

1 **Comment on “Search for explanation of the neutron lifetime**
2 **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].

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

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

40 The second issue raised by Serebrov, *et al.* concerns proton losses due to the silicon
41 detector dead layer. This was an important systematic effect in the experiment. Depend-
42 ing on the detector used, 0.2 % to 2 % of incident protons backscattered from the dead
43 layer and/or failed to deposit sufficient energy in the active volume to produce a countable
44 pulse. We considered this effect carefully from the outset and designed the apparatus and

45 experimental procedure to accommodate it. In the experiment, the neutron lifetime mea-
46 surement was repeated using surface barrier detectors with different nominal thickness gold
47 conducting layers, gold-free PIPS (Passivated Ion-implanted Planar Silicon) detectors, and
48 different detector acceleration potentials (-32.5 kV to -27.5 kV). For each case we calculated
49 the backscatter fraction both analytically and using the SRIM 2003 simulation package [12].
50 In our experience modeling, measuring, and analyzing low energy proton spectra, we have
51 found that SRIM predictions of the total backscatter probability are in good agreement
52 with analytical modeling. However we have not succeeded in obtaining reliable predictions
53 of the (energy, angle)-dependent backscatter spectrum from either SRIM or GEANT [13].
54 Therefore we felt we could not correct the measured neutron lifetime values for backscatter
55 effects using a detailed Monte Carlo simulation. Instead we followed a strategy of extrapo-
56 lation. We plotted the measured neutron lifetime *vs.* calculated backscatter probability and
57 extrapolated to zero backscatter as shown in Ref. [3], figure 20. We expected, with good
58 reason, the dependence of measured neutron lifetime on backscatter fraction to be mono-
59 tonic, but we emphasize that we did not *a priori* assume, as suggested by Serebrov, *et al.*,
60 a linear relationship. We extrapolated to zero using the simplest monotonic function that
61 fit the data, which happened to be linear. We regard the true functional form of lifetime
62 *vs.* backscatter fraction to be unknown. Given that we obtained a good fit to the data with
63 a linear function, a more complicated function with additional parameters would not have
64 improved the result. We agree with Serebrov, *et al.* that the energy spectrum of backscat-
65 tered protons depends on the dead layer thickness and incident energy, and that this could
66 in principle cause the measured lifetime *vs.* backscatter probability to be nonlinear. This
67 was understood at the time of the 2005 experiment, but we did not observe evidence of such
68 nonlinearity in our data at a statistically significant level.

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

77 omitted the preacceleration of protons produced by the ramp potential in the trap.

78 Finally Serebrov, *et al.* consider the possible interactions of trapped protons with residual
79 gas in the trap. First they make a simplified model of the vacuum environment of the trap
80 as a vessel with cold walls located inside another vessel with warm walls (the outer vacuum
81 system). They assume that residual gas flows from the outer vessel into the inner vessel,
82 remaining in gas phase at thermal equilibrium with the walls in the two vessels. Therefore
83 the molecular density in the inner vessel reaches equilibrium at $n = P/k\sqrt{T_1T_2}$, where P
84 is the vacuum pressure in the outer chamber, k is the Boltzmann constant, and T_1 , T_2
85 are the vessel temperatures. Using $P = 10^{-9}$ mbar as the ion gauge pressure (actually
86 the upper limit as the gauge was under range), $T_1 = 300$ K, and $T_2 = 4$ K, they obtain
87 $n = 2.1 \times 10^8 \text{ cm}^{-3}$ inside the trap. Unfortunately this model omits the important effect of
88 cryocondensation on the cold bore of the magnet, a crucial feature of the trap vacuum.

89 The arrangement of the bore, trap, and detector is shown in figure 1. The magnet
90 bore was a 45 cm long, 12 cm inner diameter stainless steel tube in direct contact with
91 the liquid helium bath. Its operational temperature was measured to be 8 K. At this
92 temperature the condensation coefficients of most gases are close to unity so residual gas
93 will condense on the wall after just a few collisions, rather than remain in the gas phase and
94 reach thermal equilibrium. The bore is effectively a cryopump. According to the theory of
95 cryocondensation (see for example Refs. [14–16]) the partial pressure of all gases other than
96 hydrogen, helium, and neon will be negligible ($< 10^{-18}$ Pa) at 8 K. There is no reason to
97 expect neon in the vacuum system. Hydrogen is certainly present and in fact is the dominant
98 residual gas. Helium is also a possibility due to its emission into the guide hall atmosphere
99 from various cryogenic systems. Lacking important information about our vacuum system,
100 Serebrov, *et al.* embark on a highly speculative discourse on the residual gas spectrum in
101 our trap. They include the possibility of cryocondensation on the trap surfaces, which they
102 assume to be in the range 20 K to 30 K. The trap was actually somewhat warmer, about
103 40 K, due to its weak conductive contact with the bore. At that temperature water will be
104 pumped effectively but not other important gases such as air and methane. However they
105 neglect to consider the far more powerful effect of cryopumping by the bore that surrounds
106 the trap.

