MAGNETIC TRAPPING OF ULTRACOLD NEUTRONS

The demonstration of three-dimensional magnetic trapping of neutrons was performed this past year at NIST [1]. The techniques developed should lead to improved precision in the measurement of the neutron beta-decay lifetime, thereby expanding our knowledge of the weak nuclear force and our understanding of the creation of matter during the Big Bang.

Magnetic traps are formed by creating a magnetic field minimum in free space. The confining potential depth is determined by the magnetic moment of the neutron and the difference between the magnitude of the field at the edge of the trap and at the minimum. A neutron in a low-field-seeking state (one with its magnetic moment anti-aligned with the local magnetic field vector) feels a force pushing it towards the trap minimum and will remain confined within the trapping region.

In order to load a neutron into a static conservative trap, its energy must be lowered while it is in the potential well. We rely on a loading technique that employs the “superthermal process” [2]. Superfluid helium fills the trapping region and serves as a neutron scattering medium. A neutron with kinetic energy near 11 K (where the free neutron and Landau-Feynman dispersion curves cross) that passes through the helium can lose nearly all of its energy in a single scattering event. Neutrons that scatter to energies less than the trap depth (1 mK) and in the appropriate spin state are trapped. Neutrons in this energy range are called ultracold neutrons (UCN).

Isotopically pure superfluid helium is contained in a tube located inside the superconducting magnet and centered axially within its trapping field (see Fig. 1). The superconducting magnet, trapping region, and other key parts of the apparatus reside within a cryogenic dewar. The incident neutron beam is collimated, passes through the trapping region, and is absorbed by the beam stop. As the beam traverses the trapping region, about 1 % of the neutrons scatter in the helium. Some of these neutrons are trapped and the remainder are absorbed by shielding materials that surround the helium. Low-field-seeking UCN are trapped and remain in the trapping region until they decay.

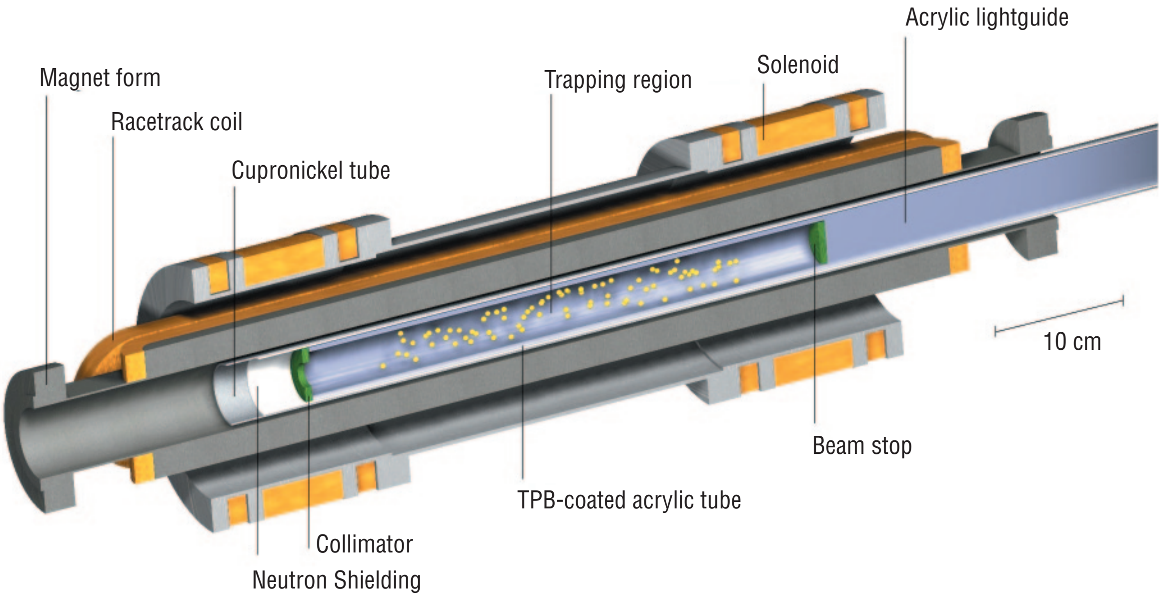

FIGURE 1. Half-section view of the neutron trapping apparatus. A beam of cold neutrons enters from the left, is collimated, passes through the trapping region and is absorbed at the rear. Scattered neutrons (yellow) in the low-field-seeking spin state and with energy below the trap depth are magnetically confined. Electrons from neutron beta-decay create EUV scintillations in the superfluid helium which are wavelength shifted to the visible and transported to the photomultiplier (to the right).

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The trapped neutrons are detected when they decay. When a trapped neutron decays (into an electron, proton and anti-neutrino), the resulting high-energy electron travels through the helium leaving a trail of ionized helium atoms. These ions quickly combine with neutral helium atoms to form metastable diatomic molecules. Most of these molecules decay within 10 ns, emitting a pulse of light in the extreme ultraviolet (EUV), $\lambda \approx 70$ nm to 90 nm. This pulse of scintillation light is the signal of a neutron decaying in the trap.

