Ultracold Neutron Physics at the Los Alamos National Laboratory

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Los Alamos National Laboratory uses one of the highest density sources of ultracold neutrons in the world to perform precision measurements in neutron decay. The UCNA experiment's most recent dataset is expected to determine the beta asymmetry with half-percent uncertainty. Currently in progress are the UCNB experiment to measure the neutrino asymmetry, and the UCNτ experiment to measure the neutron lifetime. Finally, a new effort is underway to improve the sensitivity to the neutron EDM by an order of magnitude.

1 The UCN source at LANSCE

The ultracold neutron (UCN) facility at the Los Alamos Neutron Science Center (LANSCE) is used for a number of precision studies of the electroweak interaction through the decay of the neutron and the search for symmetry violations that could generate an electric dipole moment. UCN have energies of less than about 300 neV or 4 mK temperature, rendering them sensitive to all four of the fundamental forces at levels achievable in the laboratory. They are completely reflected by some material potentials, are constrained to heights of about 3 m by gravity, can be completely polarized by magnetic fields of about 6 T due to the neutron's magnetic moment, and decay due to the weak interaction with an experimentally convenient lifetime of about 15 minutes.

The pulsed 800 MeV proton beam from the LANSCE linear accelerator incident on a tungsten target produces spallation neutrons, which are moderated in graphite and cold polyethylene. The resulting cold neutrons can then single scatter in a solid deuterium crystal and convert into UCN. The UCN then escape the source, which is subsequently closed off by a butterfly valve, and are transported by a stainless steel guide system out of the biological shielding into the experimental area, where densities of up to 50 UCN/cc have been achieved [1].

2 UCNA

One of the most important tests of our understanding of the electroweak interaction is the unitarity of the Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix, which is sensitive to new physics beyond the Standard Model [2]. The matrix element V_{ud} contributes to the most precise such test. In neutron decay, two measurements are required to extract V_{ud}: the lifetime and a correlation coefficient, such as the asymmetry between the neutron spin and the emitted electron, A, to set the value of λ, the ratio of axial-vector to vector couplings. Currently, V_{ud}

is determined most precisely from the set of superallowed $0^+ \rightarrow 0^+$ Fermi decays [3]. It is extracted from neutron decay with about an order of magnitude greater uncertainty, primarily due to the uncertainty in λ. However, as the neutron is not sensitive to nuclear-structure dependent corrections, with reduced experimental error this system should be able to achieve a lower ultimate uncertainty.

The UCNA experiment is the first to determine the beta asymmetry A using UCN. The UCN are 100% polarized by a 6 T superconducting magnet and adiabatic fast passage spin flipper. The UCN are bottled by a copper guide with thin, beryllium foil end caps inside a 1 T decay spectrometer, which aligns their spins along the spectrometer axis. The decay electrons are guided along the magnetic field lines to a detection system consisting of multi-wire proportional chambers for position sensitivity and fast timing for backscatter reconstruction, and plastic scintillators for energy determination.

The most recent published result, resulting in the extraction of $\lambda = -1.2756(30)$, includes 20M beta decay events after all cuts applied, and a total systematic uncertainty of 0.8% and statistical uncertainty of 0.5% [4]. The most important uncertainties include the rate of depolarization of UCN, the backscattered fraction of electrons, and the determination of the electron energy as a function of angle. Several improvements significantly reduced the uncertainty of the 2011-2013 data set, now in analysis. A shutter installed between the polarizing 6 T magnet and the decay trap allowed for an improved determination of depolarization fraction. Thinner foils for the end caps on the decay trap reduced both the backscatter correction and uncertainty. A fast timing source using an avalanche photodiode to detect the Auger from ^{113}Sn in coincidence with the monoenergetic conversion electrons detected by the UCNA detectors improved characterization of scattering and energy loss as a function of pitch angle. Finally, calibrations using xenon and LED studies improved the uncertainty of the energy reconstruction. The systematic uncertainty is expected to improve by almost a factor of 3 in this data set, and is statistics limited. Future ventures to improve the determination of A would require a significant improvement in the neutron decay rate.

3 UCNτ

The lifetime of the neutron is a necessary input to extract V_{ud} along with the beta asymmetry, and is also a critical input for predicting the primordial helium abundance in the early universe. The accuracy of the determination of the lifetime is called into question by the current discrepancy between the lifetime as measured by either beam or bottle experiments, of about 8 s out of ~880 s [5]. One important uncertainty in previous material bottle traps is the determination of the wall loss due to the material interactions. A magneto-gravitational trap eliminates all material interactions and significantly reduces this effect. The asymmetric shape also mitigates the effect of quasi-bound orbits which are not quickly cleaned and are not completely trapped, and can be lost at similar time scales to the decay lifetime. A storage time of $\tau_{store} = 860 \pm 19$ s has recently been demonstrated in the trap [6], and new methods for UCN detection within the trap are being developed. The current apparatus is being developed for a 1 s measurement of the neutron lifetime, ultimately leading to the design of a sub-1-s experiment.

