much improved performance in the future.

The Ultracold Neutron Facility

The new ultracold neutron facility is being set up in Area B. The proton beam line is designed to transport pulses (duration ~600 μs) of 800 MeV protons from the beam switchyard to the UCN source. The beam into the UCN source will be limited to an average current of 10 μA with the present radiation shielding in the beam line and the UCN cave. Using the fast kicker magnet located in the switchyard, four proton pulses will be delivered in a fraction of a second, and this operation will be repeated every 10 seconds.

UCNs are produced using a new technique based on a solid deuterium (SD_2) moderator that was developed at LANSCE. A short pulse of protons impinges on a tungsten spallation target to produce MeV neutrons. These neutrons are first cooled to < 100 K using conventional cold moderators, and then further cooled to < 0.004 K via phonon interactions in the SD_2. A prototype SD_2 source at LANSCE achieved the world's highest density of stored UCNs of 140 UCN/cm^3.

During the LANL site visit, long-term plans were discussed for creating a national UCN facility based on the techniques similar to those being used at the new LANL facility. Tests of different moderator materials are now being pursued at LANL that could lead to even larger UCN densities in the future. Such a facility could be sited at LANSCE or the SNS.

Manuel Lujan Jr. Neutron Scattering Center

The Lujan Center receives a pulsed proton beam of up to 150 μA (typically 20 Hz, 250 ns pulse width), which impinges on a tungsten spallation target surrounded by a liquid hydrogen moderator. The majority of the neutron flight paths are equipped with neutron scattering instruments for materials research. One beam line (FP12) is dedicated to fundamental neutron physics experiments. The $\vec{n} + p \rightarrow d + \gamma$ experiment is currently under construction on this flight path. The same flight path will also be used for R&D for the proposed EDM experiment.

The beam line consists of a 20 m long neutron guide, which was completed and installed this past spring, the biological shield surrounding the guide, plus a shutter and chopper. The neutron beam is monitored before and after passing through a ^{3}He polarizer. An RF spin solenoid spin flipper precedes the LH_2 target. The EDM experiment, as proposed, will use the same beam line for its initial set of measurements. In order to accommodate the EDM experiment, a section of neutron guide will be installed through the $\vec{n} + p \rightarrow d + \gamma$ cave. Following a Bi filter, a t_0 chopper will be located in place of the existing beam stop. Downstream of the chopper, the 0.89 nm neutrons from the filter will be split into two beams, polarized in opposite directions, and guided to the measurement area located 31 m from the moderator.

Physics Program at LANSCE

An active program in fundamental physics with neutrons has been on going for more than a decade at LANL/LANSCE. Studying fourteen different target isotopes, the TRIPLE collaboration observed 75 non-zero parity-violating asymmetries in compound-nuclear resonances. These (remarkably large) asymmetries ranged from 10^{-1} to 10^{-3}. The factor of ~10^6 enhancement results from the admixture of s-wave resonances, which have large neutron scattering cross sections, into weak p-wave resonances. This work has led to eight Ph.D. theses, a Bonner Prize, and has stimulated several theoretical articles. In addition, the LANL group developed the use of polarized ^{3}He neutron polarizers. They demonstrated the ability to produce a neutron beam with very well measured polarization (better than 0.1%).

Two major new experiments on fundamental physics with neutrons are in progress at LANSCE. The present programs comprise an experiment to measure the parity-violating asymmetry in $\vec{n} + p \to d + \gamma$ at the Lujan Neutron Scattering Center and a measurement of the A coefficient in polarized neutron beta decay – UCN-A – using the new UCN facility. An effort also is underway to develop a new experiment to measure the EDM of the neutron. Each of the experiments is being carried out by collaborations that include university, national laboratory and foreign groups with leadership provided by members of the LANL Physics Division.

The goal of the $\vec{n} + p \to d + \gamma$ experiment is to provide a definitive measurement of the parity-violating πNN coupling constant h_π. A previous experiment on γ circular polarization in ^{18}F disagrees with a result based on the interpretation of the ^{133}Cs anapole moment. A 10% determination of h_π in the two-body process $\vec{n} + p \to d + \gamma$, as was proposed in 1997, would certainly clarify the situation. The experimental technique relies on a measurement of the up-down asymmetry in the γ-rays resulting from the capture of polarized neutrons. The 2.2 MeV γ-rays will be detected using an array of 48 CsI(Tl) crystals, operated in current mode, which surround a 20-liter LH_2 target and cover 80% of the solid angle.

One of the major advantages of carrying out the $\vec{n} + p \to d + \gamma$ experiment at a spallation source is that time-of-flight information can be used to study the energy dependence of the asymmetry. This will be very important to the understanding of systematic uncertainties. Unfortunately, several factors have conspired to reduce the sensitivity of the $\vec{n} + p \to d + \gamma$ experiment in its present configuration. Four major issues have led to a reduction of between 7 and 15 in statistical precision (2.7 to 4 in sensitivity) over the proposal estimates: (1) a reduction of a factor of 2.2 in moderator brightness; (2) a reduction of up to a factor of 1.8 due to lower proton beam current on the target station than anticipated; (3) additional losses of a factor of 2.2 in usable flux from the neutron guide and the experiment; (4) interference from the fringe field of a superconducting magnet in a neighboring beam line. When the superconducting magnet is in use, the fringe field is significantly larger than can be tolerated in the asymmetry experiment. To date, attempts to provide magnetic shielding for the beam line have not been successful. Consequently during the 2003 run cycle an agreement has been established to split the beam time so that the magnet can be used during 50% of the scheduled time. Recent studies have been performed of the moderator brightness problem and it now appears that the factor of two reduction is real.

The group's current plan is to commission the experiment in 2003 and continue the measurement in 2004. The precision that would be achieved will of course depend on the value of h_π; if it is large, a 20% or better measurement should be possible at LANSCE.

A measurement of the β-asymmetry coefficient *A* in polarized neutron decay will be the first experiment to use the new UCN source. The motivation for the measurement – as discussed in the previous section – is to determine λ, the ratio of axial vector to vector coupling constants (g_A/g_v). This result, when coupled with the neutron lifetime, yields V_{ud}. The advantages of UCN's for this measurement are that they can be transported over long distances and stored in bottles for times comparable to their half-life, and that they can be essentially 100% polarized. In the present design of the experiment, UCN's are transported 15 m from the source through a polarizer to the decay volume within a 1.0 T solenoid. The emitted β's spiral along the magnetic field lines into detectors (MWPC's plus plastic scintillators) at either end of the decay volume. Count rates of several hundred per second are expected.

To date no problems have been identified in the UCN-A experiment that compromise its goals. Several upgrades of the UCN-A detector are also planned for the near future. The major changes will be an upgrade from plastic scintillator to silicon β detectors and the addition of recoil proton detection. The upgrades will allow for a measurement of the energy dependence of the asymmetry *A*(E), a search for the Fierz interference term (*b*) and the measurement of the other allowed angular correlations.

Facility Staff and Support

Fundamental physics with neutrons is the largest program in basic nuclear physics research in the Physics Division at LANL. During this past year, there were 4.7 FTE at LANL working on $\vec{n} + p \rightarrow d + \gamma$, 4.3 FTE on the UCN-A experiment and an additional 4.6 FTE who were involved with R&D for the EDM experiment. It represents the largest overall group in the US in this field. DOE supports the two ongoing experiments with research funding of about $1.8 M/year. The EDM project is supported by LANL discretionary funds – LANL has already provided about $4.2 M to this experiment through laboratory directed funding (LDRD), and has committed LDRD funds for 2004, 2005, and 2006 of $1.4 M per year. During this time, the R&D should be completed, and a full proposal will be written. LANL also supplied about $4.8 M in LDRD funds since 1994 for developing the new UCN source.

During the site visit, the subcommittee asked LANSCE management about the long-term plans for the facility after the SNS begins operation. They replied that their goal is to create a facility that is reliable, sustainable, and complementary (in its neutron scattering capabilities) to SNS. The aim is for a sustained beam availability of > 85%. This figure was in fact exceeded last year at both WNR and the Lujan Center.

4.2 NIST

The National Institute of Standards and Technology (NIST) Center for Neutron Research (NCNR), located in Gaithersburg, MD, houses a 20 MW heavy-water moderated research reactor. NCNR operates as a national user facility providing both thermal and cold neutron beams for a variety of scientific research programs, including materials science, biological, polymer, and fundamental physics research. Cold neutrons are produced using a large liquid hydrogen cold source operated at 20 K that is located on one of the reactor's thermal neutron beam ports. Viewing this cold source are eight cold neutron guide tubes, varying from 20 to 60 meters in length. The cold guides, rectangular ^{58}Ni-coated guides that are 15 cm tall and 6 cm wide, are housed in a large experimental guide hall.

