Measurement of neutron lifetime with a gravitational trap for ultracold neutrons

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The lifetime of the neutron has been measured through confinement of ultracold neutrons in a gravitational trap. The result is $\tau_n = 888.4 \pm 2.9$ s. This lifetime corresponds to a ratio $G_A/G_V = \lambda$ of $-(1.2677 \pm 0.0025)$. The discrepancy in the results on the parameter λ found from measurements of the neutron lifetime and from measurements of the electron-spin asymmetry of the β decay of the neutron is discussed.

Precise measurements of the neutron lifetime and of the correlation coefficients in the β decay of the neutron provide an additional opportunity for testing the standard *V–A* model and for seeking possible deviations from it. The vector weak-interaction constant can be determined highly accurately, as we know, from data on $f\tau$ for superallowed Fermi $(0^+ - 0^+)$ transitions:

$$(f\tau)^{0-0}(1-\delta_c)(1+\delta_R) = \frac{\pi^3\hbar^7}{m_e^5c^4G_V^2(1+\Delta_\beta)}, \tag{1}$$

where f is the phase-space factor, τ is the observed lifetime, δ_c is the nuclear structure correction, δ_R is the external radiation correction, Δ_β is the internal radiation correction, and G_V is the vector weak-interaction constant. Because of the low energy of the β decay of a neutron, the form factors which depend on the energy play a very minor role ($\sim 10^{-3}$), and the β decay of the neutron can be described essentially completely by a single parameter: the ratio of the axial and vector weak-interaction constants, $G_A/G_V = \lambda$. The neutron lifetime τ_n and the electron-spin asymmetry of the β decay, A, are related by

$$(f\tau)^n(1+\delta_R^n) = \frac{2\pi^3\hbar^7}{m_e^5c^4G_V^2(1+\Delta_\beta)(1+3\lambda^2)}, \tag{2}$$

$$A = -2\frac{\lambda^2+\lambda}{1+3\lambda^2}. \tag{3}$$

The experimental task is to independently determine the parameter λ from the neutron lifetime (λ_τ) and from the electron-spin asymmetry of the β decay of the neutron (λ_A).

In this letter we are reporting new measurements of the neutron lifetime, carried out through confinement of ultracold neutrons in a gravitational trap.

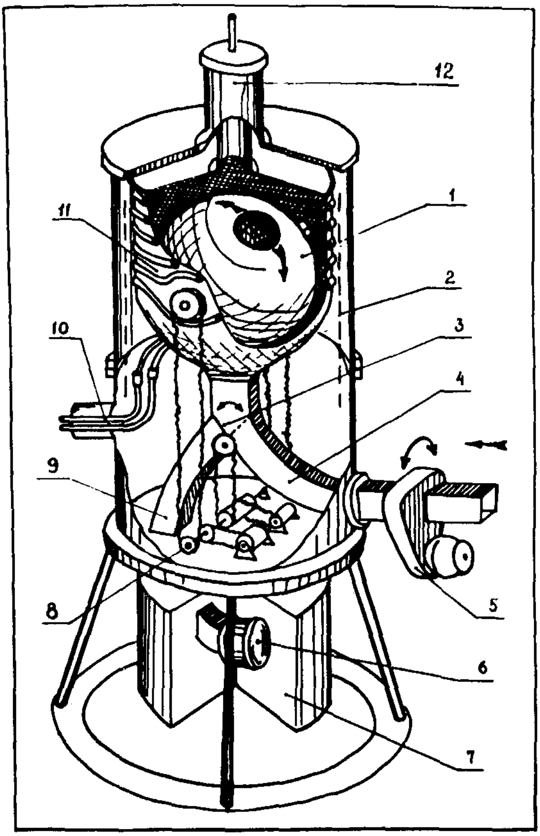

FIG. 1. 1—Trap for confining ultracold neutrons; 2—liquid-nitrogen screen; 3—distribution valve; 4,9—inlet and outlet guides for ultracold neutrons; 5—inlet valve; 6—detector; 7—detector shielding; 8—valve and trap drive mechanism; 10—cryogenic conductors; 11—volume held at cryogenic temperature; 12—lock for the coating-freezing system.

The basic purpose of this experiment was to significantly suppress the loss of ultracold neutrons during their storage in the trap and to approach direct observation of the exponent of the neutron decay. For this purpose, we used low-absorption materials (Be and O_2) and low temperatures (15 K).

Figure 1 shows the experimental layout. The apparatus is a trap with a gravitational gate for the confinement of ultracold neutrons. The trap doubles as a gravitational spectrometer. The ultracold neutrons are trapped by rotating the trap around a horizontal axis from the position with the aperture down to the position with the aperture up. The low-energy neutrons are then trapped by virtue of the gravitational field. The choice of mode (storage or outlet) is made with a distribution valve and an inlet valve. After confinement for a given time, the spectrum of the neutrons is measured by a sequential step-by-step rotation of the trap back to its original position. In general, the probability (τ_{loss}) for the loss of ultracold neutrons in the trap is proportional to the loss factor η and is a function of the neutron energy E, the size and shape of the trap (R), and the limiting energy of the wall material (E_{lim}):

$$\tau_{st}^{-1} = \tau_n^{-1} + \eta\gamma(E, R, E_{lim}). \tag{4}$$

Equation (4) is a linear function of the argument γ, which can be calculated for a given trap geometry and for the energy intervals selected experimentally. The limiting energy of the wall material can be found directly in the course of the experiments. The neutron lifetime is found by extrapolating to a zero value of the argument γ. A necessary condition for high measurement accuracy and reliable results is that the second term in Eq. (4) be small, i.e., that the probability for the loss of ultracold neutrons from the trap during their storage be much lower than the probability for the decay of a neutron.

