The use of ultracold neutrons for measurement of the neutron lifetime

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A method of measuring the neutron lifetime by storing ultracold neutrons (UCN) in an aluminum container is described. A method of measuring the loss of UCN in the container walls is proposed. The losses were measured by varying the number of collisions per unit time. The systematic measurement errors are given and possible ways to reduce them are discussed.

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The experimental values of the lifetime of a neutron, which were obtained by recording the products of its β decay, differ in the case of each author by a value that exceeds the measurement error.[1,2] In view of this, the development of new methods of measuring this value is of interest.[3]

In this paper the neutron lifetime was determined from the rate of decrease with respect to time of the UCN that were stored in a container. To determine the loss of UCN due to collision with the container walls, we investigated experimentally the dependence of the total probability of UCN loss on the number of collisions per unit time, after which the determined dependence was extrapolated to a collision frequency equal to zero.

In the experiment we used a cylindrical aluminum container 1 (Fig. 1) 29 cm in radius and 30 cm high. The frequency of collisions of the UCN against the container walls was varied by inserting into it $20\times25\times0.1\text{-cm}^3$ vertical aluminum plates (fins) 5. The total number of fins was 30. The container was inserted into a vacuum jacket that was evacuated to a pressure of 3×10^{-5} Torr by a diffusion pump with a nitrogen trap. The container and fins were sprayed with metallic layers without disturbing the vacuum and were degassed by heating. The container was filled with neutrons from a device that was used for production of UCN in the CM-2 reactor.[4] The storage time of the UCN in the container was measured by using shutters 2, 3, and 4.

The total probability of neutron loss per unit time for the monoenergetic UCN is

$$\lambda = \lambda_r + \eta\gamma_n(E), \tag{1}$$

where λ_r is the neutron decay constant, η is the experimentally determined ratio of the imaginary part of the potential of interaction of a neutron with the wall to its real part, and $\gamma_n(E)$ is the geometry factor of the experiment, which is proportional to the frequency of collisions of a neutron with the container wall.

For the cylindrical container used in the experiment[5]:

$$\eta\gamma_n(E) = \int_{(S)} \bar{\mu}(E')E'ds \Big/ \int_{(\Omega)} \sqrt{E'}d\Omega = \eta\gamma_0(E) + \eta\gamma'(E)n: \tag{2}$$

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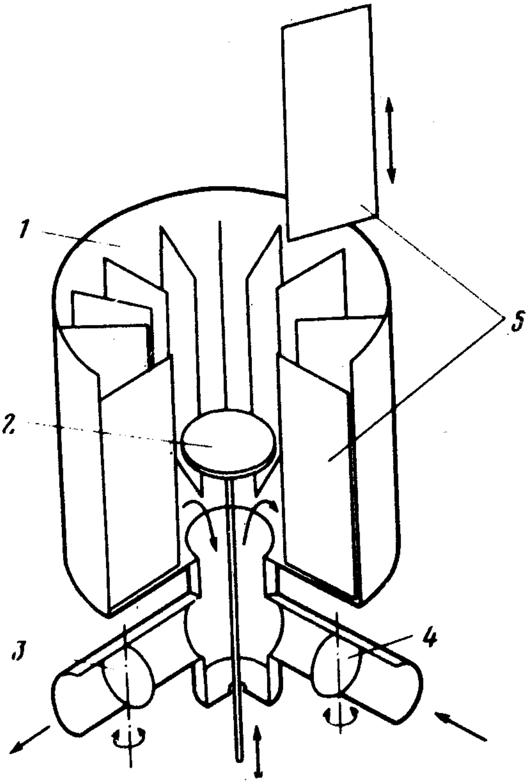

FIG. 1. Storage container for UCN: 1, cylindrical container; 2, disk shutter; 3, output shutter.