Four NCNR beams are currently dedicated to fundamental physics experiments. Three beams, used nearly exclusively for nuclear physics research, are located on the NG-6 cold neutron guide: a high-intensity polychromatic beam, a 0.496 nm monochromatic beam, and a 0.89 nm monochromatic beam. The fourth beam, a state of the art neutron optics and interferometry facility located on the NG-7 cold neutron guide is used for a variety of fundamental physics measurements, including nuclear scattering length measurements of interest to nuclear physics. Supermirror polarizers are available for producing or analyzing polarized neutron beams. There is also a dedicated program to develop practical ^{3}He based neutron spin filters based on two different techniques for polarizing ^{3}He: metastability-exchange optical pumping and spin exchange optical pumping.

The high-intensity polychromatic beam, which has been the workhorse beam for studies of fundamental neutron physics, uses neutrons that exit from the upper 7 cm of the NG-6 guide and pass through a ^{6}Li-loaded-glass collimator that defines a 6 cm diameter beam. The wavelength distribution of the beam is roughly Maxwellian with an average temperature of 30 K. To minimize backgrounds, single crystal, cooled (77 K) bismuth filters (5 cm to 15 cm long) are placed in the beam to attenuate gamma rays from upstream components in the guide. The neutron fluence rate with 15 cm of bismuth is $(1.5 \pm 0.1) \times 10^{9}$ cm^{-2} s^{-1}. The maximum fluence rate with no filters is approximately 2.3×10^{9} cm^{-2} s^{-1}. A double-sided supermirror bender polarizer obtained from the ILL is available for experiments requiring a source of polarized neutrons. The polarizer has an overall transmission of 24% and produces a high degree of stable polarization, typically greater than 95%. The beam line became operational in 1991. Recent experiments performed on NG-6 include a Penning-trap based neutron lifetime measurement, a test of time reversal symmetry in neutron beta decay (emiT), a preliminary test of a parity non-conserving neutron spin rotation experiment in liquid helium, and the initial effort to develop a neutron lifetime measurement using magnetically trapped UCNs.

The 0.496 nm monochromatic beam line, commissioned in May 1998 and designated as NG-6M, uses two monochromators positioned in the lower 8 cm of the polychromatic beam exiting the NG-6 guide. After the neutron beam reflects from the second monochromator, it passes through 10 cm of cooled beryllium to remove the $\lambda/2$ component of the beam. The neutron fluence rate available at a typical experimental position (approximately 2 m from the crystal) is 6.5×10^{5} cm^{-2} s^{-1}. This beam is used for neutron calorimetry experiments, polarized ^{3}He development, precision measurements of neutron cross sections and for neutron dosimetry work.

A 0.89 nm monochromatic beam line, NG-6U, has been constructed for optimized ultracold neutron production and became operational in January 2002. It is based on a two stage potassium-intercalated graphite monochromator, with additional filters to reduce the $\lambda/2$ and $\lambda/3$ beam components. The reflectivity between 0.88 nm and 0.90 nm is (85.4 ± 0.5)%, yielding a capture fluence rate at 1 m from the crystal of 4.7×10^6 cm^{-2} s^{-1}. This beam line is currently dedicated to the UCN lifetime measurement.

During the past decade, the NIST reactor has been a very reliable source for cold neutrons. It is also very likely that future upgrades, such as adding guide tubes similar to those proposed at SNS, could increase the NG-6 fluence by over an order of magnitude, thus further extending its capabilities.

Facility Staff, Support, and User Program

The fundamental physics research program at the NCNR is carried out by eight scientific staff based in the NIST Neutron Interactions and Dosimetry Group. Currently the NG-6 fundamental neutron physics programs have 2.5 full time equivalent (FTE) staff members, the interferometry efforts, which include some nuclear physics research, consist of 1.5 FTEs, and the ^{3}He polarization program includes 1.1 FTEs. The operational budget is currently at $2.2 M per year. The bulk of the group's operation funding, $1.6 M, comes directly from NIST, while DOE provides $80 k for fundamental neutron physics and another $80 k for nuclear theory cross-section measurements. DOE Basic Energy Sciences provides another $350 k for the ^{3}He development work and other materials science projects. During presentations to the committee, the NIST group requested $420 k additional annual support for carrying out the fundamental neutron physics program. This additional support would provide $135 k for current staff (0.7 FTE), $135 k for a new NG-6 Instrument-Responsible Physicist, $100 k for engineering/technical support, and $50 k for supplies/equipment.

The fundamental neutron physics user community working at NIST has included staff and faculty from over twenty universities and national laboratories. The facility has been extremely successful in training students and future researchers in the field. In the past decade, thirteen PhD's have been awarded for research done primary at the NCNR beam lines and there are currently six students actively working on their Ph.D. dissertations. Since 1995 twenty-seven undergraduates and high-school students have participated in educational outreach programs. Half of the 16 postdoctoral fellows that have been closely associated with the NCNR based research efforts in the past decade now hold tenure track or tenured faculty positions, while another quarter hold positions at national laboratories.

Physics Program at NIST

The current set of experiments running on NG-6 includes the DOE funded emiT experiment – a search for the P-conserving, T-violating decay coefficient in neutron decay, the NSF funded UCN lifetime measurement on NG-6U, and on NG-6M an absolute calorimetry study supported by NIST and NSF that should reduce the Penning-trap lifetime measurement uncertainty.

The emiT experiment should be completed by the end of 2003, at which time several other experiments are proposed to run on the polychromatic beam. Potential future experiments include a second run of the neutron spin-rotation experiment to measure the parity non-conserving spin-rotation of cold neutrons in liquid helium. The spin rotation apparatus has been undergoing upgrades and should be ready in approximately one year. Other proposed future measurements include a new proposal to measure the electron-antineutrino correlation coefficient *a* in neutron decay, a radiative decay mode of the neutron measurement to detect and measure the radiative spectrum of the neutron for the first time, and a spin-proton asymmetry experiment using the existing Penning-trap lifetime apparatus to measure the spin-proton asymmetry in polarized neutron decay.

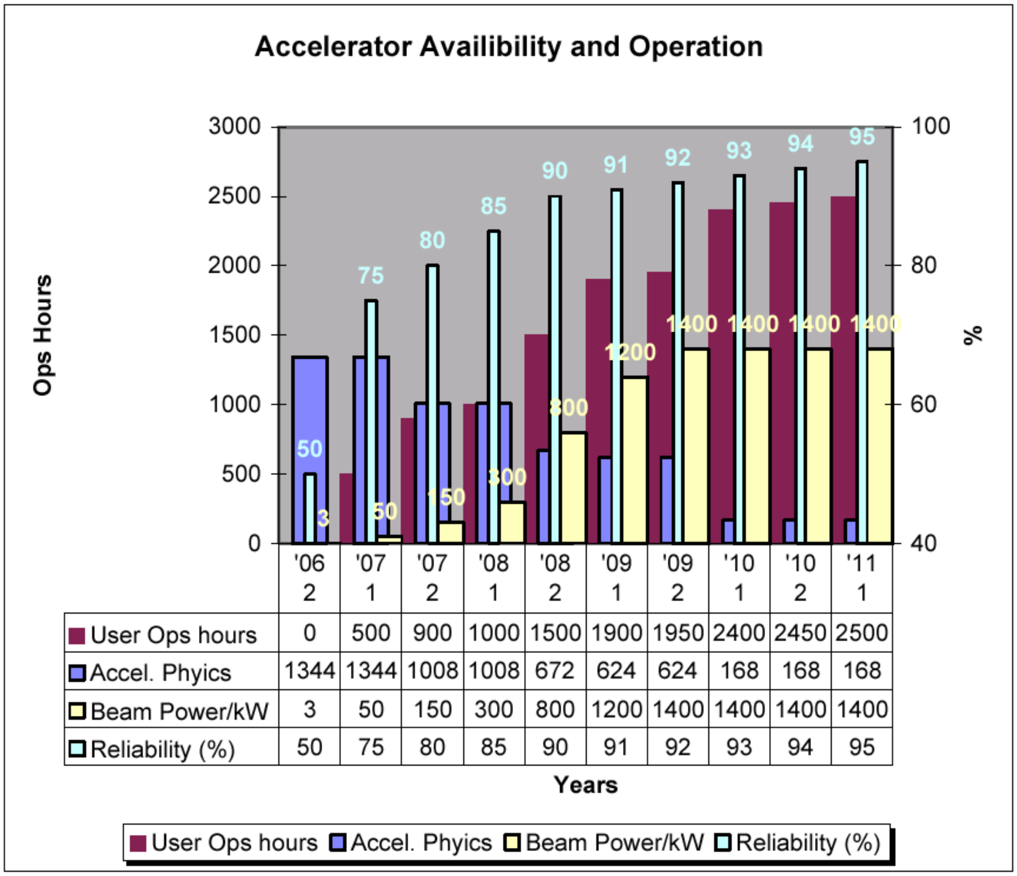
The UCN lifetime experiment on NG-6U expects to continue its current measurements using magnetically trapped neutrons and anticipates an upgrade to a deeper trap using a magnet procured from KEK. Although this beam line is currently dedicated to the UCN lifetime experiment, it could also provide an excellent facility for development and testing for the neutron EDM experiment. Future use of the NG-6M beam line will include further ^{3}He polarizer development work that will be required by future measurements of decay correlation experiments planned for SNS experiments. It is likely that other future SNS based experiments may also request developmental beam time at NIST while awaiting the commissioning of the SNS fundamental neutron physics facility.

