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Physics Today **53** (4), 19–20 (2000);
https://doi.org/10.1063/1.883031

Ultracold Neutrons are Magnetically Trapped at NIST

Although the neutron was discovered in 1932, its lifetime wasn't measured until 18 years later, when nuclear reactors became available. Obtaining a precise measurement was a tough experimental challenge back then. John Robson was the first to report such a measurement—at the Chalk River reactor in Canada. Fifty years later, improving the precision is still challenging experimenters.

The 1998 *Review of Particle Physics* by the Particle Data Group gives the world average value of the neutron beta-decay lifetime as 886.7 ±1.9 s (about 0.2% uncertainty). A more precise value for the neutron lifetime would improve calculations of Big Bang nucleosynthesis by providing input for the primordial ratio of helium to hydrogen. A more precise value would also help to test the Standard Model of particle physics.

Recently John Doyle (Harvard University) and his collaborators—from Harvard, the National Institute of Standards and Technology, the Hahn-Meitner-Institut (HMI) in Berlin, and Los Alamos National Laboratory—have demonstrated that a new approach to measuring the neutron lifetime works: They confined ultracold neutrons in a three-dimensional magnetic trap.[1] The tour de force experiment was done at the NIST Center for Neutron Research in Gaithersburg, Maryland. Doyle regards this first result as a proof of principle, and at present the lifetime determination has large error bars—the value reported is 750^{+330}_{-200} s. But as Doyle and Steve Lamoreaux of Los Alamos discussed in the original proposal for the experiment, they believe that the technique will eventually yield a factor of 100 improvement in the precision of the world average value. And many features of the technique are suitable for a new attempt to observe the electric dipole moment of the neutron, a property predicted to be nonzero by many extensions to the Standard Model.

Other approaches

For many years, measured values for the neutron lifetime were consistently higher than the present world average, by at least 10%, says Michael Pendlebury (University of Sussex). They stayed high, even though the measurement errors were thought to have decreased. All the early measurements were done by creating a beam of neutrons, counting the number that passed through a well measured volume, and observing the rate of decay into a proton, an electron, and an antineutrino. Such an approach was very difficult because one had to make absolute determinations of the neutron flux, and of the number of either electrons or protons. The most precise lifetime measurement using this beam technique has been done at the Institut Laue–Langevin (ILL) in Grenoble, by a group led by James Byrne (University of Sussex). The value,[2] originally reported in 1990 and later revised in 1996, has an error of 4.8 s. A group of experimenters led by M. Scott Dewey at the NIST reactor hopes to improve the precision of beam measurements to 1 s.

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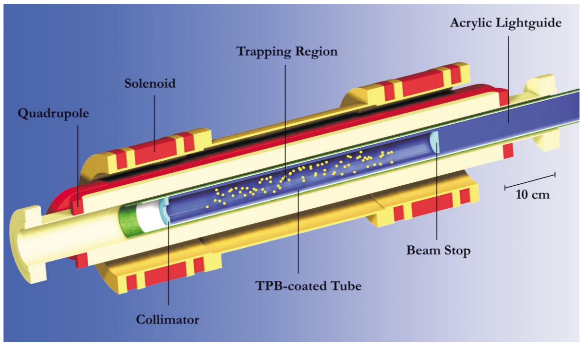


NEUTRON TRAPPING APPARATUS is filled with ^{4}He at 250 mK. A cold neutron beam enters the helium from the left and passes through the trap. About 1% of the 11-K neutrons scatter in the superfluid helium. Those neutrons (yellow) in the correct spin state and with low enough energy are magnetically confined. Superconducting magnets create the magnetic trapping field. Electrons from neutron beta decay cause EUV scintillations in the helium, which are wavelength shifted by the TPB-doped polystyrene coating. (Figure courtesy of Paul Huffman, NIST, adapted from ref. 1.)

In the mid 1980s, lifetime experiments involving trapping began. At first, ultracold neutrons were put into boxes, and the neutrons bounced against the walls due to the positive Fermi potential. Vassily Morozov (Kurchatov Institute in Moscow) and his colleagues pioneered this so-called bottle technique.[3]

Walter Mampe and his collaborators at ILL used bottled neutrons for the lifetime experiment called MAMBO-I. When you put neutrons in a box and watch them disappear, says MAMBO-I team member Pendlebury, you then need to open the door or insert a detector in the box to mop up the neutrons and count them. If you fill the box and detect after, say 10 s, fill again, detect after 1000 s, and take the ratio, you can measure the neutron lifetime independent of the detector efficiency. In practice, the neutrons also disappear through wall interactions. That, in turn, causes the neutron velocity distribution to evolve during storage. If you use boxes of two different sizes with different surface-area-to-volume ratios, you essentially get two simultaneous equations to solve—for the decay lifetime and the wall loss lifetime. But, says Pendlebury, "you need to be very cunning how you choose the times for which the neutrons are shut inside the two boxes. You choose the times so they're in the ratio of the surface-area-to-volume ratios of the boxes so that the number of wall collisions is the same in both the small and large boxes." The MAMBO-I value[4] was 887.6±3 s.

A new version of the experiment at ILL, called MAMBO-II, led by Klaus Schreckenbach (Technical University of Munich), aspires to reduce the error to 1 s. MAMBO-II's preliminary result[5] is 881±3 s. Another group at ILL, led by Lev Bondarenko (Kurchatov), has reported[6] a lifetime of 885.4±1.05 s.

