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Comment on “Search for Explanation of the Neutron Lifetime Anomaly”

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Comment on "Search for explanation of the neutron lifetime anomaly"

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Abstract

We respond to issues raised by Serebrov, *et al.* in a recent paper [1] regarding systematic effects in the beam neutron lifetime experiment performed at NIST [2–4]. We show that these effects were considered in the original analyses and that our corrections and systematic uncertainties were appropriate. We point out some misunderstandings in the analysis of Serebrov, *et al.*. None of the issues raised in Ref. [1] lead us to alter the value of the neutron lifetime reported in Ref. [4].

At different times over the past 60 years, experimental neutron lifetime results have been either in good or poor agreement. Currently the agreement is poor. In particular the value reported by the most precise beam experiment conducted at the NIST Center for Neutron Research [2–4] is 9.3 s (3.9 standard deviations) higher than the average of recent UCN storage lifetime results using material and magnetic bottles [5]. Other beam method results are similarly higher but with larger uncertainties. This discrepancy has been widely discussed in recent years in both the scientific literature and popular media [6–11]. Due to its higher reported precision compared to other beam measurements, the NIST experiment plays a key role here. One or more unaccounted systematic effects in that result could effectively explain the discrepancy, so it has justifiably been subject to scrutiny by both the experimental team and by other scientists. In a recent paper, Serebrov, *et al.* [1] discuss and analyze three potential systematic effects in the NIST experiment: 1) protons missing the active area of the proton detector; 2) losses due to the detector dead layer; and 3) residual gas effects. We note that the authors of Ref. [1] based their work on what was written and published in Refs. [2–4] but did not seek additional details from us in advance of their publication. Here we respond to the analysis and conclusions in [1] and correct some misunderstandings about our apparatus.

The first question Serebrov, *et al.* consider is whether all trapped neutron decay protons will strike the active region of the detector when the trap is opened for counting. This was already carefully addressed in the experiment and analysis as described in Ref. [3]. Neutron beam intensity images were made at various positions using the dysprosium foil method. The images taken 10 cm downstream of the last trap electrode were used to estimate the proton distribution in the trap. We concluded that $< 1.1 \times 10^{-3}$ of protons will miss the detector, an upper limit due to the beam expansion, which implies a correction of -1.0 s or less. We assigned a large uncertainty, 1.0 s, to this estimate. Serebrov, *et al.* essentially repeat this estimate, but without the benefit of the beam image data and reach a similar conclusion that the effect was <1 s in the neutron lifetime.

The second issue raised by Serebrov, *et al.* concerns proton losses due to the silicon detector dead layer. This was an important systematic effect in the experiment. Depending on the detector used, 0.2 % to 2 % of incident protons backscattered from the dead layer and/or failed to deposit sufficient energy in the active volume to produce a countable pulse. We considered this effect carefully from the outset and designed the apparatus and experimental procedure to accommodate it. In the experiment, the neutron lifetime measurement was repeated using surface barrier detectors with different nominal thickness gold conducting layers, gold-free PIPS (Passivated Ion-implanted Planar Silicon) detectors, and different detector acceleration potentials (-32.5 kV to -27.5 kV). For each case we calculated the backscatter fraction both analytically and using the SRIM 2003 simulation package [12]. In our experience modeling, measuring, and analyzing low energy proton spectra, we have found that SRIM predictions of the total backscatter probability are in good agreement with analytical modeling. However we have not succeeded in obtaining reliable predictions of the (energy, angle)-dependent backscatter spectrum from either SRIM or GEANT [13]. Therefore we felt we could not correct the measured neutron lifetime values for backscatter effects using a detailed Monte Carlo simulation. Instead we followed a strategy of extrapolation. We plotted the measured neutron lifetime *vs.* calculated backscatter probability and extrapolated to zero backscatter as shown in Ref. [3], figure 20. We expected, with good reason, the dependence of measured neutron lifetime on backscatter fraction to be monotonic, but we emphasize that we did not *a priori* assume, as suggested by Serebrov, *et al.*, a linear relationship. We extrapolated to zero using the simplest monotonic function that fit the data, which happened to be linear. We regard the true functional form of lifetime *vs.* backscatter fraction to be unknown. Given that we obtained a good fit to the data with a linear function, a more complicated function with additional parameters would not have improved the result. We agree with Serebrov, *et al.* that the energy spectrum of backscattered protons depends on the dead layer thickness and incident energy, and that this could in principle cause the measured lifetime *vs.* backscatter probability to be nonlinear. This was understood at the time of the 2005 experiment, but we did not observe evidence of such nonlinearity in our data at a statistically significant level.