On the NG-7 interferometry beam line, recent fundamental neutron physics measurements include precision coherent scattering length determinations of D_2 and H_2. Future plans include precision measurements of the scattering lengths of samples important for nuclear many body calculations such as ^{3}He gas.

4.3 The SNS

The SNS will be the most powerful pulsed, spallation neutron source for the foreseeable future. It is expected that the facility will produce the first beam in 2006 and begin providing user operations hours in 2007 at a level of 1400 hours per year and relatively low beam power as indicated in Fig. 4.1. The SNS is expected to be operating at essentially full potential by the end of 2009. By 2010 the facility is expected to operate at full power and high reliability for approximately 5000 hours per year. The fundamental neutron physics research program should be ready to take advantage of the SNS facility by the second half of 2008. The schedule in the beam line proposal will lead to commissioning of the beam line by mid 2008. In order to meet this time frame, work must begin on construction by early 2004.

The proposed fundamental neutron physics beam-line will be one of 24 beam-lines at the SNS facility. The beam-line and moderator choices are designed to maximize the total neutron fluence. The new beam-line will make use of a coupled, unpoisoned liquid hydrogen moderator, $m > 3.0$ supermirror guides, where possible, and the largest guide that can be fully illuminated by the moderator in order to achieve the highest possible cold neutron fluence. Background neutrons will be minimized by using supermirror benders to eliminate line-of-sight views of the source and a series of choppers to eliminate frame overlap. The $m = 3.5$ supermirrors are becoming commercially available. However, aluminum substrate guides must be used for the first 1.2 m to minimize heating of the supermirror. Preliminary results from tests of such guides at PSI indicate that the performance should be acceptable if the aluminum substrate can be adequately cooled. Because of its projected high brightness and fluence, the SNS cold beam line would be the source of choice in the U.S. for fundamental neutron experiments that make use of pulsed neutron beams.



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■ User Ops hours	0	500	900	1000	1500	1900	1950	2400	2450	2500
☐ Accel. Phyics	1344	1344	1008	1008	672	624	624	168	168	168
☐ Beam Power/kW	3	50	150	300	800	1200	1400	1400	1400	1400
☐ Reliability (%)	50	75	80	85	90	91	92	93	94	95

Figure 4.1. The projected SNS accelerator availability and operations data are from SNS document 102000000-TR0004-R00.

Two experimental areas are proposed for the SNS fundamental neutron physics program: a cold neutron beam line with an experimental station inside the SNS experimental hall at 18 m and a 0.89 nm beam-line and experimental area outside the SNS experimental hall at 50 m for UCN experiments. The 0.89 nm beam will be selected from the cold beam by a double-crystal monochromator so that both experimental areas may be operated simultaneously.

The UCN beam line depends on the performance of double-crystal monochromators. The stage-2 potassium intercalated crystals have been developed at NIST and successfully operated for relatively long-term, high-flux neutron exposures there. Although the 0.89 nm double-crystal monochromator has not been simulated, extrapolation from the performance at NIST gives reasonable confidence in the expected performance.

Because the UCN hall is located outside the SNS experimental hall, it can be isolated from seismic noise and vibrations more effectively. Experiments, such as the neutron EDM measurement, that are sensitive to acoustic and mechanical noise would benefit from the construction of a new hall. Anechoic panels installed in the shielding should help minimize acoustic noise. In addition, the new hall would be relatively far away from other experimental halls and would be less sensitive to stray electromagnetic fields from those halls. Such a new hall would likely be essential to measure the neutron EDM at the proposed precision.

There appear to be no major technical issues that would be considered high risk for the construction of the beam lines. ORNL has proposed that approximately \$1.5 M per year would be necessary for operation of the beam lines. This amount is likely to be necessary, especially in the early years of commissioning and experiment installation. The requested additional \$1.3M per year for optimal operations was not clearly justified.

4.4 Other Initiatives

The subcommittee heard a presentation on the LENS (Low Energy Neutron Source) project at Indiana University. This is a university-based pulsed cold neutron facility, in which a low-energy, high-intensity proton beam would be used to produce neutrons via Be(p,xn) reactions. The source, coupled to a cold (22 K) solid methane moderator, would yield a time-averaged cold neutron brightness between that of IPNS and LANSCE. A proposal for the accelerator, target, moderators, guides and two neutron scattering instruments, approximately \$10 M, was submitted to the MRI program in the NSF Materials Science Division; the proposal received preliminary approval in July.

Although its primary focus is materials science, LENS could contribute to the fundamental neutron physics program by serving as a test facility for new cold moderators to feed "superthermal" UCN moderators. No fundamental neutron physics experiments were proposed for LENS. The facility would be suitable for educating students at all levels from a variety of disciplines. The subcommittee believes that such a facility could play a valuable role in training the next generation of SNS users and researchers in fundamental neutron physics.

A proposal to build a UCN source at the NCSU PULSTAR reactor was presented to the subcommittee. The primary aims of the project are to establish a university-based UCN facility with a strong focus on nuclear physics applications for UCNs, to integrate the UCN facility into the undergraduate curriculum, and to involve the local nuclear physics groups at NCSU, the University of North Carolina, and Duke University in fundamental physics with cold and ultracold neutrons.

With the proposed solid ortho D_2 source and the reactor operating at 1 MW, calculations show the UCN flux and density to be competitive with other proposed facilities (UCN-A, Mainz, PSI). The major goals of the research program at the proposed facility are to measure the T-violating D coefficient in neutron decay, to serve as a test facility for the EDM experiment, and to perform UCN source development work. With improved UCN flux, a possible future program could include a search for $n-\bar{n}$ oscillations.

A university-based UCN facility would have several advantages. The accessibility of the source would be excellent, essentially available year-round and the reactor is operable by students. The proposal has a strong educational component. Local facilities are a powerful draw for graduate students, as well as for attracting undergraduates to the field.

5. International Perspectives

The research reactor at the ILL has been the premier facility in the world to provide intense neutron beams. For many years now two fully supported instrumental facilities there have been devoted exclusively to fundamental physics; *PF1* provides a cold neutron beam and *PF2* provides UCNs that can be switched at intervals of about 200 s between three different experiments. Typically the ongoing EDM experiment and one other experiment in fundamental physics use the UCN source. The stored UCN density in a stainless steel vessel available at the experiments is 30 /cm^3, about 1/3 that obtained at the LANL UCN facility. Recently *PF1* has been transferred to a new 4-times more intense cold neutron beam where it is called *PF1b*; see Table 4.1.

Paid-up membership of the ILL is required to propose and carry out experiments there – the overall cost of operating the ILL amounts to about $2 M per instrument facility per year, a useful figure to have in mind if negotiating membership. The US has not been a member of ILL. Consequently, European groups have dominated the field of fundamental physics with neutrons for the past several decades. The present best measurements of the neutron lifetime, the β decay correlation coefficient A and the limit on the neutron EDM are from experiments carried out at the ILL.

In addition to the ILL facility, PSI in Switzerland provides neutrons from a spallation source and a new research reactor is now set to begin operation in Munich, Germany. Two years ago, first beams were obtained from a cold neutron beam line at PSI. The repetition rate of the accelerator at PSI is such that the facility has characteristics that make it similar to a reactor rather than a traditional spallation source. Neutrons from different primary beam buckets overlap so that time of flight cannot be used to determine the neutron beam energy. Consequently its properties are shown compared to other continuous sources in Table 4.1. A UCN source is being designed for the PSI facility that is estimated to output about 3000 UCN/cm^3. A volume of 1000 liters will be filled with UCNs every 10 minutes from the source.

The new facilities at PSI and Munich, along with upgrades at ILL, will continue to provide the European community access to first-rate intense beams of cold and ultracold neutrons. Japan is now constructing a new spallation neutron source as part of the J-PARC project. The new facility will have a beam power of 1 MW and will begin operations at about the same time as the SNS. A program of experiments is now being developed for the facility but it is not clear at this time if the program will include measurements in fundamental physics.

