# REPORT TO THE NUCLEAR SCIENCE ADVISORY COMMITTEE

## *Submitted by the Subcommittee on Fundamental Physics with Neutrons*

***DECEMBER 1, 2011***

# Executive Summary

In December 2010, DoE and NSF charged NSAC to review and evaluate the research program, capabilities and opportunities for fundamental nuclear physics with neutrons. A 10-member subcommittee was formed by NSAC to carry out the charge. The subcommittee received community input in two open meetings, and held a series of teleconferences and one final closed meeting. The subcommittee presented its principal recommendations, findings and scientific priorities to NSAC in the form of an Interim Report, at the NSAC meeting in June 2011. This document is the final report of the subcommittee.

Fundamental neutron science forms an integral part of the nuclear physics enterprise, focusing on a deeper understanding of the underlying symmetries that govern our universe, and on semi-leptonic and hadronic weak interactions of nucleons. The US neutron science effort continues to be world-class, with searches for the neutron electric dipole moment and measurements of the neutron lifetime, radiative decay, beta decay correlation coefficients, hadronic parity violation, and interferometry. The US neutron science community carries out its program predominantly at three US facilities: the National Institute for Standards and Technology (NIST), Oak Ridge National Laboratory (ORNL) and Los Alamos National Laboratory (LANL).

The subcommittee heard presentations of all initiatives in the ongoing program, and of future directions driving the subfield. Many excellent projects were presented.

The principal *scientific* priorities found by the subcommittee, ranked in descending order, are:

I. The search for a neutron electric dipole moment with the nEDM experiment.
II. Continuation of the UCNA experiment to obtain improved precision on $\boldsymbol{\lambda}$, the ratio of the weak axial-vector to vector coupling constants of the neutron.
III. Completion of the NPDGamma experiment to obtain a precision measurement of the weak isovector nucleon-nucleon-pion coupling constant.
IV. Investment in the Nab apparatus with the main goal to determine $\boldsymbol{\lambda}$ to unprecedented precision, using a complementary observable to that of UCNA.
V. Continuation of the NIST experiment to perform the most precise cold beam-based measurement of the neutron lifetime.

The findings and recommendations of the subcommittee are described in detail in the main document. We present here a summary of them according to sub-area: nEDM experiment, hadronic parity violation, neutron decay correlations, and neutron lifetime. Note that the numbered recommendations below *do not* represent a rank-ordering.

The subcommittee finds that the scientific motivation for EDM searches remains as compelling as ever. In particular, a measurement with sensitivity at the anticipated reach of the US nEDM experiment ($\sim 4\times10^{-28}$ e-cm) would have a profound impact on nuclear physics, particle physics and cosmology, even in the event of a negative result. The US nEDM project is the only technical concept among various worldwide efforts that is explicitly proposed with capabilities to reach this level of sensitivity.

The nEDM collaboration has already resolved many important technical challenges and developed a first-pass engineering design of the apparatus. However, significant further R&D is needed on several issues, such as the HV studies, electric field monitoring, background from irradiation of the electrode coating, and the scintillation photoelectron yield. The subcommittee makes the following five recommendations for the nEDM project:
*1) We recommend that the nEDM collaboration immediately focus the bulk of its efforts on a well-structured and strategically targeted R&D plan to address the outstanding technical issues.*
*2) We recommend that ORNL and Los Alamos National Laboratory (LANL) jointly establish an external standing Technical Review Committee (TRC) to review the R&D progress and to report periodically to the management of both institutions.*
*3) We recommend that long-lead-time procurements be contingent upon resolution of the major outstanding technical issues in the measurement technique.*
*4) We recommend that the agencies provide continued support for a period of two years given implementation of the aforementioned recommendations.*
*5) We recommend, in the event that major outstanding R&D issues remain unresolved after two years, that consideration be given to discontinuing the Major Item of Equipment (MIE) Project and re-evaluating the US strategy for achieving a precise neutron EDM measurement.*

Measurements of parity-violating interactions of neutrons with few-body systems provide fundamentally important and unique insight into nucleon dynamics, as the only practical tool for the study of the strangeness-conserving hadronic weak interaction among light quarks. Precision measurements of neutron beta decay parameters are an integral part of a comprehensive strategy to test electroweak interactions. The subcommittee makes three recommendations covering these topics:
*6) We recommend strong support for the NPDGamma experiment as the highest priority measurement in hadronic parity-violation, and urge that every effort be made to reach the design goal, an asymmetry determination of one part in $10^8$.*
*7) We recommend continued support for the UCNA experiment at LANL to improve the measurement precision of the A-coefficient by exploring a cost-effective and expeditious path to the original design sensitivity of 0.2%. We further recommend parallel R&D to develop the experiment to measure the a-coefficient with the Nab spectrometer, with a sensitivity of 0.1%.*

*8) We recommend that high priority be given to acquiring new data with the cold beam-based lifetime measurement at the National Institute for Standards and Technology (NIST), following its planned improvements.*

The principal US experimental initiatives provide excellent environments for technical innovations and for training of the next generation of scientists. However, we find that coordination of scientific effort and utilization of resources available in this area are not optimal at present. The subcommittee's final recommendation is:
*9) We recommend that consideration be given to establishing a standing committee to review and prioritize various initiatives in US fundamental neutron science.*

We estimate that the five high priority initiatives enumerated above might be accommodated within a scenario of funding at constant level of effort, exclusive of MIE construction funding, though moderate additional funding may be required, as elaborated in the main document. We find that the workforce for fundamental neutron science consists of about 140 researchers, with a roughly three-way split between (a) university faculty, (b) research scientists & postdoctoral researchers and (c) graduate students, which is sufficient to carry out the highest priority initiatives.

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## Introduction

In December 2010, the Department of Energy (DoE) and the National Science Foundation (NSF) charged the Nuclear Science Advisory Committee (NSAC) to review and to evaluate the current and proposed research program, scientific capabilities and opportunities for fundamental nuclear physics with neutrons, and to make recommendations of priorities consistent with projected resources and funding constraints. The original charge letter is reproduced in Appendix A.

In response, NSAC authorized the formation of a subcommittee in January 2011 consisting of eight experimentalists, including an international representative, and two theorists with expertise in the broader subfield of fundamental symmetries in nuclear physics. The subcommittee membership is given in Appendix B. The subcommittee began deliberating in February and devised a plan to review the ongoing projects and future initiatives proposed by members of the subfield.

The bulk of the fact-finding was achieved in two open meetings in April. The first meeting focused on the nEDM project and the second meeting covered the full complement of projects on measurements of the neutron lifetime, radiative decay, beta decay correlation coefficients, hadronic parity violation, and neutron interferometry. With this collection of projects, US fundamental neutron science has maintained a world-class program. Tim Hallman (Associate Director for the DoE Office of Nuclear Physics) and Brad Keister (Program Officer, NSF Nuclear Physics Program) provided the subcommittee with an overview of the neutron science program in the context of the full nuclear physics program.

Throughout the process, the subcommittee had extensive discussions in periodic teleconferences, and arrived at scientific priorities and primary recommendations at a final closed meeting in early June. Representatives from DoE and NSF were present at every face-to-face meeting and teleconference of the subcommittee. The results of the deliberations were presented to NSAC in the form of an Interim Report at the NSAC meeting in June, 2011.

In the following, we present the scientific motivation behind the principal initiatives, describe the ongoing program and the facilities in which they are carried out, and present our detailed findings and recommendations, accompanied by justifications where appropriate. We conclude with comments on manpower and resources.

## Scientific Overview

Testing the electroweak interactions of hadrons with progressively higher sensitivity, thereby gaining insights into the symmetries that govern our universe, and obtaining a quantitative understanding of weak interactions among nucleons, are both central to the nuclear physics enterprise. It has long been recognized that precision measurements of the interactions of the neutron, the simplest unstable nucleus, is particularly suited to pursuing these topics. We provide the scientific overview of the principal studies with neutrons in four broad categories.

### The Neutron Electric Dipole Moment

Starting with the pioneering experiment of Smith, Purcell and Ramsey, the search for the permanent electric dipole moment (EDM) of the neutron has provided one of our most important tests of the parity and time-reversal properties of fundamental interactions. Over the course of more than five decades, the sensitivity of neutron EDM searches has improved by over six orders of magnitude. The null results at these increasing levels of sensitivity have placed severe constraints on possible sources of T-violation within the Standard Model (SM) and beyond it (BSM).

These constraints continue to have far-reaching implications, not only for fundamental interactions, but also for cosmology. In the SM, CP-violation can arise through the known "Cabibbo-Kobayashi-Maskawa (CKM) phase" within the quark mass matrix as well as through the "$\theta$-parameter" in the QCD Lagrangian, whose value is not known but tightly constrained by existing neutron (and atomic) EDM measurements. The EDM limit on $\theta$ ($<10^{-10}$) contrasts with the naive expectation that coefficients in the QCD Langrangian should be of order unity. This limit has motivated extensions of the SM in which new symmetries are imposed to keep $\theta$ small, as was done by Peccei and Quinn. The spontaneous breaking of the Peccei-Quinn symmetry produces a Goldstone boson, the axion, that is a viable candidate for the cold dark matter that pervades our universe. Thus, the discovery of a neutron EDM in the next generation of searches would not only require new sources of CP-violation beyond the CKM phase, such as a nonzero $\theta$, but could also have important implications for direct dark matter searches.

