

Short Communication

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Possible explanation for the neutron lifetime puzzle

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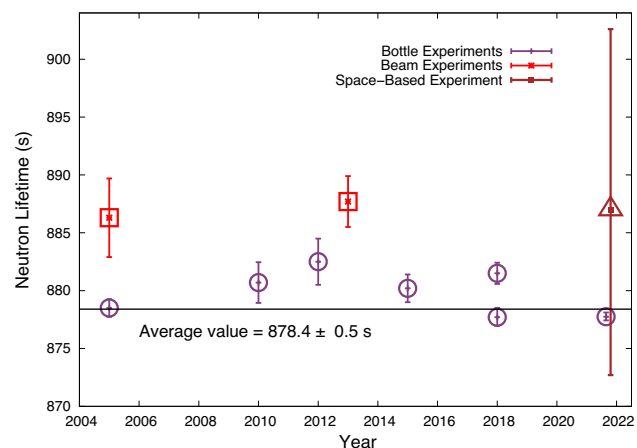
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Abstract: The discrepancy in the measured value of neutron lifetime has significance in big-bang nucleosynthesis and testing the accuracy of the standard model. A discrepancy of approximately 10 s still persists between the average value of the neutron lifetime obtained by storing ultracold neutrons in traps and the most accurate method of using neutrons in beams. This discrepancy is thought to be due to an unknown systematic uncertainty in these experiments or the existence of new physics. This article discusses a possible explanation for this discrepancy in neutron lifetime. This neutron lifetime anomaly is likely attributed to an increase in the decay probability caused by multiple elastic collisions between neutrons and between neutrons and trap walls.

Keywords: neutron lifetime, UCN, multiple elastic scattering, CKM matrix, primordial nucleosynthesis

1 Introduction

A free neutron transforms into a proton by emitting an electron and an antineutrino. The precise value of the lifetime of a neutron has an impact in particle physics and cosmology. In conjunction with other neutron decay parameters, such as the asymmetry parameter A , the neutron lifetime can be used to test whether the Cabibbo-Kobayashi-Maskawa matrix is unitary [1]. Furthermore, neutron lifetime is also crucial in determining the primordial abundance of ^4He [2]. The two primary approaches used to measure the neutron lifetime are the “bottle” and “beam” methods. The “beam” method involves simultaneously measuring both neutron flux and neutron decay products, such as electrons and protons [3,4]. The “bottle” method involves trapping ultracold



Graphical abstract

neutrons (UCNs) in a material container [5,6] or magnetic container [7,8] for varying durations. The neutron lifetime can be calculated by counting the number of surviving neutrons after a specific time interval and fitting the resulting decay curve. The value of the neutron lifetime measured using these two methods has shown a significant discrepancy. This discrepancy between the high-precision measurement of the neutron lifetime obtained using the beam method, $\tau_n^{\text{beam}} = 887.7 \pm 1.2_{\text{stat}} \pm 1.9_{\text{sys}}$ [4], and the bottle method, $\tau_n^{\text{bottle}} = 877.75 \pm 0.28_{\text{stat}} + 0.22/-0.16_{\text{sys}}$ s [8], could be caused by either an unknown systematic uncertainty in the methods used in these experiments or the existence of new physics.

The value of the neutron lifetime reported by the particle data group is $\tau_n = 878.4 \pm 0.5$ s [9]. To obtain this value, they averaged eight of the nine best measurements that used UCNs. The value measured using the Beam Lifetime 1 (BL1) experiment by Yue et al. [4] was excluded. Serebrov et al. [10] studied the systematic error of the BL1 experiment and suggested a correction due to the loss of the proton, which could decrease the measured value of the neutron lifetime. The issues brought forth by Serebrov et al. were refuted by Wietfeldt et al. [11] who reported that the effects and issues pointed out were adequately analyzed in the experiment, and that the value of the neutron lifetime measured using the BL1 experiment remains unaltered. Hoogerheide et al. [12] reported the

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status of the Beam Lifetime 2 (BL2) experiment for measuring the neutron lifetime. Owing to the improved neutron and proton counting, along with a better understanding of systematic errors, they expect to measure the value of the neutron lifetime with an uncertainty smaller than 1 s.

To resolve the neutron lifetime discrepancy, Fornal and Grinstein [13] proposed that the final state of neutron decay involves one or more dark matter particles. Several theoretical and experimental studies have been conducted to test this hypothesis. Tang et al. [14] in their experimental study excluded the possibility of the decay channel $n \rightarrow \gamma + \chi$ in the energy range of photon $0.782 \text{ MeV} < E_\gamma < 1.664 \text{ MeV}$ in explaining the discrepancy of the “bottle” and the “beam” method. χ here is a dark particle and γ is a photon. Another study conducted by Sun et al. [15] reported that the decay channel $\chi + e^+e^-$ for χ masses corresponding to $100 \text{ keV} \ll E_{e^+e^-} \ll 644 \text{ keV}$ was also ruled out to resolve the neutron lifetime anomaly. Here, $E_{e^+e^-}$ is the summed kinetic energy of the leptons.

Another possible explanation for this discrepancy is the conversion of neutron n into mirror neutron n' within the parallel mirror sector [16,17]. The $n - n'$ oscillation has not been observed in several experimental studies that have been carried out [18–20]. Serebrov [21] while investigating a possible explanation of the neutron lifetime anomaly suggests that even if $n - n'$ oscillation is observed, it will be unable to explain the neutron lifetime discrepancy as the $n - n'$ oscillation will be suppressed in the presence of the earth’s magnetic field.

