Measurement of the Free Neutron Lifetime

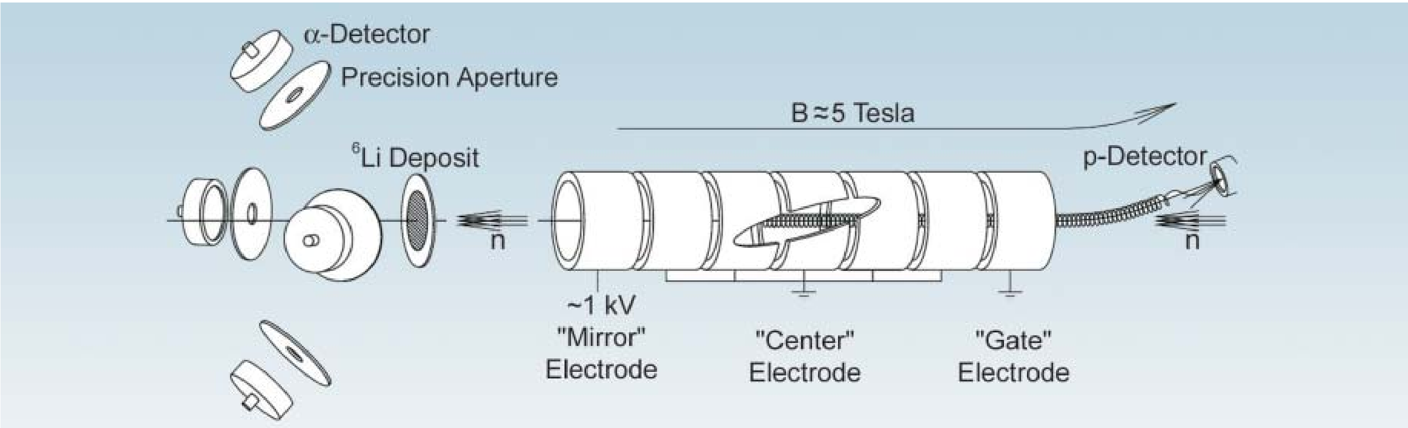

FIGURE 1. Schematic drawing of the NIST Penning trap neutron lifetime experiment.

Free neutrons are unstable and decay with a lifetime of about 15 minutes into a proton, an electron, and an antineutrino. Accurate determination of this natural lifetime is important for tests of the Standard Model of Fundamental Particles and Interactions, as well for understanding certain aspects of cosmology and astrophysics. The neutron lifetime influences the predictions of the theory of Big Bang nucleosynthesis for the primordial helium abundance in the universe and the number of different types of light neutrinos. Since the dominant uncertainty for the primordial helium abundance comes from the accuracy of the neutron decay rate [1], improved neutron decay rate measurements are needed for sharpening this prediction.

The measurement of the lifetime of free neutrons in a cold neutron beam was one of the first experiments operating in the NCNR Guide Hall. The experiment occupied the NG-6 Physics Station alternatively with other fundamental physics experiments through December 2000. A statistical precision of one part per thousand was achieved in the final result. An overall standard uncertainty of about four parts per thousand has been obtained, and that uncertainty may be eventually reduced by as much as a factor of two by ongoing developments in characterization of the neutron counting for this experiment.

Figure 1 shows a schematic diagram of the apparatus. An axial 5 Tesla magnetic field provides radial containment of the decay protons, while axial containment is achieved by the positive electrostatic charge on two end electrodes, called the mirror and the gate. This combination of magnetic and electrostatic fields is called a "Penning Trap." The neutron detector consists of a well-characterized isotopic target of ^{6}Li, viewed by a set of four charged particle detectors. The charged particles from neutron reactions in the isotopic targets are counted with an accuracy of better than one part per thousand. The reaction cross sections for these standard cross sections are known to about 0.25 %.

When a neutron in the beam decays inside the trapping region, the recoil proton is trapped. Periodically, the gate electrode is lowered to ground potential to allow the accumulated trapped proton(s) to exit the trap and be counted by the proton detector. A bend in the magnetic field makes it possible to locate the proton detector outside of the incoming neutron beam. The trapped protons have a maximum energy of less than 800 eV and are undetectable at those low energies, but by holding the proton detector at a negative high voltage of the order of –30 kV, the protons may be detected with a signal well above noise levels. Counting for only a short time (less than 100 µs) after the trap is opened in each counting/trapping cycle further enhances the signal-to-noise ratio. Typical trapping times are of the order of 10 ms, and typical decay event rates are of the order of a few protons per second.

