Measurement of the neutron lifetime in a gravitational trap and analysis of experimental errors

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We present measurements of the neutron lifetime (τ_n) carried out with a gravitational trap for ultracold neutrons. We show that statistical uncertainty in the measured storage time is the principal contributor to experimental error. Measurements using oxygen-coated traps yield $\tau_n = 888.4 \pm 3.1_{\text{stat}} \pm 1.1_{\text{syst}}$ s. Since the systematic errors derive from a large number of independent factors, we quote a final value of $\tau_n = 888.4 \pm 3.3$ s.

1. INTRODUCTION

Measurements of the neutron lifetime and beta-decay asymmetry coefficients make it possible to determine the fundamental constants of the weak interaction, and to test the validity of the standard *V–A* model to high accuracy.[1–3] Furthermore, a knowledge of the neutron lifetime is important to the solution of a number of questions central to astrophysics and cosmology.[4,5] This situation has stimulated a number of novel experiments and more accurate measurements.[6–9]

In a recent experiment at the Saint Petersburg Institute of Nuclear Physics,[8] we achieved 0.3% accuracy, which was principally limited by statistical measurement errors. The present paper provides a detailed account of the experimental technique that we employed, and an error analysis.

2. NEUTRON LIFETIME MEASUREMENT TECHNIQUE

2.1. Basic plan

We have measured the neutron lifetime by capturing ultracold neutrons (UCN) in cryogenic traps that are effectively closed by a gravitational seal. The basic goal in the setup phase of the experiment was to obtain storage times close to the neutron lifetime; this turned out to be feasible by coating the interior surfaces of the well (at low temperature) with a lightly-absorbing material. Losses at the trap walls were accounted for via dimensional extrapolation, making use of the energy dependence of the losses.

Trap surface. The interior walls of the trap were coated with materials that have a low neutron capture cross section (oxygen, beryllium). Losses due to inelastic scattering at the walls (either from the wall material itself or from hydrogen-bearing contaminants) were suppressed by operating at low temperature (10–15 K). This enabled us to approximate a direct measurement of the exponential decay constant. In measurements with traps whose interior surface was oxygen-coated, the mean probability of UCN losses at the walls was approximately 3% of the beta-decay probability; the losses were twice as high with a beryllium coating. The main series of measurements was carried out using beryllium-coated traps; the surface of the beryllium was coated with oxygen.

Extrapolation. UCN losses at the walls were taken into account via dimensional extrapolation, making use of the energy dependence of the losses. The UCN storage time in a time, τ_{st}, is determined by the probability of beta decay and by losses at the trap walls:

$$\tau_{st}^{-1} = \tau_n^{-1} + \tau_{los}^{-1}, \tag{1}$$

where τ_{los} is the loss time (the length of time neutrons would remain in the trap if there were no beta decay). The accurate measurement of τ_n requires that the storage time be close to the neutron lifetime, and that losses at the walls be taken into consideration.

The UCN loss probability at the trap walls, τ_{los}^{-1}, is proportional to the loss coefficient η, and it depends on the size and shape of the trap, the neutron energy E, and the limiting energy E_{lim} for the matter in the trap wall, so that

$$\tau_{st}^{-1} = \tau_n^{-1} + \eta\gamma. \tag{2}$$

The parameter γ has dimensions sec^{-1}; physically, it signifies the effective UCN collision rate with the trap walls.

The reciprocal lifetime of the neutron can be obtained from (2) by linearly extrapolating $\tau_{\text{st}}^{-1}(\gamma)$ to $\gamma = 0$. The loss coefficient is then equal to the slope of the straight line. Different-size traps and neutrons of different energies correspond to different values of the effective collision rate γ.

When losses are estimated to within about 10%, the neutron lifetime can be determined to an accuracy of approximately 3 sec, or $\approx 0.3\%$ of the lifetime itself. Since the probability of UCN losses at the walls is much lower than that of beta decay, the extrapolation of the UCN storage time in a well to the neutron lifetime is fairly accurate. The problem of UCN leakage through gaps in the mechanical valve traditionally used in such experiments has been avoided by eliminating the mechanical valve altogether, instead using a gravitational field to trap the neutrons. This same gravitational valve also enables one to make spectral measurements of the storage time.

2.2. Experimental setup: UCN trap

The experimental setup is illustrated in Fig. 1.

Operation. Trap filling and UCN detection are controlled by the intake valve *5* and the steering valve *3* in accordance with the predetermined timing of the storage cycle. It has been shown experimentally that the filling valve *5* admits at least 10^{-5} of the incident UCN. The steering valve has two positions, *FILL* and *DETECT*. The basic design ensures that no high density valve is required, since neutrons making

