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A path to a 0.1 s neutron lifetime measurement using the beam method

F. E. Wietfeldt[a]*, G. Darius[a], M. S. Dewey[b], N. Fomin[c], G. L. Greene[c,d], J. Mulholland[c], W. M. Snow[e], A. T. Yue[b,f]

[a]*Tulane University, New Orleans, LA, USA*
[b]*National Institute of Standards and Technology, Gaithersburg, MD, USA*
[c]*University of Tennessee, Knoxville, TN, USA*
[d]*Oak Ridge National Laboratory, Oak Ridge, TN, USA*
[e]*Indiana University, Bloomington, IN, USA*
[f]*University of Maryland, College Park, MD, USA*

Abstract

The beam method obtains the beta decay lifetime of the free neutron from the specific activity of a slow neutron beam. The best previous result had an overall uncertainty of 3.4 s [Nico, *et al.* (2005)]. We present a plan for a phased experimental program that will improve the overall uncertainty using this method to 0.1 s or below and may help elucidate systematic effects that could explain the current disagreement between the most recent beam and bottle method neutron lifetime experiments.

Keywords: neutron lifetime; neutron decay; beta decay.

1. Introduction

The free neutron decays via the charged weak interaction (beta decay) into a proton, electron, and antineutrino with a lifetime of about 15 minutes. The neutron lifetime is among its most basic properties; it has been the subject of

* Corresponding author
E-mail address: few@tulane.edu

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over 20 major experiments since 1950. It depends on the vector and axial vector weak coupling constants G_V and G_A which govern all charged current weak interactions involving a free neutron and proton — such interactions are also found throughout solar physics, cosmology, and neutrino detection. The value of the neutron lifetime plays an important role in Big Bang nucleosynthesis. It directly provides the combination $G_V^2 + 3G_A^2$ that gives the temperature of nucleon "freeze-out", the point shortly after the Big Bang (about 1 s) when free protons and neutrons fell out of thermal equilibrium. It also determines the fraction of neutrons that decayed prior to the onset of light element nucleosynthesis. The neutron lifetime value dominates the theoretical uncertainty in the primordial helium abundance. Neutron lifetime experiments fall into two broad categories: "beam" experiments which measure the specific activity of a cold neutron beam; and "bottle" experiments in which neutrons are trapped and stored (magnetically, gravitationally, and/or by material walls) for a time comparable to the beta decay lifetime and the loss rate is measured. Detailed theoretical and experimental reviews of the neutron lifetime can be found in Nico and Snow (2005), Abele (2008), Dubbers and Schmidt (2011), and Wietfeldt and Greene (2011).

2. The Beam Method

The beam method, first employed by Robson (1951) at the NRX reactor in Chalk River, Canada, is the oldest approach for measuring the neutron lifetime. A slow (thermal or cold) neutron beam is passed through a known detection volume V. The neutron decay rate Γ in this volume is governed by the differential form of the radioactive decay equation:

$$\Gamma = -\frac{dN}{dt} = \frac{N}{\tau_n} \tag{1}$$

where τ_n is the neutron lifetime and N is the number of neutrons in the detection volume, which can be found from the neutron flux ϕ and velocity v:

$$N = \frac{\phi V}{v}. \tag{2}$$

An important feature of most beam neutron lifetime experiments is that the flux is obtained from the reaction rate of neutrons absorbed by a thin foil with an absorption cross section inversely proportional to the neutron velocity (the "$1/v$ law"), an excellent approximation for most neutron absorbers. Therefore the factor ϕ/v in Eq. (2) can be replaced by $\phi_{\mathrm{th}}/v_{\mathrm{th}}$ where ϕ_{th} is the thermal equivalent "capture flux" measured by the foil and $v_{\mathrm{th}} = 2200$ m/s is the reference thermal neutron velocity for the known thermal absorption cross section σ_{th}. The $1/v$ absorption probability compensates for the $1/v$ dependence of the time spent by a neutron within the detection volume, so the actual neutron velocity is not needed to determine N and in fact a "white" neutron beam with a broad velocity spectrum can be used with no loss of accuracy in principle.

The detection rate R_p of final state particles from neutron decay (protons and/or electrons) in the detection volume is measured with efficiency ε_p. The detection rate R_n of the reaction products from neutron capture in the foil, over the full beam area, is measured with the thermal equivalent efficiency $\varepsilon_{\mathrm{th}}$ that includes the cross section σ_{th}, the areal density of the foil, the geometric efficiency of the detectors, and the beam profile. Combining these with Eqs. (1) and (2) we have an expression for the neutron lifetime in terms of experimentally measured quantities and L_{det}, the length of the detection volume along the beam direction:

$$\tau_n = \frac{R_n \varepsilon_p L_{\mathrm{det}}}{R_p \varepsilon_{\mathrm{th}} v_{\mathrm{th}}} \tag{3}$$

