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The neutron lifetime has been measured by counting the neutrons remaining in a fluid-walled bottle as a function of the duration of storage. Losses of neutrons caused by the wall reflections are eliminated by varying the bottle volume-to-surface ratio. The result obtained is $\tau_\beta = 887.6 \pm 3$ s.

The β decay of the neutron $(n \to p + e^- + \bar{\nu}_e)$ offers the possibility of determining the coupling constants of the weak interaction (g_A, g_V) directly and with good precision. An essential part of this information is contained in the neutron lifetime $(\tau_\beta^{-1} \propto g_V^2 + 3g_A^2)$. τ_β plays, moreover, an important role in some fundamental questions in astrophysics and cosmology. Consequently, over the last 40 years, an intense experimental effort has produced a great variety of values for τ_β with an average value[1] of 891.6 ± 5.1 s, not including the present work.

Earlier experiments counted the β-decay products from a section of a continuous or pulsed neutron beam of which the volume and neutron density had to be determined with high precision. More recently intense sources[2,3] of ultracold neutrons (UCN's) became operational. UCN's $(E_{UCN} < 3 \times 10^{-7}$ eV) can be confined in either material containers or magnetic-field traps. Storage experiments[4-7] therefore measure directly the number of surviving neutrons, $N(t)$, in a closed bottle as a function of storage time t, where, if β decay were the only neutron-loss process, we would get

$$\tau_\beta = (t_2 - t_1)/\ln[N(t_1)/N(t_2)] . \tag{1}$$

The ratio of neutron counts $N(t_1)/N(t_2)$ does not depend upon the detector efficiency, the original neutron density $n(t_0)$, or the decay volume. A detector for decay products is obviously not needed. Further advantages are that the measurement time interval $t_2 - t_1$ is comparable to the particle lifetime, count rates are high in the experiment described, and the background is negligible. Many parameters can be varied to check for systematic errors and only a ~1% correction is necessary due to the effect of gravity on the UCN and a slight bottle-volume-dependent deformation of the UCN spectrum.

We confined UCN's to the storage volume by reflection at glass walls coated by Fomblin oil,[6] a fully

fluorinated polyether $(F_3CCF_2OCF_2CF_5)_n$. Fomblin Y Vac18/8 is a viscous liquid with average molecular weight of 2650 providing a perfect sealing of physical gaps. The vapor pressure at $20\,°C$ is 2×10^{-8} Torr. The oil forms on glass a stable, easily renewable,[8] uniform and smooth surface, with a low UCN reflection-loss probability of $(2-3) \times 10^{-5}$/bounce at $20\,°C$. The surface mean Fermi potential step is 106.5 neV, which corresponds to a maximum velocity v_{lim} of 4.55 m/s for storable UCN's.

In the absence of other losses such as gaps or gas scattering the measured fractional loss rate is $\theta_m = \theta_\beta + \theta_w$, where the wall loss rate θ_w can be expressed as $\theta_w = \mu(v)v/\lambda$, with $\mu(v)$ representing the velocity-dependent loss rate per bounce for an isotropic distribution of velocities v, and λ the mean free path between two wall collisions. Therefore,

$$\theta_m = \theta_\beta + \mu(v)v/\lambda = \theta_\beta + \mu(v)v/(4V/S) , \tag{2}$$

with $\lambda = 4V/S$ for an isotropic and homogeneous particle population in a container of volume V and surface area S. The relation remains valid even when we include the influence of gravity on the UCN density distribution, provided that all UCN's have enough energy to reach the bottle roof. $\tau_\beta = 1/\theta_\beta$ can be obtained by measuring θ_m as a function of λ, i.e., by varying the bottle volume-to-surface ratio. In this way the wall losses are fully accounted for, irrespective of their origin (absorption, inelastic scattering, surface vibrations, etc.). The requirement is that the surface is perfectly homogeneous and reproducible in its loss properties, with respect to both time and position. This should be true for a liquid which continually reorders its surface.

This direct elimination of the wall losses is only possible with monoenergetic neutrons. An extended neutron spectrum softens with increasing duration of storage

since $\bar{\mu}$ (averaged over the spectrum) becomes time dependent due to the velocity dependence of $\mu(v)$:[9]

$$\mu(v) = 2f[\arcsin(y)/y^2 - (1-y^2)^{1/2}/y], \quad (3)$$

where f is determined by the absorption and scattering properties of the wall material and $y = v/v_{\lim}$. The velocity dependence of the loss probability $\mu(v)$ on the oil surface, as measured in a separate experiment, is in excellent agreement with the assumption of an ideal step function of the wall potential as assumed for Eq. (3).