where $E' = E - mgZ$, Z is the height to which the neutron rises relative to the container's bottom, E is the neutron energy at $Z = 0$, m is the neutron mass, and g is the gravitational acceleration,

$$\bar{\mu}(E') = \frac{2\eta}{y^2}\left(\arcsin y - y\sqrt{1-y^2}\right)\ [6]; \qquad y = \sqrt{E/E_{e.p.}};$$

$E_{e.p.}$ is the end-point energy of the material of the walls and fins of the container, $\gamma_0(E)$ is the geometry factor of the container without the fins, $\gamma'(E)$ is the geometry factor corresponding to one fin, n is the number of fins introduced into the container, S is the surface of the container and of the fins, and Ω is the volume of the container.

For a broad spectrum of UCN that are stored in the container, with the boundaries E_1 and E_2, the geometry factor depends on the time:

$$\gamma_n(t) = \int_{E_1}^{E_2} \rho(E)\gamma_n(E)\exp(-\eta\gamma_n(E)\,t)/dE \Big/ \int_{E_1}^{E_2} \rho(E)\exp(-\eta\,\gamma_n(E)t)\,dE\,, \qquad (3)$$

where $\rho(E)$ is the spectrum of UCN in the container at $t = 0$. In this case the time dependence of the number of UCN in the vessel can be described approximately by the

Table I

№ series	$\eta \times 10^4$	$\lambda_r \cdot 10^3$ sec^{-1}	$(\Delta\lambda_r)_{met} \cdot 10^3$ sec^{-1}	$\Delta\eta_{met} \cdot 10^4$
1	4,43 ±0,10	1,152 ±0,093	±0,168	±0,47
2	1,23 ±0,14	1,143 ±0,130	±0,027	±0,068

constant of the total loss probability $\lambda = \lambda_r + \eta\bar{\gamma}_n$, where $\bar{\gamma}_n$ is determined by averaging[3] in the range of 0 to t_{max} (t_{max} is the maximum neutron storage time in the container).

The spectrum of neutrons stored in the container at zero time is determined approximately as follows:

$$\begin{cases} \rho(E) = \text{const} & E_1 < E < E_2; \\ \rho(E) = 0 & E < E_1;\ E > E_2; \end{cases} \tag{4}$$

where $E_1 = 5\times10^{-9}$ eV and $E_2 = 18\times10^{-9}$ eV. This can be seen in Fig. 2 which shows the integral spectrum of the stored UCN, which was measured after inserting a UCN absorber into the container.[7] The $\bar{\gamma}_n$ was calculated by averaging according to Kosvintsev *et al.*[3] with use of the spectrum measured experimentally.[4]

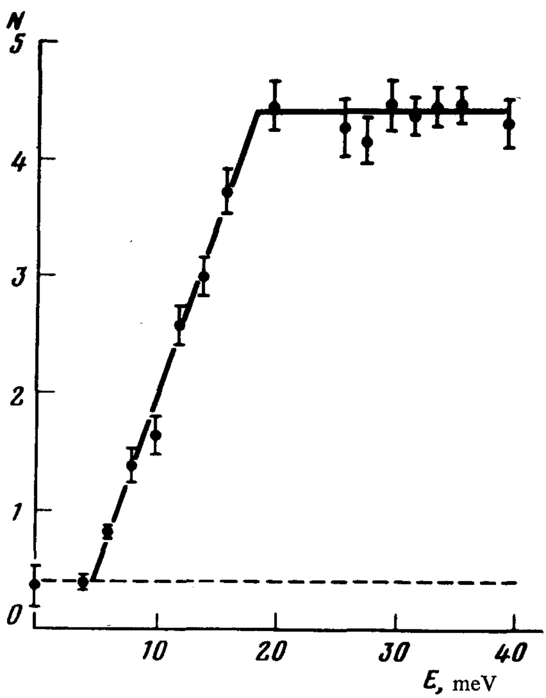

FIG. 2. Integral spectrum of stored UCN at zero time (the dashed line represents the background level).