For the past several decades the Sussex-ILL-NIST program [Byrne *et al.* (1990); Byrne *et al.* (1996); Dewey *et al.* (2003); Nico *et al.* (2005); Dewey *et al.* (2009)] has produced the most precise beam neutron lifetime results. The neutron beam is passed through a quasi-Penning trap consisting of a 4.6 T axial magnetic field and an axial electrostatic trap. When a neutron decays inside the trap the recoil proton is confined radially by the magnetic field and axially by +800 V potentials on each end (the maximum recoil kinetic energy is 752 eV). Periodically (typically every 10 ms) the trap is opened by grounding the electrodes at one end. Protons are guided by a bend in the magnetic field to a silicon surface barrier detector where they are counted. Due to end effects in the proton trapping efficiency, the absolute effective length of the trap L_{det} is not well known, so the trap is segmented and the experiment is repeated with different trap lengths allowing the end effects (incomplete proton trapping efficiency near the ends of the trap) to be removed by extrapolation. Downstream of the trap, beyond the magnetic field region, the beam passes through a thin layer of ^{6}LiF deposited on a silicon crystal wafer and the products (alphas and tritons) of ^{6}Li(n,t) reactions are counted by a set of four silicon detectors. The latest experiment of this program, carried out at the NIST Center for Neutron Research in Gaithersburg, MD, obtained a result of $\tau_n =$ 886.3 ± 3.4 s. The final uncertainty was dominated by systematic uncertainties in the quantities contained in ε_{th}. Further information about this experiment along with detailed discussions of the data analysis and systematic effects can be found in Nico *et al.* (2005). Also see Table 1.

3. Previous Results

Figure 1 gives a summary of neutron lifetime measurements since 1990, showing both beam and bottle experiments. Prior to 2010 there were serious discrepancies between different bottle results [Nakamura, *et al.* (2010)], but since then several have been reevaluated and their current agreement is reasonably good. The beam results also agree with each other. However when evaluated separately the weighted averages of the beam and bottle methods disagree by 7.7 s, or 2.7 standard deviations. As the two methods are systematically very different it seems likely that the difference originates from unaccounted systematic errors in either or both methods. Any significant improvement in our knowledge of the neutron lifetime will require further work on both to better understand and reduce systematic effects. A new generation of experiments to reduce the overall uncertainty to 0.1 s or below will likewise require the use of both the beam and bottle methods to obtain a reliable conclusion.

4. A Path to a 0.1 s Beam Neutron Lifetime Measurement

We present an outline for a phased experimental program that will improve the neutron lifetime from the beam method to a precision of 0.1 s or less. We adopt the Sussex-ILL-NIST approach as we believe it gives the best chance for success. It has achieved the best precision to date for the beam method and it is a very mature program. Many systematic effects and issues, both major and minor, have been thoroughly studied over several decades of work. The first column of Table 1 lists the systematic and statistical uncertainties that contributed to the 3.4 s total uncertainty of the previous experiment completed at NIST. It is adapted from the equivalent table in Nico *et al.* (2005), combining some (in quadrature) for the purpose of this discussion and omitting those at 0.1 s or below.

The dominant systematic uncertainty was in the thermal equivalent efficiency of the neutron flux detector. Until very recently there was no way to perform an absolute calibration of the system to a useful accuracy. Instead the efficiency was calculated from the ENDF/B-VI evaluated ^{6}Li(n,t) cross section [Carlson, *et al.* (1993)], a careful estimation of the ^{6}Li areal density in the deposit, and the detector geometry. Recognizing this as the most limiting systematic, we have since pursued an independent absolute calibration with $< 0.1\%$ accuracy using a variety of methods. Success was achieved two years ago by an alpha/gamma spectrometer based on neutron absorption in ^{10}B [Yue (2011)]. The flux detector was recalibrated, reducing the efficiency uncertainty from 2.7 s to 0.5 s in the neutron lifetime. Phase I of the program is to apply this new efficiency to the 2005 data and improve that neutron lifetime result. This work is now complete and has been submitted for publication; the result is available on arXiv [Yue, *et al.* (2013)].

With the limiting systematic thus greatly reduced, Phase II of the program will be to repeat the experiment with incremental improvements to the existing apparatus in order to reduce the other uncertainties and aim for a 1.0 s result, as shown in Table 1. Preparations for this phase are now underway and we expect to begin collecting data at NIST in 2014. Specific improvements include:

- Neutron absorption and scattering in the in ^{6}LiF deposit and its substrate. This includes calculations of the slight hardening of the neutron spectrum as it passes through the ^{6}Li deposit as well as neutron scattering from the 400 μm thick silicon crystal substrate, effects that depend on the *in situ* neutron velocity spectrum so they are not included in the absolute calibration which is performed on a monochromatic test beam. A detailed spectral measurement using a chopper system, not done in the previous experiment, will improve the net uncertainty of these by at least a factor of three.

