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Production and Storage of Ultra Cold Neutrons in Superfluid Helium

Geoffrey L. Greene,* and Steve Lamoreaux

Abstract

This is the final report of a one-year, Laboratory Directed Research and Development (LDRD) project at the Los Alamos National Laboratory (LANL) concerning the investigation of a new method for the experimental exploitation of ultra-cold neutrons. The production and storage of ultra cold neutrons in superfluid helium has been suggested as a tool for the production of high densities of ultra cold neutrons for fundamental nuclear physics as well as for sensitive measurements for condensed matter. A particular application of this technique has been suggested by Doyle and Lamoreaux [1] that involves the trapping of neutrons in a magnetic field within the superfluid helium volume. Neutron decays within the trap volume are detected by the scintillation light produced in the liquid helium. A cryostat and magnetic trap have been constructed as well as a prototype light detection system. This system was installed on a cold neutron beam line at the NIST Cold Neutron Research Facility in the summer of 1997. Preliminary results indicate the detection of helium scintillation light from the detection vessel.

Background and Research Objectives

The beta decay lifetime of the neutron is a parameter of great importance in nuclear physics, particle physics, astrophysics and cosmology. An improvement in the experimental determination of the neutron lifetime would have important implication for tests of the "Standard Model" of particle physics. To date, the most accurate determinations of the neutron lifetime have used "ultra-cold" neutrons (UCN) [2] confined in "bottles" having material walls. Such measurements are ultimately limited by the ability to measure the loss rate of UCN on the wall. The current effort represents a new approach in which the UCN are created and stored in a magnetic bottle, which employs the interaction between inhomogeneous magnetic fields and the neutron's magnetic moment to confine the neutrons without material walls. The purpose of the funded activities was to carry out initial tests of this concept. Ultimately it is hoped that this approach will lead to measurement of the neutron lifetime with significantly reduced uncertainty.

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Importance to LANL's Science and Technology Base and National R&D Needs

Nuclear physics is one of LANL's core competencies and neutron science is one of its strategic goals. The effort to determine the neutron lifetime is thus directly pertinent to the Laboratory mission. It should also be noted that activities related to the determination of the neutron lifetime have been endorsed and supported by both the NSF and the DOE Division of Nuclear and Particle Physics.

Scientific Approach and Accomplishments

The free neutron is an unstable elementary particle that beta decays into a proton, an electron and an anti-neutrino with a mean lifetime of about 10 minutes. The beta decay of the neutron may be considered to be the archetype for all nuclear beta decay and its rate (i.e. the reciprocal of the mean life) provides a fundamental measurement of the strength of the weak nuclear force. An accurate value of the neutron lifetime is of importance to a wide variety of disciplines including nuclear theory, particle physics, nuclear astrophysics and cosmology.

Currently, the most accurate determinations of the neutron lifetime have employed so-called UCN "bottles" having material walls. Very low energy neutrons (kinetic energies on the order of 100 neV) can be confined in such bottles due to the coherent nuclear scattering from the material wall. In principle, the lifetime measurement is made by filling the bottle, waiting a known time (typically a few minutes to perhaps an hour), and then opening the bottle and counting the number of remaining neutrons. While in principle quite simple, this method is ultimately limited by systematic errors associated with the loss of UCN on the walls of the bottle. The ideal UCN bottle would involve a method whereby the UCN are totally confined without the use of material walls.

Recently, Doyle and Lamoreaux [1] proposed a method to trap neutrons in a "magnetic" bottle, which confines the UCN through the interaction of an inhomogeneous magnetic field and the neutron's magnetic dipole moment. Such a bottle has no material wall and all possible loss mechanisms are well understood. Thus it should be possible to attain a significant improvement in the experimental measurement of the neutron lifetime.

The actual approach used in this work involved the use of a liquid-helium-filled magnetic dipole trap. The liquid helium serves two important functions for the experiment. First it serves as the medium for the production of ultra cold neutrons. Secondly it serves as the detection medium for neutron decay. In the experiment, UCN are produced by down scattering of neutrons having energies of about 1 meV (approximately 10,000 times the energy of typical UCN). Neutrons of this energy can easily pass through the cryostat containing the liquid helium and, if they down scatter, they will be trapped in the magnetic bottle. If such a trapped neutron decays in the liquid helium, it will create UV scintillation light that can be detected using low-noise photon detectors. If the liquid helium is extremely pure (i.e. very little ^{3}He), there is essentially no loss due to interactions with the helium itself.

As the initial step in this experiment, a suitable magnetic UCN trap (fabricated at Harvard University) was installed on a low-energy neutron beamline at the National Cold Neutron Research Facility at NIST in Gaithersburg, Maryland. The purpose of the initial test was to confirm that the scintillation light from neutron decay would be visible when the magnetic trap was subjected to the 1-meV neutron beam. The apparatus was successfully deployed at NIST and scintillation light was detected. However, the background count rate was higher than anticipated due to the observation of previously unknown excitations in the shielding material. The initial test was extremely important in determining what material is suitable for a final measurement. This work is now continuing with support from the National Science Foundation and NIST.

References

[1] Doyle, J. and Lamoreaux, S. "On Measuring the Neutron Beta Decay Lifetime of the Neutron using Ultracold Neutrons Produced and Stored in a Superfluid ^{4}He filled Magnetic Trap," *Europhysics Letters* **58**, 253-258 (1994).

[2] Golub, R., Richardson, D., and Lamoreaux, S., Ultra-Cold Neutrons, Adam Hilger, Bristol (1991).