Fundamental Physics with Cold Neutrons

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Experimentation using cold neutrons is an integral part of studies spanning fields as diverse as nuclear and particle physics, fundamental symmetries, astrophysics and cosmology, and gravitation [1–9]. The field possesses a coherence that derives from the unique properties of the neutron as an electrically neutral, strongly interacting, long-lived unstable particle that can be used either as a probe or an object of study. Experiments include measurement of neutron-decay parameters as tests of the Standard Model (SM), the use of parity violation to isolate the weak interaction between nucleons, and searches for a source of time-reversal violation beyond the SM. These experiments provide information that is complementary to that available from accelerator-based nuclear and particle physics facilities. Neutron physics measurements also address questions in astrophysics and cosmology. The theory of Big Bang Nucleosynthesis needs the neutron lifetime and the vector and axial vector weak couplings as input, and neutron cross sections on nuclei are necessary for a quantitative understanding of element creation in the universe.

The approach to this class of experiments requires performing measurements with a high degree of statistical precision. A large fraction of the experiments using cold neutrons is statistically limited. Thus, in order for progress to be made, it is critical that more intense sources of neutrons be made available. The experiments that probe these questions are largely performed at reactors or spallation sources that are able to generate large densities of cold neutrons. In the US, the three primary facilities where experiments can be done are at the Spallation Neutron Source at ORNL, the NIST Center for Neutron Research, and the LANSCE facility at LANL. It is important to note that the operational costs of the facilities are not borne by the DOE or NSF nuclear physics programs. Thus, there is a very cost-effective use of research funding directly for the science. This brief note presents some of the current research efforts in the US and well as the anticipated program extending approximately five years from now. The principle scientific priorities in the 2011 NSAC report by the subcommittee on Fundamental Physics with Neutrons [10] that are relevant to cold neutrons are included here. A few of the recent accomplishments in the field are also mentioned.

The last decade has seen advances in the quantitative understanding of nuclei, especially few body systems, and in the connection between nuclear physics and quantum chromodynamics (QCD). Low energy properties of nucleons and nuclei, such as weak interactions in n-A systems, low energy n-A scattering amplitudes, and the internal electromagnetic structure of the neutron are becoming calculable in the SM despite the strongly interacting nature of these systems. These theoretical developments are motivating renewed experimental activity to measure undetermined low energy properties, such as the weak interaction amplitudes between nucleons, and to improve the precision of other low energy neutron measurements.

Independent of the theoretical model, several experimental approaches are required to narrow the range of the predictions. There are two mature experimental efforts that are able to provide input. One is the NPDGamma experiment, which measures the gamma-ray asymmetry in the process p(n,γ)d. It had a successful run at LANL, demonstrating that the systematics were tractable at an acceptable level, but the measurement was statistics limited [11]. The experiment moved to the SNS where there is a significantly higher cold neutron flux, and it is currently acquiring data on the asymmetry with the liquid hydrogen target. The goal of the experiment is to measure the asymmetry at the level of 1×10^{-8}. The other experiment seeks to measure the parity-violating spin rotation of a polarized neutron beam through a liquid helium target. It ran on the NG-6 beam at NIST where it was statistics limited as well [12]. It is currently undergoing an upgrade and will run next on the higher flux NG-C beam. The goal is to measure the rotation angle at the level of $< 2 \times 10^{-7}$ rad/m. The experiments are largely complementary in terms of their sensitivity to the effective field theory parameters (or meson exchange amplitudes). Improved measurements from both experiments are essential to produce parameters that can be extracted in a theoretically clean manner. The successor experiment to NPDGamma at the SNS is an experiment to look at the asymmetry in the $\vec{n}$-^{3}He system [13].

Neutron decay is an important process for the investigation of the Standard Model of electroweak interactions. As the prototypical beta decay, it is sensitive to certain SM extensions in the charged-current electroweak sector. Neutron decay can determine the Cabibbo-Kobayashi-Maskawa (CKM) matrix element $|V_{\mathrm{ud}}|$ through increasingly precise measurements of the neutron lifetime and the decay correlation coefficients. The best determination of $|V_{\mathrm{ud}}|$ comes from superallowed nuclear decays [14], but neutron beta decay offers a somewhat cleaner theoretical environment than the superallowed transitions due to the absence of other nucleons (although some radiative corrections are common to both systems). Presently, the experimental uncertainties from the neutron measurements are significantly larger than those from superallowed decays and arise from systematic uncertainties, more specifically there are disagreements among experiments. Once those systematic effects are sorted out, modest improvements in the statistical precision will enable the precision of neutron experiments to be comparable to that obtained from the nuclear decays.

The angular correlation between the beta electron and antineutrino in nuclear beta decay is characterized by the dimensionless parameter a. It has the same sensitivity as the beta asymmetry A to the ratio of the weak coupling constants g_A and g_V, but it is less well known. It also does not require polarized neutrons. The aCORN experiment is currently carrying out an experiment at NIST using a new method that relies on constructing an asymmetry that directly yields a without requiring precise proton spectroscopy [15]. The goal is to achieve a 2 % relative measurement of a on NG-6 before moving the apparatus to the new beam NG-C in early 2013 where the fluence rate should be roughly five times higher and a 0.5 % measurement possible.