Many new mechanisms for CP-violation arise in extensions of the SM, and cosmological arguments make it very likely that some of these mechanisms operate in nature. As first observed by Sakharov over 40 years ago, CP-violation is one of the requirements for generating the small baryon number asymmetry we observe in our universe. Since the CP-violation associated with the CKM matrix appears to be too weak to account for the size of the asymmetry, some new BSM source is indicated. EDM searches, B-meson decays, and tests of leptonic CP-violation in long-baseline neutrino physics are the key tools for finding the needed new physics. In the case of supersymmetric electroweak baryogenesis, for example, the ultimate sensitivity of the nEDM experiment is near the level needed to conclusively test this scenario for the minimal model.

More generally, BSM CP-violation can appear through a number of low-energy effective interactions having their ultimate origin in an as yet unknown high-energy theory. Consequently, a comprehensive strategy involving searches for the neutron, electron, and atomic EDMs and studies of CP-violating observables in the decays of B-mesons, is required. These searches typically provide complementary information about the possible sources of CP-violation. In the case of the Minimal Supersymmetric Standard Model, for example, there exists a handful of CP-violating phases that generate flavor-diagonal CP-violation. The current limit on the $^{199}$Hg atomic EDM places the most severe constraints on many but not all of these phases. An improvement of the neutron EDM search sensitivity by two orders of magnitude would provide new and powerfully complementary information to what is currently known from the atomic searches.

## The Neutron Lifetime

A free neutron decays with an average lifetime of 881.5 ± 1.5 s (PDG 2011). The lifetime is a fundamental parameter that impacts areas of nuclear physics, particle physics, and cosmology. A precisely determined lifetime can be used to search for BSM physics. In Big Bang nucleosynthesis, the neutron-to-proton conversion rate, determined from the free neutron decay rate, competes with the Hubble rate to determine the primordial $^4$He abundance.

The lifetime has been determined by counting the decays of cold neutrons in a beam, and those of ultra-cold neutrons (UCNs) confined in either a material bottle or a magnetic trap. The worldwide effort has resulted in increasingly precise values. However, recent measurements using the bottle method disagree with the previously accepted value (PDG 2010), causing the PDG value to be shifted down by 4 s, and the uncertainty expanded from 0.8 s to 1.5 s.

The current experimental thrust on the neutron lifetime is to improve the consistency of worldwide measurements to a precision of 1 s. In the long term, measurement of the lifetime to a precision of 0.1 s is well motivated, especially when combined with precise decay correlation measurements, which we discuss next.

## The Neutron Decay Correlations

The study of neutron decay provides important constraints on the couplings of weak currents to the nucleon. Precise measurements are important to astrophysics, where uncertainties on the axial-vector coupling $G_A$ influence predictions of the p-p solar neutrino flux, and to BSM physics, where new scalar or tensor interactions could be revealed through beta decay correlation studies.

At lowest order in an expansion of $E_e/M$, where $E_e$ is the electron energy and $M$ the neutron mass, the neutron lifetime depends on two parameters: the vector and axial-vector couplings, $G_V$ and $G_A$, respectively. Both are proportional to the CKM matrix element $V_{ud}$. In addition, $G_A$ receives significant strong interaction renormalization from the u-d-W coupling in the SM Lagrangian, whereas $G_V$ is protected by the CVC (Conserved Vector Current) property of the Standard Model, broken only by tiny isospin-breaking effects.

Due to the theoretical reliability with which $G_V$ can thus be interpreted, its determination provides a theoretically clean means of obtaining $V_{ud}$. At present, the most precise determination of $G_V$ has been obtained from the study of superallowed $0^+ \rightarrow 0^+$ nuclear beta decays, from which one extracts $V_{ud}$ to a fractional error close to $2 \times 10^{-4}$, with principal error contributions (in increasing order of importance) being from experimental statistics and systematics, theoretical wavefunction corrections, Coulomb distortion of the outgoing β wavefunction, and hadronic effects in the one-loop electroweak radiative corrections. Combining this result with the value of $V_{us}$ taken from semi-leptonic kaon decays (the value of $V_{ub}$ is negligible), one obtains a test of the unitarity property of the CKM matrix with better than per mil precision.

The value of $G_V$ may be extracted from neutron decay using the lifetime $\tau_n$ and an independent determination of $G_A$. Doing so is possible through the measurement of one of a number of neutron decay correlations, which may be parameterized in terms of $\lambda = G_A/G_V$. One goal of neutron decay measurements is to obtain sufficient accuracy in the determinations of $\tau_n$ as well as λ so as to obtain a value of $G_V$ with precision comparable to the superallowed result, providing an independent check of this input into the CKM unitarity test.

The neutron differential decay rate can be written as:

$$dw = dw_0 \left[ 1 + a \frac{\vec{p}_e}{E_e} \cdot \frac{\vec{p}_\nu}{E_\nu} + b \frac{m_e}{E_e} + \langle \vec{\sigma} \rangle \cdot \left( A \frac{\vec{p}_e}{E_e} + B \frac{\vec{p}_\nu}{E_\nu} + D \frac{\vec{p}_e}{E_e} \times \frac{\vec{p}_\nu}{E_\nu} \right) \right] ,$$

where $m_e$ is the mass of the electron, the $p$'s and $E$'s stand for the momenta and energies of the electron and neutrino ($e$ and $\nu$) and $a$, $b$, $A$, $B$, and $D$ are the correlation coefficients. The spin-proton momentum correlation called "*C*" can also be measured, providing redundant information since $C \propto A+B$.

To date, the most precise value of λ has been extracted from measurement of the β-asymmetry parameter, or "*A*". There is potential to achieve comparable precision by measuring the beta-neutrino correlation parameter "*a*".

The test of first-row CKM unitarity can probe a number of possible beyond Standard Model scenarios, including extended gauge sectors with right-handed W-bosons, a fourth generation of fermions, and supersymmetry. Additional scenarios, including those involving certain classes of leptoquarks or novel supersymmetric loop effects, can induce interactions that do not have the SM $(V-A)\times(V-A)$ structure (*i.e.,* scalar and tensor interactions).

Because the "*A*" and "*a*" correlation coefficients depend only to second order on the scalar and tensor coupling constants, they are less sensitive to these new interactions than the correlations that depend on interferences with SM couplings. Examples of the interference-like correlations are the Fierz interference term "*b*" that affects the shape of the $E_e$-spectrum and the $E_e$-dependent part of the neutron spin asymmetry parameter "*B*". The interesting sensitivity goal is of order $10^{-4}$, which could allow a probe of novel supersymmetric loop effects.

T-violation in neutron decay can arise from P-odd/P-even and T-odd nucleon-nucleon interactions or T-odd semi-leptonic charged current interactions. The T-violating "*D*"-coefficient provides a way to search for BSM physics such as left-right symmetric models, exotic fermion models and models with leptoquarks.

## Hadronic Parity Violation with Neutrons

While the SM weak currents are generally well studied, the weak interaction among hadrons is an exception. Aspects of this interaction have been tested in flavor-changing decays, but not those mediated by the neutral current, which is flavor-diagonal at tree-level and nearly so at loop level due to the GIM mechanism. Consequently, the hadronic weak neutral current can only be studied in flavor-conserving interactions, of which the nucleon-nucleon interaction is the only practical example. The weak interaction is a tiny perturbation on the dominant strong and electromagnetic interactions between nucleons, with a relative strength typically $\sim 4\pi\, G_F m_\pi^2 / g_{\pi NN} \sim 10^{-7}$. However it can be isolated in the presence of these stronger interactions because the weak interaction violates parity, producing, for example, distinctive asymmetries and decay polarizations arising from the interference between weak and strong amplitudes.

The low-energy NN weak interaction can be described in terms of one-boson exchanges, where one vertex is weak and parity-violating, and the second is strong. Equivalently this interaction can be represented as a sum of five independent NN *S*-*P* amplitudes. The weak vertex arises from the SM current-current effective interaction, where the currents are either neutral or charged. This product of currents produces an interesting behavior in isospin, *I*. The symmetric product of the main component of the charged current (which is isovector and strangeness conserving) produces only $\Delta I$ =0 or $\Delta I$=2, $\Delta S$=0 amplitudes. While there is a $\Delta I$ =1 $\Delta S$=0 charged-current contribution arising from the product of strangeness-changing currents, this term is Cabibbo-suppressed, proportional to $\sin^2\theta_C$. It follows that the parity-violating $\Delta I$=1 NN interaction should be dominated by neutral current terms, making it possible to isolate and study this new aspect of hadronic weak interactions. In a boson-exchange model, this contribution is dominated by long-range pion exchange.

There have been indications, based largely on studies of parity violation in nuclei, that the expected neutral current enhancement of the $\Delta I$=1 NN interaction is in fact not realized in nature: analyses based on a limited data set (asymmetries measured in the scattering of polarized protons in proton and helium targets, the circular polarization of γ rays emitted in the decay of the 1081-keV state in $^{18}F$, and the γ-ray asymmetry measured in the decay of the 110 keV state in $^{19}$F) show that the $\Delta I$=0 weak NN interaction has about the expected strength, but that the $\Delta I$=1 interaction is a factor of three or more weaker than expected.