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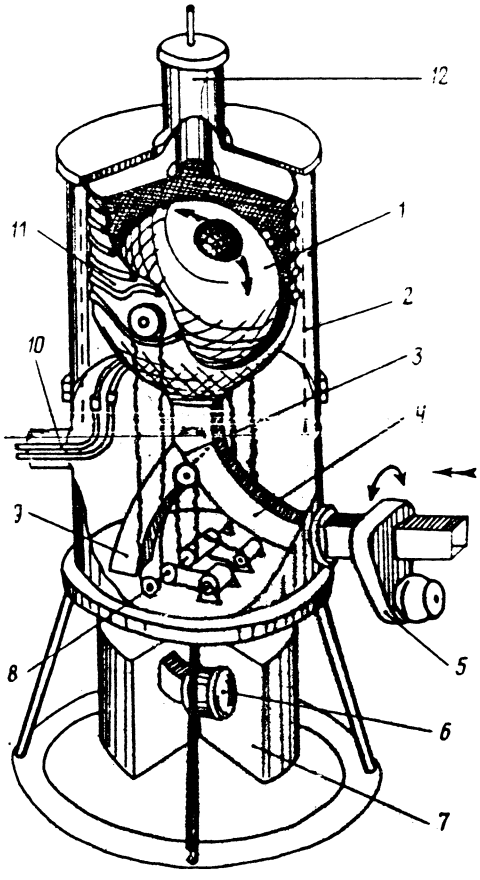

FIG. 1. Experimental setup. *1*) Trap for holding ultracold neutrons; *2*) nitrogen jacket; *3*) steering valve; *4, 9*) entry and exit feeds for UCN; *5*) intake valve; *6*) detector; *7*) detector shielding; *8*) drive mechanism for rotating joint and trap; *10*) cryogenic supply lines; *11*) cryostat; *12*) feed for coating deposition system.

it through such a valve in the closed state produce no systematic effects.

The gravitational trap *1*—a figure of revolution pivoted about a horizontal axis—is simultaneously a gravitational spectrometer. The trap is filled, and trapped neutrons are detected, through the opening. Filling takes place with the opening pointing downward; the trap is then rotated into the upright position. Ultracold neutrons—which have too little energy to leave the trap—are confined there by the gravitational field. The UCN storage time can be derived from a measurement of the time dependence of the number of neutrons remaining in the trap in the latter position by direct observation of the exponential decay constant of the number of UCN. It is not necessary to know the efficiency of the detector *6*, since the measurements are relative ones. The number of neutrons remaining after the required storage time has elapsed can be determined by turning the trap upside-down again.

The spectral dependence of losses can be measured by turning the trap face-downward in steps. The trap is then maintained in each intermediate position long enough to detect most of the UCN in the corresponding energy range. This same procedure enables one to simultaneously measure the spectrum of the trapped UCN.

The trap is made of aluminum. After polishing, its inner surface is coated with a beryllium film 3000–5000 Å thick, which then receives a 3–7 μm overcoat of oxygen at a trap temperature of 13 K. The oxygen is 99.99% pure.

The trap itself is an interchangeable element. In the first phase of the experiment, we employed a roughly spherical trap consisting of a cylinder about 75 cm in diameter and 32 cm high, capped by two truncated cones each approximately 22 cm high, with small diameters of 31 cm. For high-precision determination of the neutron lifetime, we also used a 72-cm diameter cylindrical trap that was 15 cm tall between its end faces. The latter raised the neutron collision rate with the walls of the trap by a factor of about 2.5, producing a more accurate measurement of the loss factor. The cylindrical trap used the same beryllium substrate and precipitated oxygen overlayer as the spherical trap. As part of our investigation of oxygen surfaces, we also employed a titanium-coated trap made, by to surface absorption, incapable of storing UCN. More specifically, these measurements demonstrated that at least 99% of the surface of the trap was covered with oxygen. A technique for precipitating oxygen was also worked out for an aluminum trap that had no beryllium coating.

Oxygen-coating system (12). Gaseous oxygen was precipitated onto the cold surface of the trap (under working conditions, the wall temperature was 13 ± 1 K when coating was initiated) at a 15–30 Å/sec rate through a heated tube terminated by a porous sphere. The oxygen coating rate was regulated by a leak valve.

Vacuum. The system maintained separate "clean" and "dirty" vacuum lines. Both were pumped out through nitrogen traps. Residual gas in the system at 10^{-7}–10^{-6} Torr has no effect on the UCN storage time in the trap. To support heat exchange between the trap and the helium cooling bath, thereby holding the trap at constant temperature throughout the measurement, the helium pressure in the clean vacuum is normally set to $\approx 10^{-5}$–10^{-4} Torr, which does not reduce the UCN storage time (to an accuracy of at least 0.3 sec).

Trap temperature. The experimental setup consists of a helium cryostat with a liquid nitrogen jacket. The lowest temperature to which the trap can be cooled is approximately 10 K. A constant temperature can be established and maintained by controlling the flow rate of gaseous helium circulating in the heat exchanger. Heating elements make it possible to heat the clean vacuum system and trap to 400 °C.

2.3. Temporal history of a storage cycle

A storage cycle enables one to measure the number of UCN in the trap after some holding time, either for the spectrum as a whole or in some set of energy bins, depending on the measurement mode. A typical temporal spectrum is shown in Figs. 2 and 3. The UCN storage time in the trap can be determined from the number of remaining UCN as a function of the holding time of the trap.

The background is measured with the intake valve closed. Possible slow variations in the background conditions can be monitored by repeating the background measurement at the beginning of every cycle. In the actual experiment, the background was 0.07 neutrons/sec at a reactor power of 15 MW, and showed no variation with time at constant power. This was 10^{-3}–10^{-2} of the number of trapped UCN that were present during the detection phase.