The program in fundamental physics at ILL is focused on measuring the properties of the neutron and its decay. Measurements of the lifetime of the neutron continue to be improved. Recently a major effort has been devoted to lifetime measurements of UCNs trapped and stored in a bottle. This has provided the most accurate determination of the neutron lifetime to date, $\tau_n = 885.4 \pm 0.9 \pm 0.4$ s. The primary systematic effect that appears to limit the measurements is neutron capture on the walls of the bottle. New materials are being used to coat bottle surfaces in an attempt to reduce this effect. Plans are now being developed to store UCNs in magnetic traps in place of a material bottle for a new lifetime measurement that would be carried out at the Munich reactor.

Searches for a neutron EDM have been actively pursued at the ILL for many years. The present generation EDM experiment uses UCNs stored in a room temperature cell with a cohabiting ^{199}Hg magnetometer. The experiment, which has been carried out by a collaboration from the University of Sussex, the Rutherford Lab and ILL has set the best limit to date for the EDM. Their result is consistent with 0 with a 1σ uncertainty of 1.7×10^{-26} e cm. The group expects to reduce this uncertainty to 1.3×10^{-26} e cm by the end of 2004. Several new EDM projects are being developed in Europe using beam lines at ILL, PSI and Munich. An experiment has been endorsed by the PSI program committee to run on the new UCN line there when it becomes operational in 2006. The experiment is close to final approval. It is configured as a room temperature mu-metal shielded experiment using an in-line array of 8 three liter measurement cells along with neutron and cesium magnetometers. The experiment is projecting a 1σ sensitivity of about 1×10^{-27} e cm by 2007. Development of a new EDM experiment at the ILL has been underway for several years and a proposal is now in the final stages of approval. It is based on producing, manipulating and detecting UCNs in liquid ^{4}He at 0.5 K. The experiment will utilize a superconducting magnetic shield and neutron magnetometers. Squids will be used in the initial setup. The experiment will initially be run on the *PF1-old* cold beam line at the ILL, where a 1σ uncertainty of 1×10^{-27} e cm should be achievable by the end of 2006. It might then move to a 5 times more intense cold neutron beam where an ultimate 1σ sensitivity of 1×10^{-28} e cm is anticipated. Another experiment is in the early planning stages to run at the future UCN source at the new reactor in Munich. The preliminary design is for a room temperature experiment using ^{3}He magnetometers. Following a very different approach, a Russian team has proposed an experiment at the ILL using the interatomic electric fields in a quartz crystal to measure the neutron EDM. The ultimate sensitivity of this approach is hard to predict without carrying out some measurements to better understand systematic uncertainties.

A series of measurements have been carried out over the last two decades in Europe to determine the *A* correlation coefficient in neutron β decay. The most recent experiment, which claims the most precise result, $\lambda = -1.2739(19)$, does not agree with other measurements made during the past decade. When the new value for λ is coupled with the neutron lifetime, it results in a somewhat smaller value for V_{ud} than that obtained from $0^+ \to 0^+$ β decay.

Present plans call for about 500 days of beam time on the new cold beam line *PF1b* during 2004 - 2006. About 100 days will be devoted to a measurement of the time reversal violating *D* coefficient. The experiment was set up on an old beam line for initial testing and debugging and has now been moved to *PF1b* which provides a factor of 30 times more polarized neutron flux than was available for the last measurement of *D* at the ILL. Following this experiment, about 150 days will be devoted to a re-measurement of the *A* coefficient using a slightly modified version of the previous experiment (Perkeo II) to reduce background. Several other experiments, including new ones to measure correlation coefficients and one using a new technique for measuring the neutron EDM, will compete for the remaining time.

At PSI, a measurement is underway to determine the T-violating, parity-violating *R* correlation coefficient. The aim is to obtain a result with a 0.5% uncertainty. New correlation coefficient experiments are also likely to be proposed for the research reactor in Munich. At the present time, a group from Munich is working on a spectrometer to measure the spin independent *a* correlation coefficient.

Only a small program of measurements searching for *P* and *T* violating neutron interactions with matter has been carried out recently in Europe. A group from Heidelberg attempted to determine a parity-even photon asymmetry from polarized neutron capture on a polarized hydrogen target at ILL in the latter part of the ‘90’s in order to test strong interaction *NN* calculations. The experiment set an upper limit for the asymmetry that is several orders of magnitude larger than the theoretical prediction. Also measurements of neutron spin rotation through Lanthanum have been carried out in several institutions.

6. Subcommittee Findings and Recommendations

During the two site visits, the subcommittee was presented with a very compelling scientific program to be carried out over the next decade. Major experiments are now underway, new opportunities are being explored, and a new world-class facility will soon become available in the US. Clearly the potential exists in this subfield for great discoveries that will affect the development of a new SM. But fiscal realities will ultimately dictate the progress. Below we summarize our findings and give four recommendations for the future program. Then in the following section, we discuss how budget constraints will impact the program. The recommendations must, of course, be considered in the context of the budget scenarios that are presented in section 7.

Construction is nearly complete on two new experiments at LANL – a measurement of the neutron spin - electron correlation coefficient A in neutron β decay using a new UCN source and a measurement of the asymmetry in $\vec{n} + p \to d + \gamma$ with polarized cold neutrons. Both experiments are scheduled to take data during the 2003-2004 running period. The LANL group is to be congratulated on developing the new technology that has led to the UCN source and the new UCN-A experiment. According to preliminary tests, the UCN-A experiment should reach or exceed its designed sensitivity. Two proposed upgrades of the UCN-A spectrometer – adding a silicon detector array and recoil proton detection – would allow for additional measurements of correlation coefficients. These cost-effective upgrades should proceed if the spectrometer performs as designed.

Work has progressed on completing the construction of the $\vec{n} + p \to d + \gamma$ asymmetry experiment. The group is to be commended for their efforts to address a number of challenging technical issues. But several problems have led to loss of sensitivity relative to the initial goal. The full impact of these losses may not be known until the first set of measurements is complete. The subcommittee urges that initial tests and data collection be carried out for the asymmetry experiment during the next two running cycles at LANSCE and that the future of the experiment then be reevaluated.

NIST has operated an end station and beam line for experiments in basic nuclear physics for over a decade. Recently two additional beam lines have been commissioned. The NIST program continues to support first-rate fundamental neutron physics and provides an excellent training ground for the next generation of scientists in this field. The present program includes measurements of the neutron lifetime and the time-reversal violating coefficient, D, in neutron beta decay. A preliminary experiment to study neutron spin rotation in liquid helium has been completed and a next generation experiment is now being constructed. Several development projects aimed at improving measurements of neutron spin orientation are also underway.

! The US has an active program in fundamental physics with neutrons using cold and ultracold neutrons at LANSCE and NIST where measurements of neutron β decay and hadronic parity violation are underway. It is important to successfully complete the commissioning of the two major experiments that are poised to begin operation at LANL.

The subcommittee urges the groups in these experiments to focus their efforts on them. The subcommittee strongly recommends that the existing program at NIST continue.

A new experiment to measure the electric dipole moment of the neutron is being developed by a collaboration led by a group at LANL. The subcommittee viewed the discovery potential of this experiment to be the highest of those envisaged for the future fundamental neutron physics program. The present estimate of the EDM group suggests that a factor of 500 improvement in sensitivity can be gained over existing measurements. Realization of this goal – which would come in several stages – could produce the first non-zero measurement of the neutron EDM. Such a result would have a profound impact on our understanding of the electroweak and strong interactions and cosmology. To reach this level of sensitivity, the experiment requires the ultracold neutron flux predicted for the proposed UCN beam line at the SNS. The experiment, as presented to the subcommittee, has several technical issues that must be answered before a funding proposal can be submitted. Two competing experiments in Europe – one at ILL and the other at PSI – are in the final stages of funding approval. The new experiment proposed for operation at the ILL has an ultimate sensitivity goal that is about 4 times less than that proposed by the US EDM collaboration. But we do note that historically it has been very difficult to predict ultimate sensitivity goals in these types of measurements.

! The EDM experiment has the highest discovery potential of all proposed experiments. The subcommittee strongly supports it. We encourage the collaboration to address the technical issues surrounding this experiment and recommend that R&D funding be provided to accomplish this.

The nuclear physics community has voiced strong support for the development of intense cold and ultracold neutron beams for many years. The physics case for these beams remains compelling. And now we are in a position to capitalize on a major investment by the Basic Energy Sciences Division of the Department of Energy – the spallation neutron source which is under construction at Oak Ridge National Laboratory – to make these beams a reality. The SNS will be the brightest spallation source in the world when it becomes operational. At 1.4 MW of primary proton beam power, it will provide an unprecedented pulsed cold neutron beam capability. The intense cold beam will be ideal for measurements of hadronic parity violation with neutrons and for precision measurements of the decay of the neutron. The measurement of the neutron EDM is the primary experiment envisaged for a UCN beam at the SNS. Given the potential physics impact of the experiment, provision needs to be made to ensure that the UCN line can be built in the near future. The subcommittee strongly believes that access to beams from the SNS will be key to the future US program in this field.