The situation is superficially similar to that found in strangeness changing decays, where the $\Delta I$=1/2 rule describes the anomalous ratio of $\Delta I$=1/2 to $\Delta I$=3/2 amplitudes. Such suppression suggests that strong interactions within the nucleon have an important effect on certain weak interactions, renormalizing the strengths of couplings relative to their bare-quark SM values.

This result, the apparent absence of the expected neutral-current enhancement of the weak pion-nucleon coupling $f_\pi$, has been known for over 25 years. The conclusion rests effectively on measurements in $^{18}$F, where nuclear effects fortuitously enhance the $\Delta I$=1 parity-violating observable by several orders of magnitude. While some unusual properties of this system suggest the measurements and their interpretation are reliable, it is widely recognized that a confirming experiment is needed in an elementary system, where the size of the parity violating effect will be much smaller, but where the theoretical analysis can be done with *ab initio* methods. One additional reason such a measurement is now important is the recent demonstration in lattice QCD that this coupling may be directly calculable from first principles.

The long-term goal of the subfield is to devise at least five precise measurements of parity-violating N-N interactions in few-body systems in such way as to disentangle the five independent NN S-P amplitudes and thus completely characterize the low energy hadronic neutral weak interaction.

## Other Physics Topics with Neutrons

*Neutron radiative decay:* The neutron beta-decays predominantly into a proton, electron and antineutrino. However, it has a weak branch in which these decay products are accompanied by a continuous spectrum of soft photons. This inner-bremsstrahlung branch has been observed with 10% accuracy and the goal now is to improve the statistical and systematic reach by a further order of magnitude. At this level of precision the result could begin to test theoretical effects, such as those of recoil-order terms, which lie beyond the leading-order contributions.

*Neutron interferometry:* Neutron interferometry measurements are used for a wide variety of purposes such as measurements of spin-independent and –dependent few-body neutron scattering lengths and the neutron charge radius.

# Facilities for Fundamental Neutron Physics

## US Facilities

### ***The Spallation Neutron Source (SNS) at ORNL***

*Facility:* The SNS is based on a proton accelerator and liquid mercury target, which generates the world's highest intensity pulsed neutron beams. The facility is designed to deliver 1.4 MW of proton beam power to the target.

*Fundamental Neutron Physics (FNP) capabilities:* One of the 24 SNS beam lines, beam line 13, is available for the study of fundamental physics with neutrons. This "Fundamental Neutron Physics Beam Line" (FNPB) was constructed as a DOE Major Item of Equipment, with CD-0 approval in August 2003 and completed on schedule in September 2008. The FNPB in fact contains two beam lines: the primary Cold Neutron (CN) line providing a "white beam" of cold neutrons, with the secondary line restricted to a very narrow wavelength slice at 8.9Å, via diffraction from the primary cold-neutron beam in a double-crystal intercalated alkali monochromator. The wavelength of the scattered beam is chosen to be optimum for down-scattering by superfluid $^4$He to generate ultra-cold neutrons (UCNs), as required for the nEDM experiment. However, the monochromator efficiency has been measured at 75% of its design value, yielding a flux of $0.75 \times 10^9$ n/s/Å/MW, with no steps evident at present to improve the efficiency significantly. A UCN flux that is larger by a factor of 5 can be achieved for the nEDM experiment by instrumenting the main cold-neutron beam line with beam choppers that limit the wavelength bandwidth.

*Management and support:* The FNPB User program is managed by the ORNL Physics Division. Proposals are reviewed by the FNPB Proposal Review and Advisory Committee (PRAC). The PRAC is advisory to the ORNL Physics Division Director, who is responsible for approving experiments and allocating beam time. To date the PRAC has reviewed ten proposals, with six approved and four deferred. Currently there are 12 scientific personnel in residence at the FNPB facility, comprising five permanent staff members, one sabbatical visitor, two post-doctoral fellows, and four graduate students.

### ***The National Institute of Standards and Technology (NIST)***

*Facility:* The NIST Center for Neutron Research (NCNR), in Gaithersburg, MD, is based on a 20MW heavy-water moderated research reactor, providing thermal-energy neutron beams from heavy-water and graphite moderators, and intense cold neutron beams from a large-area liquid-hydrogen moderator. Its user community includes researchers from industry, universities, and other government agencies.

*FNP capabilities:* Until recently, two of the Cold Neutron guides (#6 and #7) were used for fundamental physics experiments. Guide #6 produced a high-intensity polychromatic beam at end station NG-6, and three monochromatic side-beams were available at NG-6A, NG-6M (CN) and NG-6U (UCN). Guide #7 delivered a monochromatic beam at NG-7.

The NCNR reactor is currently shut down for upgrades, with restart planned for spring 2012. The upgrades include doubling the size of the guide hall and the installation of five new guide tubes. One new guide tube, NG-C, will be a special focusing ballistic guide that will increase the CN flux by a factor of five. The end position of this tube will be dedicated to fundamental physics experiments, and a second monochromatic beam will also be added to NG-7 for this purpose.

A further improvement, scheduled for completion by December 2014, is the installation of a liquid-deuterium cold source to replace the existing moderator. This is projected to attain integrated capture flux at NG-C of $1.6 \times 10^{10}$ $n \cdot cm^{-2} \cdot s^{-1}$. By that time all fundamental physics experiments now on neutron guide #6 will have been relocated to guide #3.

*Management and support:* Proposals are submitted to NCNR management, who solicits written scientific reviews by external referees, and safety and technical feasibility reviews by NCNR staff. The Beam Time Allocation Committee (BTAC) rank-orders the proposals and advises NIST and NCNR management on the assignment of beam time for each experimental station. There are currently nine NIST staff scientists and two technicians in the neutron science program, about one-half of whom are primarily focused on fundamental physics research.

***Ultra-Cold Neutron Source at LANL***

*Facility:* The UCN source utilizes protons from the LANSCE 800 MeV accelerator impinging on a 12-cm W target to generate high-energy neutrons that are then moderated in polyethylene to produce cold neutrons (CN). The CN are cooled to ultra-cold neutrons (UCN) via phonon excitation in a 2-liter solid deuterium system ($SD_2$) that is cooled by liquid helium. The source has been operating since 2007, delivering UCNs for the UCNA experiment and for R&D for the nEDM experiment.

*FNP capabilities:* The configuration of the facility allows one asymmetry-measuring experiment, mounted in the UCNA spectrometer, and one storage-type experiment, such as a lifetime experiment, to run simultaneously by utilizing a UCN beam switcher. For the UCNA experiment the UCNs are polarized by a 7-T solenoid, with RF to flip the UCN spin using adiabatic fast passage, resulting in a density of about 2 UCN/$cm^3$ with polarization P = 0.995 +-0.002.

*Management and Support:* At present, allocation of the source's beam time is determined by the UCNA executive committee. Additional proposals are expected in the future, at which point a Program Advisory Committee will be formed to allocate the time of the UCN source. There are currently seven scientific staff members and four technical staff members with responsibilities for the UCN beamline and experiments, totaling about 5 FTE of effort.

## International Facilities

### *The Institut Laue-Langevin (ILL)*

*Facility:* ILL in Grenoble, France, is an international research centre operating a 58.3 MW high flux beam reactor with a maximum thermal neutron flux of 1.2 x $10^{15}$ $cm^{-2}$ $s^{-1}$. This is the most intense continuous neutron source available, providing beams of hot, thermal, cold and ultra-cold neutrons.

*FNP capabilities:* Beamline PF1b, which is devoted to particle physics and neutron property studies, has a CN capture flux of $2.0\times10^{10}$ $cm^{-2}$ $s^{-1}$ over a cross-section of 6 cm×20 cm. The PERKEO II and PERKEO III experiments that measure the neutron decay correlation coefficients were carried out at this beamline. Thermal position S18 is used for interferometry and Ultra Small Angle Neutron Scattering spectroscopy with wide range tunability of wavelength, to study fundamental questions in quantum mechanics. UCNs are generated by means of a curved neutron guide and rotating turbine, achieving a UCN density of 50 $cm^{-3}$. Additional UCN sources are under construction, based on down-scattering in superfluid $^4$He.

### *Forschungsneutronenquelle Heinz Maier–Leibnitz (FRM-II)*

*Facility:* FRM-II in Munich, Germany, operates a reactor with maximum undisturbed thermal neutron flux density of $8\times10^{14}$ $cm^{-2}$ $s^{-1}$ at a nominal thermal power of 20 MW. Beam tubes and neutron guides supply the experiments with neutrons. The cold neutron source consists of cold liquid deuterium, generating a spectrum of low-energy neutrons with a Maxwell distribution centred around ~5 meV.

*FNP capabilities:* The MEPHISTO facility provides a neutron beam for basic research, with a measured capture flux of $2\times10^{10}$ $cm^{-2}$ $s^{-1}$ that is among the highest worldwide. In the near future, MEPHISTO will move to a new end-position for cold neutrons and host an instrument called PERC, which will generate a well-defined beam of decay electrons and protons separated from the cold neutron beam. PERC is a general-purpose source of neutron decay products, suitable for a variety of experiments in neutron decay correlation spectroscopy. A new source of ultra-cold neutrons is being planned, based on solid deuterium at a temperature of ~5 K.