The Nab experimental collaboration proposes high precision measurements of the a and b (Fierz interference) coefficients in neutron beta decay at the level of 0.1 % [16]. The apparatus will be designed using a novel electric and magnetic field spectrometer [17]. Such a measurement would significantly improve determinations of the weak coupling constants g_A and g_V from neutron decay and place important new limits on tensor and scalar weak couplings. The collaboration has received funding to design and construct the magnetic spectrometer and work is proceeding. A prototype of the custom segmented silicon detectors has been tested using protons with very good results. The current plan is that Nab would run at the SNS after the completion of the $\vec{n}$ - ^{3}He experiment.

For several years, there has been uncertainty in the value of the neutron lifetime [18] at a level beyond the uncertainty quoted in the Particle Data Group. This ambiguity is unacceptable. A number of proposals have been put forth for new experiments to resolve the situation, but with the exception of one experiment [19], all the experiments involve trapped or confined ultracold neutrons. The most precise cold neutron beam determination of the neutron lifetime was based on the absolute counting of decay protons, and the largest uncertainty was attributed to the uncertainty of the fluence monitor efficiency. Recent success in the absolute counting of neutrons at the 0.1 % level has removed the most significant obstacle to improving the precision of beam experiment. As a result, a new effort is underway to measurement the neutron lifetime at the 1 s level using a cold beam at NIST. The apparatus is anticipated to be ready for beam within approximately 2 years.

Searches for violations of time-reversal symmetry and/or CP symmetry address issues which lie at the heart of cosmology and particle physics. The next generation of neutron electric dipole moment (EDM) searches, which plan to achieve sensitivities of $10^{-27}\, e \cdot \mathrm{cm}$ to $10^{-28}\, e \cdot \mathrm{cm}$, is the most important of a class of experiments aiming to search for new physics in the T-violating sector. One of major efforts to improve the limit using ultracold neutrons via the superthermal process [20] is being planning for the SNS [21]. Thus far, all observations of CP violation can be entirely accounted for by a phase in the Cabbibo-Kobayashi-Maskawa matrix; however, this phase is insufficient to account for the known baryon asymmetry in the context of Big Bang cosmology, and there is good reason to search for CP and the related time-reversal violation in other systems. Because neutron beta-decay is theoretically straightforward and final state interactions are generally small and calculable [22], the neutron is clean system in which to look for the effects of new physics. The emiT experiment recently published the most restrictive limit of time-reversal invariance in beta decay [23]. Taking advantage of higher flux cold neutron sources, one could conceive of making a factor of 10 improvement and nearing the final state corrections although at present there is no plan to mount another experiment.

A neutron can β-decay with the emission of an accompanying soft photon. At present, the comparison of the empirical branching ratio with theory reveals that experiment probes just the inner bremsstrahlung component of the decay [24]. It would be interesting to probe nonleading order contributions to the decay. For example, radiative beta decay can be used to probe the triple product correlation $\mathbf{l_p} \cdot (\mathbf{l_e} \times \mathbf{k})$, where $\mathbf{l_p}$ and $\mathbf{l_e}$ are the proton and electron momenta, respectively, and $\mathbf{k}$ is the photon momentum [25]. The correlation is naively time-reversal-odd and parity-odd, and it probes the imaginary part of the interference of the Harvey, Hill, and Hill interaction [26], with the leading contribution from the weak vector current. Under an assumption of CPT symmetry, the correlation probes sources of CP violation beyond the standard model. The correlation induced by electromagnetic final-state interactions has been recently computed [25]; after integrating over the full final-state phase space it would be $\mathcal{O}(10^{-5})$ for a photon-energy threshold of 15 keV as per Ref. [24] with a relative accuracy of $\mathcal{O}(10^{-3})$.

Quantum chromodynamics describing the strong interaction between quarks is non-perturbative making rigorous direct calculations at low energies impossible. Instead complex, multi-parameter phenomenological models have been developed to tackle nucleon-nucleon (NN) interactions. At the Neutron Interferometer and Optics Facility at NIST, there is a program of experiments to provide data to test the predictions. Recent experiments have yielded precision measurements of scattering lengths in low A systems (H, D, ^{3}He, and $^3\vec{\mathrm{He}}$). New experiments are in progress or planned for ^{4}He and T. In addition, there is an idea to use ultracold neutrons with noble gas admixtures as a probe of long-range nuclear forces [27]. In order to yield meaningful constraints, such measurements require accurate knowledge of the noble gas scattering lengths. As a result, there are investigations in progress to perform precision measurements of the scattering lengths of Ar and Ne within the next few years. Finally, an experimental effort has commenced to measure the neutron mean square charge radius using a novel approach in neutron interferometry [28].

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