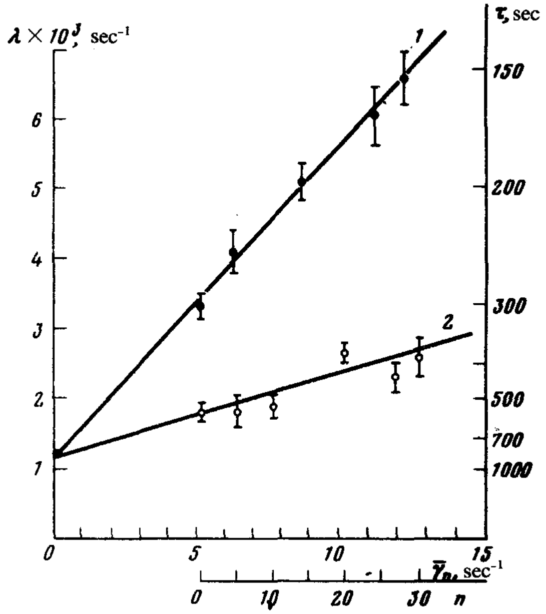

FIG. 3. Experimental dependeces of $\lambda_{\rm exp}$ on $\bar{\gamma}_n$:1, first series of measurements; 2, second series of measurements.

In the experiment we investigated the dependence of $\lambda_{\rm exp}$ on $\bar{\gamma}_n$, which was varied by inserting a different number of fins into the container. The λ_r was determined by extrapolating to $\bar{\gamma}_n = 0$ the linear dependence of $\lambda_{\rm exp}$ on $\bar{\gamma}_n$, which was constructed by the method of least squares.

The first series of measurements (curve 1 in Fig. 3) was performed with a container and fins etched in a NaOH solution and annealed in a vacuum of $\sim 10^{-5}$ Torr at 300° C for three hours.

The second series of measurements (curve 2 in Fig. 3) was performed with a container and fins coated with aluminum 1000 Å in thickness. After coating them with aluminum, the container and fins were exposed to air for seven hours and annealed again in a vacuum of $\sim 10^{-5}$ Torr for twelve hours. The results of evaluation of the measurements are given in Table I.

The systematic errors in determining λ_r and η, according to $(\Delta\lambda_r)_{\rm met}$ and $\Delta\eta_{\rm met}$, are attributable primarily to substituting $\bar{\gamma}_n$ for the $\gamma_n(t)$ function in the analysis of the data. A possible additional contribution to the systematic error in determining λ_r ($\leqslant$3–5%) may be due to the difference in the parameters η for the container and the fins. The deviations in the values of η from one fin to another cannot contribute to the error, since $\lambda_{\rm exp}$ was determined as the average of all the possible sets of n fins numbering 30 in all. The error due to possible heating of UCN by the residual gas, assuming that it consists entirely of hydrogen, does not exceed 0.9%. The filtering of UCN through the slit of the disk shutter does not influence the result to within 0.06%.

Since the systematic error in determining λ_r is much smaller in the second series of measurements than in the first, the neutron lifetime was determined from the results of the second series and is

$$\tau_r = 875 \pm 95 \text{ sec}.$$

As follows from the relation (3) and from the given results, the error $(\Delta\lambda_r)_{met}$ decreases appreciably with decreasing η.

For the value of η obtained in this work, the minimum ratio is $\eta\bar{\gamma}_n/\eta_r + n\bar{\gamma}_n = 0.36$. Further increase of the measurement accuracy depends on whether or not the parameter η can be reduced.

For the theoretical value of η equal to 0.24×10^{-4} for aluminum, which would correspond to $n\bar{\gamma}_n/\bar{\lambda}_r + n\bar{\gamma}_n = 0.1$, the systematic error does not exceed 0.2%. In this case the accuracy of measuring λ_r, which can be determined only statistically, may be $\leqslant 1\%$.

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