### *St. Petersburg Nuclear Physics Institute (PNPI)*

*Facility:* PNPI in Gatchina, Russia operates an 18 MW research reactor that generates a neutron flux of $3\times10^{14}$ $cm^{-2}$ $s^{-1}$ in the central light-water trap.

*FNP capabilities:* A Universal Liquid Hydrogen Source of Polarized Cold and Ultracold Neutrons feeds a channel of cold neutrons. CNs are currently not available, because of maintenance work. The previously achieved beam intensity of polarized cold neutrons was $3\times10^{10}$ $s^{-1}$, with a flux of $6\times10^{8}$ $cm^{-2}$ $s^{-1}$ and polarization of 90 ± 5%.

### *Paul Scherrer Institute (PSI)*

*Facility:* PSI in Villigen, Switzerland runs the Spallation Neutron Source SINQ, utilizing a 590 MeV proton beam at a current up to 1.8 mA, with beam power available for SINQ of roughly 0.75 MW. The neutron flux is about $10^{14}$ $cm^{-2}$ $s^{-1}$ in continuous mode. A cold moderator of liquid deuterium provides neutrons for cold neutron research.

*FNP capabilities:* The Polarized Cold Neutron Facility (FUNSPIN) views the cold source of SINQ, a moderator of about 20 l of liquid deuterium at a temperature of 25 K. The polarized CN capture flux at the experimental location is $6 \times 10^{8}$ $cm^{-2}$ $s^{-1}$ $mA^{-1}$, with average polarization exceeding 97%. A reconfiguration of the experimental areas is under way.

### *The European Spallation Source (ESS)*

ESS, a new European neutron source currently in the planning stage, is a joint project of several European countries. ESS will be constructed in Lund, Sweden, with construction beginning in 2013, initial operation in 2019, and full operation projected for 2025. Experiments will include neutron beta-decay and fundamental physics studies.

### *The UCN source at TRIUMF*

*Facility:* A new UCN facility is being constructed at TRIUMF (Canada's National Laboratory for Particle and Nuclear Science, in Vancouver). The source is presently being developed in Japan, at the Research Center for Nuclear Physics (RCNP) in Osaka. The proton beam at TRIUMF will be increased to 20 kW and will bombard a solid, water-cooled spallation target. Neutrons will be moderated and converted into Ultra Cold Neutrons (UCN) via down-scattering in superfluid $^{4}He$. A prototype UCN source is already operational in Japan, and the second generation source is nearing completion (cold tests are on-going as of late 2011). There is an MOU between TRIUMF and Japan to complete experiments at RCNP in 2014 and move the source to TRIUMF in 2015.

*FNP capabilities:* There will initially be one UCN beamline coupled to a neutron EDM experiment, also presently under development at RCNP, Osaka. The UCN density in the EDM cell is projected to be 5000 UCN/$cm^{3}$.

# Experimental Initiatives

## Neutron EDM

The experimental techniques for neutron EDM searches have incorporated a number of innovations since Ramsey's first neutron beam experiment. Production of ultra-cold neutrons allowed storage of neutrons in a bottle for many seconds, which dramatically increased statistical precision of EDM searches and largely eliminated the leading systematic effect due to motion of neutrons in the electric field. Introduction of co-magnetometer techniques reduced sensitivity to external magnetic noise and allowed more detailed studies of systematic effects.

The theoretical significance of EDM searches has led to a large increase in the experimental activity in this area. Whereas for the previous 30 years there were only two active EDM experiments (ILL, PNPI), there are currently half a dozen experiments either beginning to take data or constructing new apparatus. Currently, the best limit on the neutron EDM are from the RAL/Sussex experiment at ILL.

A new neutron EDM experiment at ILL is now being carried out by the cryoEDM collaboration. They have started to produce neutrons from a superthermal source, using downscattering of UCN in superfluid $^4$He. The EDM experiment will be performed in a neutron bottle containing superfluid helium, where electric field values several times larger than those used in the past experiment can be obtained.

The nEDM collaboration at PSI will use a UCN source, which is currently under construction. The neutron bottle will consist of a double chamber storage cell, making it possible to suppress magnetic field fluctuations from simultaneous measurements in chambers with opposite electric fields. A set of laser pumped Cs magnetometers are placed outside the storage cells to measure the magnetic field. An alternative is to use SQUID magnetometers for this purpose. These might be used in the proposed EDM experiments at FRM-II or at the TRIGA reactor in Mainz. To overcome the geometric phase shift, which is linear in E and cannot be distinguished from a true EDM effect, new concepts make use of magnetometers operating in a field region which is free of electric fields and separated from the UCN.

The US nEDM experiment represents a particularly ambitious advance in experimental techniques for neutron EDM searches. It incorporates both a new technique for production of UCNs by down-scattering in superfluid $^4$He and a new technique for neutron spin detection, based on absorption of neutrons by polarized $^3$He and scintillation in liquid $^4$He. In addition, it uses $^3$He spins as a convenient co-magnetometer, since their magnetic moment is only 10% different from that of the neutron. By combining all three steps of a neutron EDM measurement (UCN production, magnetic field monitoring, and neutron detection) in a single system, it can achieve an unprecedented level of statistical sensitivity. It also provides new handles on systematic effects, particularly the effects of a geometric phase, which has recently been identified as the most significant systematic effect in EDM searches at the current level of sensitivity. No other EDM effort currently has as comprehensive a set of diagnostics as the US nEDM experiment. A summary of the main parameters of the principal neutron EDM experiments is shown in Table 1.

**Table 1 Summary of principal nEDM initiatives worldwide**

| | Neutron EDM | | |
|---|---|---|---|
| PDG value 2011 | $< 290\times10^{-28}$ (90% CL) | | |
| Experiment | Facility | Target sensitivity ($\times10^{-28}$ e-cm) | Status |
| nEDM | SNS | <4 | R&D |
| ILL Crystal | ILL | <100 | running |
| cryoEDM Phase 1 | ILL | 50 | running |
| cryoEDM phase 2 | ILL | <5 | R&D |
| PSI EDM Phase 2 | PSI | 50 | R&D |
| PSI EDM Phase 3 | PSI | <5 | R&D |
| PNPI group | ILL | <100 | running |
| Munich EDM | FRM-II | <5 | R&D |
| TRIUMF EDM | TRIUMF | <10 | R&D |
| JPARC EDM | JPARC | <5 | R&D |
| NIST Crystal | NIST | <5 | R&D |

## Neutron Decay Correlations

To date, the most precise value of λ has been extracted from measurement by the PERKEO collaboration of the β-asymmetry parameter "*A*". They have measured angular correlation coefficients "*A*" and "*B*", with increasing accuracy, and "*C*" for the first time. In these *A*-coefficient measurements, the necessary corrections to the data have been reduced by a factor of 100. The instrument PERKEO III is measuring neutron decay correlation coefficients using both a continuous cold neutron beam as well as a pulsed beam, virtually eliminating the four leading sources of error typical for correlation coefficient experiments using magnetic fields.

The subcommittee reviewed several US initiatives to measure λ. An independent determination of "*A*" is underway using UCNs at Los Alamos. The UCNA experiment has been taking data since 2007 and proposes to continue to take data to determine the beta asymmetry to better than 0.3%. In addition, there are ongoing experiments to understand the production of UCN using alternative ideas (solid oxygen as opposed to the $SD_2$).

An alternative determination of λ is ongoing at the aCORN experiment at NIST via measurement of the beta-neutrino correlation parameter "*a*". The aim of the aCORN technique is to get to the sensitivity range of 0.5-1%. A new spectrometer has been proposed by the Nab collaboration at the SNS, with the ultimate goal of achieving an "*a*" measurement approaching 0.1%. In addition, the Nab spectrometer would also allow a determination of "*b*". Finally, abBA/PANDA would use polarized neutrons with the same spectrometer to obtain independent high precision measurements of "*A*", "*B*" and "*C*" to 0.1%. The subcommittee was also presented with an internally funded pilot project at Los Alamos to explore the feasibility of a "*B*" measurement using UCNs ("UCNB") on the path toward a precision of order $10^{-4}$, which could allow a probe of novel supersymmetric loop effects.

The principal ongoing initiatives for measurements of various neutron correlation coefficients are summarized in Tables 2 through 5.