Filling. The intake valve is opened, and at the same time the steering valve is switched to *fill*. At this point, counts in

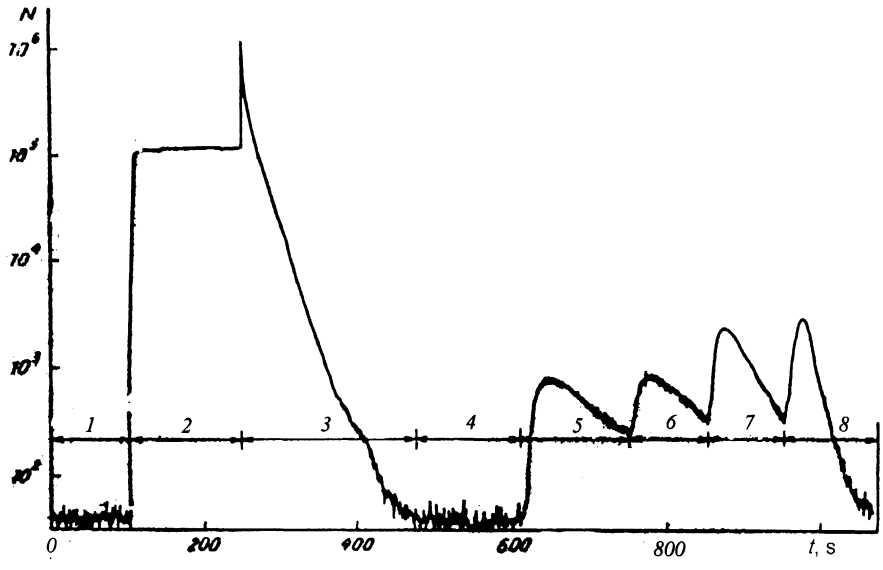

FIG. 2. Typical temporal spectrum obtained from measurements in a cylindrical trap with 100-s holding time. *1*) Background measurement, intake valve closed; *2*) trap filling with neutrons (detector counts due to flux past leaks in the steering valve); *3*) monitoring, intake valve closed, trap positioned with opening 25–35° off the vertical; *4*) trap held with opening straight up; *5–8*) counts of UCN remaining through four successive trap positions.

the detector are due to neutrons that have negotiated their way through small leaks in the steering valve. After the equilibrium density is reached in the trap, the latter is rotated to the *monitor* position, in which the opening sits 25–35° off the vertical. Neutrons escaping from the trap when it is rotated are balanced by the flux into the trap, since the input and steering valves have not yet been reset at that point. Neutrons that are not energetic enough to leave the trap are confined there by the gravitational field.

Monitoring. The intake valve is closed, the steering valve is switched to *detect*, and the trap has already been turned from its low position to the *monitor* position. This operation is required to get rid of neutrons whose energy exceeds the gravitational height of the trap (in units such that the free-fall acceleration $g = 1$). These neutrons continue to leave the trap, even during the *hold* procedure, essentially acting as an additional UCN leakage channel and giving rise to a systematic effect: high-energy neutrons "evaporate" from the trap, and for those neutrons, the gravitational seal is not a perfect one. The detector signal during monitoring is produced both by neutrons within the apparatus but outside the trap, and by those that are still in the trap, but have sufficient energy to emerge from it.

If the mechanical components (steering valve, intake valve, trap rotation mechanism) operate reproducibly, the detector count during the monitoring and filling period can be used to control the constancy of the UCN input flux. In fact, the reason why this procedure is called *monitoring* is that it enables one to track the initial UCN density in the trap.

Holding neutrons in the trap. After discounting from the spectrum those neutrons with high enough energy to emerge from the trap in the *hold* position with the opening upright, the trap is rotated to that position. A "turbine" effect induced by surface roughness leads to UCN diffusion in velocity space as the trap is rotated, so after monitoring, the

