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Prospects for a new cold neutron beam measurement of the neutron lifetime

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ABSTRACT

In the most accurate cold neutron beam determination of the neutron lifetime based on the absolute counting of decay protons, the largest uncertainty was attributed to the absolute determination of the capture flux of the cold neutron beam. Currently an experimental effort is underway at the National Institute of Standards and Technology (NIST) that will significantly reduce this contribution to the uncertainty in the lifetime determination. The next largest source of uncertainty is the determination of the absolute count rate of decay protons, which contributes to the experimental uncertainty approximately at the 1 s level. Experience with the recent neutron radiative decay experiment, which used the neutron lifetime apparatus, has provided valuable insights into ways to reduce other uncertainties. In addition, the cold neutron fluence rate at NIST is presently 1.5 times greater than in the 2003 measurement, and there is the prospect for a significantly higher rate with the new guide hall expansion. This paper discusses an approach for achieving a determination of the neutron lifetime with an accuracy of approximately 1 s.

1. Introduction

For many years, experimental determinations of the neutron lifetime were in agreement with each other. However, a recent measurement [1] is forcing the community to consider the possibility that one or more of these measurements suffers from unidentified systematic effects. The marked disagreement of the new result with existing measurements has created serious uncertainty in the value of the neutron lifetime at the 1% level, which is a factor of 10 larger than the relative uncertainty quoted in the PDG [2]. All of the recent experiments except one have employed ultracold neutrons (UCN) stored in bottles. The most accurate cold neutron beam experiment was carried out at NIST [3,4] using a technique pioneered by Byrne and Greene [5,6]. For the moment, UCN bottle and cold neutron beam experiments represent the two distinct methods available for carrying out this measurement. It is to be hoped that an experiment employing magnetically trapped UCN presently underway at NIST will soon contribute a third distinct method [7]. Since each method has unique sources of systematic uncertainty, consistency among the different methods is an important indicator of the reliability of the world average. For this comparison to be useful, the uncertainties must be of comparable size.

The uncertainty budget from the NIST cold neutron beam experiment is reprised in Table 1. The first three uncertainties pertain to the efficiency of the neutron detector ε_0. Neutron counting was accomplished by counting charged particles produced as the neutron beam passed through a thin, well characterized ^{6}Li deposit. Together these uncertainties constitute the largest source of uncertainty in the final result. We further note that one of these, the cross-section uncertainty for the reaction $^6\mathrm{Li(n,t)}$, must be taken (along with its value) from evaluated nuclear data files, the latest of which is ENDF/B-VII.0 [8]. Most of the measurements of the $^6\mathrm{Li(n,t)}$ cross-section have been made in the neutron energy region well above thermal. In the meV energy region the only direct measurements are limited to two determinations from integral-type measurements [9,10]. Therefore, the existing evaluation of the $^6\mathrm{Li(n,t)}$ cross-section uses other absolute data as well as ratios of this cross-section to other reaction cross-sections such as $^{10}\mathrm{B(n,\alpha)}$, $^{235}\mathrm{U(n,f)}$ and $^{238}\mathrm{U(n,f)}$. These data span a wide neutron energy range. *Each time a new evaluation is adopted, our lifetime result must be adjusted.*

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In this paper we discuss a project underway at NIST to calibrate the neutron counter independent of its geometry, deposit mass and the ^{6}Li cross-section. Under the assumptions that its geometry and the ^{6}Li deposit's areal density remain unchanged (both testable hypotheses), an after-the-fact calibration can be used to simultaneously adjust the 2005 result and reduce its uncertainty. The calibration can also be used to extract a direct measurement of the ^{6}Li(n, t) cross-section, given knowledge of the deposit's areal density and the neutron detector's solid angle. We further discuss what could be expected in a second campaign of proton counting at the NIST Center for Neutron Research (NCNR).

2. Neutron counting

The neutron detector used in the lifetime experiment employs a rigid fixed geometry and was designed to be demountable in order to facilitate after-the-fact calibration. In order to calibrate it, a totally absorbing neutron detector based on neutron absorption by ^{10}B has been built (the Alpha–Gamma device) [11]. The device is presently installed on the monochromatic cold neutron beam NG-6M at the NCNR [12]. Calibration is based on relating the total rate of neutrons striking the Alpha–Gamma device to the event rate seen in the lifetime experiment's neutron detector (Fig. 1).

Table 1
Summary of the systematic corrections and uncertainties for the NIST cold neutron lifetime measurement (taken from Ref. [4]).