! We recommend the construction of the cold beam line at the SNS and the program of measurements in fundamental neutron science that it can support. We further recommend that provision be made for the construction of an ultracold neutron beam line.

Realizing the full potential for the physics impact of this program will require resolution of various theoretical issues. For example, calculations of radiative corrections are needed in order to test the unitarity of the SM quark-mixing matrix using neutron-decay measurements. At present, there exists no model-independent, first principles calculation of these corrections, and the associated theoretical uncertainty in SM tests may be as large as the proposed experimental uncertainty. This problem can be addressed through a concerted future effort involving techniques in electroweak theory, effective field theory (EFT), and lattice QCD. Similarly, the implications for cosmology of future EDM constraints on non-SM CP violation remain to be delineated in a consistent and comprehensive manner. And the recent application of EFT to hadronic parity-violation has led to the need for a new program of few- and many-body calculations. At present, sufficient resources and manpower do not exist to address all of these issues in a timely manner. At least two senior theorists and four post-doctoral research associates are needed. Without additional resources devoted to theoretical efforts related to fundamental neutron physics, the impact of the experimental effort will not be maximized.

! Resources should be allocated or redirected to increase the size of the theoretical community associated with fundamental symmetries with effort directed to neutron physics. Such growth could occur through the creation of new senior theory positions at laboratories and at universities where there are strong experimental efforts, faculty bridge positions involving laboratories and universities, and post-doctoral positions in theory groups addressing issues relevant to the fundamental neutron physics program.

The subcommittee heard presentations about a possible national UCN facility at LANL and two university-based initiatives in neutron science. The concept of a national UCN source is now being developed by a LANL group but the project is at an early stage so little information is available about a future science program. One of the university initiatives, PULSTAR, is a proposed UCN source to be built at the NCSU research reactor. The project would establish a university-based UCN facility that would provide a strong focus on nuclear physics applications for UCNs, integrate the UCN facility into the undergraduate curriculum, and involve the local nuclear physics groups at NCSU, University of North Carolina, and Duke University in fundamental physics with cold and ultracold neutrons. The major science goal of a program based at PULSTAR is a measurement of the T-violating *D* coefficient in neutron decay. PULSTAR also could possibly serve as a test facility for the EDM experiment and UCN source development work. The subcommittee felt that the primary impact of PULSTAR would be in undergraduate and possibly graduate education. LENS is a neutron source to be built at Indiana University that would serve the condensed-matter and biology communities. Nuclear physics use of LENS would be limited to developing new source techniques such as testing new moderators for future cold neutron sources. Use of the LENS facility appears to be a cost effective way to carry out such development projects.

7. Funding Constraints and the Future Program

7.1 Overview

During the two site visits, a broad program in fundamental physics with neutrons was presented to the subcommittee covering essentially all of the science discussed above. With full funding of that program, the US community would be very competitive with our European colleagues. The capital equipment and operating budgets, projected through FY08, needed to support the full effort presented to the subcommittee, are shown in Figs. 7.1 and 7.2. No attempt to prioritize the requests or remove redundant experiments was done in what is shown in the figures. The capital equipment budget includes projects that would be funded by DOE and NSF

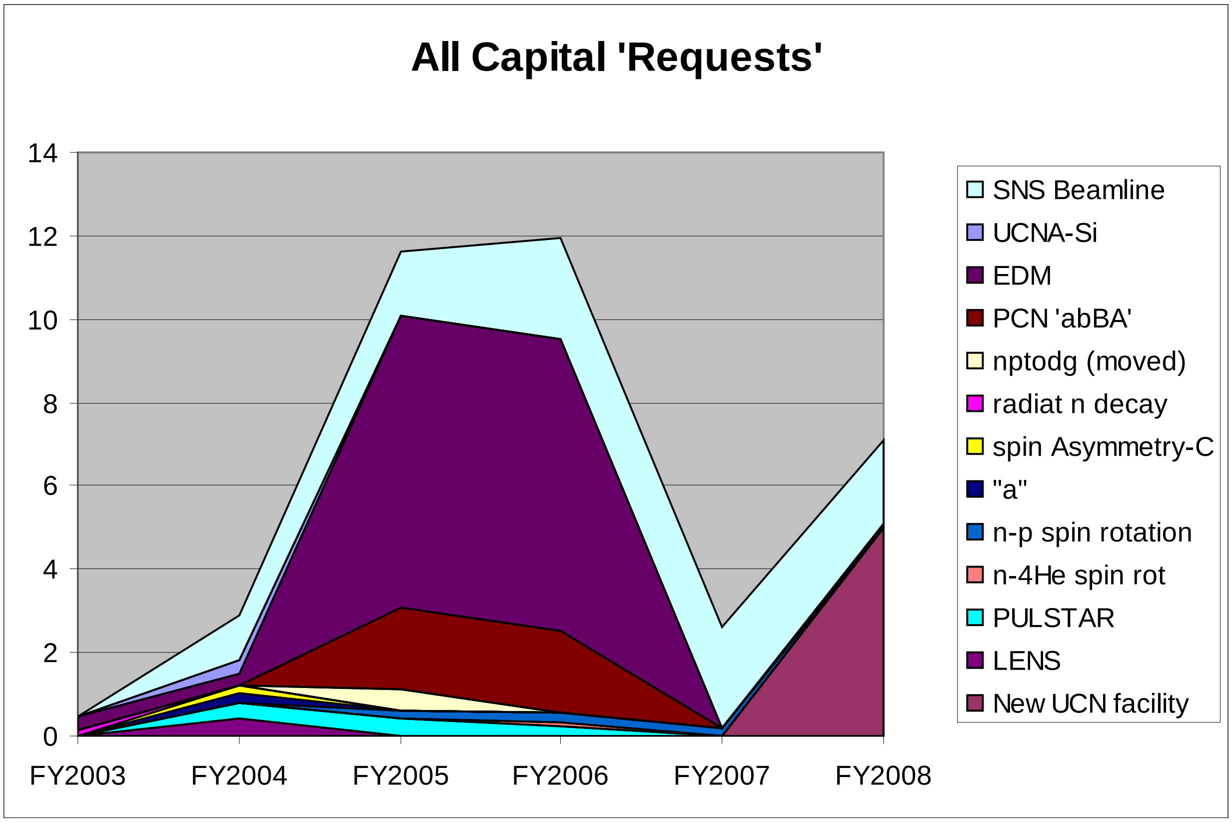

Figure 7.1. Funding needed to support the full program of fundamental nuclear physics with neutrons presented to the subcommittee. The vertical axis is in millions of dollars. The projects listed are: the SNS beamline; upgrade of UCN-A with Si detectors; the EDM experiment; a new correlation coefficient measurement initiated at LANSCE and then moved to the SNS; the $\vec{n} + p \rightarrow d + \gamma$ experiment moved to a reactor; five experiments planned at NIST including radiative neutron decay, proton spin asymmetry $C = A + B$ and the a coefficient in neutron β decay, and neutron spin rotation in H and He; a new UCN facility at a research reactor – PULSTAR; moderator tests at LENS; and a new UCN facility at LANL.

but the operating budget figures are just those for DOE supported efforts. The major equipment costs shown in Fig. 7.1 are those needed to support construction of the EDM experiment, the SNS beam line, and a new correlation coefficient experiment (*abBA*). In the out years, funding would commence for construction of a new UCN facility. The operations budget would support the ongoing program and new construction. It is clear that full program funding would require a major increase in support relative to the FY03 funding levels.