In a recent article by Oks [22] on neutron two-body decay, in which the neutron decays into a hydrogen atom and an antineutrino, the author reported that the theoretical branching ratio of this decay increases when considering a second solution to the Dirac equation for hydrogen atoms, which leads to a second flavor of hydrogen atoms. The author calculates the theoretical branching ratio for the neutron two body decay to be approximately 1.3%, which could potentially explain the discrepancy in the neutron lifetime measurement as the “beam” experiments only detects protons as decay products and not hydrogen atoms. However, to date, there has been no experimental evidence to support the reported amplification of the branching ratio of neutron two-body decay.

A third method to address the neutron lifetime anomaly is a measurement of neutron lifetime in space [23,24]. As these experiments have different systematic uncertainties, they can provide independent neutron lifetime measurements. The neutron lifetime value of $\tau_n = 887 \pm 14_{\text{stat}} + 7/-3(\text{sys}) \text{ s}$ was measured by Wilson et al. [24] using a neutron spectrometer on NASA’s Lunar Prospector mission. Although the

uncertainty in these measurements is large, the measured neutron lifetime value is in agreement with the value reported by the “beam” method.

2 Possible explanation of the discrepancy in the neutron lifetime

Koshelkin [25] investigated the influence of multiple elastic collisions on particle decay in an equilibrium medium. He concluded that the probability of decay consistently increased because of the multiple elastic scatterings of the decay particles within the medium. The increase in the decay probability in two-particle collisions depends on the observation time, collision frequency, and square of the maximum energy transferred in the collisions. If the energy fluctuation over the observation period, defined by at_0 , is greater than or equal to the matter temperature, that is $at_0 \geq T$, then there is a strong effect on the decay probability due to the multiple elastic collisions. Here, a is the amount of energy transferred to the particle in unit time and t_0 is the observation period. Furthermore, in the calculation of a real scattering problem of the Dalitz decay of pions in an equilibrium pion gas, Koshelkin found an increase of at least 32% in the decay probability. This increase in the decay probability of 32% was calculated when the energy fluctuation during scattering was of the order of matter temperature [25]. Moreover, a considerable increase in the probability of pion decay was calculated for a large number of particle collisions.

To date, no experimental study has been performed to investigate the effects of multiple elastic scatterings on decay probability. As this effect may not be limited to only high energy and high temperatures, a slight increase in decay probability of 1% due to the multiple collisions among neutrons and between neutrons and container walls could explain the discrepancy between the values obtained using the “bottle” and “beam” methods. This effect, in the case of the decay of neutrons in material or magnetic bottles, is possible because of the long observation times of neutrons within the bottle, which will lead to a large number of elastic collisions. In addition, due to the long observation time, the condition for the influence of multiple elastic collisions on particle decay, $at_0 \geq T$, could be satisfied.

In the presence of this effect, there should be an increase in the decay probability in a smaller trap size when compared to a larger trap size, owing to higher neutron density and more frequent collisions between the neutrons and between neutrons and the trap walls. This

could be one of the reasons why the measurements on the magneto-gravitational trap by Ezhov et al. [7] reported a lower neutron storage lifetime value, $\tau_{st} = 874.6 \pm 1.7$ s when compared to the measurement reported by UCN τ collaborators [4], which has a larger trap size [26]. Moreover, the measured neutron lifetime values are even lower for smaller and narrower traps, such as the Ioffe-type magnetic trap at National Institute of Standards and Technology [27,28], Halbach octupole permanent magnet [29], and τ SPECT [26,30,31] experiments, suggesting the effect of multiple elastic collisions in increasing the neutron decay probability.

If this phenomenon exists, the neutron lifetime measured by UCN storage experiments will depend slightly on the shape and size of the trap. Hence, systematic uncertainty due to the effects of multiple elastic collisions must be considered. In doing so, the true neutron lifetime value can be closer to the measurement obtained using the “beam” method. Another supporting point suggesting that the lifetime measurement obtained using the “beam” method might be the true neutron lifetime is the neutron lifetime value measured by the space-based measurements. Even though the uncertainty in space-based measurement [24], which has different systematic uncertainty, is large, the value of the measured lifetime is close to that obtained using the “beam method.”

3 Conclusion

I claim that the discrepancy in the value of the mean lifetime of the neutron decay measured using the “beam” and “bottle” methods could be due to the increase in the decay probability due to multiple elastic collisions of neutrons in the material or magnetic trap. This effect might depend on a random change of energy of the decaying particles due to collisions between them. The short neutron lifetime in small-size traps also indicates that the neutron lifetime can vary due to an increase in the collision frequency and neutron density. To resolve the neutron anomaly, an upgraded magnetic-gravitational trap experiment UCN τ + [32] and an upgraded pulsed beam experiment Beam Lifetime 3 (BL3) [33] are currently under development. Due to the improvements in the pulsed beam experiment, the BL3 experiment aims to measure the value of the neutron lifetime with a 0.1 s uncertainty [33]. If this discrepancy in the neutron lifetime measurement persists, the underestimation of the neutron lifetime in UCN storage experiments due to multiple elastic collisions of neutrons will be a strong possibility for explaining the anomaly. I hope that this will motivate researchers to explore the possibility of testing the effects of multiple elastic collisions on neutron decay.

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