Measurement of neutron lifetime through storage of ultracold neutrons

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The lifetime of the neutron has been measured by a method of storage of ultracold neutrons in a cooled, hermetically sealed aluminum vessel. The result is 903 ± 13 s. Preliminary data from measurements of the neutron lifetime during the storage of ultracold neutrons in a vessel with walls made of heavy-water ice are reported.

In this letter we report measurements of the neutron lifetime τ_β by a method of strorage of ultracold neutrons in a vessel cooled to 80 K. A special cleaning of the surface of the vessel, combined with the cooling, has made it possible to lower the loss of ultracold neutrons due to collisions with the wall to ~20% of the total loss. It has thus become possible to measure τ_β within a relative error of 1.4%; this figure does not represent a limit on the method.

The method gas is accumulated and stored in a cylindrical aluminum vessel 105 cm in diameter and 75 cm high (Fig. 1). The vessel is cooled to 80 K and heated to 750 K by means of liquid-nitrogen coils and heater coils. The vessel is filled with neutrons by injection through an inlet gate from the ultracold-neutron installation of the SM-2 reactor.[1] The ultracold neutrons then move along a vertical channel through an aluminum membrane and a hole in the bottom into the vessel, where they are blocked by a disk-shaped gate. The height to which the vessel is raised with respect to the transport neutron duct is chosen in such a way that the ultracold neutrons that are accumulated in the vessel rise no more than $H_{\max} = 48$ cm above the bottom of the vessel. The ultracold neutrons remaining in the vessel are detected by a He^3 gas-filled proportional detector.

Four packets of plane aluminum plates (the plates are separated by gaps of 1 cm) are suspended by aluminum filaments in the upper part of the vessel, which is inaccessible to the ultracold neutrons. The packets, which are used to change the frequency at which the neutrons collide, are lowered and raised by means of movable solenoids. The steel cores in these solenoids are attached to the filaments by which the packets are suspended.

The neutron vessel is a hermetically sealed unit in a load-bearing vacuum housing. The housing and the vessel have independent evacuation systems. The vacuum in the housing is maintained at $\sim 10^{-5}$ torr. The ultracold-neutron vessel is evacuated by an NORD-250 vacuum pump to $\sim 10^{-6}$ torr and then hermetically sealed.

In the case of the storage of ultracold neutrons which have a velocity v_0 at the bottom of the vessel ($z = 0$), the probability of loss due to collisions with the walls is

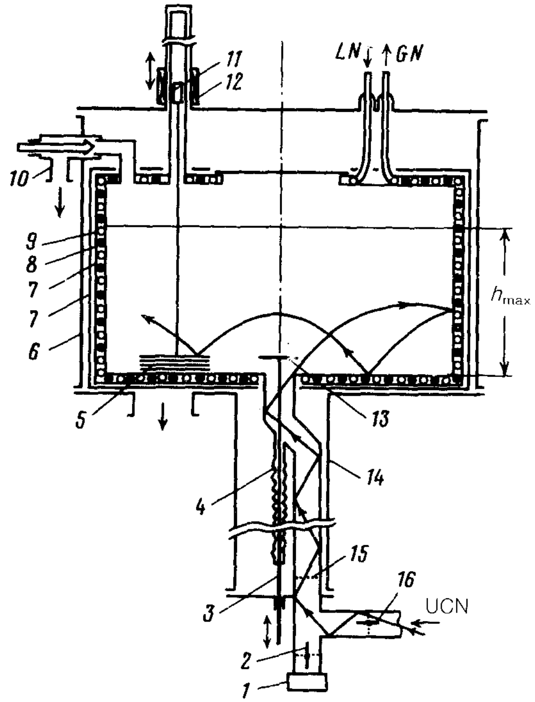

FIG. 1. The experimental apparatus. 1—Ultracold-neutron detector; 2—detector gate; 3—shaft of disk-shaped gate; 4—bellows unit; 5—packet of plates; 6—vacuum housing; 7—heat shields; 8—heater; 9—liquid-nitrogen coil; 10—hermetically sealed valve for evacuating the vessel; 11—core; 12—solenoid; 13—disk-shaped gate; 14—lower cylinder of housing; 15—aluminum membrane; 16—inlet gate for ultracold neutrons.

$$\lambda_l = \eta\gamma(v_0) = \frac{\eta \int\limits_{(s)} v_{\text{lim}}^2 \left(\arcsin \sqrt{\dfrac{v_0^2 - 2gz}{v_{\text{lim}}^2}} - \sqrt{\dfrac{(v_0^2 - 2gz)(v_{\text{lim}}^2 - v_0^2 + 2gz)}{v_{\text{lim}}^4}} \right) ds}{2 \int\limits_{(\Omega)} \sqrt{v_0^2 - 2gz}\, d\Omega}, \tag{1}$$

where η is the ratio of the imaginary and real parts of the neutron-wall interaction potential,[2] v_{lim} is the limiting velocity for aluminum, s is the surface area of the vessel and of the plates in the neutron storage volume, z is the height above the bottom, and $\gamma(v_0)$ is a geometric factor of the experiment.

If the vessel is filled with ultracold neutrons with a broad velocity spectrum, we have

$$\lambda_l = \eta\gamma(t) = \frac{\eta \int\limits_0^{v_{\max}} f(v_0)\gamma(v_0)\exp[-\eta\gamma(v_0)t]\,dv_0}{\int\limits_0^{v_{\max}} f(v_0)\exp[-\eta\gamma(v_0)t]\,dv_0}, \tag{2}$$

where $f(v_0)$ is the spectrum of the ultracold neutrons in a vessel at the beginning of the storage, and $v_{\max}$ is the upper boundary of the spectrum.