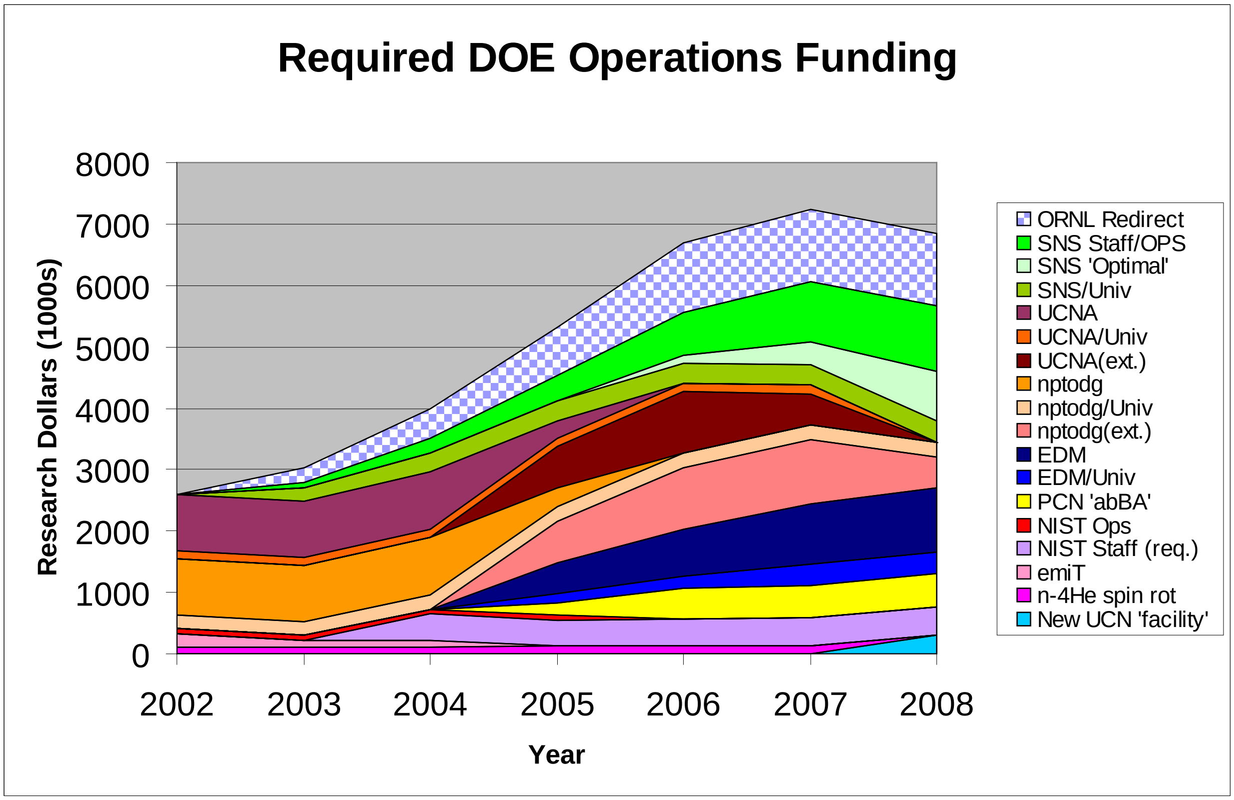

Figure 7.2. DOE operations and research support required to fund the full program of fundamental nuclear physics with neutrons presented to the subcommittee. The categories listed are: redirected research at ORNL; minimal SNS operations support; additional SNS operations support; university-based SNS research; the UCN-A program at LANL, universities, and extensions; the $\vec{n} + p \rightarrow d + \gamma$ program at LANL, universities and moved to a new location; the EDM program at LANL and universities; a new correlation coefficient experiment; present NIST operations support; requested future NIST operations support; the emiT and neutron spin rotation in He programs at NIST; and a new UCN facility at LANL. Separate funding from NSF would also be required.

7.2 Funding Scenarios

As part of our charge, the subcommittee was asked to address what future program could be carried out in fundamental nuclear physics with neutrons at a constant level of effort based on the FY04 DOE Nuclear Physics Congressional Request level, and recommend priorities for further investment with additional funds beyond this level. The pertinent DOE FY04 operations and research budget request is \$2.5 M and the capital equipment request is \$0.5 M. Future capital equipment requests are scheduled to increase to \$2 M by FY06. The subcommittee assumed that funding from NSF and other sources would remain approximately constant at the projected FY04 level. A full commitment of DOE capital equipment funds for this program through FY07 is sufficient to construct the SNS cold beam line, but with little remaining. ORNL will require funds to operate the beam line thus reducing support available for *research* at a constant level of effort. This loss will be partly offset since ORNL will redirect existing research funding into fundamental nuclear physics with neutrons. Nevertheless, level funding and no increase in capital equipment monies will severely restrict the future program.

The experiment deemed to have the highest physics impact by the subcommittee, a new measurement of the neutron EDM, simply cannot be done within the baseline budget, even with reasonable (20%) increases. Present cost estimates for the EDM experiment construction are approximately \$14 M. Additionally, the ultimate sensitivity requires a new UCN beam line at the SNS, implying an additional investment at the SNS of about \$3 M beyond the construction of the cold line which will cost about \$6 M. Thus to construct the new equipment for the experiment and ensure the beam line to run it will require resources beyond those available to the present program. The subcommittee places very high priority on this experiment and stresses that discovering a non-zero EDM, or limiting its value to the level indicated as the 2nd stage sensitivity in Table 3.1, will have a major impact in nuclear and particle physics and cosmology. If R&D efforts verify feasibility, new funding should be found outside the core program in fundamental physics with neutrons to construct and operate the EDM experiment.

The Lujan center at LANL has provided an important spallation neutron source facility for the US fundamental neutron physics program. However, the significant improvement in cold neutron beam performance promised at the SNS leads naturally to the desire to seize the opportunity to move the program there. The subcommittee deems this move to be of very high importance for the growth and competitiveness of the program in the long run.

NIST provides a facility that is complementary to the spallation sources. Furthermore it traditionally supports small university-based projects. The subcommittee recognizes that a future program at NIST is important. The reactor operates much of the year which makes it ideal to carry out projects that are based on developing totally new techniques to carry out measurements. At present, DOE Nuclear Science provides about \$80 k/year to support operations at NIST. During the NIST presentation, a request was made to increase operations support to \$500 k/year. The subcommittee foresees the need for both reactor and pulsed neutron beams in the future and recommends that DOE and NSF Nuclear Physics work with the NIST management to maintain a program at the NIST reactor. However, the subcommittee does not have sufficient information to recommend specific levels of support and recognizes that funding constraints and proposal pressure will ultimately dictate the level of effort in the long term.

With these considerations, the subcommittee has formulated the following funding scenarios.

Scenario 1: Funding at the base program level

The EDM measurement is dropped. The SNS cold beam line is built over a time period dictated solely by the available funding. The current experimental program at LANL is significantly reduced. The subcommittee recommends, based on the near term physics impact and present experimental status, that priority be given to complete the UCN-A experiment and its follow up measurements. Consequently the $\vec{n} + p \rightarrow d + \gamma$ experiment is delayed and becomes the first effort at the SNS. This would be followed by other hadronic PV measurements that would move from NIST. Money for new experiments at the SNS, e.g. new correlations experiments, or new hadronic PV experiments, is delayed with significant funding available only after beam line construction is completed. (The subcommittee expects, of course, that the actual order in which experiments run at the SNS will be determined by a future program advisory committee for the facility.)

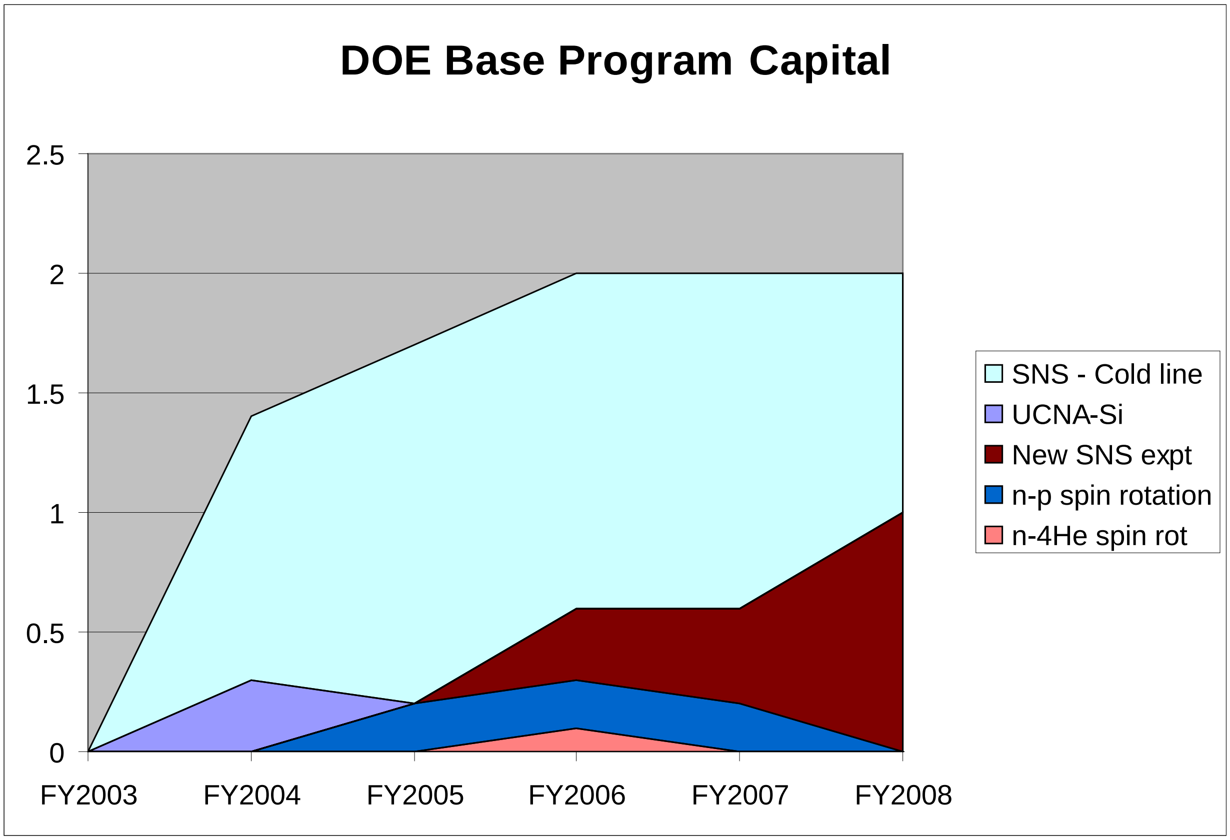

Figure 7.3. Capital equipment expenditures that fit within the DOE base program. The entries are described in the figure caption for Fig. 7.1.