A different approach is to store neutrons with specific trajectories and in a band of velocities (typically 10–14 m/s) in a magnetic storage ring similar to those used in high-energy physics. In the storage ring, the neutrons are confined radially, so they have a small radial velocity. But they have a very large axial velocity, so betatron oscillations can occur, in which the momentum in the axial direction gets transferred to the radial direction, producing enough energy to kick the neutrons out of the storage ring. Starting in 1977, Wolfgang Paul of the University of Bonn and his collaborators magnetically trapped neutrons in a storage ring at ILL. They designed their field configuration to minimize betatron oscillations and they also restricted the trapping volume. In 1989, they reported[7] a lifetime of 877±10 s.

Three-dimensional magnetic trap

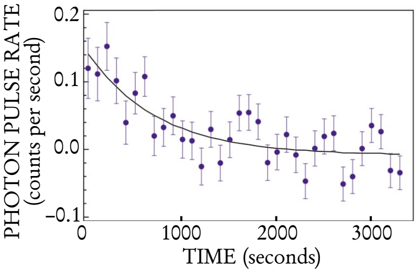
The new magnetic trapping experiment relies on the so-called superthermal process, pioneered 25 years ago by NIST team member Robert Golub (HMI) and Pendlebury. This process produces ultracold neutrons by inelastic scattering of cold neutrons (with an energy of 11 K) in superfluid ^{4}He.

The NIST researchers fill their three-dimensional trapping region with superfluid ^{4}He, which is used both to load the neutrons into the trap and as a scintillator to detect neutron decay. A beam of cold neutrons enters the long, sausage-shaped trapping region (see the figure on page 19). An assembly of superconducting magnets produces the trapping field. Radial confinement is provided by a quadrupole made from four racetrack-shaped coils, and axial confinement is provided by two sets of solenoids.

Neutrons with a critical momentum can be scattered to near rest by emission of a single phonon in the superfluid. The critical value corresponds to a neutron energy of 11 K. An 11-K neutron can enter the liquid helium, come to rest, and emit an 11-K phonon. Provided the helium temperature is low enough, the 11-K phonon dissipates into the helium. Once the neutrons are in the trap and are in the appropriate spin state, they stay in the trap because they don't interact with the helium at these low energies.

When a neutron decays, the electron is shot out like a bullet and produces diatomic helium molecules along its path. The helium dimers relax and emit extreme ultraviolet light, which is down-converted into visible light (blue). That light is detected with photomultiplier tubes.

In each experimental run, the cold-neutron beam passes through the trapping region for 1350 s, then the beam is blocked, and light pulses are counted for 3600 s. While the beam is on, neutrons interact with the helium, and the number of ultracold neutrons in the trap increases. When the beam is turned off, a background signal obscures the trapped-neutron signal. The background is subtracted by taking data for trapping runs and non-trapping runs (magnetic field off). The figure on this page shows the photon pulse rate as a function of time. By fitting to the exponential decay curve, the experimenters extract a neutron lifetime that is independent of the number of neutrons in the trap.



Photon Pulse Rate as a function of time after the neutron beam is turned off. By subtracting the background and fitting to the exponential decay curve, the experimenters at NIST extract a neutron lifetime. (Courtesy of P. Huffman, adapted from ref. 1.)

"The nice feature of the technique," says Berkeley experimenter Stuart Freedman, "is that it puts the neutron in a very clean environment. You do have to worry about how efficiently the magnet traps the neutrons, so there are some issues of potential systematic errors in this. But it's a change of course in a good direction, where there is a likely way of getting more precise neutron lifetimes. It also has the potential of trapping large numbers of neutrons. That's a problem with the other methods, which are pretty much maxed out on neutron density."

It might appear that because of an inhomogeneity in the magnetic field, there is some risk of a neutron flipping its spin (and thus being lost, because only one spin state is trapped). However, says Doyle, the experimenters can employ an additional axial field that brings the trap minimum to 0.2 T to suppress the rate of spin-changing transitions to the untrapped state.

In about a year, the experimenters expect to have upgraded their apparatus at NIST. They are increasing the size and depth of the trap to increase the number of trapped neutrons. Meanwhile, the NIST cold source will be upgraded, the apparatus will be moved closer to the cold source, and the detection efficiency is expected to be increased.

Ultracold neutrons at work

Lamoreaux, a member of the NIST trapping team, is working with a Los Alamos group to create a source of ultracold neutrons using solid deuterium. He and his collaborators plan to measure the neutron beta decay asymmetry parameter, A. With A and the neutron lifetime, one can extract uniquely the weak force coupling constants, g_A (axial vector) and g_V (vector). Byrne and his collaborators are doing a similar experiment at ILL, but they are measuring the electron neutrino angular correlation coefficient, a. With a and the neutron lifetime, one can also extract g_A and g_V.

Golub and Lamoreaux are studying superthermal production of ultracold neutrons in superfluid helium as a way to search for the neutron's electric dipole moment (EDM). The entire experiment would be done in a superfluid bath doped with a small concentration of polarized ^{3}He, which would serve as a polarizer, magnetometer, and ultracold neutron spin precession analyzer. Just as in previous EDM measurements, you put slowly precessing neutrons in a very high electric field, then reverse the field, and attempt to detect a shift in the precession frequency caused by the torque of the field on the neutron's EDM. According to Golub and Lamoreaux, the technique could provide a hundredfold improvement in sensitivity over the current experimental limits.

Impact on theory

Last year, Michael Turner (University of Chicago) and his collaborators carefully analyzed predictions of Big Bang nucleosynthesis. They found that the theoretical uncertainty in the predicted ^{4}He abundance has been reduced essentially to that in the neutron lifetime.[8]

Many extensions of the Standard Model predict detectable EDMs, some close to the current experimental limits. And, says theorist Frank Wilczek (Institute for Advanced Study), one of the most promising ways to probe for supersymmetry is to improve the current experimental limits on the neutron EDM.

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