4 UCNB

The correlation between the neutron spin and the neutrino direction B is sensitive to possible scalar and tensor currents predicted by theories beyond the Standard Model [7]. The neutrino direction must be determined from the decay proton and electron detected in coincidence. A greater sensitivity to b_ν, the electron energy dependent component of a scalar/tensor contribution to B, can be obtained by taking the ratio of the proton and electron asymmetry. By performing a simultaneous fit to the observed electron energy spectra for each proton/electron direction, the proton/electron asymmetries, and the spin-averaged electron energy spectrum, b, b_ν and λ can be extracted simultaneously with precision at the 10^{-3} level from 10^8 total decays [8].

The UCNB experiment uses novel 2 mm thick, large area (12 cm diameter active area), highly segmented (127 hexagonal pixels) silicon detectors installed in the UCNA spectrometer to detect the electron and proton from neutron beta decay in coincidence [9]. The detection system was developed in collaboration with the Nab experiment [10], which will measure the electron-neutrino correlation and Fierz interference term b at the Spallation Neutron Source. Custom preamplifiers are being developed which must meet the requirements of fast timing ($\sim$10 ns) for distinguishing electron backscatter events and very low noise to detect the protons. The protons are emitted with less than 800 eV and could not pass the deadlayer of the detector. Therefore they are accelerated by a -30kV high voltage bias applied to the detection system, including detector and mounting structure, preamplifiers and data acquisition system.

This detector has achieved the first direct observation of both the proton and electron from neutron beta decay in coincidence, using an 8 channel prototype preamplifier. The system can clearly resolve signals above 20 keV with 3 keV (σ) resolution, sufficient for triggering on proton events. A 24 channel prototype has been developed with improved noise characteristics and faster rise time of 20 ns, and after successful demonstration with neutron beta decay, the full 128 channel (127 pixels + ganged partial pixels) system will be implemented. The system has been operated stably at -30 kV and in the 0.6 T expansion region for 100 hours without damage to detectors or electronics. The detector connections can be mechanically damaged during installation, however. A new design using pogo-pin style connectors similar to those used in KATRIN [11] has been tested using 1 cm diameter prototype silicon detectors and have been demonstrated to be robust with many mechanical and cooling cycles. Full-size detectors fully instrumented with pogo-pins are now in development.

5 LANL nEDM

The existence of an electric dipole moment (EDM) in a non-degenerate system requires a violation of time and parity and is a clear indication of the presence of new physics, especially regarding the important question of the observed baryon asymmetry in the universe. Searches for EDMs provide sensitive tests of Beyond the Standard Model theories well beyond the reach of the LHC [12]. The most precise search for an EDM in the neutron was performed at the ILL, using Ramsey's method of separated oscillatory fields. The UCN spins were rotated into the plane perpendicular to the magnetic field, allowed to precess with an electric field aligned parallel and anti-parallel to the magnetic field, then rotated to complete the spin flip. This experiment achieved the limit $d_n < 2.9 \times 10^{-26}$ e-cm (90% C.L.) [13]. To improve this limit, an increase in density to about 100 UCN/cc is required.

With modest improvement to the LANSCE UCN source, the required UCN density for a 10^{-27} e-cm sensitivity is achievable. The most straightforward gains, of about a factor 3, come from improvement in the proton beam delivery and in increasing the current. Currently the proton pulse structure consists of a large burst every 5 s, resulting in significant UCN losses as UCN that fail to escape the source volume before the next beam burst fall back into the solid deuterium crystal when the butterfly valve reopens. Increasing the period to 30 s significantly reduces this loss, but requires an upgrade to beam safety hardware that inaccurately measures the average current, which still falls short of the design specification of 10 μA. A redesign of the UCN source, including better modeling of the moderator configuration, improved cooling, and moving the deuterium closer to the tungsten target is expected to deliver another factor of 2 improvement. Improved transport of the UCN out of the source volume and through the guide system should increase the density by a factor of 3 or more. To take advantage of the increased density, further improvements to the ILL design will be implemented. A prototype high voltage chamber is currently being constructed to test improvements to the geometry and materials used in the electrodes to permit an electric field greater than 10 kV/cm during precession. The PSI collaboration has demonstrated the required improvements to the magnetometry using a ^{199}Hg co-magnetometer to look for variations in the magnetic field over time [14].

6 Summary

The LANSCE UCN facility has a vibrant program for fundamental symmetries and precision searches for physics beyond the Standard Model. The facility was designed to allow for very low background measurements of polarized neutron decay correlations, especially the beta-asymmetry and neutrino-asymmetry, and has expanded to support efforts to determine the neutron lifetime and a search for an electric dipole moment. Planned upgrades to proton beam delivery and source performance will ensure this facility remains one of the most competitive UCN sources in the world.

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