The capital equipment and operating support funding profiles for this scenario are shown in Figs. 7.3 and 7.4. Redirection of research funds at ORNL partly offsets the funds that are needed to support operations for the SNS beam line but an overall loss in *research* capability will occur. Thus it will not be possible to simultaneously proceed with the construction of the cold beam line at the SNS and carry out the present program of measurements. Nevertheless, the subcommittee recommends that priority be given to the SNS beam line as it is critical for the future program for this field. With the elimination of the EDM experiment, this scenario would leave the US effort far behind that piece of the program in Europe, but it will provide facilities for the important series of hadronic PV measurements which could then be followed by new correlations experiments. Thus part of the compelling scientific program will proceed.

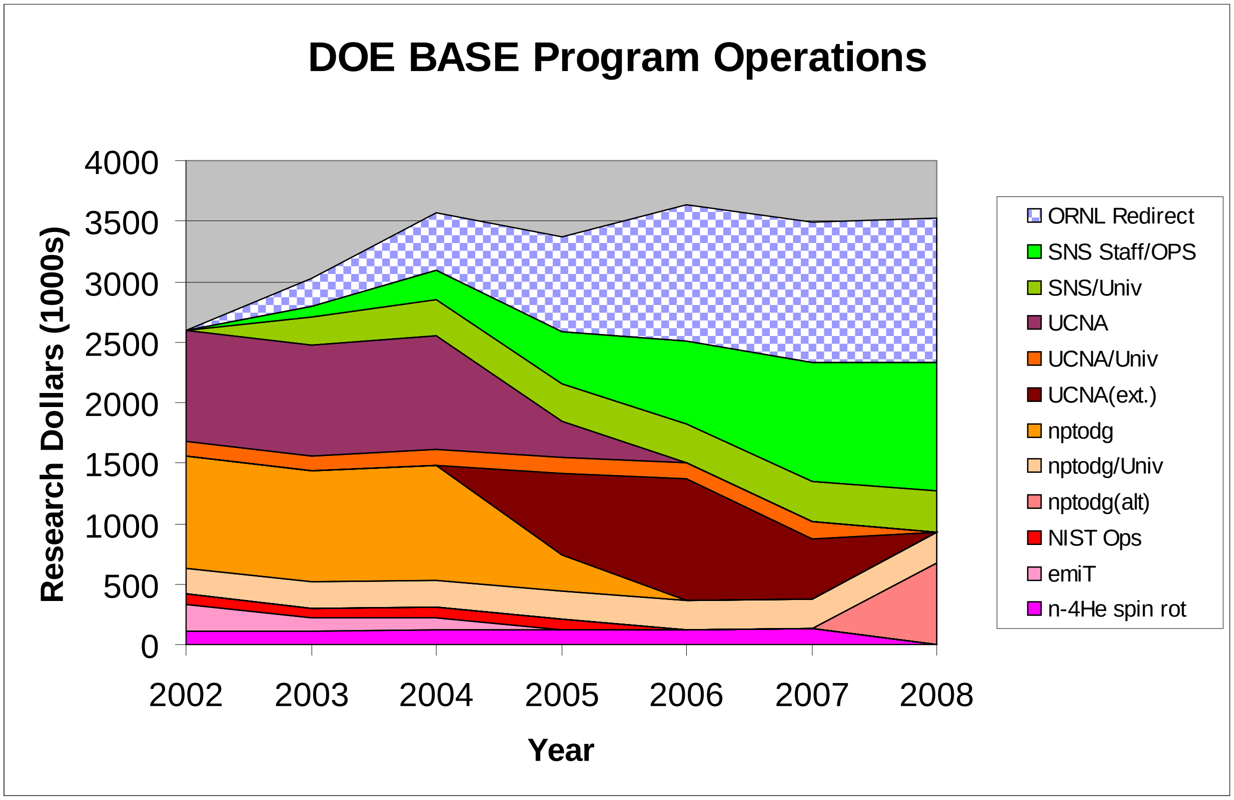

Figure 7.4. Operations and research funding that fits within the DOE base program. The entries are described in the figure caption for Fig. 7.2.

Scenario 2: Funding at the base program level and additional funding for the EDM experiment

This scenario would provide for the top priority experiment to be carried out. But the remaining program would have the same restrictions as shown in *scenario 1*. The staging of the EDM experiment with initial running at LANSCE followed by a move to the SNS, as presently proposed, would depend on the level of support available and the status of the beam line at LANSCE.

This scenario assumes that the R&D effort for the EDM experiment is successful and that a proposal from the collaboration receives strong positive reviews. Addition of the EDM experiment would greatly strengthen the program envisioned for the new SNS beam line and help close the gap between efforts in this field in the US and Europe.

Scenario 3: Increase in base program level by 20% ($500 k increase for *research* and $400 k in capital equipment) but no funding for the EDM experiment

If either the R&D for the EDM experiment is not successful or monies for the project cannot be found, additional funding for the base program would provide much needed support allowing operations funding for the new SNS beam line to begin without severely impacting the existing program. This additional support would allow continued funding for the $\vec{n} + p \rightarrow d + \gamma$ experiment at LANL without the delays imposed under *scenario 1*. Construction of the cold beam line at the SNS proceeds expeditiously. The NIST program continues and is provided with appropriate support to ensure efficient use of its facilities. This funding profile would provide sufficient manpower to carry out the full set of parity violation experiments that are needed to constrain the model parameters and to simultaneously begin developing a new generation decay correlation experiment.

Scenario 4: Increase in base program level by 20% and additional funding for EDM

This combines the positive features of scenarios 2 and 3. Here funds are available for the EDM experiment to evolve in two stages, as proposed. Initially, it is constructed and run at LANL (subject to a demonstrated adequate flux of neutrons). Assuming success, the UCN beam line at SNS is completed and the EDM measurement is moved to the SNS for stage 2.

Theory support

The four funding scenarios above are directed toward the experimental program in fundamental physics with neutrons. But additional theory support, as indicated by the fourth recommendation from the subcommittee, will also be needed as the program progresses. This will require new or redirected funding. Depending upon the nature of the senior positions, the cost can be expected to fall between $250 k and $500 k per year.

7.3 Funding Details

The scenarios outlined above have a number of assumptions built into them. Chief among them is the construction of the SNS beam line. But this will entail a major change in the operations and research funding for the field. In FY03, nearly all of the $2.5 M DOE funding for operations and research goes to support *research*. ORNL will require new funds to *operate* the new beam line; beginning in FY04 with about $0.25 M, the minimal requested level of funding ramps up to $1.5 M by the start of cold beam line operations (FY09). An additional $1.3 M/yr of new funding will be needed, according to ORNL, to provide optimal support at the new facility in the out years. The subcommittee did not have sufficient information to carry out a detailed operations review for the SNS beam line but it acknowledges the need for operation support. Consequently we assumed that the minimum requested amount would be provided for *operations*, with a concomitant reduction in DOE *research* funding. ORNL will redirect part of its existing program (approximately $1.2 M by FY09) to focus on SNS research activities. These research funds, which will be new to the program in fundamental physics with neutrons, will help offset the reduction incurred by supporting operations. The subcommittee concluded that without this redirection of effort, a program at the SNS could not happen at the existing budget level. Even with it, there appears to be a substantial loss in *research* funds in the program for the out years (approximately $0.4 M) due to the conversion of *research* funds into monies to support *operations*. Indeed much of the operations and research funding for fundamental physics with neutrons would be centered at ORNL by FY07 according to *scenario 1*. This could cause severe problems for other strong research groups in the field. The subcommittee is concerned that such a shift in funding would not lead to efficient use of the new beam line and could represent a poor investment by the community. However, the alternative of not proceeding with the construction of the SNS beam line will surely result in an extremely limited future for this important field.

A. Charge to NSAC

U.S. Department of Energy
and the
National Science Foundation

Professor Richard F. Casten
Chairman
DOE/NSF Nuclear Science Advisory Committee
Wright Nuclear Structure Laboratory
Yale University
New Haven, CT 06520

Dear Professor Casten:

With this letter the National Science Foundation (NSF) and Department of Energy (DOE) request that the Nuclear Science Advisory Committee (NSAC) provide guidance beyond its recommendations in the most recent Long Range Plan with respect to three specific issues of interest to the agencies.