Traps for neutron storage were fabricated from aluminum. The inner surface of the traps was coated with a beryllium sublayer 3000–5000 Å thick, on which an oxygen layer 3–7 μm was frozen. The purity of the oxygen used in these experiments was 99.99%. The trap was cooled to a low temperature (15 K) to suppress the loss of neutrons due to inelastic scattering.

The first experiments, with a spherical trap 75 cm in diameter, revealed that the probability for the loss of ultracold neutrons during storage was 3% of the probability for β decay of the neutron. This figure is a measure of how closely we are approaching direct measurements of the neutron lifetime ($\tau_{\mathrm{loss}} = 8$–10 h). Incorporating the loss of neutrons, with a 10% error, for example, makes it possible to achieve an error of 0.3% in the measurement of the neutron lifetime. However, the range over which the function γ could be varied on the sole basis of the energy dependence of the loss function turned out be inadequate to achieve such an accuracy. In a second phase of the experiments, we accordingly used a cylindrical trap 72 cm in diameter but with a small distance (15 cm) between the flat walls.

The results of these measurements are shown in Fig. 2 as a plot of Eq. (4). Plotted along the ordinate are the experimental values of τ_{st}^{-1} versus the calculation argument γ. The measurements with the beryllium traps have a poorer statistical accuracy; the purpose of those experiments was to demonstrate the conditions for carrying out the measurements before the deposition of the oxygen.

The measurements yielded the following values for the neutron lifetime: $\tau_n = 885.0 \pm 7.7$ for traps with a beryllium coating and $\tau_n = 889.0 \pm 3.1$ for traps with an oxygen coating. The values of the loss factor η are $(28.1 \pm 4.0) \times 10^{-6}$ for beryllium and $(6.1 \pm 0.6) \times 10^{-6}$ for oxygen. The normalized value of χ^2 confirms the validity of the extrapolation; for the traps with an oxygen coating, this value is 0.81. The final result for the neutron lifetime according to these experiments is 888.4 ± 2.9, and the corresponding value of λ_τ is $-(1.2677 \pm 0.0025)$.

In evaluating the possibilities for further improvement of the accuracy in this experiment, we should note that it would seem to be possible to improve the accuracy by a factor of 1.5–3 by continuing to increase the statistical base or by using a more intense beam of ultracold neutrons. However, there is considerable interest in continuing the effort to further reduce the role played by the loss of ultracold neutrons during storage.

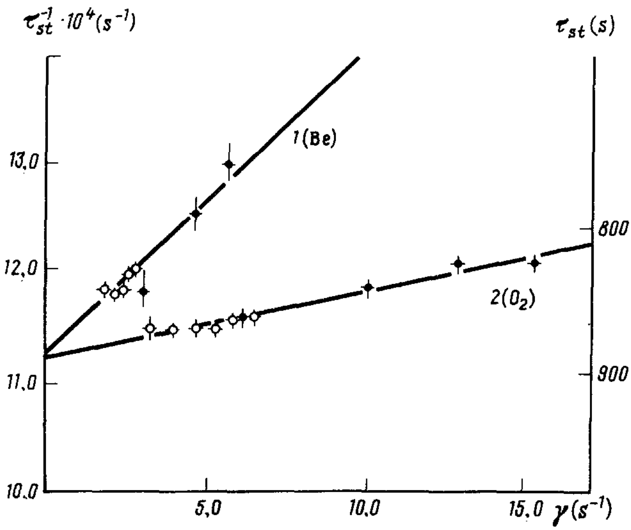

FIG. 2. Results of the measurements of τ_{st}^{-1} versus the calculation parameter γ. 1(Be)—Extrapolation to the neutron lifetime according to data from traps with a beryllium coating; 2(O_2)—extrapolation to the neutron lifetime according to data for traps with an oxygen coating and a beryllium sublayer. ○—Results for a spherical trap; ●—results for a cylindrical trap.

The result found agrees with the most accurate results of Refs. 1 and 2, according to which the values of τ_n are 887.6 ± 3.0 and 893.5 ± 5.8 s. Working from the results of other experimental data[1-7] on the lifetime of the neutron and the results of our own experiments, we find the following value for the neutron lifetime and for the parameter λ_τ:$\tau_n = 888.52 \pm 1.85$ s and $\lambda_\tau = -(1.2676 \pm 0.0016)$. From measurements[8-11] of the electron-spin asymmetry coefficient A, on the other hand, one finds $\lambda_A = -(1.2570 \pm 0.0028)$. The discrepancy in the results on λ is 0.0106 ± 0.0033 or 3.2σ.

