Nuclear Instruments and Methods in Physics Research A324 (1993) 496–500
North-Holland

NUCLEAR
INSTRUMENTS
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RESEARCH
Section A

Method for calibration of losses in neutron lifetime experiments with UCN

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Received 28 February 1992 and in revised form 25 June 1992

A method for the calibration of ultra-cold neutron (UCN) losses in neutron lifetime experiments with storage of UCN in material traps is proposed. Calculations of losses depending on the geometry and the size of the trap, on the energy limit of the trap wall material and on the UCN energy spectrum, can be replaced by direct experimental measurements. A new scheme of an experimental setup for the neutron lifetime measurement is proposed. The uncertainty of the measurement is estimated to be 1 s or less.

1. Introduction

Measurements of the neutron lifetime and asymmetry coefficients make it possible to determine weak interaction fundamental constants and to test the validity of a standard V–A model at a high level of accuracy [1–3]. In addition, a knowledge of the neutron lifetime value is of importance for solving a number of important questions of astrophysics and cosmology [4,5].

The most accurate results have been reported in the works [6–9]. Three of four of these experiments have been performed using the technique of UCN confinement in material traps.

The time of UCN storage in a trap τ_{st} is determined by a probability of its β-decay (τ_{n} – lifetime) and by the probability of losses on the trap walls:

$$\tau_{\mathrm{st}}^{-1} = \tau_{\mathrm{n}}^{-1} + \tau_{\mathrm{los}}^{-1}. \tag{1}$$

τ_{los} is the mean survival time for wall losses (the time neutrons would store in the trap without β-decay). To measure τ_{n} reliably it is necessary to obtain values of τ_{st} close to τ_{n} and to take into account the losses on the walls.

In general, the race of UCN loss on the trap walls τ_{los}^{-1} is proportional to the loss coefficient η and also depends on the trap size and form, as well as on the energy of the neutron E and energy limit of the trap wall material E_{lim}:

$$\tau_{\mathrm{i}}^{-1} = \tau_{\mathrm{n}}^{-1} + \eta\gamma(\mathrm{Geometry}, E, E_{\mathrm{lim}}). \tag{2}$$

The quantity τ_{los}^{-1} can also be obtained by integrating the product of the loss probability averaged over angle of incidence at one collision ($\bar{\mu}$) by the incident flux density (f) along a surface of the trap:

$$\tau_{\mathrm{los}}^{-1} = \frac{\int_{s} \bar{\mu} f \, \mathrm{d}s}{\int_{\Omega} n \, \mathrm{d}\Omega}, \tag{3}$$

where n is the local UCN gas density.

The parameter γ has the dimension s^{-1}; it is an effective frequency of UCN collisions with trap walls, while η is the corresponding effective loss probability per collision.

Making use of eq. (2) one can obtain a reciprocal neutron lifetime value by linear extrapolation of the relation $\tau_{\mathrm{st}}^{-1}(\gamma)$ to the value $\gamma = 0$. The loss coefficient η equals the tangent of the straight line slope angle. Using traps of different dimensions and neutrons of different energies one can produce different values of effective frequency γ.

The effective frequency γ for each case can be calculated [6,8] or measured experimentally [9]. In previous cases where the values of γ were calculated, the measurements were carried out in two ways:

1) Only size extrapolation was used, the effect of UCN spectrum on the result having been made very small by the design of the experiment [6];

2) Suitable spectral measurements were carried out and both size extrapolation and energy extrapolation were used resulting in improved statistics for the experiment [8].

0168-9002/93/$06.00

To make the extrapolation to zero γ it is sufficient just to measure some quantity which is proportional to γ, for example, the flux of thermal neutrons created by upscattering of UCN on the trap wall material at a given temperature [9].

The following experimental scheme seems attractive. For the trap walls a substance is used where the losses are much less than those due to β-decay as for example in the works [8,10]. The effective frequency γ is measured, but not calculated. This conditions are met using a technique of experimental loss calibration with the help of UCN.