**Table 2: Principal initiatives for A-coefficient measurements worldwide**

| | Electron asymmetry "*A*" | | |
|---|---|---|---|
| PDG value | -0.1176±0.0011 (0.9%) | | |
| Experiment | Facility | Target sensitivity | Status |
| UCNA | LANL | 0.2% | running |
| abBA/Panda | SNS | 0.1% | R&D |
| PERKEO III | ILL | 0.2% | running |
| PERC | FMR-II | 0.03% | R&D |

**Table 3: Principal initiatives for a-coefficient measurements worldwide**

| | Electron-neutrino correlation parameter "*a*" | | |
|---|---|---|---|
| PDG value 2011 | -0.103±0.004 (3.9%) | | |
| Experiment | Facility | Target sensitivity | Status |
| aCORN | NIST | 0.5-1% | running |
| Nab | SNS | 0.1% | R&D |
| abBA/Panda | SNS | 0.1% | R&D |
| aSPECT | ILL | 0.3% | running |
| PERC | FMR-II | 0.1% | R&D |

**Table 4: Principal initiatives for B-coefficient measurements worldwide**

| | Neutrino asymmetry "*B*" | | |
|---|---|---|---|
| PDG value | 0.9807±0.0030 (0.3%) | | |
| Experiment | Facility | Target sensitivity | Status |
| abBA/Panda | SNS | 0.1% | R&D |
| UCNB | LANL | 0.1% (long term 0.01%) | R&D |
| PERC | FMR-II | | R&D |

**Table 5: Principal initiatives for the Fierz interference term b worldwide**

| | Fierz interference term "*b*" for the neutron | | |
|---|---|---|---|
| PDG value | Not reported | | |
| Experiment | Facility | Target sensitivity | Status |
| Nab | SNS | $3\times10^{-3}$ | R&D |
| abBA/Panda | SNS | $3\times10^{-3}$ | R&D |
| UCNb | LANL | 0.01 | R&D |
| PERC | FMR-II | | R&D |

## Hadronic Parity Violation

NPDGamma is an improved version of the LANL experiment to measure the parity-violating asymmetry in $\vec{n} + p \rightarrow d + \gamma$, and is now being commissioned at the SNS. There is a proposed follow-up SNS experiment on n-$^3$He; the collaboration is requesting to prepare for and carry out the measurement after the completion of NPDGamma. There is also R&D in progress to improve the published NIST spin-rotation measurement in $^4$He. These initiatives are summarized in Table 6.

**Table 6: Principal initiatives in neutron hadronic parity violation**

| | Hadronic parity violating observable | | |
|---|---|---|---|
| Experiment | Facility | Target sensitivity | Status |
| NPDGamma | SNS | $10^{-8}$ | running |
| n-$^3$He | SNS | $2 \times 10^{-8}$ | R&D |
| n-$^4$He | NIST | $10^{-7}$ | R&D |

## Neutron Lifetime

An experiment from PNPI at the PF2 beamline at ILL uses permanent magnets, a magneto-gravitational ultra-cold neutron trap, where wall losses are small. The accuracy goal is about 0.2-0.3 s. PENELOPE at FRM-II is a superconducting magneto-gravitational trap for a precise neutron lifetime measurement. Its main component is a double cylinder of superconducting coils with alternating current directions. The accuracy goal is of order 0.1 s. The storage volume is 800,000 cm$^3$ with more than $10^6$ neutrons expected per filling.

In the US, there are three ongoing initiatives pursuing neutron lifetime measurements. The NIST beam-based lifetime project records the absolute count rate of neutrons and decay protons. R&D is in progress to improve the accuracy of the method to 1 s. The NIST trap-based lifetime project proposes to make the measurement by trapping UCNs in a Ioffe superconducting magnetic trap. The designed sensitivity is 3 s. At LANL, there is R&D in progress to develop a magneto-gravitational trap to be filled with UCNs for the lifetime measurement. The ultimate design goals are 1 s in Phase I and 0.1 s in Phase II.

| | Neutron Lifetime | | |
|---|---|---|---|
| PDG value | 881±1.5 s | | |
| Experiment | Facility | Target sensitivity | Status |
| NIST beam-based | NIST | 1 s | Running |
| NIST magnetic bottle | NIST | 3 s | Running |
| PNPI group | ILL | 0.2 s | R&D |
| PENELOPE | FRM-II | 0.1 s | R&D |
| Magneto-gravitational trap | LANL | 0.1 s | R&D |

## Other Neutron Physics

Radiative neutron decay was first observed and measured at the NG-6 end station at NCNR. In Run I, they recorded the photon spectrum in the energy range from 15 to 340 keV and determined the branching ratio for photons in this range to be $(3.09 \pm 0.32) \times 10^{-3}$, a result that compares favorably with calculations from heavy baryon chiral perturbation theory (and QED), which predict $2.85 \times 10^{-3}$. This result has been published.

The ~10% uncertainty on the result from Run I was dominated by systematic uncertainty, which the team believed could be reduced considerably. As a result, their equipment has been substantially upgraded and the team is now analyzing a much-improved Run II data-set, which has the goal of reducing the branching-ratio uncertainty to 1% and obtaining a precise measurement of the photon energy spectrum. At this level of precision the result could begin to test theoretical effects, such as those of recoil-order terms, which lie beyond the leading-order contributions.

Neutron interferometry measurements are mounted at the NG-7 beamline at NIST and have been used for a wide variety of purposes. Several are of particular interest in the context of nuclear physics. One class of experiments measures few-body neutron scattering lengths: so far these have led to results for the n-H, n-D and n-$^3$He (polarized and un-polarized) systems, with data analysis in progress for n-$^4$He; plans are underway to measure the n-T system. There is also an experiment in progress to extract the neutron charge radius from the neutron-electron scattering length, which can be determined from the neutron's dynamical phase shift in a perfect crystal aligned close to the Bragg condition. This difficult experiment began in 2005 and still continues.

A group from Vienna operates thermal position S18 at ILL, which is used both for interferometry and Ultra Small Angle Neutron Scattering spectroscopy with wide range tunability of wavelength. The focus is several fundamental topics in quantum mechanics.

## Subcommittee Findings and Recommendations

In the preceding sections, the scientific overview has been presented, and the status and capabilities of facilities both in the US and in Europe have been described with regard to a program of Fundamental Neutron Science. The subcommittee's input on the status of the main initiatives in US neutron science was obtained in the two open meetings mentioned in the introduction, one meeting focused on the nEDM project and the second focused on the remainder of the program. The agendas of the two meetings are listed in Appendix C. Based on this input, and in the context of the US capabilities and the capabilities abroad, a ranked list of priority experiments was established, under the assumption of a constant level-of-effort investment in neutron science.

In this section, we present these scientific priorities followed by an unordered set of recommendations to best realize this program. We note that, while the principal driving factor for prioritization was the importance of the physics goals in the larger context of tests of fundamental symmetries, secondary considerations such as capitalization of past investments as well as the latest progress towards competitive physics results were also important. Following this section, a discussion of resources, which provided important input to these recommendations, is presented.

### Scientific Priorities

The principal scientific priorities, ranked in descending order are given below. Each priority item is followed by a short supporting statement.

I. **The search for a neutron electric dipole moment with the nEDM experiment**

   The subcommittee finds that the scientific goal of the nEDM experiment remains the most compelling within the neutron science program. Its pursuit was given high priority in the NSAC Long Range Plan. Subject to the recommended guidance given below, we believe the nEDM continues to have great promise to be the highlight of the program.

II. **Continuation of the UCNA experiment to obtain improved precision on λ, the ratio of the weak axial-vector to vector charge of the neutron**

   After a number of years of development, the UCNA Collaboration has recently reported a world-competitive result for the decay asymmetry parameter *A*. We believe that building on this investment by pushing this proven experiment to its ultimate sensitivity is a cost-effective path forward toward higher precision, which remains highly motivated.

III. **Completion of the NPDGamma experiment to obtain a precision measurement of the weak isovector nucleon-nucleon-pion coupling constant**

   A lengthy development effort, first at LANL, then ORNL has led to the NPDGamma experiment's present status of "ready for physics production running". We strongly endorse the investment in realizing the physics from this development with continued support of the running and analysis phases of the experiment.

IV. **Investment in the Nab apparatus with the main goal to determine λ to unprecedented precision using a complementary observable**

Several next-generation plans for ~0.1% level determination of neutron beta decay parameters exist worldwide. We judge Nab, which obtains λ from the asymmetry parameter "a", to be highly competitive and worthy of pursuit.

V. **Continuation of the NIST-hosted experiment to perform the most precise cold beam-based measurement of the neutron lifetime**

While the future trend in neutron lifetime experimental design is to develop material and/or traps for UCNs, with sub-second uncertainty goals, the current ambiguities in the published results warrant continued support of the NIST cold-beam experiment. Even with 1 s precision as an ultimate goal, this will provide an important and cost-effective result by a complementary technique.

We estimate that these five high priority initiatives might be accommodated within a scenario of funding at constant level of effort, exclusive of MIE construction funding, though moderate additional funding may be required. The ranking indicates the priority with which each effort should be supported, in the event of funding below the constant level of effort. The priority of UCNA and NPDGamma should be considered comparable for this purpose. The resource requirements are discussed in more detail in the section on "Resources".

## Specific Recommendations, Associated Findings and Supporting Commentary

In the following, we first address the nEDM experiment, identifying the issues that emerged from our review, and providing a set of recommendations based on our findings. We then address the rest of the program, dividing it into three subareas: hadronic parity violation, neutron decay correlations and the neutron lifetime. In each of the sub-areas we provide recommendations that correspond to the highest priority items listed above, and discuss our findings in the context of the full scientific program. We note that the numbered recommendations in the following *do not* represent a rank-ordering.

### The nEDM Experiment

As described in the scientific overview, the search for a non-zero electric dipole moment (EDM) has long been recognized as a test of possible new sources of CP-violation within the Standard Model and as a way to discover what might lie beyond it. In response to the strong recommendations from the 2002 Long Range Plan (LRP) and the 2003 subcommittee on neutron science, DOE and NSF have made significant investments in a next-generation neutron EDM experiment (nEDM) at FNPB at the Oak Ridge National Laboratory (ORNL). The 2007 LRP reinforced the high priority for the science, singling out the importance of the search for T-violation in one of the primary recommendations.