In an experimental run, the cold neutron beam is allowed to pass through the trapping region, after which the beam is blocked and pulses of light are counted. A background signal, with both constant and time-varying components, obscures the trapped neutron signal. These backgrounds are subtracted by collecting data where the magnetic field is on during the initial loading phase, so that UCN are confined by the trap and subtracting data where the magnetic field is off initially, so that no neutrons are trapped. Equal numbers of each data set were taken, pooled and subtracted to give the background subtracted data.

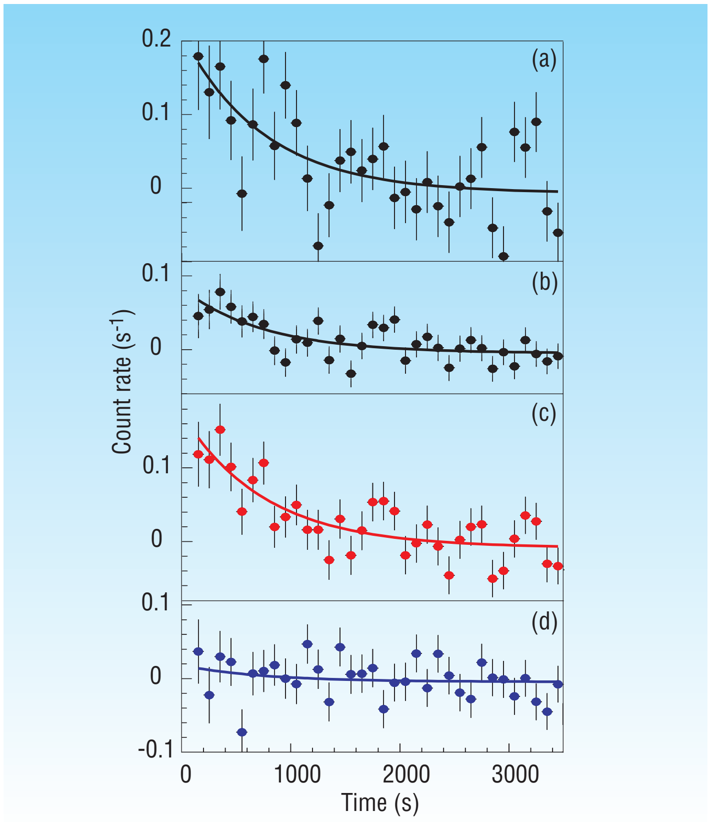

FIGURE 2. Counting rate as a function of time after the neutron beam is turned off (pooled background subtracted data). (a) Trapping data set I, $N_I = 560 \pm 160$, (b) Trapping data set II, $N_{II} = 240 \pm 65$, (c) Combined trapping signal, $\tau = 750^{+330}_{-200}$ s, (d) Combined ^{3}He data, $N_{3He} = 53 \pm 63$.

Two sets of background subtracted data were collected: set I with a trap depth of 0.76 mK (Fig. 2a) and set II with a lower trap depth of 0.50 mK (Fig. 2b) due to problems with the magnet. For each set, the pooled background subtracted data are modeled to extract the amplitude and lifetime of the decaying neutron signal. The best fit values for the initial counting rates combined with the measured detection efficiency gives $N_I = 560 \pm 160$ and $N_{II} = 240 \pm 65$. Calculations using the known beam flux, trap geometry and the theory of the superthermal process predict $N_I = 480 \pm 100$ and $N_{II} = 255 \pm 50$, in good agreement with the measured values. The best fit value for the trap lifetime, $\tau = 750^{+330}_{-200}$ s, is consistent with the presently accepted value of the neutron beta-decay lifetime of 886.7 ± 1.9 s [3].

To verify that our signal is in fact due to trapped neutrons, we doped the isotopically pure ^{4}He with ^{3}He at a concentration of 2×10^{-7} ^{3}He/^{4}He. This amount of ^{3}He absorbs the trapped neutrons in less than 1 s without affecting anything else in the experiment (less than 1 % of the cold neutron beam is absorbed by ^{3}He). The data (Fig. 2d) is modeled with the lifetime fixed at $\equiv 750$ s, yielding $N_{3He} = 53 \pm 63$, consistent with zero. This confirms that our signal is due to trapped neutrons.

Magnetic trapping of neutrons is a new technique that should allow a higher precision measurement of the neutron lifetime, and offers the prospect of precision much greater than the current limit of one part in 10^3. In order to realize the potential of this technique, we are in the process of improving our apparatus in many ways, including increasing the size and depth of the trap. We expect to make a competitive neutron lifetime measurement in the near future.

REFERENCES:

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

[3] Particle Data Group, "Review of Particle Physics," Eur. Phys. J. C **3**, 1 (1998).