107 Residual gas interactions with trapped protons has been an important consideration in
108 this experiment from the outset decades ago. We have extensively studied the potential

109 effects of trapped proton interactions with hydrogen and helium, and there is recent theo-
110 retical work by others [17, 18]. The main concerns are charge exchange between a trapped
111 proton and a H_2 molecule or He atom, leaving a H_2^+ or He^+ ion inside the trap, or binding
112 of a trapped proton with a monatomic H atom, leaving a H_2^+ . The key point is both such
113 trapped ions would be detected by the proton detector at a slightly later time relative to
114 trapped protons. Due to the detector dead layer, the H_2^+ will appear at a lower, but de-
115 tectable energy and the He^+ at slightly higher energy relative to the protons. We did not
116 observe either of these in the 2005 experiment. In more recent data taken with the same
117 apparatus, but with a different vacuum configuration, we believe we were able to observe
118 trapped H_2^+ in certain vacuum conditions, but not at a level where they would significantly
119 affect the neutron lifetime result given the way our data were analyzed. This was recently
120 reported [19] and will be described more fully in an upcoming publication. The trap timing
121 plot shown in Ref. [1], figure 16 is based on incorrect assumptions about our trap and detec-
122 tor geometry. Serebrov, *et al.* claim that the H_2^+ (shown in blue) would not be observed but
123 would at the same time cause an overcounting of the background in region III. In reality, if
124 such events were present at a statistically significant level, they would be visible and appear
125 in region II, at approximately $43 \mu\text{s}$ in that figure. The conclusion of Serebrov, *et al.* that
126 this should be a $> 3 \text{ s}$ correction, based on an analysis that lacked important details of the
127 experiment, is incorrect.

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

138 A large class of potential systematic effects in the beam lifetime experiment, including
139 residual gas interactions, will cause a loss of protons from the trap with a time scale of ms.
140 Such effects would be made apparent by repeating the neutron lifetime measurement using

141 a range of trapping times from 1 ms to 100 ms. This was not achievable in the original NIST
142 experiment [2–4] due to trap instability at times over 10 ms. With improved trap stability
143 such a program of measurements is an important goal for the current BL2 effort as well as
144 the upcoming BL3 experiment.

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

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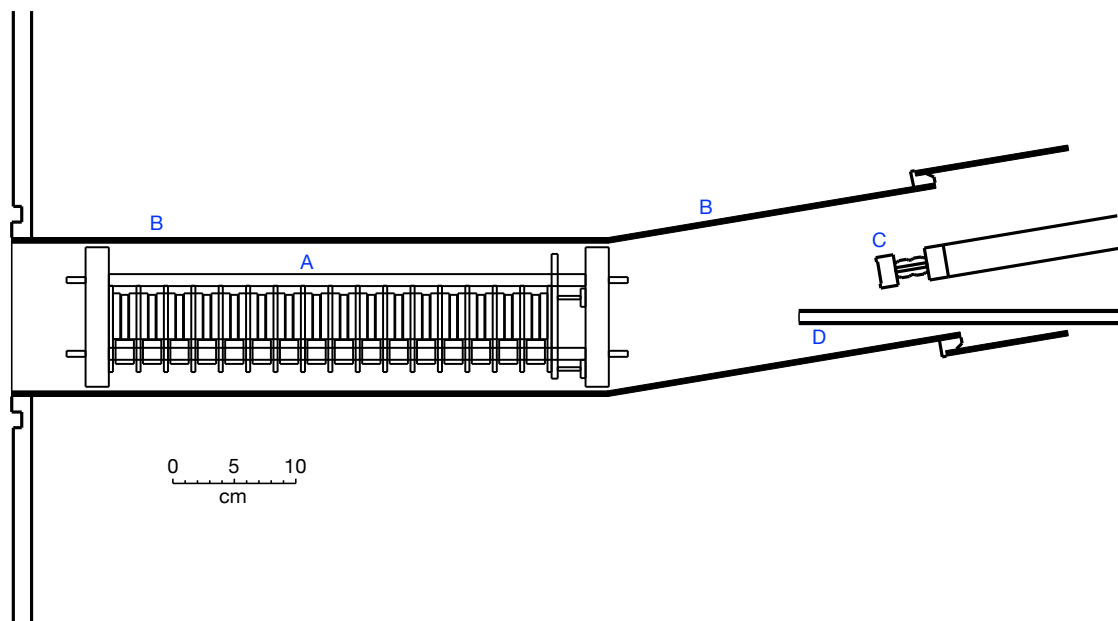


FIG. 1. Arrangement of the proton trap apparatus in the NIST beam neutron lifetime experiment [2, 3]. A) proton trap; B) 8 K magnet bore; C) silicon proton detector; D) quartz neutron guide.