The subcommittee finds that the scientific motivation for EDM searches remains as compelling as ever. ***In particular, a measurement with sensitivity at the anticipated reach of the US nEDM experiment (~4 x $10^{-28}$ e-cm) would have a profound impact on nuclear physics, particle physics and cosmology, even in the event of a negative result.*** If the ultimate reach is limited to 10 x $10^{-28}$ e-cm (a factor of 30 better than the current limit), the project is still worth pursuing at its current level of scope and effort, as long as final results are obtained before 2025.

The nEDM conceptual design uses a large active measuring volume aimed at acquiring a data sample having a statistical error in the range 1-10 x $10^{-28}$ e-cm, with comparable or smaller total systematic uncertainty. Several novel techniques will be employed to explore and constrain systematic effects at this level. ***The US nEDM project is the only technical concept among various worldwide efforts that is explicitly proposed to reach this level of sensitivity.*** Projects elsewhere are focused on intermediate steps having sensitivity goals about an order of magnitude short of that of the US nEDM. These projects have significantly shorter projected time-scales for first results, with competitive sensitivity projections for yet-to-be-designed future efforts.

Tight integration of all experimental steps also makes the nEDM experiment particularly challenging. Over the past several years, the US nEDM collaboration has carried out numerous feasibility studies verifying the physics concepts driving the experimental design, which remains close to that originally proposed. The collaboration has resolved many important technical challenges and developed a first-pass engineering design of the apparatus.

However, significant further R&D is needed on several issues, such as the HV studies, electric field monitoring, background from irradiation of the electrode coating, and the scintillation photoelectron yield. Successful resolution of the outstanding R&D issues is of paramount importance. While none of the issues the committee identified appears to be a showstopper, the time and effort required to demonstrate acceptable performance, or to find solutions to problems that are uncovered, are not easily quantified; but, in our view, the R&D program is unlikely to be completed in the near term.

> *1) We recommend that the nEDM collaboration immediately focus the bulk of its efforts on a well-structured and strategically targeted R&D plan to address the outstanding technical issues.*

Expertise is required in an unusually broad set of techniques to implement the experimental design concept. The collaboration includes many talented and diverse research groups, and it needs to exploit fully all the available expertise necessary to resolve the primary R&D issues. This may require the inclusion of individuals currently outside the current collaboration, as well as redirection of effort within the collaboration. Given the technical complexity of nEDM, it is important that several of the key PIs dedicate nearly 100% of their research time to the experiment, beginning now.

The recommended action would effectively redirect the focus of research effort away from obtaining construction funding, and more towards a concentrated effort on all the major technical challenges in the measurement technique. The subcommittee's consensus was that this should entail a restructuring of the collaboration's scientific and technical management to enable greater coherence of the scientific, engineering and R&D efforts.

Improved coordination and continuous communication are needed among physicists performing R&D, physicists and engineers designing the apparatus, and collaboration leadership, to avoid significant future reengineering and retrofitting as the outcomes of various R&D efforts become known.

*2) We recommend that ORNL and Los Alamos National Laboratory (LANL) jointly establish an external standing Technical Review Committee (TRC) to review the R&D progress and to report periodically to the management of both institutions.*

The primary focus of the TRC would be to monitor technical progress and evaluate mitigation of technical risk. ORNL and LANL should consult with experts both within and outside the nEDM collaboration to build the membership of the TRC. It is hoped that an effective partnership between the leadership of the two laboratories, the nEDM collaboration, and the TRC will ensure that resources are deployed promptly to address any corrective actions that are identified. More generally, the subcommittee believes that, given the project's magnitude and scope, an increased and sustained institutional commitment from the host laboratory (ORNL), and continued significant support from LANL will both be necessary for successful completion of the project.

*3) We recommend that long-lead-time procurements be contingent upon resolution of the major outstanding technical issues in the measurement technique.*

The subcommittee expects that additional time resulting from delay of these procurements will be useful, for instance for the cryogenic system, which is unusually large in scale and low in temperature, and would profit from further study to forestall delays later. Advice should be sought from senior members of the accelerator divisions of nuclear physics facilities, as well as others in the field with experience managing large projects, to centralize and focus engineering coordination and especially to bolster large-scale cryo-engineering expertise.

*4) We recommend that the agencies provide continued support for a period of two years given implementation of the aforementioned recommendations.*

The outstanding technical problems are unlikely to be resolved soon, and near-term management of the project should not assume a stable design configuration or a fixed cost for the central detector system.

Given the long time scale of construction and commissioning of the experiment as well as competition from other EDM and accelerator-based efforts, the subcommittee believes that the time window for a high-impact neutron EDM result may start to close if the project is not ready to be baselined in the next two years.

> *5) We recommend, in the event that major outstanding R&D issues remain unresolved after two years, that consideration be given to discontinuing the Major Item of Equipment (MIE) Project and re-evaluating the US strategy for achieving a precise neutron EDM measurement.*

The successful completion of an nEDM experiment, the initiative with the highest scientific priority in US neutron science, would represent an impressive scientific and technical achievement for nuclear physics, with ramifications that extend far beyond the field.

## Semi-Leptonic and Hadronic Weak Interactions with Neutrons

As described in the scientific overview, precision measurements of neutron beta decay parameters are an integral part of a comprehensive strategy to test electroweak interactions, and to understand the symmetries that govern our universe. Measurements of parity-violating interactions of neutrons with few-body systems provide fundamentally important and unique insight into nucleon dynamics. As also emphasized in the scientific overview, parity-violation in nucleons and nuclei provides our only practical tool for the study of the strangeness-conserving hadronic weak interaction, and thus of the underlying weak quark-quark interaction. Over the past decade, the US program has made significant progress on these physics topics and it is poised to capitalize on recent investments.

### *Hadronic Parity Violation*

Following preliminary results from their installation at LANL, the NPDGamma experiment—now on the beamline at the FNPB—aims to measure the parity-violating asymmetry $\vec{n} + p \rightarrow d + \gamma$ with an uncertainty of $\pm 10^{-8}$ on an anticipated asymmetry of about $10^{-7}$. This measurement will determine the isovector weak nucleon-nucleon-pion coupling $f_\pi$, which is proportional to the measured asymmetry. Successful completion NPDGamma would determine whether the suppression observed in the $^{18}$F γ-decay results from many-body dynamics or from a more fundamental interplay of the strong and weak interactions.

> *6) We recommend strong support for the NPDGamma experiment as the highest priority measurement in hadronic parity-violation, and urge that every effort be made to reach the design goal, an asymmetry determination of one part in $10^8$.*

While the broader program to measure the five S-P amplitudes is scientifically well motivated, the Committee feels other major efforts should not be mounted until $\vec{n} + p \rightarrow d + \gamma$ is successfully completed. We encourage continued R&D on future experiments, depending on technical milestones reached and availability of funding. The proposed follow-up SNS experiment on n-$^3$He is one example. The complementary initiative of an improved NIST spin-rotation measurement in $^4$He should be reviewed for its physics motivation, technical feasibility, and cost effectiveness in a few years.

### *Neutron Decay Correlations*

The $A$- and $a$-coefficients in neutron decay, introduced in the scientific overview section, are fundamentally important since they measure the ratio of the weak axial-vector to vector charge ratio, $\lambda = G_A/G_V$, of the neutron, which impacts many areas of nuclear and particle physics and cosmology. Strong motivation exists to pursue a fractional accuracy level of 0.1% in these coefficients.

In 2010, the UCNA experiment published a 1.1% determination of the $A$-coefficient. The result marks the first US contribution to an area dominated to date by European efforts. By the end of 2011, the UCNA is expected to achieve a precision of 0.4%. In principle, the experiment can do even better, building on its learning curve and collaboration experience.

Another approach to determine λ is a measurement of the $a$-coefficient, which comes from the electron-neutrino correlation and does not require polarized neutrons. The Nab experiment aims to measure $a$ to 0.1% precision using a unique spectrometer that will measure the electron and proton energies. Additional physics will be a determination of the Fierz interference term, the $b$-coefficient that is obtained from the shape of the electron energy spectrum.

While the subcommittee has identified the UCNA and Nab programs designed to determine λ as the highest priority among US-based neutron decay studies, it supports the Los Alamos R&D effort aimed at a "*B*" measurement with UCNB. However, more substantial agency investment should be contingent on the outcome of the R&D, the ultimate success of UCNA, and progress on the Nab program.

In the nearer term, the US would make a substantial contribution to the worldwide neutron decay program through a determination of λ at the level anticipated with the UCNA and Nab experiments. We note that realizing the full impact of the PERKEO, UCNA, and Nab experiments also requires theoretical input to properly analyze energy-dependent asymmetry effects generated by recoil-order and radiative corrections and to further reduce the hadronic uncertainties in the electroweak radiative corrections.