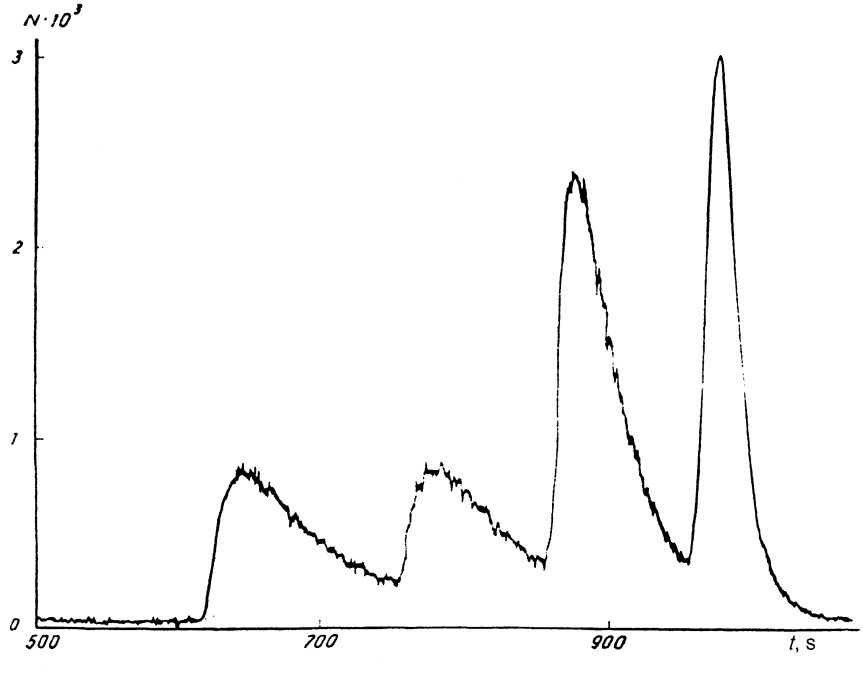

FIG. 3. Part of the spectrum in Fig. 2 plotted on a linear scale.

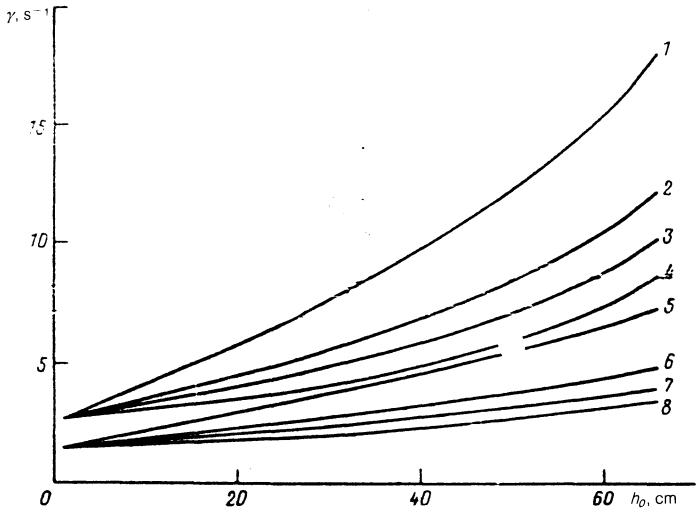

FIG. 4. The calculated effective collision rate γ as a function of UCN energy for various traps and thin-film limiting velocities. *1*) cylindrical trap, diameter 72 cm, height 15 cm; *2*) height 30 cm; *3*) height 45 cm; *4*) the actual "spherical" trap. Limiting velocity 3.66 m/s for curves *1–4*, 6.85 m/s for curves *5–8*.

"purged" spectrum again acquires a small number of UCN with undesirable energies. To purge the spectrum of these as well, a minimum hold time is established, during which the detector count rate drops to the background level as predicted and as confirmed experimentally. Thus, after the minimum hold time, the detector count rate during the hold period also corresponds to the background level, and can be used both to monitor the constancy of the latter and to estimate it more accurately.

UCN counting after hold. Detection of the UCN remaining in the trap begins after the required hold time. The detection period starts when the trap begins to turn. When the energy dependence of the storage time is being measured, the trap is rotated intermittently and remains in each successive position for 60–200 sec. When the full spectrum is measured, the trap is immediately turned so that its opening faces down. The fact that it takes a long time for the trap to empty precludes the possibility of discriminating between adjacent energy bins separated by less than a few percent—the counting statistics deteriorate and the procedure takes much longer. In practical terms, however, the present procedure is adequate.

To properly measure the storage time, it is important not to begin the background measurement until essentially all of the UCN from the previous cycle have been detected, and the count rate has fallen to the true background. This then mandates a dead time between cycles, during which preliminary data processing can take place.

3. NEUTRON LIFETIME MEASUREMENT RESULTS

We have measured the neutron lifetime via dimensional extrapolation, making use of the experimental energy dependence of the storage time through Eq. (2). The reciprocal lifetime is obtained by extrapolating $\tau_{st}^{-1}(\gamma)$ to $\gamma = 0$, i.e., to the situation in which there is no interaction between the neutrons and the walls, and the effective collision rate with the trap walls is zero. The loss coefficient equals the slope of the extrapolated straight line.

For a specific trap shape and a known limiting surface velocity, the effective collision rate γ can be calculated using the following expressions:

$$\gamma(h_0) = v_{lim}^2 I_1 / 2I_2,$$

$$I_1 = \int_0^{h_0} dz l(z) \{\arcsin(y(z)) - y(z)[1-y^2(z)]^{1/2}\},$$

$$I_2 = \int_0^{h_0} dz s(z) V(z), \tag{3}$$

$$y(z) = V(z)/V_{lim}, \quad V^2(z) = 2g(h_0 - z),$$

where $dzl(z)$ is the area swept out by a loop between z and $z + dz$, $s(z)$ is the cross-sectional area of the storage vessel at height z, h_0 is the maximum height to which a UCN rises in the gravitational field, and V_{lim} is the limiting surface velocity.

Figure 4 illustrates how the effective UCN collision rate with the trap walls depends on UCN energy for traps of various shapes, coated with different substances. Obviously, the combination of spherical and narrow cylindrical traps makes it possible to obtain a large enough range in γ to accurately extrapolate the experimental data out to the neutron lifetime.