However, we can extend all arguments used above to any spectral distribution if the storage times $t_n(i)$, for different volumes (i,j), are scaled according to the bottle mean free paths:

$$\frac{t_2(i)}{t_2(j)} = \frac{t_1(i)}{t_1(j)} = \frac{\lambda(i)}{\lambda(j)} = \frac{t_2(i)-t_1(i)}{t_2(j)-t_1(j)}. \quad (4)$$

This condition ensures that neutrons of any given velocity bin have made the same number of collisions in each volume during the corresponding times $t_n(i)$, and thus suffered the same wall losses. Hence the spectral evolution during storage becomes volume independent. A rigorous proof will be given in a more detailed publication. We include in the times $t_n(i)$ an offset $t'(i)$ such that the number of wall collisions for different volumes stays the same in spite of different emptying times. The losses slightly load the UCN source at filling, leading to a small difference in the initial spectra. The area of the bottle entrance was adapted to the bottle size in order to minimize spectral distortions during filling.

The UCN storage volume is a rectangular box, with constant height $=30$ cm and width $=40$ cm but variable length $x < 10$ cm, where x was defined to better than 0.05 mm. The side walls and the roof of the box are made of 5-mm float-glass plates. The oil spray head[8] is mounted on the metal base plate and the assembly is immersed in a 1-mm-deep lake of oil. The movable rear wall, composed of two glass plates with a 1-mm oil-filled gap in between, has a 0.1-mm play with respect to the neighboring walls, except for the base plate where it dips into the oil. The surface of the rear wall was covered with 2-mm-deep, 2-mm-wide sinusoidal corrugations. For half the surface the wave crests were horizontal, and for the other half vertical. This arrangement transforms within a few seconds the forwardly directed incoming neutron flux into the isotropic distribution essential for the validity of the mean-free-path formula $\lambda = 4V/S$. The UCN inlet and outlet shutters situated 8 cm above floor level are sliding glass plates with 65-mm holes matching holes in the front wall (Fig. 1).

Oil drains off by gravity from an elevated reservoir onto the neutron shutters and into the interspace of the movable rear wall, thus sealing the gaps. A pressure of 2×10^{-7} Torr is maintained by a turbo molecular pump and a N_2 cold trap. After contact with atmosphere the oil is outgassed under vacuum at $\sim 200\,°C$. After four
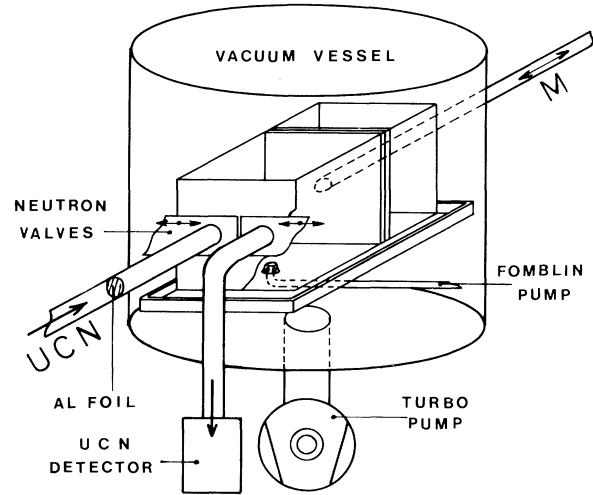

FIG. 1. Sketch of the apparatus.

days of pumping from initial pumpdown no more release of gas from the oil into the hermetically sealed bottle was observed.

The bottle was filled with UCN's from the neutron turbine[2] at the Institut Laue-Langevin. The turbine vacuum was separated from the experiment by a 0.1-mm-thick aluminum foil with the additional function of eliminating those neutrons which could not reach the bottle roof against gravity [$E_{\text{cutoff}}(\text{Al}) = 55$ neV]. To test the independence from the incoming neutron spectrum we performed measurements with a 20-cm elevation between the Al window and the bottle entrance, thus storing UCN's with energies $35 < E_{\text{UCN}} < 106.5$ neV in the bottle. In this case the count rate from a 70-l volume, extrapolated to storage time $t = 0$, was 1.2×10^5 per filling on the test beam and 4×10^5 on a main UCN beam. The background was 15 counts in 250 s ($=$eight emptying time constants) for a 55-cm-long bottle. The background was monitored during the storage phase and found to be constant.