Source of correction	Correction (s)	Uncertainty (s)
^{6}LiF deposit areal density		2.2
^{6}Li cross-section		1.2
n detector solid angle		1.0
Absorption of n by ^{6}Li deposit	+5.2	0.8
Beam profile and detector Ω	+1.3	0.1
Beam profile and ^{6}Li deposit shape	−1.7	0.1
Beam halo	−1.0	1.0
Absorption of n by Si substrate	+1.2	0.1
Scattering of n by Si substrate	−0.2	0.5
Trap nonlinearity	−5.3	0.8
p backscatter calculation		0.4
n counting dead time	+0.1	0.1
p counting statistics		1.2
n counting statistics		0.1
Total	−0.4	3.4

In the beam lifetime experiment, the neutron lifetime is given by the simple expression

$$\tau_n = \frac{L}{r_p}\frac{r_{\alpha,t}}{\varepsilon_0}\frac{\varepsilon_p}{v_0} \tag{1}$$

where r_p is the proton rate observed from a section of length L of the neutron beam, $r_{\alpha,t}$ is the rate of alphas + tritons detected in the neutron detector, ε_p is the efficiency with which protons are detected ($\approx 100\%$), and $v_0 \equiv 2200\,\mathrm{m/s}$ is the thermal velocity. On a monochromatic beam whose mean wavelength is λ_{mono}, the same quantity $r_{\alpha,t}$ is given by

$$r_{\alpha,t} = \varepsilon_0 \frac{\lambda_{\mathrm{mono}}}{\lambda_0} r_n \tag{2}$$

where r_n is the rate of neutrons passing through the detector, λ_0 is the wavelength of a 2200 m/s beam, and as before ε_0 is the efficiency of the neutron detector. Simultaneously, the response of the Alpha–Gamma device is

$$r_\gamma(\mathrm{thick}) = \varepsilon_\gamma b_\gamma r_n \tag{3}$$

where $r_\gamma(\mathrm{thick})$ is the rate of gammas detected from the reaction $\mathrm{n} + {}^{10}\mathrm{B} \longrightarrow {}^4\mathrm{He} + {}^7\mathrm{Li}^* + \gamma(478\,\mathrm{keV})$ ("thick" refers to the fact that a target capable of stopping all neutrons is present in the Alpha–Gamma device), and b_γ is the precisely known branching ratio for the branch that leaves ^{7}Li in an excited state. Combining Eqs. (2) and (3) one obtains

$$\varepsilon_0 = r_{\alpha,t} \frac{\varepsilon_\gamma b_\gamma}{r_\gamma(\mathrm{thick})} \frac{\lambda_0}{\lambda_{\mathrm{mono}}}. \tag{4}$$

ε_γ and λ_{mono} must be measured in two ancillary experiments.

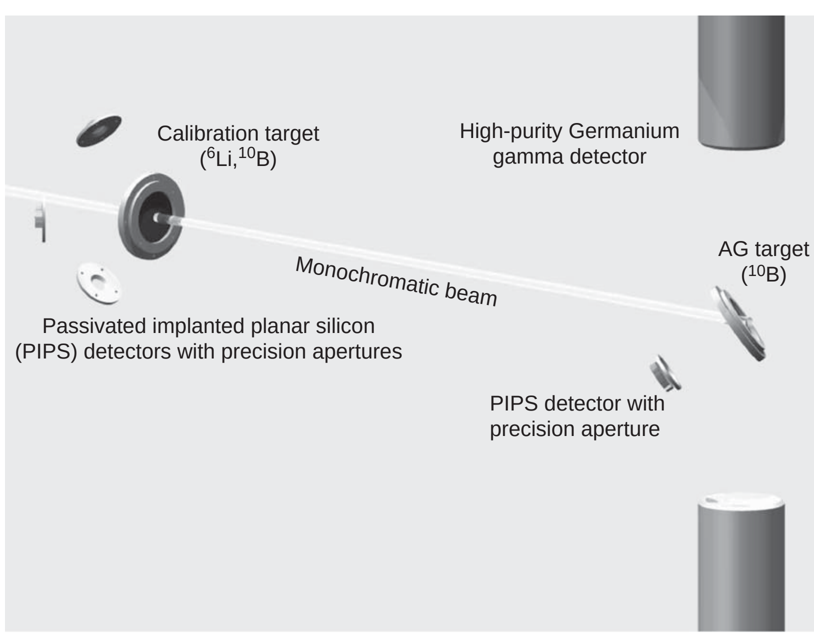

Fig. 1. Schematic illustration of the Alpha–Gamma technique. A highly collimated monochromatic neutron beam passes through a thin ^{6}Li deposit surrounded by four silicon detectors with precision apertures (the lifetime neutron detector). It is then incident on a totally absorbing ^{10}B target and the resulting gamma and alpha particles are detected (the Alpha–Gamma device). In the calibration experiment both detectors share a common vacuum system.