The extrapolation of the UCN reciprocal storage times to the neutron lifetime in traps coated inside with oxygen and beryllium is shown in Fig. 5. The points that relate to a

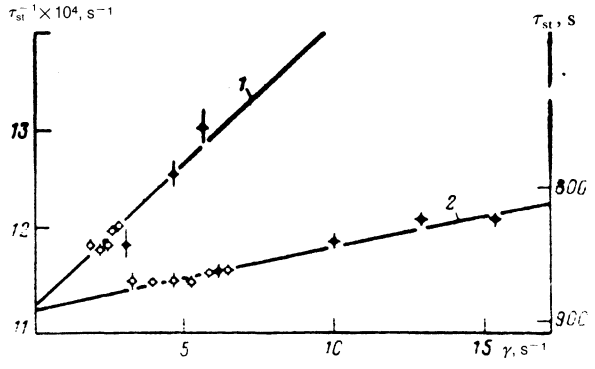

FIG. 5. Reciprocal of the UCN storage time in a trap as a function of effective collision rate γ. Measurements made with spherical (open circles) and cylindrical (filled circles) traps. *1*) Beryllium-coated traps; *2*) oxygen-coated traps.

TABLE I. Measurements of the neutron lifetime.

	τ_n, s	η, 10^{-5}	χ^2
O_2	889.0±3.1	6.1±0.6	0.81
Be	885.0±7.7	28.1±4.0	1.41

given coating correspond to various-size traps and different energy ranges within the full spectrum of trapped UCN. Open circles signify a spherical trap, filled circles a cylindrical one.

The bulk of the data was obtained with an oxygen coating, with which we obtained better storage performance. Measurements were made on beryllium traps in order to study the requisite conditions for UCN storage prior to the precipitation of oxygen. The results from a two-parameter fit (Fig. 5) to two months' worth of data for the oxygen coating and three weeks' worth for the beryllium are given in Table I. The indicated errors (χ^2) are statistical. The spread in the results corresponds to statistical uncertainty (2.9 sec for oxygen-coated traps, average over all trapped UCN). We analyze the errors in the effective collision rate γ in Sec. 4. Errors in the determination of the storage time (statistics) make the principal contribution to the overall experimental error.

It is clear from Fig. 5 and Table I that, to within the indicated errors, the two straight lines extrapolate to the same value of the neutron lifetime, corroborating both the UCN storage conditions on the beryllium substrate and, to a certain extent, the applicability of our approach in the face of a large loss coefficient.

The accuracy of the extrapolation is dictated largely by how close the experimental storage times come to the neutron lifetime. The UCN storage conditions for the very lowest energies correspond to so-called trapping on the plane at infinity. The experimentally derived loss coefficients can be transformed into loss times $\tau_{los}(0)$ for that part of the spectrum, or into the difference between the neutron lifetime and the storage time $\tau_n - \tau_{st}(0)$. Let $\bar{\tau}_{los}$ and $\bar{\tau}_{st}$ be the spectrally averaged loss and storage times in a spherical trap. We use this notation in Table II to characterize the nearness of the derived storage times to the neutron lifetime.

In measurements with traps whose inside surface is oxygen-coated, the mean probability of UCN losses at the walls of the trap is approximately 3% of the beta decay probability. Assessing losses to about 10% accuracy has enabled us to determine the neutron lifetime to within approximately 0.3%. In the next section we analyze the systematic errors and show that they contribute at a level of approximately 3% of the mean loss probability, i.e., about 0.1% of the neutron lifetime.

TABLE II.

	$\tau_{los}(0)$, h	$\tau_n - \tau_{st}(0)$, s	$\bar{\tau}_{los}$, h	$\tau_n - \tau_{st}$, s
O_2	17.0±1.7	12.6±1.3	≈9	≈23
Be	6.9±1.0	30.7±4.4	≈4	≈50

TABLE III. Errors and corrections to the neutron lifetime: Measurements with oxygen-coated traps.

Source of error	$\Delta\tau_n$, s
Statistical error (storage time determination)	± 3.1
Dynamical correction (overlap of adjacent energy bins)	− 0.9 ± 0.2
Spectroscopic correction	+ 0.3 ± 0.6
Turbine effect	< 0.3
Possible discrepancy between loss probability $\mu(h)$ and model	< 0.5
Possible temperature dependence of losses	< 0.5
Uncertainty in measured limiting velocity	< 0.2
Uncertainty in measured trap geometry	< 0.3
Extraneous ballast He	< 0.3
Detector and detection train efficiency as functions of UCN spectrum, systematic errors in background determination, trap "lofting", anisotropy of UCN flux in the trap, milliheating, vibration, substrate effects	< 0.1

4. ERROR ANALYSIS

The bulk of the errors considered here result from our imperfect knowledge of the effective rate γ of UCN collisions with the trap walls. These errors include dynamical effects associated with the fact that the boundaries of the energy bins that we use do not equal the gravitational heights of the bottom of the trap opening, owing to the finite energy resolution of the gravitational spectrometer; spectroscopic corrections that take account of the actually measured spectrum of UCN confined to the trap; the turbine effect, which results from the nonspecular reflection of UCN from the moving walls of the trap, with consequent diffusion of the UCN spectrum in velocity space; and finally, uncertainties in the measured limiting velocity of the oxygen coating and trap geometry. Moreover, there are systematic errors related to possible departures of the mean probability of UCN loss per collision at a wall, $\mu(h)$, from the model value, to a possible temperature dependence of UCN losses at the trap walls, to extraneous ballast He in the trap, etc. In Table III, we list errors and corrections to the value of τ_n for measurements made with oxygen-coated traps.