The UCN detector filled with 20 Torr ^{3}He and 1000 Torr argon has an efficiency of ~ 0.8. The detector with its 0.1-mm Al window is situated 1.2 m below the bottle outlet. The dead-time effect of the UCN detection system was negligible even for short storage times and with the main beam intensity.

Measurements were typically performed over a period of 24 h for one bottle volume, setting successively storage times $2^n t_1$(s), for $n = 1$–5 and $t_1 = 112.5$ s for a bottle of length $x = 55$ cm. In the following all detailed results are given for the reference volume with $x = 55$ cm unless stated otherwise. Storage times less than 100 s are too short to be certain of eliminating the UCN close to the cutoff, and lead to very short time settings for small volumes. Though the bottle lifetimes were stable for more than 48 h, the surface was reoiled prior to each run
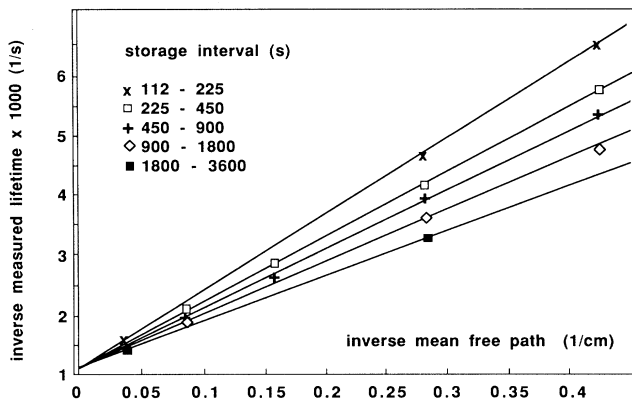
FIG. 2. Measured inverse bottle lifetimes as a function of the bottle inverse mean free path and for different storage intervals, from a 10-d run. The error bars are smaller than the data points.

with a new volume in order to produce a well defined starting condition. Over several weeks no drift of the measured bottle decay times was observed within the error limits.

Clean data were obtained during one year of operation under varied experimental conditions. The statistical accuracy obtainable in 24 h for τ_β is $< 1\%$. A typical run, including different storage times and different volumes is shown in Fig. 2. The error bars are derived from the standard deviation obtained from a sample of individual measurements including all contributions from experimental instabilities (reactor power, temperature, etc.). τ_β^{-1} is the value of θ_m for infinite bottle volume, i.e., $\lambda^{-1} = 0$. The error $d\tau_\beta$ results from an error-weighted least-squares fit considering the error ranges on the individual points as well as their values.

Two corrections must be made to the results obtained from the intercepts of Fig. 2. The most important one ($\sim 0.6\%$) is caused by the action of gravity on the neutrons which spoils the equivalence between the roof, floor, and side wall surfaces. The second correction, amounting to about $+0.3\%$, is caused by the small differences in the initial spectra depending on the bottle size, and on the volume (3.5 1) as well as the decay time (~ 15 s) of the filling tube section between the Al foil and the bottle entrance. The bottle-size dependence causes a slight deviation from linearity of the inverse bottle lifetimes. The consequential corrections in τ_β of up to -2 s for the smallest volume is included in the values with the label "uncorrected" (Table I). A more detailed description of the analytic calculation and computer simulations will be given elsewhere.

Table I lists our final results obtained with three different rear wall surfaces. Each value is the result of a series of individual runs performed at different temperatures and different bottle lengths. The average value after correction is $\tau_\beta = 887.6 \pm 1.1$ s. The uncertainty of $\pm < 3$ s in the total correction modifies this result to

TABLE I. Results of τ_β for different storage intervals.

Storage interval (s)	τ_β uncorrected (s)	$\Delta\tau$ correction (s)	τ_β corrected (s)
112–225	893(10)	~ -2	891(10)
225–450	858.0(4)	$+3.5$	888.5(4)
450–900	881.2(2.5)	$+8$	889.2(2.5)
900–1800	878.0(1.5)	$+9$	887.0(1.5)
1800–3600	878.5(2.6)	$+8.6$	887.1(2.6)

$\tau_\beta = 887.6 \pm 3$ s.