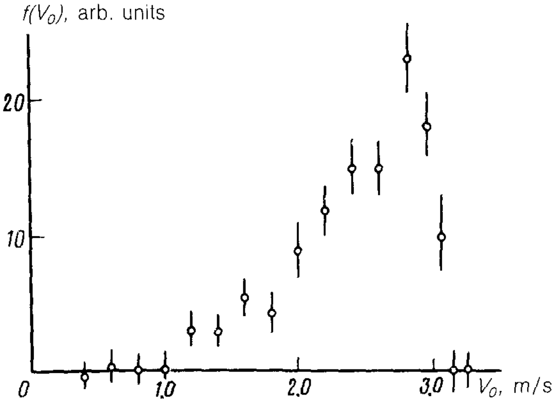

FIG. 2. Spectrum of ultracold neutrons accumulated in the vessel.

In this case the time evolution of the number of ultracold neutrons in the vessel can be described by the total loss probability $\lambda = (1/\tau_\beta) + \eta\bar{\gamma}$, where $\bar{\gamma}$ is determined by averaging $\gamma(t)$ over the interval from 0 to $t_{\max}$ (the maximum time the neutrons are held in the vessel). If $\bar{\gamma}$ is varied in a controlled way in the course of the experiment, then by measuring the dependence of λ on γ we can determine the value of $\lambda_p = 1/\tau_\beta$ by extrapolating γ to zero.

Figure 2 shows the spectrum of ultracold neutrons accumulated in the vessel, determined by the method of an absorber gas immersed in the neutron gas.[3] Before the measurements, the inner surface of the vessel and the surfaces of the plates are processed in an identical way. The processing includes etching in NaOH, washing with distilled water, heating in 2 vacuum, and annealing in oxygen at 750 K. At the end of the processing, the vessel is evacuated and sealed hermetically until the measurement cycle is completed. Figure 3 shows the dependence of λ on γ at a wall temperature of 80 K and a plate temperature of 300 K. This behavior is the result found in four cycles of measurements, in each of which the surface treatment was repeated. The values of γ were calculated for $v_{\text{lim}} = 3.2$ m/s. After an extrapolation of γ to zero by the method of least squares, we find $\lambda_p = (111.8 \pm 3.8) \times 10^{-5}$ and $\eta = (6.42 \pm 0.20) \times 10^{-5}$ for

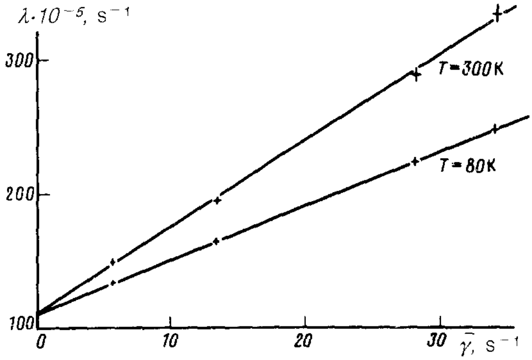

FIG. 3. The total probability (λ) for the loss of ultracold neutrons as a function of the factor γ for various vessel temperatures.

the vessel at 300 K. At 80 K, these values are $\lambda_p = (111.24 \pm 1.46) \times 10^{-5}$ and $\eta = (4.08 \pm 0.15) \times 10^{-5}$. The error in our results on λ_p is due exclusively to the statistical scatter in the number of ultracold neutrons in the vessel and random deviations of the parameter η from the mean value. To find the final result, we used the value of λ_p measured at 80 K. For this purpose, we took into account the methodological errors in the determination of λ_p, due to the following factors:

(a) the replacement of the function $\gamma(t)$ by the mean value $\bar{\gamma}(\Delta\lambda_p/\lambda_p = 0.2\%)$;

(b) possible deviations of $v_{\rm lim}$ from 3.2 m/s (aluminum) to 5.2 m/s (Al_2O_3) and corresponding changes in the calculated values of $\bar{\gamma}(\Delta\lambda_p/\lambda_p = 0.1\%)$;

(c) the experimental error in the determination of $f(v_0)$ and the resulting error in the calculation of $\bar{\gamma}(\Delta\lambda_p/\lambda_p = 0.2\%)$;

(d) the escape of ultracold neutrons from the vessel through the slit under the gate $\Delta\lambda_p/\lambda_p = (-0.4 \pm 0.4)\%$;

(e)the heating and capture of the ultracold neutrons by the residual gas in the storage vessel $\Delta\lambda_p/\lambda_p = (-0.05 \pm 0.04)\%$.

Taking the methodological errors into account, we find $\lambda_p = (110.75 \pm 1.55) \times 10^{-5} s^{-1}$, which corresponds to $\tau_\beta = 903 \pm 13$ s or a decay half-life $T_{1/2} = 626 \pm 9$ s. The accuracy of this result is at the level of that of the best results which have been achieved by the conventional measurement methods.[4,6] A further improvement in the accuracy will involve reducing the statistical error of the measurements and using "clean" neutron vessels.[7] This apparatus is presently being used to measure τ_β by the method of the storage of ultracold neutrons in a vessel on whose wall a layer of D_2O ice is condensed at 80 K. According to preliminary results, the loss of ultracold neutrons at the vessel walls is 3–4% of the total loss. The statistical base which has been achieved to data yields the estimate $\tau_\beta = 892 \pm 20$ s. A further improvement in the statistical error may make it possible to reduce the error in the measurement of τ_β to 1% or less.

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