(1) NSAC is asked to do an assessment of how the present NSF and DOE educational investments relevant to nuclear science are being made and to identify key strategies for preparing future generations of nuclear physicists and chemists.

Education of young scientists is integral to any vision of the future of the scientific field and the nation's nuclear-related activities. It is an important responsibility for both agencies. A substantial fraction of the agencies' research funds is used for support of students at the undergraduate and graduate levels and junior scientists at the postdoctoral level. It is important that these investments be made in an optimal way. Your assessment should take into account such factors as: the necessary qualifications and skills of nuclear scientists and their roles in the public and private sectors; the annual number of Ph.D. degrees presently awarded; the number projected as needed in the future to maintain a world-leadership role in fundamental research and also to meet the nation’s needs in applied areas such as nuclear medicine and national security; and the present and projected demographics of nuclear scientists, including the participation of women and under-represented minorities.

Your report should document the status and effectiveness of the present educational activities, articulate the projected need for trained nuclear scientists, identify strategies for meeting these needs, and recommend possible improvements or changes in NSF and DOE practices. Your report should also identify ways in which the nuclear science community can leverage its capabilities to address areas of national need regarding K-12 education and public outreach. We request that an interim report be submitted by September 2003 and a written report responsive to this charge be provided by November 2003.

(2) NSAC is asked to review and evaluate current NSF and DOE supported efforts in nuclear theory and identify strategic plans to ensure a strong U.S. nuclear theory program under various funding scenarios.

Among the opportunities and priorities identified in the 2002 NSAC Long Range Plan is an enhanced effort in nuclear theory and a large-scale computing initiative. Further guidance is requested at this time of how available resources might be targeted to ensure that the needed theoretical underpinnings are developed to realize the scientific opportunities identified by the community.

Your report should document your evaluation of the present national program in theoretical nuclear physics and its effectiveness in achieving results in the science areas highlighted in the recent 2002 Long Range Plan. It should identify the scientific needs and compelling opportunities for nuclear theory in the coming decade in the context of the present national nuclear theory effort, and what the priorities should be to meet these needs, including the development of a diverse highly trained technological workforce.

For both the DOE and NSF programs your report should provide advice on an optimum nuclear theory program under funding scenarios of i) a constant level effort at the FY2004 Nuclear Physics Congressional Requests and ii) with the increases recommended in the recent NSAC long range plan. For these funding scenarios the priorities, impacts and benefits of the various activities should be clearly articulated in the framework of a strategic plan. Your assessment should take into account the differences in the programs of the two agencies, as well as the unique roles of university investigators, the DOE national laboratories, and the Institute for Nuclear Theory. We request that an interim report be submitted by September 2003 and a written report responsive to this charge be provided by November 2003.

(3) NSAC is requested to review and evaluate the current and proposed scientific capabilities for fundamental nuclear physics with neutrons and make recommendations of priorities consistent with projected resources.

The recent NSAC Long-Range Plan identified and recommended pursuit of promising new initiatives in fundamental physics with neutrons. Further guidance is requested at this time in the implementation of this recommendation. It is important that the available resources are directed to optimize investments by NSF and DOE for a strong national research program in this scientific area for the coming decade.

Your report should identify the most compelling scientific opportunities, and the infrastructure and effort required to address them. Your assessment should be placed in the context of scientific efforts and capabilities in the United States and elsewhere. It should establish priorities for these opportunities with constant level of effort at the FY 2004 DOE Nuclear Physics Congressional Request level, and recommend priorities for further investment with additional funds beyond this level. In dealing with the proposed activities at the various funding levels, guidance regarding the appropriate mix of facility operations, research, investments in instrumentation and R&D to optimally exploit these opportunities should be provided. We request that an interim report be submitted by June 1, 2003 and a written report responsive to this charge be provided by September 2003.

Thank you very much in advance for your efforts on these important issues.

Sincerely,

John B. Hunt	Raymond L. Orbach
Acting Assistant Director	Director
Directorate for Mathematical and Physical Sciences	Office of Science
National Science Foundation	Department of Energy

Bcc:
Bradley D. Keister, NSF
DOE SC-20

B. Charge to Subcommittee

From: Richard F. Casten <rick@riviera.physics.yale.edu>

Subject: NSAC subcommittee on fundamental nuclear physics with neutrons

Dear Bob,

As you know, Ray Orbach, Director of the Office of Science at DOE, and John Hunt, Acting Assistant Director for the Division of Mathematical and Physical Sciences at the NSF, have charged NSAC to review and evaluate the current and proposed scientific capabilities for fundamental nuclear physics with neutrons and to make recommendations of priorities consistent with projected resources. The purpose of this review is to enable DOE and NSF to optimize their investments in this area in the next years.

I am writing to formally ask you to serve as the Chair of an NSAC subcommittee to consider this charge and to report back to NSAC. I have previously forwarded to you the charge letter. The work of this subcommittee is extremely important since this is an active and important area of research where there are significant issues of how best to proceed.

As you know, the timescale is very short since the agencies have requested an interim report by June 1, 2003 and a written report by September, 2003. I would ask you to present the findings of your subcommittee to NSAC so that that body can discuss them and decide on transmission to the agencies. In order for NSAC to make an informed assessment, it would be useful if your interim report could be distributed to the NSAC membership a week before the NSAC meeting. The date of the NSAC meeting has not yet been finally decided but it clearly will be before the end of May. Likely dates are in the range May 28-30, 2003.

I realize that this imposes an extra burden on you, especially in light of the highly compressed timescale, and I just want to express in advance my real appreciation to you that you have agreed to take on this responsibility. I will be available to help you in any way I can and will attend the subcommittee meetings in an ex officio capacity.

Best regards,

Rick Casten
Chair, NSAC

C. Subcommittee Membership

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jfw@dirac.phys.washington.edu

D. Meeting Agendas

LANL
Thursday, April 17

Morning Badging of visitors
Tour of facilities
12:00 - 1:00 Catered lunch provided for committee (Executive Committee closed session for about 15 minutes)
13:00 – 15:00 UCN - Area B plans/user facility
15:00 – 16:00 np → d gamma
16:00 - 16:15 Break
16:15 - 17:15 Neutron beta decay
17:15 - 19:15 EDM
Working dinner for committee

Friday, April 18
8:00 - 8:30 Executive Committee
8:30 - 9:00 Plans for UCN at NCSU
9:00 - 9:30 Neutron program at IU
9:30 - 10:30 LANCSE
operations, funding outlook, management interactions, . . .
10:30 – 12:00 Executive session

ORNL
Wednesday, April 23

SNS session
8:00 – 8:15 Executive Session
8:15 – 8:30 Agency Introduction
8:30 – 8:45 Welcome, Bill Madia, Director, ORNL
8:45 – 9:15 The SNS, Thom Mason, Associate Director for the SNS
9:15 – 9:45 Neutron Science at ORNL, Jim Roberto, Associate Director for Physical Sciences
9:45 – 10:05 Neutron Nuclear Physics at ORNL, Glenn Young
10:05 – 10:30 Break
10:30 – 10:45 The Fundamental Neutron Physics Instrument Development Team, Mike Snow
10:45 – 11:30 The The Fundamental Neutron Physics Beam Line at the SNS, Geoff Greene
11:30 – 12:00 The SNS beamline construction project, Vince Cianciolo
12:00 – 13:00 Lunch- Executive Session
13:00 – 13:20 The Neutron Electric Dipole Moment, Martin Cooper
13:20 – 13:40 Overview - opportunities in hadronic weakinteractions with neutrons, Mike Snow
13:40 – 14:00 PNC spin rotation at SNS: D. Markoff

14:00 – 14:20 Break
14:20 – 14:40 Overview of opportunities in neutron decay, D. Pocanic
14:40 – 15:00 Neutron Decay correlation coefficient measurements, D. Bowman
15:00 – 15:20 Measurement of the Neutron lifetime, J. Doyle/P. Huffman

NIST session
16:00 – 16:15 Accomplishments and Support David Gilliam
16:15 – 16:55 Fund. Phys. Facilities Overview/Tech. Capabilities Paul Huffman
16:55 – 17:15 Beam Lifetime Scott Dewey
17:15 – 17:35 emiT Pieter Mumm
17:35 – 17:55 “a” Fred Wietfeldt
18:00 – 19:00 Executive Session

Thursday, April 24
8:30 – 8:50 NCNR Overview Pat Gallagher
8:50 – 9:10 NIOF facility Muhammad Arif
9:10 – 9:25 Neutron Flux Mike Snow
9:25 – 9:40 ^{3}He Tom Gentile
9:40 – 9:55 Radiative Decay Jeff Nico
9:55 – 10:10 Proton Asymmetry Gordon Jones
10:10 – 10:25 Precision Polarimetry Tim Chupp
10:30 – 12:30 Executive Session