- Neutron beam halo. While the collimated neutron beam inside the proton trap has a nominal diameter of 7 mm, a faint neutron halo extends well beyond that. If a halo neutron decays inside the trap its recoil proton, when transported by the magnetic field during the counting period, may miss the active region of the 300 mm^2 (9.8 mm radius) proton detector. Larger 600 mm^2 surface barrier detectors are now available that will greatly reduce this effect.
- Trap nonlinearity. In the previous experiment we varied the length of the central trap region from 6.5 cm to 21.6 cm (3-10 grounded trap electrodes) in order to extrapolate away the end effects. For the longest trap the magnetic field near the end was insufficiently uniform so the extrapolation required a large correction. If in future we limit the longest trap to 9 grounded electrodes the correction and its uncertainty are much smaller.

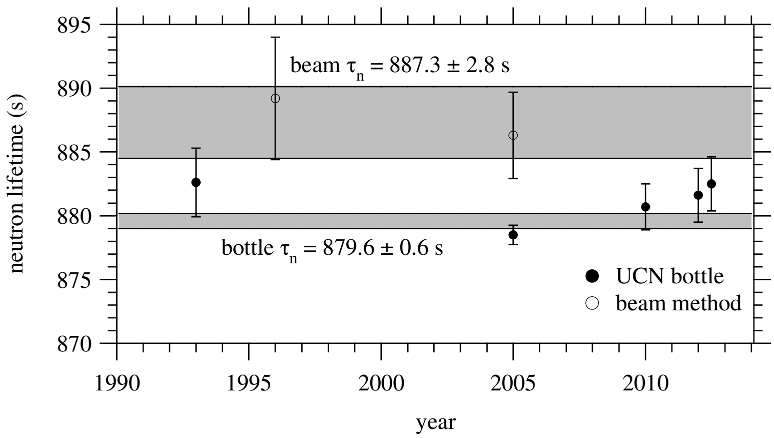

Fig. 1. Neutron lifetime results since 1990 using the beam (open) and bottle (solid) methods. See the Particle Data Group (PDG) [Beringer *et al*. (2012)] for individual references. The current PDG recommended average is 880.0 ± 0.9 s.

Table 1. Column 1 lists the systematic and statistical uncertainties, in seconds, from the previous NIST beam neutron lifetime experiment, adapted from Nico *et al.* (2005). The next two columns give estimated improvements for phases II and III of our planned program described in the text.

Source of uncertainty	Previous (s)	Phase II (s)	Phase III (s)
Neutron flux detector efficiency	2.7	0.5	< 0.1
Abs/scatt in ^{6}LiF deposit and Si substrate	0.9	0.3	< 0.1
Neutron beam halo	1.0	0.1	< 0.1
Proton trap nonlinearity	0.8	0.2	< 0.1
Proton backscatter correction	0.4	0.4	< 0.1
Counting statistics	1.2	0.6	< 0.1
Quadrature sum	**3.4**	**1.0**	**0.1**

Phase III of the program is considerably more ambitious. We are planning an entirely new and larger version of the apparatus, based on similar principles, designed to reduce all of the uncertainties in Table 1 to below 0.1 s. Specific features of this plan are:

- A factor of 600 increase in statistical power will be achieved by increasing the beam diameter to 35 mm (factor of 25), doubling the trap length (factor of 2), longer run time (factor of 4), and higher neutron flux (factor of 3 or more at NIST or the ESS).
- A larger and more uniform magnet and trap are needed to allow a larger beam and further reduce nonlinearity effects.
- A more sophisticated focusing electrode system at the proton detector will reduce the backscatter correction and its uncertainty.
- A much larger proton detector is needed. We are considering a 6 cm diameter segmented ion-implanted silicon detector similar to that being developed for the Nab experiment [Wilburn (2011)].
- An upgraded version of the alpha/gamma ^{10}B calibration device is needed to accommodate larger absorber foils and reduce some systematic effects. Such a device is described in Yue, *et al.* (2013).
- Thinner absorber deposits and substrates will proportionally reduce the neutron absorption and scattering uncertainties. Running the experiment at a pulsed beam facility such as the European Spallation Source would be helpful as the neutron spectrum can be separated by time-of-flight.

5. Conclusions

A new generation of neutron lifetime experiments is being planned that will push its overall uncertainty to below 0.1 s (*e.g.* Workshop on Next Generation Experiments to Measure the Neutron Lifetime, Santa Fe, NM, Nov. 9-12, 2012). Given the history of these measurements over the past six decades, and the present 7.7 s disagreement between the beam and bottle experiments, much more work is needed to fully understand systematic effects in both the beam and bottle methods, and both methods must be pursued to this new desired precision. We have presented a plan for a phased experimental program to obtain a 0.1 s result using the beam method.

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