> *7) We recommend continued support for the UCNA experiment at LANL to improve the measurement precision of the A-coefficient by exploring a cost-effective and expeditious path to the original design sensitivity of 0.2%. We further recommend*

*parallel R&D to develop the experiment to measure the a-coefficient with the Nab spectrometer, with a sensitivity of 0.1%.*

Having multiple measurements worldwide of these coefficients at better than 0.2% over the next few years is timely. A ~0.5-1% measurement of the *a*-coefficient by the aCORN experiment at NIST would provide an intermediate step. In the longer term, successful implementation of the Nab experiment would provide an order-of-magnitude improvement. Measurements of the *B*- and *b*-coefficients could be considered for further R&D if funds are available, especially if it can be judged that there is the potential to reach a precision of $10^{-4}$ in the long term. The motivations for the full-scale UCNB and abBA/Panda projects should therefore be revisited in a few years.

### *Neutron Lifetime*

The lifetime has been determined by counting the decays of cold neutrons in a beam, and of UCNs confined in either a material bottle or a magnetic trap. The worldwide effort has resulted in increasingly precise values and, because the PDG error has been expanded to 1.5 s to cover the wide range of values, competitive experiments must aim at 1 s or preferably better precision to make a difference.

Measurements based on the bottle method, all carried out by European collaborations, have so far reported the most precise though inconsistent values. The systematics of the beam method are entirely different and we judge that a robust beam-based lifetime measurement with a precision of 1 s would be very timely. The beam method developed at NIST over the past two decades has been used to measure the lifetime with an uncertainty of 3.4 s. The proposed continuation of this effort aims to reduce the uncertainty down to 1 s, which is a meaningful and significant goal.

*8) We recommend that high priority be given to acquiring new data with the cold beam-based lifetime measurement at the National Institute of Standards and Technology (NIST), following its planned improvements.*

The US program has also attempted to carry out a bottle experiment at NIST, where magnetic trapping of UCNs produced in a "super-thermal" process has been demonstrated. A magnetic field is used to confine UCNs, aiming to avoid wall-collision-based systematic errors. The current design is projected to achieve an uncertainty on the lifetime of 2-3 s. While the technique appears promising, the ongoing effort is not on track to produce a competitive measurement at the 1 s level in the near future.

A new proposal at LANL aims to capture UCNs in a magneto-gravitational trap for storage and monitoring. Laboratory funds have supported the partial development of the apparatus. If realized as described, impressive statistical precision could be achieved. However, the effort will not be viable without substantial further R&D and significant funding support. The study of likely systematic errors and the demonstration of the feasibility of achieving a precision of 0.1 s using this technique must precede the continuation of expensive construction. The project does not appear to have an adequate effort, considering the complexity and ambition of its goals.

The subcommittee noted that the numerous groups working in the neutron lifetime subfield are often engaged in related technical developments, and thus could benefit from a broader coordination of R&D efforts and possibly collective focus on the most promising single technique. We encourage the proponents to work together to chart out the most effective future strategies for improved lifetime measurements.

### Additional Findings and Recommendation

Neutron beams are being used for several other important measurements. A new result from the emiT experiment provides the best limit on the *T*-violating *D*-coefficient in neutron beta decay. An improved measurement of neutron radiative decay is ongoing, with the spinoff of a better understanding of the NIST lifetime apparatus. Neutron interferometry measurements continue at NIST with a wide array of applications. Of particular interest are measurements of the neutron charge radius and spin-dependent and -independent scattering lengths of few-body systems, where first results have already been published, and improvements are under way.

The radiative decay and interferometry initiatives are largely independent of the resources that fall under the charge of the subcommittee. While new results from these efforts will remain of significant interest to the nuclear physics community, the subcommittee did not prioritize them along with all the other projects that were considered.

The full program of experiments presented in the open "fact-finding" meetings cannot be carried out by the existing US work force in neutron science. We present some details on this observation in the following section. The principal recommendations above have singled out the highest priority initiatives for the immediate future, which may be consistent with a scenario of constant funding or may require moderate additional funding, as discussed in the "Resources" section. We find that the workforce in the US community is large enough, with sufficient expertise and depth, to carry out our high priority recommendations. The subcommittee urges the active participants in the subfield to devise a strategic plan to direct effort towards the highest priority topics.

The US neutron science program compares well with other initiatives worldwide. At NIST, there is steady productivity, projected increase in neutron flux and a new beamline. At the FNPB at ORNL, a new pulsed, cold beam is poised to initiate data collection for the first experiment. At LANL, there is steady increase in the usable flux of UCNs. The experimental initiatives at these laboratories provide excellent environments for technical innovations and for training of the next generation of scientists. However, we find that coordination of scientific effort and utilization of resources available in this area are not optimal at present. At present it is awkward to coordinate priorities among competing efforts at the different facilities.

*9) We recommend that consideration be given to establishing a standing committee to review and prioritize various initiatives in US fundamental neutron science.*

Such a committee could provide guidance to the agencies, laboratories, and community as a whole in several areas, including: prioritization of new initiatives; guidance on allocation of R&D funds; improved collaboration across research groups to consolidate techniques and instrumentation; optimization of utilization of neutron beams and mitigation of redundancies at the various facilities; and improved communication to the broader physics community of the role and significance of neutron measurements in the exploration of fundamental symmetries.

## Resources

For funding of neutron physics by DOE Office of Nuclear Physics, the subcommittee was presented with a constant-effort funding scenario based on the FY11 Presidential Request, totaling $9.33M. This amount is divided among: University Research ($1.3M), Laboratory Research ($3.8M), FNPB operations ($330K), Capital Equipment excluding nEDM ($1.0M), and nEDM MIE ($2.9M). The constant-effort budget presented for FY12-16 corresponded to these amounts, adjusted for inflation. NSF funding for fundamental neutron science is currently at the level of $4M/year, of which about $2M/year is directed towards nEDM and the remainder to university grants on other projects.

We note the following considerations:

1. Capital Equipment does not include funding for the nEDM project. Our definition of "constant effort" underlying the recommendations in this report is based on the assumption that the nEDM Collaboration receives the appropriate level of MIE funding.
2. We further assume that the Nab spectrometer magnet (a major component of the proposed project) will be built using NSF instrumentation funds.
3. FY10 Laboratory Research contains $650K for UCNA, which is not continued in successive years. Continuation of the UCNA experiment to achieve a 0.2% precision in the β-asymmetry parameter A, as recommended in this report, requires additional support at LANL, for scientific staff and for operation of the UCN source. LANL management estimates this additional support to be $1.3M/year.
4. Further R&D and development of other LANL UCN experiments are assumed to be supported by LANL LDRD funds.

We estimate that these five high priority initiatives presented in the "Scientific Priorities" subsection could be accommodated within the above scenario of funding at constant level of effort, exclusive of MIE construction funding, though moderate additional funding may be required, depending upon detailed considerations that are beyond the scope of the subcommittee.

### Workforce

In order to assess the US workforce in fundamental neutron physics, each experiment was requested to provide a list of participants, together with an estimate of the FTE obligation of each participant to that experiment. The data were tabulated by the Subcommittee, and are presented in summary form in this section.

We thank all the experiments for providing us with this input. Such estimates are by their nature imprecise, and different experiments reported their estimates in different ways. In some cases only participation of individuals was noted, without an FTE estimate. Nevertheless, this database provides a valuable snapshot of the community at this time, and it helped the Subcommittee to assess the viability of the various experimental initiatives under consideration.

We classify individuals into four categories, according to their employment status: University Faculty, Research Scientist (which includes career National Lab employees), Postdocs, and Students (PhD only). In a number of instances student and postdoc positions were reported as available positions without specific names, but we do not distinguish between this case and a currently filled position.

The fraction of time available for research was assumed to be 50% for Faculty and 100% for all other categories. All effort was calculated as FTE (fraction of total effort), which for some experiments required scaling of Faculty effort relative to the estimates that were reported.

We did not assess the workforce as a function of time. Some of the experiments under consideration are running now, while others will only run several years in the future. In a number of cases an individual has significant obligations to more than one experiment, with the relative emphasis changing with time. Accurate tracking of the evolution of effort with time is impossible, and any such estimate would have limited utility. Rather, we checked the consistency of obligations of individuals to the experiments corresponding to our highest priority recommendations, taking into account the expected time sequence of the experiments, and found no evidence of significant over-commitment or multiple-counting of effort. We conclude that those individuals with significant multiple commitments have apportioned their time in a realistic way.

### Overview of Workforce

We first provide a broad overview of the workforce in fundamental neutron physics. We define a participant in the field as an individual whose reported contribution to any one of the experiments presented to the Subcommittee exceeds 0.2 FTE, i.e. at least 10 weeks of research per year, which we take as indication of commitment to this area of physics. We consider multiple smaller commitments that sum to greater than 0.2 FTE to be below the threshold for consideration.

By that definition, the community currently has 140 participants, of which 41 are Faculty, 27 are Research Scientists, 25 are Postdocs, and 47 are current students or identified student positions. This sets the scope of the field.

We note that this definition also includes research being carried out at NIST, which is beyond the agency scope of this review.