Dynamical and spectroscopic corrections. The experimentally measured storage times correspond to the mean effective collision rates $\bar{\gamma}(h_{01}, h_{02})$ in the energy bin spanning the range from h_{01} to h_{02}:

$$\bar{\gamma}(h_{01}, h_{02}) = \int_{h_{01}}^{h_{02}} \gamma(h_0) n(h_0) dh_0 \Big/ \int_{h_{01}}^{h_{02}} n(h_0) dh_0, \qquad (4)$$

where $n(h_0)$ is the UCN density. Uncertainties associated with the determination of $\bar{\gamma}$ relate to errors in h_{01} and h_{02}, as well as errors in measuring the spectrum. The smallness of the dynamical corrections and the fact that the result is quite insensitive to the shape of the spectrum within the energy range dictated by the measurement technique makes it possible to split the procedure for measuring $\bar{\gamma}$ into two parts: 1) calculate $\bar{\gamma}$ for a Maxwellian spectrum and values of h_{01} and h_{02} corresponding to the geometrical location of the opening in the trap, and then 2) calculate the spectroscopic and dynamical corrections.

Dynamical correction. Dynamical errors correspond to the overlap of peaks that belong to different energy ranges in the neutron-trapping timing diagram (Figs. 2 and 3). The

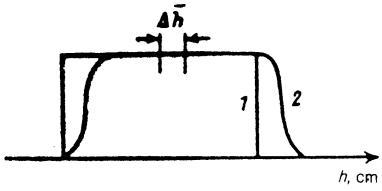

FIG. 6. Sketch of the displacement of mean UCN energy (over some portion of the spectrum) associated with dynamical corrections: *1*) ideal, and *2*) actual response functions of the gravitational spectrometer.

net result is an offset (increase) in the mean UCN energies relative to the energy bins. To find the offset in $\bar{\gamma}$ with respect to the values given by the geometrical position of the trap opening (h_{01} and h_{02}), it is necessary to know how long it takes UCN of a given energy to leave the trap in different positions. By analogy with the UCN loss probability at the trap walls [see Eq. (3)], we have

$$\tau^{-1}(h, h_0) = \int_h^{h_0} V^2(z) l(z)\, dz \Big/ 4 \int_0^{h_0} s(z) V(z)\, dz, \qquad (5)$$

where $\tau^{-1}(h,h_0)$ is the reciprocal of the UCN outflow time for a neutron of energy h_0, where the bottom of the trap is at a height h; $V^2(z) = V_0^2(z) - 2gz$; and $l(z)dz$ is the cross sectional area of the trap window from z to $z + dz$.

We have made two assumptions in deriving Eq. (15): neutrons do not return, once having left the trap, and the spatial distribution of the UCN gas density in the trap does not change during outflow, i.e., the density "forgets" its history uniformly throughout the trap. It can easily be shown that these two approximations yield results that are accurate to 10% at worst. To take dynamical effects into consideration, we replace $n(h_0)$ in (4) with

$$n(h_0)\left\{1-\exp\left[-\frac{\Delta t(h_{01})}{\tau(h_{01}, h_0)}\right]\right\}\exp\left[-\frac{\Delta t(h_{02})}{\tau(h_{02}, h_0)}\right]$$

and replace the upper limit of the integral by infinity (in fact, the integrals cut off a few centimeters from h_{02}, so the actual upper limit is largely irrelevant). In this expression, $\Delta t(h_{01})$ and $\Delta t(h_{02})$ are the UCN detection times at positions h_{01} and h_{02}.

Figure 6 sketches the offset in $\bar{h}$ associated with dynamical corrections; we have compared the ideal (1) and actual (2) instrumental responses of our gravitational spectrometer, thereby illustrating the energy resolution of the latter.

The physical import of the dynamical correction is that UCN with energy $h_0 > h_i$ fail to leave the trap in a finite time $\Delta t(h_i)$. To some approximation, this is equivalent to saying that the actual position h_i of the bottom of the opening has been replaced by an effective position $h_i + \Delta h_{i_{dyn}}$ such that all of the neutrons below it remain in the trap, and all of the neutrons above it escape.

Repeating the extrapolation of $\tau_{st}(\gamma)$ using the foregoing dynamical corrections, we obtain the dynamical correction to the extrapolated neutron lifetime, $\Delta\tau_{n_{dyn}} = -0.9 \pm 0.2$ s. Uncertainties in this quantity stem from the limited accuracy to which we can calculate $\tau(h,h_0)$ and the fact that we have made use of the spectrum of trapped UCN to determine the dynamical correction; that spectrum is only known to finite accuracy.