A large fraction of the total running time had to be devoted to systematic checks of various parameters:

One category of error sources can be checked directly by searching for deviations of $\theta_m(\lambda^{-1})$ from linearity. In this category fall inhomogeneities in the surface coating, possible residual gaps, uncertainty in the determination of the bottle dimensions, and the gravity correction. No systematic deviation from linearity has been observed within our sensitivity even for the most extreme bottle geometry of $1.2 \times 30 \times 40$ cm^3. Replacing the turbomolecular pump by a Fomblin-driven diffusion pump did not alter the lifetimes, indicating that no geometry-dependent losses due to surface vibrations affected the result. Losses of UCN's driven over the cutoff energy by quasielastic scattering (2×10^{-14} eV/collision)[10] are also taken care of by the scaling. This speed diffusion is insufficient, even after 1 h of storage, to shift UCN below the critical energy of 30 neV required for them to reach the roof.

A second group of errors is geometry independent: The reflection-loss rate for the oil was observed to be strongly temperature dependent due to the dominance of the inelastic scattering cross section. The temperature dependence was measured using the storage experiment itself and also in a transmission experiment with 60-Å neutrons between -20 and $+100$°C. The extinction length at 20°C agreed within a factor of 1.5 with the losses on the bottle wall. Such a consistency between the bulk and surface properties has not been observed before for a low-loss wall material, possibly related to the absence of surface contamination of the liquid. Temperature stabilization (0.1°C) was indispensable. Below 0°C the oil became too viscous for respraying. The storage lifetime was 710 s at 5°C for $t > 15$ min and 730 s for $t > 30$ min. Although the measured lifetimes decreased for higher temperatures (~ 4 s/°C) the deduced neutron β-decay lifetime did not change significantly up to 28°C, thus proving the validity of the wall-loss extrapolation procedure and that losses due to inelastic scattering by oil vapor molecules were not detectable in spite of an increase of the the vapor pressure by a factor of 10. Measurements performed at a pressure of 2×10^{-5} Torr produced the same results within the error, indicating that losses due to residual gas (H_2, H_2O)
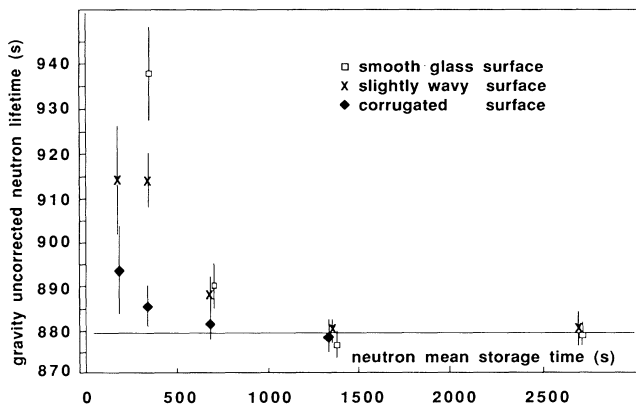
FIG. 3. Dependence of the experimental gravity-uncorrected neutron lifetime on the storage-time interval for different bottle surface structures. The remaining shift in the case of the corrugated surface and short storage times disappears after correction for gravitational effects.

scattering are not measurable.

The isotropy of the neutron distribution has been tested experimentally by modifying the surface structure of the movable bottle rear wall. A smooth float-glass surface showed, presumably due to a very high probability of specular reflection, a marked shift in τ_β for storage times less than 450 s, decreasing to $\sim 1\%$ between 450 and 900 s of storage. However, the asymptotic ($t > 900$ s) lifetime value was unchanged showing that the unequal spectral deformation affects significantly only the UCN near the cutoff. A slightly undulating surface clearly improved the situation for shorter storage times. Only a surface with deep grooves produced, after correction for gravity, storage-time-independent β-decay lifetimes even for short times (Fig. 3).

We conclude that the UCN storage method described produces a result with relatively small error: $\tau_\beta = 887.6 \pm 3$ s. The average value from other direct neutron life-time measurements is 891.6 ± 5.1 s.[1] The latest g_A/g_V value[11] with g_V from $0^+ \to 0^+$ nuclear β decays[12] and the phase space factor f from Wikinson[13] gives $\tau_\beta = 894.3 \pm 6$ s. The agreement between this indirect result and our value is satisfactory though at this point the relationship used might ask for small corrections on the quark level. The method has the potential to reach still higher precision.

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