2. Method of UCN loss calibration

2.1. Description of the method

In the experiments of a type used in refs. [10,8] τ_n is determined with the help of linear extrapolation (2). The reciprocal times of storage $\tau_{t_i}^{-1}$ are plotted as abscissa and the calculated effective collision frequency γ_i is plotted as ordinate. One can perform a direct experimental calibration of γ_i values using UCN. To do this one has to repeat the measurements in the same trap, with the same UCN spectrum and the same surface energy limit, but increasing the loss coefficient by several times:

$$\tau_{1_{st_i}}^{-1} = \tau_n^{-1} + \eta_1\gamma_i, \qquad \tau_{2_{st_i}}^{-1} = \tau_n^{-1} + \eta_2\gamma_i. \tag{4}$$

Here, $\tau_{1_{st_i}}$, $\tau_{2_{st_i}}$ are storage times for main and calibration surfaces respectively and η_1, η_2 are the corresponding loss coefficients. Obviously one variable, namely γ_i, can be eliminated from the two eq. (4). The the measured storage times and the two unknown parameters (the neutron lifetime and the ratio of loss coefficients) are related by the expression:

$$\frac{\tau_1^{-1} - \tau_n^{-1}}{\eta_1} = \frac{\tau_2^{-1} - \tau_n^{-1}}{\eta_2} \tag{5}$$

Eq. (5) determines a family of straight lines crossing each other and a straight line $\tau_1^{-1} = \tau_2^{-1}$ in the point $\tau_1^{-1} = \tau_2^{-1} = \tau_n^{-1}$, each line being characterised by a different value of the parameter:

$$K_\eta = \eta_2/\eta_1. \tag{6}$$

The neutron lifetime value corresponds to the point of crossing of the experimental straight line drawn in axes $\tau_1^{-1} - \tau_2^{-1}$ with straight line $\tau_1^{-1} = \tau_2^{-1}$ (fig. 1).

As it is seen from eq. (5) the reciprocal neutron lifetime τ_n^{-1} value is obtained by linear extrapolation of the experimental values τ_{1_i}, τ_{2_i}. Different UCN energy intervals and traps of different sizes provide the different points on a line. Actual values γ_i are not used in the extrapolation.

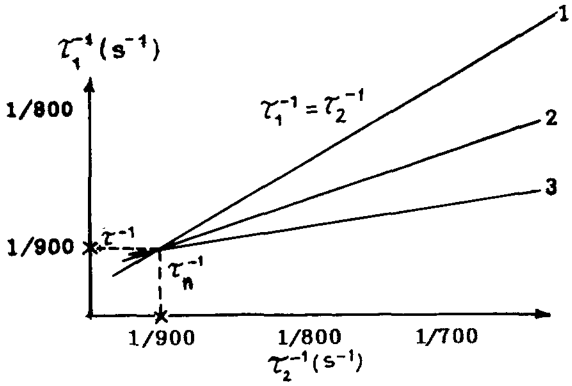

Fig. 1. Illustration of direct loss calibration technique in representation $\tau_1^{-1} - \tau_2^{-1}$. 1, 2, 3 are experimental straight lines for different K_η eq. (6).

This use of experimental loss calibration gives a simpler interpretation of results, makes them more visual and obviates a number of problems connected with a determination of the effective frequency γ, in particular many systematic errors, typical of the size extrapolation technique, are avoided.

2.2. The practical realization of method

The calibration by measuring with a suitable ratio η_1/η_2 can be performed in three ways:

1) *Temperature calibration.* At different temperatures one and the same trap has the same limiting energy but notably different loss coefficients because the cross sections for inelastic scattering depend on temperature. For example, when using a trap with a beryllium coating, measurement at room temperature will provide a calibration with a high η_1, a measurement at liquid helium or nitrogen temperature will be the main one with a low η_2.

2) *Chemical calibration.* When a trap is used on whose surface gases are condensed at low temperatures, the calibration measurement is with the trap covered by the main gas (O_2, CO_2 etc.) containing a small admixture of a strong absorbing one (e.g. with a nitrogen admixture). The limiting velocity would not be changed noticeably by the nitrogen. In any case, a compensation can be obtained by using a mixture of three gases in appropriate concentrations.

3) *Isotope calibration.* This method is a variant of chemical calibration, the difference consisting in the fact that an isotope of one of the coating components is used as an admixture (e.g. D is substituted by H). In this case the surface structure will be surely the same.