Determination of the lifetime requires either an accurately known trap length or a variable trap length with accurately known differences in length. The latter is more easily realized physically and is achieved in this apparatus by the precision machining of the segmented trap structure. Varying the trap length by applying the mirror voltage to

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different segments does not significantly change the hard-to-define end effects. Figure 2 shows a plot of the measured proton rate (after normalization to the neutron rate) as a function of trap length; the slope of this line is inversely proportional to the neutron lifetime.

Since the time when some of the present staff of this experiment participated in a closely related experiment [2] at the Institut Laue-Langevin, a large number of changes have been made to improve the accuracy. Perhaps the most important factor was simply having much more beam time

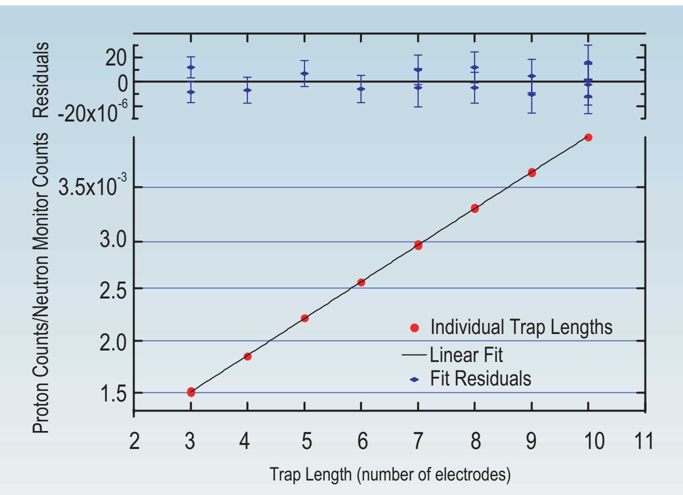

FIGURE 2. A plot of the proton count rate (normalized to the neutron monitor count rate) vs. trap length. The slope of the line is inversely proportional to the measured neutron lifetime.

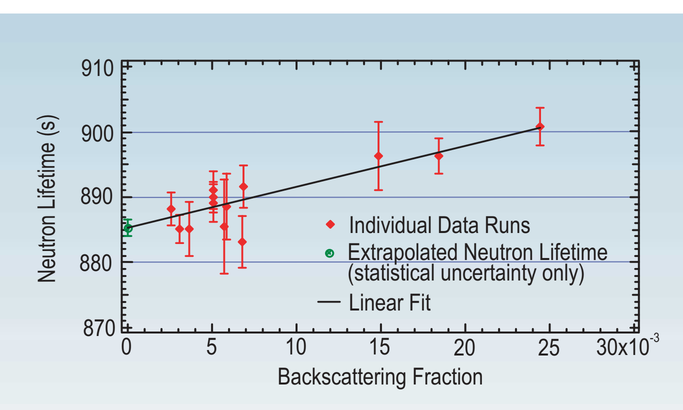

FIGURE 3. A linear fit of the measured neutron lifetime at varying values of the detector backscattering fraction. The extrapolation to zero backscattering gives the free neutron lifetime.

for evaluation of significant systematic effects and accumulation of better statistical precision. Other factors include Monte Carlo-computed corrections due to magnetic field inhomogeneities, improved beam profiles and proton alignment, better trap voltage stability and monitoring, improved definition of the areal mass density of the isotopic targets, use of a new trap designed to minimize instabilities, and improved analysis methods.

Figure 3 shows the extrapolation of the measured lifetime as a function of the backscattering fraction for protons from the detector surface to zero backscattering. The preliminary lifetime value obtained in this experiment [3] is:

$$885.3 \text{ s} \pm 4.0 \text{ s} .$$

Continuing efforts to measure the neutron count rate are underway by both calorimetric and coincidence techniques, which should reduce the final uncertainty by half. They will not only improve on the results of this experiment but will also provide a more accurate and direct calibration of the NIST Standard Neutron Source.

Also underway at NG-6 is a new experiment to measure the neutron lifetime by an independent method involving magnetic trapping of ultracold neutrons. This experiment is being carried out in collaboration with the Physics Department of Harvard University.

References

[1] S. Burles, K. M. Nollett, J. W. Truran, and M. S. Turner, Phys. Rev. Lett. **82** 4176, (1999).

[2] J. Byrne *et al*., Phys. Rev. Lett. **65**, 289 (1990); J. Byrne *et al*., Europhys. Lett. **33**, 187 (1996).

[3] M. S. Dewey *et al*., manuscript in preparation.