Spectroscopic correction to the lifetime. As noted above, the data reduction proceeds in two stages: first the effective UCN collision rate with the walls is calculated for an unperturbed Maxwellian UCN spectrum in the trap (taking trap geometry into account), and then spectroscopic corrections are introduced. This approach works because of the low sensitivity of the result to the shape of the spectrum, which is due in turn to the fact that the spectrum is the same in different traps (as has been confirmed experimentally). The most important extrapolation is a dimensional one, not an energy extrapolation. The spectral dependence on storage time can be measured directly, so it is not important to know the spectrum as a whole so much as its shape within the energy bins prescribed by the experimental technique.

To assess the shape of the spectrum and the size of the corresponding correction to the lifetime, it suffices to take advantage of the data obtained by measuring the energy dependence of the losses. Proper interpretation of the results requires that the suggested dynamical corrections be made first, along with a correction for UCN decay during the measurement period. Here we present data for UCN spectra obtained by monitoring a cylindrical trap,

Energy bin, cm	54–61	47–54	31–47	0–31
Experiment, %	15.3	16.1	37.4	31.2
Fraction in Maxwellian spectrum, %	25.0	20.7	36.5	17.1

and a spherical one,

Energy bin, cm	52–56	47–52	39–47	26–39	15–26	0–15
Experiment, %	11.0	15.0	20.0	25.5	21.5	7.0
Fraction in Maxwellian spectrum, %	14.0	23.6	28.9	22.8	8.7	2.0

The UCN spectrum is clearly depleted at high energies. Comparing the experimental spectra (including trap geometry and all necessary corrections), we see that they are the same. Spectral measurements made with traps with beryllium inner and outer surfaces are consistent with a Maxwellian spectrum. This means that the falloff in the spectrum at high UCN energies derives from losses on the outer surface of the traps used in the experiment during filling and post-storage detection. The most likely reasons for that falloff would seem to be losses in the exterior aluminum trap walls above cutoff.

Substituting the experimental UCN spectrum in the traps into (4), we obtain the correction to the effective collision rate at any point on the extrapolation of $\tau_{st}^{-1}(\gamma)$, and accordingly the correction to the extrapolated neutron lifetime: $\Delta\tau_{n_{spectr}} = 0.3 \pm 0.6$ s.

The uncertainty in this correction comes from variations of γ within the energy bins, due to the finite accuracy of the spectrum and the use of a variety of parametrizations in fitting the high-energy spectral falloff (note that the accuracy with which the corrections can be determined is governed not by the measurement accuracy of the spectrum itself, but of its first derivative, since it is the spectral shape that is important within the various energy bins).

Milliheating. Vibrations. In principle, vibrations in the trap walls will result in UCN energy variations. A similar effect obtains when a UCN interacting with a wall surface is scattered quasielastically; the resulting change in energy is much smaller than the energy itself. These processes lead to UCN diffusion in velocity space, and are related to a variety of systematic effects. Neither process has been detected, but a special experiment was carried out to control for vibrations and milliheating.

The trap was filled with neutrons of energy h_0. To ensure that there were no UCN in the initial spectrum with an energy less than some value h_1, the trap was positioned at an angle such that the lower edge of the opening was at a height h_1 above the bottom, rather than having the opening point straight downward. During a lengthy period in which the trap was monitored, neutrons with energies greater than h_2 exited the trap. To within the dynamical errors, then, the only neutrons remaining in the trap had energy h_0 in the range from h_1 to h_2. We then measured the storage time for three parts of the spectrum, namely at energies above h_2, between h_1 and h_2, and below h_1. Neutrons appeared in the first range by virtue of the turbine effect, which tends to corrupt the measurements, and due to incomplete purging of the spectrum in the finite amount of time allotted for monitoring. If vibration effects were appreciable, the measured storage time at $h_0 > h_2$ would be longer than the actual time, and during the corresponding trapping time it could even exceed the neutron lifetime. Similar effects would ensue in the other energy ranges as well. The fact that no such effects were detected leads us to conclude that vibration and milliheating cannot lead to appreciable errors in the measured lifetime. The maximum energy transfer in a single collision is at most $(3\text{–}5)\cdot 10^{-12}$ eV.

Turbine effect. An experimental check similar to the one above was carried out to study the turbine effect. The difference was that during the holding time, the trap was turned through a small angle for a specified time at a known velocity. The UCN spectrum in the trap was then measured. If neutron reflections from the surface were perfectly specular and the trap itself were a figure of revolution, the turning of the trap could not alter the UCN spectrum. Neutron diffusion in velocity space during trap rotation thus supplies information about the magnitude of the turbine effect. Any deviation of the shape of the trap from a figure of revolution would likewise induce a turbine effect, but at a much lower level.

The net result of the turbine effect is that detected neutrons have a 5–15% probability of winding up in an adjacent energy bin, depending of the position of the trap (spectral shifts beyond an adjacent bin are rare). This means that some fraction of the neutrons are trapped at one energy, with no change, and upon detection behave as if they possessed a different energy, i.e., as if they lay in some "foreign" energy bin. With the assumed $\tau_{st}^{-1}(\gamma)$, this then implies that some values of the effective collision rate γ ought to be somewhat higher (lower trap position) and some lower (higher trap position). Under these circumstances, the "center of gravity" of the experimental points for a given trap should remain essentially unchanged after corrections have been made. Direct estimates indicate that the neutron-lifetime change induced by the turbine effect is at most 0.1–0.3 s.