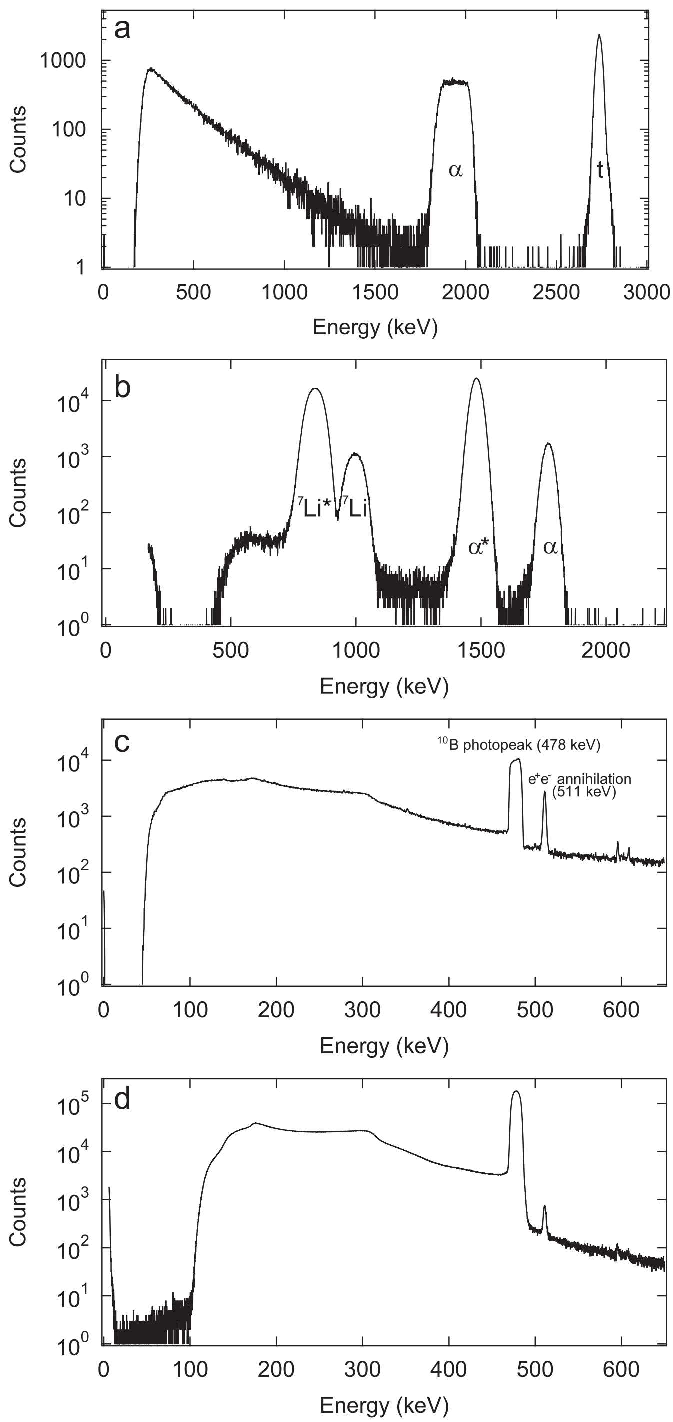

Fig. 2. Calibration data. (a) Alphas and tritons from the reaction $n + {}^{6}Li \longrightarrow {}^{4}He + {}^{3}H$ in the lifetime neutron detector. (b) Alphas and Li nuclei from the reaction $n + {}^{10}B \longrightarrow {}^{4}He + {}^{7}Li$ in the Alpha–Gamma device. (c) Thin deposit gamma spectrum from the reaction $n + {}^{10}B \longrightarrow {}^{4}He + {}^{7}Li^{*} + \gamma$ (478 keV). (d) Thick target gamma spectrum from the reaction $n + {}^{10}B \longrightarrow {}^{4}He + {}^{7}Li^{*} + \gamma$ (478 keV).

The mean beam wavelength λ_{mono} is determined by Bragg reflection of the beam from a perfect crystal silicon analyzer; extensive modeling has been performed to characterize potential systematic effects in the measurements of the wavelength [13]. Previous measurements were performed with relative uncertainties below 0.1% [14,15], while preliminary measurements by this group show repeatability at the 0.1% level.