## Workforce Commitment for High Priority Experiments

We now turn to the workforce commitment to those experiments to which we have given highest scientific priority. The table below presents the estimated workforce obligation as reported by each of these experiments.

| Experiment | Faculty FTE | Research Scientist FTE | Postdoc FTE | Student FTE | Total FTE |
|---|---|---|---|---|---|
| nEDM | 8.4 | 5.3 | 4.8 | 12 | 31 |
| UCNA | 1.2 | 0.3 | 2.6 | 7.0 | 11 |
| NPDGamma | 6.0 | 5.0 | 4.0 | 7.0 | 22 |
| Nab | 0.9 | 1.5 | 2.3 | 7.5 | 12 |
| NIST beam $\tau$ | 2.0 | 3.0 | 2.0 | 1.0 | 8.0 |

We find that, with the possible exception of UCNA, these estimates indicate sufficient effort for these experiments to succeed. Focusing specifically on nEDM, some of our principal recommendations address issues of collaboration strength and expertise. We expect that the collaboration will evolve with time, but based on the table and the list of collaborators we assess that a strong core commitment to the experiment is already in place.

## Appendix A: Charge to NSAC

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

November 29, 2010

Dr. Susan Seestrom
Chair, DOE/NSF Nuclear Science Advisory Committee
Experimental Physical Sciences
Los Alamos National Laboratory
Los Alamos, New Mexico 87545

Dear Dr. Seestrom:

The DOE/NSF Nuclear Science Advisory Committee (NSAC) is requested to review and evaluate the current and proposed research program, scientific capabilities, and opportunities for fundamental nuclear physics with neutrons and make recommendations of priorities consistent with projected resources.

In 2003, NSAC provided an assessment of fundamental physics with neutrons in the United States and made recommendations concerning the ongoing program at that time, including an experiment to measure the electric dipole moment of the neutron (nEDM) and the construction of a new neutron beam facility at the Spallation Neutron Source (SNS). The 2007 NSAC Long Range Plan recommended pursuit of a "targeted program to study the symmetries of the New Standard Model and precise measurement of electroweak phenomena." Since 2003, DOE and NSF have made progress towards the implementation of Committee recommendations and advice, including increased base funding for fundamental neutron science research, construction of a Fundamental Neutron Physics Beamline (FNPB) at the SNS, and funding of Research and Development (R&D) that has resulted in better estimates of the experimental sensitivity, and cost and schedule of a nEDM experiment that could be mounted at the FNPB.

Several precision neutron beta-decay experiments, both in the United States and abroad, have since provided new insight into some of the important questions that were identified in the 2003 report. New experiments are also in the proposal and/or planning stage.

In view of these developments since 2003, NSAC is again requested to examine and evaluate the broad suite of neutron physics research opportunities and how they complement other fundamental symmetry measurements that test the Standard Model, to identify the most compelling opportunities in this field, and make recommendations of priorities consistent with projected resources. It is important that the available resources are directed by NSF and DOE to the optimal investments for a strong national research program in this scientific area for the coming decade.

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Your report should identify the most compelling scientific opportunities, and the infrastructure and effort required to address them. Your assessment should be made in the context of existing and planned scientific efforts and capabilities in the United States and elsewhere. It should establish priorities for these opportunities with constant level of effort for neutron science research at the FY 2011 Congressional Request level, and should recommend priorities for incremental investments beyond this level. An assessment of the current scientific and technical workforce committed to these activities is requested, as well as the incremental workforce needed for further investments. 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, 2011, and a written report responsive to this charge be provided by September 2011.

Sincerely,

W. F. Brinkman
Director
Office of Science

Edward Seidel
Assistant Director
Directorate for Mathematical
and Physical Sciences

## Appendix B: Subcommittee Membership

**Professor Hartmut Abele**
Technische Universität Wien (Vienna)
Atominstitut der Ősterreichischen
Universitäten

**Professor Alejandro Garcia**
Department of Physics
University of Washington

**Professor John Hardy**
Department of Physics & Astronomy
Texas A&M University

**Professor Wick Haxton**
Department of Physics
University of California, Berkeley

**Professor David Hertzog**
Department of Physics
University of Washington

**Dr. Peter Jacobs**
Nuclear Science Division
Lawrence Berkeley National Laboratory

**Professor Krishna S. Kumar, Chair**
Department of Physics
University of Massachusetts, Amherst

**Dr. Zheng-Tian Lu**
Physics Division
Argonne National Laboratory

**Professor Michael Ramsey-Musolf**
Department of Physics
University of Wisconsin

**Professor Michael Romalis**
Department of Physics
Princeton University

## Appendix C: Open Meeting Agendas

### NSAC Neutron Physics Subcommittee

### Meeting Agenda April 1-2

*Final March 17*

**Start Duration End**

Friday April 1

| | duration | | | Speaker | talk length |
|---|---|---|---|---|---|
| 8:00 | 1:00 | 9:00 | Executive session | | |
| 9:00 | 1:30 | 10:30 | Science and experiment overview | P. Huffman | 60 |
| 10:30 | 0:15 | 10:45 | break | | |
| 10:45 | 0:30 | 11:15 | Statistical errors | B. Filippone | 20 |
| 11:15 | 0:45 | 12:00 | systematic errors | T. Ito | 30 |
| 12:00 | 1:30 | 13:30 | Executive session | | |
| 13:30 | 0:52 | 14:22 | R&D Overview | M. Cooper | 35 |
| 14:22 | 0:37 | 15:00 | 3He and Cryogenic Highlights | D. Beck | 25 |
| 15:00 | 0:30 | 15:30 | Break | | |
| 15:30 | 0:37 | 16:07 | HV Studies in Liquid He | J. Long | 25 |
| 16:07 | 0:30 | 16:37 | Prototyping of B0 Magnet System | A.P. Galvan | 20 |
| 16:37 | 0:22 | 17:00 | MC Simulation of EDM Signal | B. Plaster | 15 |
| 17:00 | 1:30 | 18:30 | Executive session | | |
| 18:30 | 0:15 | 18:45 | Overnight Homework assigmment | | |

Saturday April 2

| | | | | | |
|---|---|---|---|---|---|
| 8:00 | 0:30 | 8:30 | Collaboration response to questions; Q&A | | |
| 8:30 | 0:45 | 9:15 | International Context | B. Filippone | 30 |
| 9:15 | 0:30 | 9:45 | FNPB Context | G. Greene | 20 |
| 9:45 | 0:37 | 10:22 | Cost and Schedule Overview | V. Cianciolo | 25 |
| 10:22 | 0:22 | 10:45 | Optimizing nEDM Proj. Management | G. Capps | 15 |
| 10:45 | 0:30 | 11:15 | Break | | |
| 11:15 | 0:30 | 11:45 | Collab. Responsibilities/commitments | R. Redwine | 20 |
| 11:45 | 1:00 | 12:45 | Executive session | | |
| 12:45 | 0:30 | 13:15 | Closeout with Collaboration | | |
| 13:15 | 4:00 | 17:15 | Executive session | | |

| Friday April 15 | | | | | |
|---|---|---|---|---|---|
| | | | | | |
| Start | Duration | End | | Speaker | Talk Duration |
| 8:00 | 1:00 | 9:00 | Executive session | | |
| 9:00 | 0:30 | 9:30 | NIST Facilities Perspective | M. Arif | 20 |
| 9:30 | 0:30 | 10:00 | LANL Facilities Perspective | S. Wilburn | 20 |
| 10:00 | 0:30 | 10:30 | ORNL Facilities Perspective | G. Greene | 20 |
| 10:30 | 0:15 | 10:45 | Break | | |
| 10:45 | 1:15 | 12:00 | UCNA, B, b | A. Young | 50 |
| 12:00 | 1:35 | 13:35 | Executive session/lunch | | |
| 13:35 | 0:50 | 14:25 | The Nab/abBa/PANDA program | D. Pocanic | 35 |
| 14:25 | 0:25 | 14:50 | Polarization and Polarimetry in abBA/PANDA | T. Chupp | 15 |
| 14:50 | 0:25 | 15:15 | aCORN | F. Wietfeldt | 17 |
| 15:15 | 0:25 | 15:40 | NIST radiative decay | R. Cooper | 17 |
| 15:40 | 1:20 | 17:00 | Executive session | | |
| 17:00 | 0:30 | 17:30 | NIST trap-based lifetime | H. P. Mumm | 20 |
| 17:30 | 0:25 | 17:55 | NIST beam-based lifetime | J. Nico | 17 |
| 17:55 | 0:25 | 18:20 | LANL UCN lifetime | A. Saunders | 17 |
| 18:20 | 1:00 | 19:20 | Executive Session | | |
| | | | | | |
| Saturday April 16 | | | | | |
| | | | | | |
| Start | Duration | End | | | |
| 8:00 | 1:00 | 9:00 | Executive Session | | |
| 9:00 | 0:15 | 9:15 | What will we learn from HWI | D. Bowman | 10 |
| 9:15 | 0:24 | 9:39 | NPDgamma | D. Bowman | 16 |
| 9:39 | 0:25 | 10:04 | n-4He spin rotation experiment at NIST | M. Snow | 17 |
| 10:04 | 0:25 | 10:30 | n-3He experiment at SNS | C. Crawford | 17 |
| 10:30 | 0:30 | 11:00 | Break | | |
| 11:00 | 0:30 | 11:30 | emiT + future D-coefficient | J. Wilkerson | 20 |
| 11:30 | 0:45 | 12:15 | neutron interferometry | M. Huber | 30 |
| 12:15 | 1:00 | 13:15 | Executive Session/lunch | | |
| 13:15 | 0:15 | 13:30 | Closeout | | |
| 13:30 | 3:30 | 17:00 | Executive session | | |