Topical: Space-based Measurement of Neutron Lifetime

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Executive Summary

Free neutrons decay via the weak interaction with a mean lifetime of around 15 minutes. Knowledge of this lifetime is important as it provides constraints on the unitarity of the CKM matrix and is a key parameter for studies of Big-Bang nucleosynthesis. However, current laboratory measurements using two well-established techniques differ on average by more than 4 σ. Recent analysis of data obtained from NASA's MESSENGER and Lunar Prospector missions have demonstrated the possibility of using an alternative method, measuring the neutron lifetime from space. This new method should be explored further as a way to solve a significant and long-standing problem in fundamental physics.

Introduction

Free neutron β-decay is the archetypal semi-leptonic weak charged-current interaction. As such, it provides a direct route to study the underlying weak force. Although free neutrons are known to decay with a mean lifetime, τ_n, of around 15 minutes, there is significant disagreement about the exact value. Precise knowledge of τ_n is of great importance to both fundamental physics and cosmology [1,2].

In the Standard Model of particle physics there are three generations of quarks whose flavor eigenstates are mixtures of their weak eigenstates. The Cabibbo–Kobayashi–Maskawa (CKM) matrix describes the probability of flavor-changing weak decays, which are a consequence of the difference between quark mass and weak interaction eigenstates. By convention the negatively charged quarks are taken to be those that take part in mixing so the matrix is parameterized as

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}.$$

If only three generations of quarks exist, then the CKM matrix must be unitary. Presently, the strongest constraint on this unitarity comes from the first row of the matrix, with $|V_{us}| = 0.2245 \pm 0.0008$ from Kaon decay and $|V_{ub}| = (3.82 \pm 0.24)\times10^{-3}$ from B meson decays [3]. The most precise measurement of V_{ud} comes from experiments measuring $0^+ \rightarrow 0^+$ transitions in super-allowed nuclear beta decays with $|V_{ud}| = 0.97370 \pm 0.00014$, where both experimental and theoretical uncertainties due to radiative corrections, contribute significantly to the error [3]. Taken together, these measurements yield a 3σ tension with unitarity due to the recent update to $|V_{ud}|$ resulting from a new calculation of the universal radiative correction for β decay based on dispersion relations [e.g., 4]. This disagreement between the Standard Model and experiments highlights the importance of accurately constraining V_{ud}. Free-neutron beta decay provides us with the method of measuring the up-down quark mixing with the smallest theoretical uncertainties by avoiding nuclear structure corrections [2]. Therefore, reducing the uncertainty on the measurement of is of great value.

τ_n is also a key input to calculations of primordial helium abundance, and the uncertainties in these predictions are presently dominated by those on τ_n [5]. Primordial

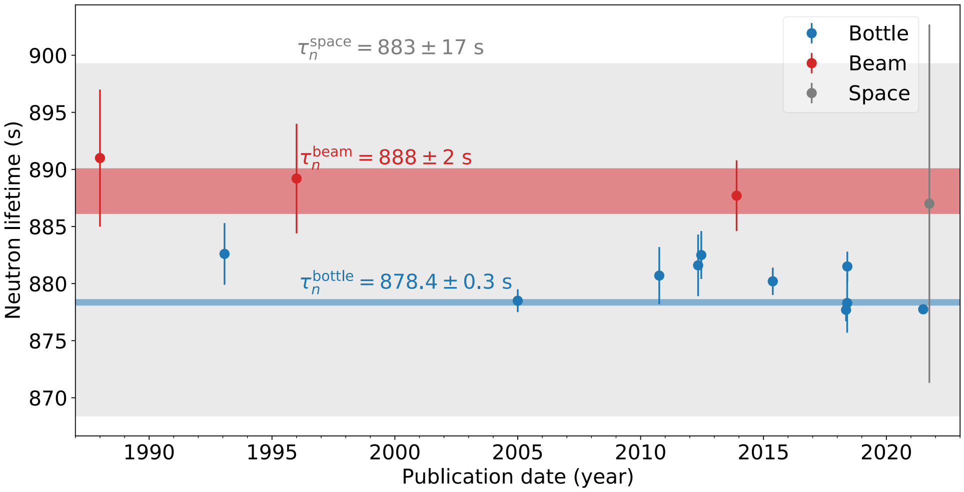

Figure 1: The history of recent beam and bottle measurements of the neutron lifetime using the beam and bottle methods. The shaded regions indicate the average of each class and its associated uncertainty.

nucleosynthesis is one of the major lines of evidence for the big bang, along with the observed expansion of the universe and cosmic microwave background. τ_n determines the primordial elemental and isotopic abundances during Big-Bang nucleosynthesis due to its influence on the rate of proton to neutron conversion, the timing of the freeze-out of these reactions, and the reduction of the neutron-to-proton ratio between freeze-out and the end of nucleosynthesis. Thus, knowledge of τ_n is critical in understanding how matter came into being and evolved in the early universe.