The measurement of ε_γ requires two steps. Firstly, a thin ^{10}B deposit is placed in the Alpha–Gamma device. Because it is thin, the alpha particles can all escape from the deposit and be detected by a surface barrier detector. Its response will be

$$r_\alpha = \varepsilon_{SB} r_{reaction} \tag{5}$$

where r_α is the detected alpha rate, ε_{SB} is the efficiency of the surface barrier detector, and $r_{reaction}$ is the reaction rate occurring on the deposit. At the same time, the response of the gamma detector will be

$$r_\gamma(\text{thin}) = \varepsilon_\gamma b_\gamma r_{reaction} \tag{6}$$

where r_γ(thin) is the detected gamma rate (“thin” refers to the fact that a thin deposit from which the alphas can escape is present in the Alpha–Gamma device). Combining Eqs. (5) and (6) yields

$$\varepsilon_\gamma = \frac{r_\gamma(\text{thin})}{b_\gamma}\frac{\varepsilon_{SB}}{r_\alpha}. \tag{7}$$

Secondly, a ^{239}Pu alpha source whose absolute alpha activity R_{Pu} is known to be less than than 0.1% relative uncertainty is inserted into the kinematically mounted target holder and counted with the surface barrier detector. The observed alpha rate is given by

$$r_\alpha(\text{Pu}) = \varepsilon_{SB} R_{Pu}. \tag{8}$$

Combining Eqs. (7) and (8), we have

$$\varepsilon_\gamma = \frac{r_\gamma(\text{thin})}{b_\gamma}\frac{r_\alpha(\text{Pu})}{r_\alpha}\frac{1}{R_{Pu}}. \tag{9}$$

Finally Eqs. (4) and (9) can be solved to give ε_0 as a function of measured quantities.

The Alpha–Gamma device and the lifetime neutron detector are currently installed on the beamline, and the calibration of the gamma detectors is ongoing. Data recently acquired with the neutron beam are shown in Fig. 2. All of the charged particle spectra feature clearly defined peaks with extremely high signal to noise ratios (including ^{239}Pu data which are not shown). The gamma spectra are a bit more problematic because of Compton scattering and reactor induced and ambient backgrounds. In all cases, the observed count rates are between 5 and 500 s^{-1}. Measurements of the ^{239}Pu alpha rate in the Alpha–Gamma device demonstrate stability at the level of 0.1%, indicating the kinematic mount is operating properly. At present the stability of the alpha- and gamma-rates is being critically assessed. Stability requires reliable background subtraction in the case of the gamma detectors and stability of the neutron beam distribution in the case of both detectors. Both of these issues are being studied. When the Alpha–Gamma measurements are completed, the wavelength of the beam will again be measured. An overall relative uncertainty of 0.1% is the goal of this project.

3. Proton counting

Subsequent experience with the our neutron lifetime apparatus in a successful search for neutron radiative decay [16] has provided valuable insights into ways to reduce the proton counting uncertainty. These ideas include:

- Detailed Monte Carlo calculations suggest that the magnetic field gradient is too large in our longest proton trap (10 electrodes); therefore the trap length will not exceed nine electrodes in the future.
- The area of the surface barrier detector used to detect decay protons can be safely doubled thereby reducing sensitivity to beam alignment and halo.

- A lower noise preamp has been successfully tested; it will allow for operation at lower acceleration voltages thereby extending the range of voltages available; this will in turn reduce the uncertainty associated with proton backscattering.
- A new data acquisition system will digitize all proton waveforms thus making it possible to study multiple-proton and background events in detail.
- The neutron detector will be operated with a deposit of ^{10}B in addition to ^{6}Li.
- In the radiative decay experiment an electrostatic mirror reduced background proton induced signals; if this worked in the lifetime experiment, it could reduce or eliminate problems with trap instabilities.

4. Facility upgrade

The NCNR cold source underwent an upgrade after the 2003 run. Today one would expect an increase of a factor of 1.5 in rate at all trap lengths based on subsequent measurements of the fluence. In addition, a significant expansion of the NCNR is underway, which comprises development of a new cold neutron moderator and a new guide hall with five state-of-the-art instruments, one of which will be devoted to fundamental physics.

5. Summary

The marked disagreement of a new result with existing measurements has created serious uncertainty in the value of the neutron lifetime at the 1% level. A competitive beam-style experiment provides distinctly different systematics from UCN bottle experiments. An effort is underway at NIST to calibrate the neutron detector used in the beam lifetime experiment. An independent calibration at the 0.1% level will remove the experiment's reliance on a cross-section evaluation while simultaneously replacing the previously published lifetime value with a new, more precise value. Subsequent experience with the our neutron lifetime apparatus has provided valuable insights into ways to reduce the proton counting uncertainty as well. This leads us to conclude that it is possible to make a $\lesssim 1$ s measurement of the neutron lifetime using a cold beam. Beyond this one expects that new UCN bottle will produce results in the near future that will help to resolve the current situation.

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