Serebrov, *et al.* produce a SRIM-based detailed Monte Carlo simulation of backscatter corrections in the NIST experiment. As explained above we do not consider such a course to be reliable. The authors of Ref. [1] lacked important details such as the experimental geometry and magnetic field shape. They apparently used only the nominal detector gold layer thicknesses. There is an additional layer of dead silicon that should be included, deduced by us using SRIM and experimental measurements of energy loss using protons and alphas. Table II in Ref. [1] implies a zero dead layer was used for the PIPS detectors, while in reality there is a small but significant silicon dead layer. Also they seem to have omitted the preacceleration of protons produced by the ramp potential in the trap.

Finally Serebrov, *et al.* consider the possible interactions of trapped protons with residual gas in the trap. First they make a simplified model of the vacuum environment of the trap as a vessel with cold walls located inside another vessel with warm walls (the outer vacuum system). They assume that residual gas flows from the outer vessel into the inner vessel, remaining in gas phase at thermal equilibrium with the walls in the two vessels. Therefore the molecular density in the inner vessel reaches equilibrium at $n = P/k\sqrt{T_1 T_2}$, where P is the vacuum pressure in the outer chamber, k is the Boltzmann constant, and T_1, T_2 are the vessel temperatures. Using $P = 10^{-9}$ mbar as the ion gauge pressure (actually the upper limit as the gauge was under range), $T_1 = 300$ K, and $T_2 = 4$ K, they obtain $n = 2.1 \times 10^8$ cm^{-3} inside the trap. Unfortunately this model omits the important effect of cryocondensation on the cold bore of the magnet, a crucial feature of the trap vacuum.

The arrangement of the bore, trap, and detector is shown in figure 1. The magnet bore was a 45 cm long, 12 cm inner diameter stainless steel tube in direct contact with the liquid helium bath. Its operational temperature was measured to be 8 K. At this temperature the condensation coefficients of most gases are close to unity so residual gas will condense on the wall after just a few collisions, rather than remain in the gas phase and reach thermal equilibrium. The bore is effectively a cryopump. According to the theory of cryocondensation (see for example Refs. [14–16]) the partial pressure of all gases other than hydrogen, helium, and neon will be negligible ($< 10^{-18}$ Pa) at 8 K. There is no reason to expect neon in the vacuum system. Hydrogen is certainly present and in fact is the dominant residual gas. Helium is also a possibility due to its emission into the guide hall atmosphere from various cryogenic systems. Lacking important information about our vacuum system, Serebrov, *et al.* embark on a highly speculative discourse on the residual gas spectrum in our trap. They include the possibility of cryocondensation on the trap surfaces, which they assume to be in the range 20 K to 30 K. The trap was actually somewhat warmer, about 40 K, due to its weak conductive contact with the bore. At that temperature water will be pumped effectively but not other important gases such as air and methane. However they neglect to consider the far more powerful effect of cryopumping by the bore that surrounds the trap.

Residual gas interactions with trapped protons has been an important consideration in this experiment from the outset decades ago. We have extensively studied the potential effects of trapped proton interactions with hydrogen and helium, and there is recent theoretical work by others [17, 18]. The main concerns are charge exchange between a trapped proton and a H_2 molecule or He atom, leaving a H_2^+ or He^+ ion inside the trap, or binding of a trapped proton with a monatomic H atom, leaving a H_2^+. The key point is both such trapped ions would be detected by the proton detector at a slightly later time relative to trapped protons. Due to the detector dead layer, the H_2^+ will appear at a lower, but detectable energy and the He^+ at slightly higher energy relative to the protons. We did not observe either of these in the 2005 experiment. In more recent data taken with the same apparatus, but with a different vacuum configuration, we believe we were able to observe trapped H_2^+ in certain vacuum conditions, but not at a level where they would significantly affect the neutron lifetime result given the way our data were analyzed. This was recently reported [19] and will be described more fully in an upcoming publication. The trap timing plot shown in Ref. [1], figure 16 is based on incorrect assumptions about our trap and detector geometry. Serebrov, *et al.* claim that the H_2^+ (shown in blue) would not be observed but would at the same time cause an overcounting of the background in region III. In reality, if such events were present at a statistically significant level, they would be visible and appear in region II, at approximately 43 μs in that figure. The conclusion of Serebrov, *et al.* that this should be a > 3 s correction, based on an analysis that lacked important details of the experiment, is incorrect.