Effects of the substrate and thin-film stability. In the design phase of the experiment, we carried out a number of test measurements, including spectral measurements of the storage time in titanium and aluminum traps coated with a layer of oxygen. Those tests demonstrated that at least 99% of the trap surface areas were covered with oxygen.

The stability of the coating was verified in measurements with an oxygen-coated titanium trap. With a thick enough layer of oxygen (a few μm), the full-spectrum storage time in a wide trap was approximately 760 s. This figure was stable from one oxygen deposition to the next, and remained constant to within 10–15 s on a time scale of days. In addition, we verified the stability and constancy (both in time and from one deposition to the next) of the turbine effect for an oxygen surface.

If the uncoated area varies at all, it does so by at most 0.1–0.15%. Since the actual measurements employed an oxygen-coated beryllium substrate, we believe that instability (and up to 1% variation in the surface cover) exercised no influence over the results.

Temperature dependence of losses for oxygen. To within the statistical errors, we observed no temperature dependence of losses in the 12–25 K range; experimentally, the loss coefficient may have varied by as much as 10^{-7}/K, which would correspond to an error in the measured neutron lifetime of 0.5 s/K. During measurements, the temperature of both the spherical and cylindrical traps was held constant to $\pm$ 1 K; possible temperature dependence of the oxygen losses thus yields an uncertainty in τ_n of $\pm$ 0.5 s. Improvement of this figure would require either more accurate measurement of the temperature dependence of the losses or better temperature stabilization.

Possible deviation of $\mu(h)$ from the model. To within the statistical uncertainties, the experimental behavior of UCN loss probability in collisions with the trap walls is consistent with the behavior predicted on the basis of the usual assumptions (step potential barrier, uniform density and composition of the surface along the entire penetration path of the UCN). An analysis of possible departures from the idealized

model shows that they exert only a minor influence on $\mu(h)$, and have a negligible influence on the value of the neutron lifetime. On the other hand, the departure of the experimentally determined loss coefficient from the calculated value leaves the door open for hypothetical explanations of that difference, for which the behavior of $\mu(h)$ can be arbitrary. The uncertainty in τ_n when one adopts various functions consistent with direct, experimental spectroscopic loss measurements is at most 0.5 s.

Limiting velocity uncertainties. In this experiment, we measured the oxygen limiting velocity using an oxygen-coated aluminum trap. Expressed as a maximum rise in neutron height, the limiting energy was 65–69 cm, with the uncertainty corresponding to a 0.2 s error in the lifetime. This quantity is small (as are the losses) because, to first order, a change in the limiting velocity results in a linear expansion of the γ axis (see Fig. 5), and only to second order does it induce nonlinear distortions.

It is characteristic of the effects described here that they exert an influence on the measured neutron lifetime proportional to the loss coefficient η. Consequently, the fact that they are small derives from the small UCN losses at the oxygen-coated trap walls. In addition, it is dimensional extrapolation, rather than energy extrapolation, that is most important, and the former is not subject to the aforementioned errors.

Since most of the uncertainties described here are ultimately statistical in origin, while the remainder stem from a large number of independent factors, we have added all of the uncertainties in Table III quadratically to obtain the overall uncertainty in the neutron lifetime, -0.6 ± 1.1 s. Measurements with an oxygen coating thus yield a neutron lifetime $\tau_n = 888.4 \pm 3.1_{\text{stat}} \pm 1.1_{\text{syst}}$ s, and we cite $\tau_n = 888.4 \pm 3.3$ s as a final result. The overall systematic error in this experiment is thus approximately 1 s, which is smaller than the statistical uncertainty (about 3 s). We therefore anticipate future improvements in experimental accuracy to come from additional measurements, which will augment the counting statistics, and from the availability of more intense UCN beams.

[1] D. Dubbers, W. Mampe, and J. Dohner, Europhys. Lett. **11**, 195 (1989).
[2] V. P. Gudkov, Leningrad Institute of Nuclear Physics, Preprint No. 1591 [in Russian] (1990).
[3] A. P. Serebrov, *Twenty-sixth Recontre de Moriond on Electroweak Interactions and Unified Theories*, Moriond, France, 17–23 March 1991.
[4] A. Bertin *et al.*, Phys. Lett. **B199**, 108 (1987).
[5] N. Terasawa and K. Sato, Phys. Rev. **D39**, 2893 (1989).
[6] W. Mampe, P. Ajeron, J. C. Bates *et al.*, Nucl. Instr. Meth. **A284**, 111 (1989).
[7] J. Byrne, D. G. Dawber, J. A. Spain *et al.*, Phys. Rev. **D65**, 289 (1990) [*sic*].
[8] V. P. Alfimenkov, V. E. Varlamov, A. V. Vasil'ev *et al.*, Pis'ma Zh. Eksp. Teor. Fiz. **52**, 984 (1990) [JETP Lett. **52**, 373 (1990)].
[9] V. I. Morozov, *International School: Physics of Weak Interactions at High Energies*, Dubna, 4–13 September 1990.

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