One must consider the validity of the assumption that the limiting velocity of the surface substance in the main and calibration measurements is the same. After the condensation of a gas mixture the surface composition may change. When the temperature changes, the surface can adsorb residual gases or degas itself and thus change its composition. But direct evaluations show this effect to be small. For example, in the installation used in the work of ref. [8], the uncertainty in lifetime determination of the order of 0.3 s corresponds to a change in the velocity limit of 10%. A limiting velocity change leads, in the first order, to a linear expansion or contraction of an axis scale. Nonlinear changes are smaller by about an order of magnitude. The linear effect is equivalent to loss coefficient renormalization. On the other hand, a 10% shift of the limit velocity constitutes about a 20% shift of the limit energy which would be equivalent to approximately 40% of hydrogen admixture in beryllium surface, which is on the verge of reasonable assumptions about hydrogen concentration.

2.3. Systematic error compensation

Use of the loss calibration method does not require the calculation of value γ_t, thereby removing a number of problems connected with such calculations.

Since details of the trap geometry are needed for the determination of the effective frequency γ values only, inaccuracies in geometry parameters and problems inhomogeneity of roughness of surfaces are also reduced. In particular, inequality of a trap surface roughness and plates inserted into it will not lead to an error in the lifetime determination. Temperature calibration makes it possible to use assembled traps because losses in the cracks at the joints are always included as an additional contribution to the effective frequency γ so that the γ values at different temperatures are equal for a given trap geometry.

The necessity for an accurate measurement of the stored UCN spectrum no longer arises. One should only meet the condition that the spectrum was the same for the main and the calibration measurements both at the beginning and at the end of a period of storage. To the first approximation this can be achieved using the idea of time scaling [6], i.e. choosing the corresponding confinement times. Then there is scarely any need for measurements of spectra.

For the previous experiment when calculating a effective frequency γ using spectral measurements one needed to know the limits of the UCN energy intervals in use. The limits are shifted as compared with geometrically determined ones because of the finite gravitational spectrometer energy resolution. If the limits are the same for the main and calibration measurements then no accurate knowledge of them is needed in this proposed calibration method.

Thus in the case of direct experimental calibration of losses systematic uncertainties are considerably reduced. Increases in the statistical errors connected with the additional calibration measurements are discussed in section 3.4.

3. Proposal of new neutron lifetime experiment

3.1. Scheme of a new trap

It is proposed to use the method of loss calibration with the help of UCN in an experiment which is a continuation of the experiment of ref. [8]. UCN losses on the walls would be determined by extrapolation of reciprocal storage times with respect to the effective frequency of UCN collisions with the trap walls. Traps of different dimensions ("wide" and "narrow") and neutrons of different energies would be used to achieve a changes in an effective collision frequency γ.

The installation, as before, represents a gravitational spectrometer. The trap can rotate around a horizontal axis so that UCN appear confined in it by a gravitational field when it is in position with the opening upwards. Storage times in it are determined directly from the rate of UCN density decrease. Measurements of storage time spectral dependence are carried out by successive rotations of the trap, step by step, into position with the opening down.

In the new installation variant it is notable that the trap contains semicircular plates, which can rotate around horizontal axis independently of the trap (fig. 2). Since UCN losses in the trap are almost fully determined by the interaction with the lower part, a trap with plates down is almost equivalent to a trap with complete plates and a trap with plates up is practically equivalent to a trap without plates (fig. 3). Thus measurements with empty and partitioned traps can be combined in one trap. Measurements with a partitioned trap are statistically equivalent to simultaneous measurements with a set of "narrow" traps. As an additional test of the results obtained one can carry out measurements with the plates in some intermediate position.

Measurements with plates up and plates down are carried out alternately. It excludes a number of system-

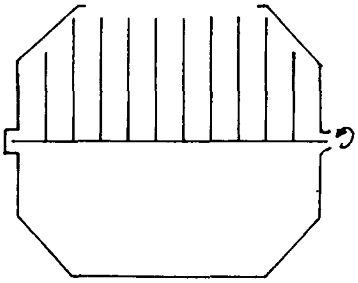

Fig. 2. Scheme of the new trap.

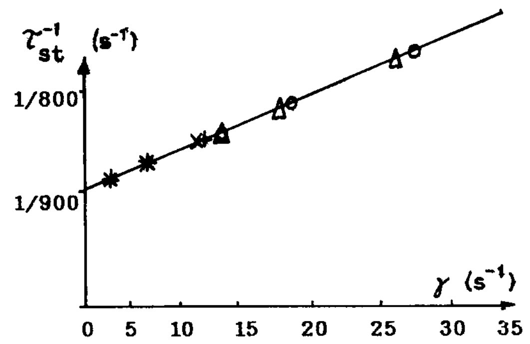

Fig. 3. Comparison of effective frequency γ values in old and new schemes of the experiment for the same UCN energy spectrum and the same trap sizes. + – plates in higher position; △ – plates in lower position; ○ – partitioned trap; × – empty trap.

atic uncertainties characteristic of the old method, for example, the possible non-equivalence of the "narrow" and "wide" trap temperature and conditions for the application of coatings.