Currently, there are two competing values for τ_n based on the results of two different classes of long-established, high-precision laboratory experiments (Figure 1). The 'bottle' experiments involve counting the number of neutrons that survive within a material, magnetic, and/or gravitational trap as a function of time. The 'beam' experiments involve measuring the rate of production of β-decay products in a neutron beam passing through a trapping region. The average beam measurement $\tau_{\mathrm{beam}} = 888 \pm 2$ s differs by over 4σ from the more precise ultra-cold trapped neutron average $\tau_{\mathrm{bottle}} = 879.4 \pm 0.6$ s. This discrepancy, which has persisted for more than 15 years, has become known as the 'neutron lifetime puzzle'. The most likely explanation for the discrepancy is the presence of an unaccounted for systematic error in one, or both, classes of experiment. However, given the direction of the disagreement, a physical explanation is possible where the neutron decays to unobserved particles outside of the standard model with a branching fraction of approximately 1% [6, 7].

Further measurements with errors comparable to those already obtained offer no prospect of resolving the discrepancy, as there will remain significant scatter in the results and no rigorous way of removing unhelpful points. Instead, progress in resolving the tension between the two methods of τ_n-measurement has been suggested to take the form of either refinement of the existing techniques to substantially reduce their uncertainty or a reexamination of the systematic effects in existing measurements. The first of these is being planned or attempted [e.g., 8, 9, 10], the latter has been attempted without success [11, 12]. However, there exists a third path: performing the measurement using a new method with systematics unrelated to both beam and bottle approaches. Recently, a space-based technique to measure τ_n has been developed and refined using data taken by the neutron spectrometers onboard NASA's MESSENGER and Lunar Prospector (LP) spacecraft [13,14].

Measuring τ_n from space

The space-based approach relies on the detection of neutrons that escape from planetary bodies following their production in the collision of galactic cosmic rays (GCRs) with nuclei in the planets' surfaces or atmospheres. Some fraction of the escaping neutrons have thermal energies and typical velocities on the order of a few kms^{-1}. Therefore, the travel time of these neutrons to altitudes a few hundred to a few thousand km above the surface is $\mathcal{O}(\tau_n)$. Measurement of the rate of change of the neutron flux with altitude can therefore be used to infer the value of τ_n.

Although no dedicated mission or instrument has ever been flown to make use of this technique for measuring the lifetime, multiple planetary science missions have included neutron spectrometers to learn about the composition, particularly hydrogen abundances, of planets' surfaces. The data taken during elliptical phases of these missions provide a ready-made resource for measuring τ_n. Recent analyses of MESSENGER and LP neutron data were able to successfully make a measurement of τ_n and function as a proof-of-principle for space-based neutron lifetime measurements [13,14]. These results are shown in Figure 1 in the context of the beam and bottle measurements. The measurements were limited by the small amount of useable data (45 minutes for MESSENGER, three days for LP) and the large systematic uncertainties due to the missions being designed to do planetary science rather than nuclear physics. However, further exploration of these and similar data sets can be used to refine the space-based method by improving understanding of systematic uncertainties and developing more advanced analysis techniques. Similar data that could be used for additional neutron analyses include those taken by Mars Odyssey during its insertion into orbit, MESSENGER during its 4.5 year orbital mission, and Dawn during its orbit of the asteroid Ceres.

A dedicated mission to measure τ_n

Although study of existing data will be useful for refining analysis techniques, a dedicated mission is likely required to achieve the 3-s precision needed to distinguish between the beam and bottle measurements. *Lawrence et al.* [15] outlined two types of space-based measurement scenarios. The first type, orbital measurements, would function by measuring the rate of change of neutron flux with altitude and comparing it to models, assuming different values of τ_n. The second type, landed measurement, would involve measuring both the rate of neutrons leaving an airless planetary body such as the Moon and the rate returning on gravitationally bound orbits. The difference between these two rates is a function of τ_n. Notional instrument designs for each of these techniques are shown in Figures 2 & 3.

A landed lunar experiment has the advantage of frequent anticipated future missions to the Moon's surface over the next decade under the Commercial Lunar Payload Services (CLPS) initiative and Artemis program. In addition, the multiple missions that have characterized the Moon's surface reduce the systematic uncertainty associated with composition. The nominal detector design illustrated in Figure 2 would be have sufficiently small mass and power requirements that it could be incorporated into any of the existing CLPS landers. These benefits motivate the further study of lunar landed measurements to assess their suitability for resolving the neutron lifetime puzzle.