Although this discrepancy is statistically significant, one cannot rule out the possibility of a random deviation or the possibility of systematic experimental errors which cannot yet be identified.

This discrepancy might be reduced by allowing for the effect of the nuclear matter on the magnitude of the internal radiation correction Δ_β. As was shown in Ref. 12, part of the radiation correction, which depends on the structure of the strong interaction, differs for the decay of a free neutron and for a nucleus. As a result, Δ_β in expression (1) is replaced by the difference $(\Delta_\beta - \Delta_\lambda)$, and λ_τ is reduced by 0.3%. The remaining discrepancy is 2.1σ. It would nevertheless be interesting to analyze other possible interpretations of this discrepancy.

If it is assumed that this discrepancy can be attributed to the introduction of right-handed currents, then by working from the results of Ref. 13 it can be found how the experimental values of A and τ are related to the model parameters η and ζ (η is the ratio of the squared masses of the left-hand and right-hand vector bosons, and ζ is their mixing angle):

$$0,23\eta^2 + 2,2\eta\varsigma + 1,1\varsigma^2 = A + 2\frac{\lambda_\tau^2 + \lambda_\tau}{1 + 3\lambda_\tau^2}. \tag{5}$$

The right-hand side of (5) is determined by the experimental results; its value is $(2.62 \pm 1.22)\times 10^{-3}$ after the correction Δ_λ is incorporated.

The region of limitations found from the neutron experiment in this manner for a 90% confidence level is shown in Fig. 3, which also shows limitations which follow from μ decay.[14] Although the limitation regions do overlap partially, and the data from the neutron and muon experiments can be reconciled, the overlap region found is at odds with the fairly strong limitation on the mixing angle which follows from an experimental test of the unitarity of the Kobayashi-Maskawa matrix:[15-17] $|\zeta| < 4\times 10^{-3}$. The contradiction remains even if one assumes that the correction Δ_λ introduced in Ref. 12 is only approximate and goes completely into a degradation of the accuracy of the unitarity test. The expanded region of limitations, which follows from the unitarity of the Kobayashi-Maskawa matrix, is shown in Fig. 3. Finally, one should note that analysis of the contribution of right-handed currents to the difference between the meson masses K_L and K_S (Ref. 18) and to the nonleptonic decays of K

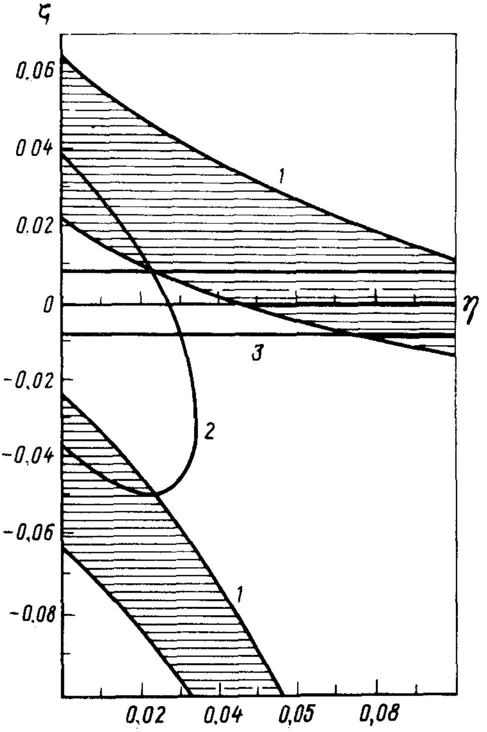

FIG. 3. Limitations on the mixing angle ζ and on the ratio of the squared masses, η, (1) found from a combination of the neutron lifetime, the asymmetry of the β decay of the neutron, and the probability for superallowed Fermi transitions; (2) from the asymmetry of μ decay; and (3) from the unitarity of the Kobayashi-Maskawa matrix (the hatched region; see the text proper).

mesons[19] impose far more severe limitations ($\eta \leqslant 3 \times 10^{-3}, |\zeta| \leqslant 4 \times 10^{-3}$). We thus see that an explanation of the discrepancy between λ_A and λ_τ on the basis of right-handed currents, as proposed in Refs. 20 and 21, runs into obvious difficulties.

Another interpretation would be possible if one assumed that there is a nonzero Fierz term ~1–2%. We know that a nonzero Fierz term is associated with the scalar and tensor versions of the interaction. A tensor interaction, however, is limited fairly strongly by experimental data, in addition to being unattractive from the theoretical standpoint.[22] There is also a limitation[15] $b_F \leqslant 0.004$ on a Fierz term with a scalar interaction, shutting the door on the possibility of a significant contribution to the difference between λ_A and λ_τ. Furthermore, from the limitations on the mass of charged Higgs bosons, $M_H > 19$ GeV (Ref. 23), one would expect an even smaller value for $b_F (b_F \leqslant 3 \times 10^{-8})$.

In summary, there are at present no grounds for believing that this difference between λ_A and λ_τ can be explained theoretically. A resolution of this question will require further experimental study of the β decay of the neutron.

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