It is important to note that, hypothetically at least, circumstances could exist in the apparatus such that residual gas vapor pressure limits at 8 K are exceeded. For example if residual gas molecules were ionized, they would be trapped by the magnetic field and may not interact with the cold surface of the bore. Gases originating inside the trap by outgassing or a virtual leak could allow much higher partial pressures within the trap compared to the outer bore region. A small fraction of gas molecules from the warm vacuum region will travel in ballistic trajectories that pass through the trap while missing the bore surface. If heavier molecules such as N_2 and CH_4 were present as trapped ions, they would lose most of their energy in the detector dead layer and be difficult to detect. Such possible residual gas effects continue to be an active area of investigation for the NIST beam experiment.

A large class of potential systematic effects in the beam lifetime experiment, including residual gas interactions, will cause a loss of protons from the trap with a time scale of ms. Such effects would be made apparent by repeating the neutron lifetime measurement using a range of trapping times from 1 ms to 100 ms. This was not achievable in the original NIST experiment [2–4] due to trap instability at times over 10 ms. With improved trap stability such a program of measurements is an important goal for the current BL2 effort as well as the upcoming BL3 experiment.

The neutron lifetime discrepancy is an important problem and we appreciate the effort made by Serebrov, *et al.* to examine our previous result and consider possible systematic effects. However, for the reasons discussed here, the issues raised in Ref. [1] do not lead us to alter the value of the neutron lifetime reported in Ref. [4].

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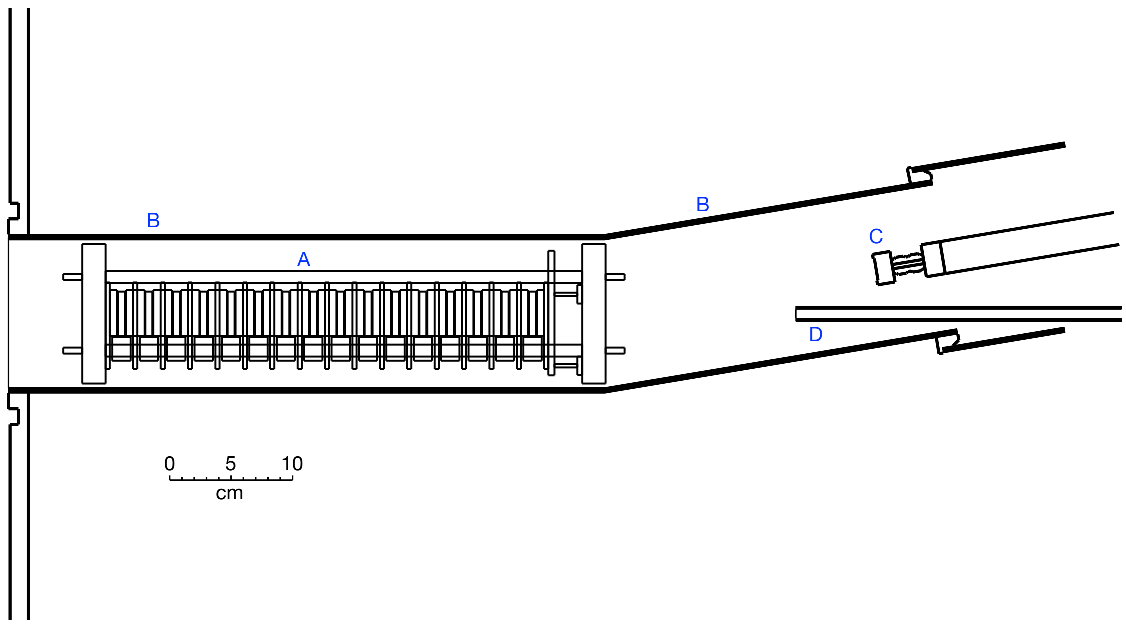

FIG. 1. Arrangement of the proton trap apparatus in the NIST beam neutron lifetime experiment [2, 3]. A) proton trap; B) 8 K magnet bore; C) silicon proton detector; D) quartz neutron guide.