Orbital measurements could be taken around any body. However, Venus is the ideal candidate location for making neutron lifetime measurements. At Venus a neutron detector, like that illustrated in Figure 3, could achieve a measurement with three-second statistical precision after less than a day and a one-second statistical precision in less than a week [15]. For the same observation time, Venus provides an almost order-of-magnitude better statistical uncertainty than an Earth orbiting or Moon-landed experiment. The reason for this good expected performance is that Venus's thick atmosphere is around 95% CO_2 and therefore produces are large number of lower-energy thermal neutrons, which are used in the lifetime measurement. The planet also offers other advantages such that its space environment is relatively benign since it has no significant magnetic field to generate energetic particles or location-dependent changes to the local GCR flux. In addition, compared to the Earth and Moon, its composition is relatively simple, being well-mixed and containing only two major components. However, more work needs to be done to understand the extent to which uncertainties in Venus' atmospheric composition and temperature would propagate to uncertainties in a derived neutron lifetime.

One of the major challenges for making neutron lifetime measurements at Venus is the difficulty in getting to orbit. However, NASA recently selected two missions to Venus as part of its Discovery program [16]. Neither of these currently includes a neutron spectrometer but they provide the potential to host a neutron lifetime experiment on a mission already traveling to Venus, which would significantly reduce costs.

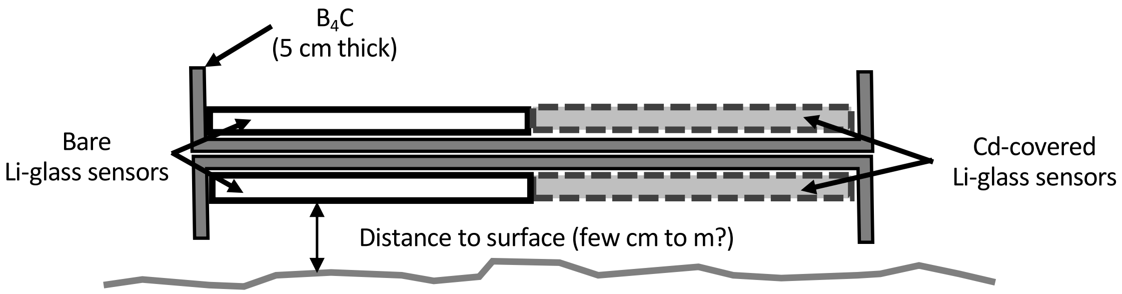

Figure 2: Notional sensor arrangement for a lunar landed neutron lifetime experiment. The experiment uses four Li-glass sensors with a size of 10 cm by 10 cm by 4 mm. One pair of sensors look upwards, and one pair look downwards. Each pair is shielded by a 5-cm thick layer of ^{10}B-enriched B_4C. For each pair, one sensor is covered in a layer of Cd and one sensor is bare. Each Cd-covered sensor provides a measure of epithermal neutrons and each bare sensor measures thermal plus epithermal neutrons. The count rate difference between each sensor within the pair provides a measure of thermal neutrons.

Earth-orbiting measurements are also possible but have poorer statistical performance than measurements at Venus. A statistically robust measurement is achieved in a few months, and < 1-s statistical precision in less than a year of operation. Measurements at Earth have the clear advantage that it is much easier to reach Earth orbit than Venus. In addition, to increase statistical precision, more detector area could be used. We note that detector area (or equivalently, total counts) scales as observation time. Thus, increasing the total detector area by a factor of two would decrease the needed observation time by the same factor of two for an equivalent statistical precision.

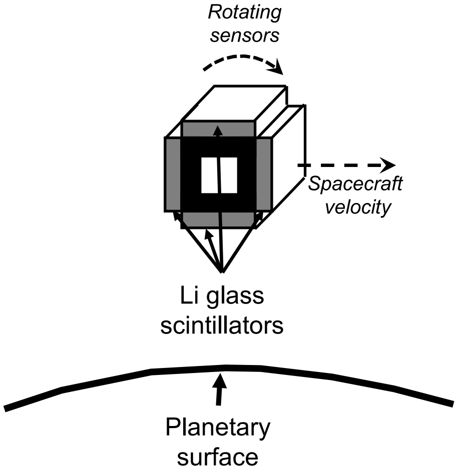

Figure 3: Notional sensor arrangement for an orbital neutron lifetime experiment. The experiment uses four Li-glass scintillators with a size of 10 cm by 10 cm by 4 mm.

Summary and recommendations

The neutron lifetime is an important parameter is several areas of physics. Resolving the existing stalemate between the two laboratory methods is necessary to make progress in this area and a space-based measurement provides a potential route to this goal. We make the following recommendations to support this project:

- Support research and analysis to understand the systematic errors involved in orbital measurements of the free neutron lifetime at Venus and the Earth and landed measurements at the Moon. These uncertainty estimates will provide guidance for future mission design.
- Support the continued investigation of existing planetary neutron data sets, taking the opportunities that are currently available to maximize the science achieved by previous missions.
- Develop a detailed design concept to fly one or more missions to measure the neutron lifetime either in Earth orbit, on a lunar lander or as part of a ride-along with upcoming Venus missions.

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