3.2. *Comparison of the statistical uncertainty of the experiment with old and new traps*

For the technique using size extrapolation, in the simplest case, the neutron lifetime measurement procedure consists of storage time determinations in two traps without measuring the energy dependence of the losses:

1) In a "wide" trap with the minimum possible value $\gamma = \gamma_1$;

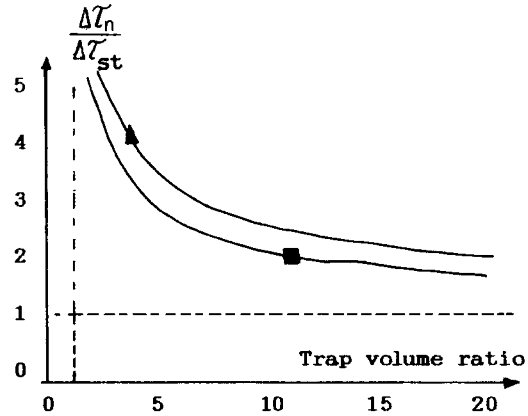

Fig. 4. Comparison of the statistical uncertainties of previous [8] and the planned experiments. ▲ – are traps from [8], the ratio between volumes of "wide" and "narrow" traps is plotted on the X-axis; ■ – is a new trap, on the X-axis is plotted (the number of plates +1). The upper and lower curves correspond to the old and new traps.

2) In a "narrow" trap with the $\gamma = \gamma_2$ value being several times more.

$$\gamma_{st_i} = \gamma_n + \eta\gamma_i, \quad (i = 1, 2);\ \gamma_{st_i} \pm \Delta\gamma_{st_i}. \tag{7}$$

The neutron reciprocal lifetime γ_n value is obtained by linear extrapolation of a function $\gamma_{st}(\gamma)$ to a value $\gamma = 0$:

$$\Delta\gamma_n = \frac{\sqrt{(\gamma_2\Delta\gamma_{st_1})^2 + (\gamma_1\Delta\gamma_{st_2})^2}}{\gamma_2 - \gamma_1}. \tag{8}$$

Let the "wide" trap be able to capture N neutrons, i.e. K_N times more than a "narrow" one.

Let

$$\frac{\gamma_2}{\gamma_1} = K_\gamma. \tag{10}$$

Optimization of eq. (8) consist in a choice of durations of storage times measurements in "wide" and "narrow" traps so that $\Delta\gamma_n$ has minimum value, while the total duration of the experiment is fixed. At the optimum measurement strategy we get:

$$\frac{\Delta\gamma_n}{\gamma_n} = \frac{\Delta\tau_{st}}{\tau_{st}} \frac{K_\gamma + \sqrt{K_N}}{K_\gamma - 1}, \tag{11}$$

$$\frac{T_1}{T_2} = \frac{K_\gamma}{\sqrt{K_N}}. \tag{12}$$

$\Delta\tau_{st}/\tau_{st}$ is the uncertainty of the storage time determination in the "wide" trap during the total measurement time. T_1 and T_2 are measurement times for the "wide" and "narrow" traps respectively. T is total measurement time. $T = T_1 + T_2$. Eq. (12) determines optimum relationship of the times T_1 and T_2.

The precision of a neutron lifetime determination can be made approximately equal to the precision of the storage time termination in the "wide" trap at sufficiently big K_γ.

For the new scheme of a trap with semicircular plates:

$$\frac{\Delta\gamma_n}{\gamma_n} = \frac{\Delta\tau_{st}}{\tau_{st}} \frac{K_\gamma + 1}{K_\gamma - 1}, \tag{13}$$

$$\frac{T_1}{T_2} = K_\gamma. \tag{14}$$

An improvement in the statistical performance of the new trap scheme follows from a comparison of the eqs. (11) and (13).

Fig. 4 illustrates a comparison of the two variants of the trap (measurements of the energy dependence of the storage times were taken into account).

3.3. Comparison of the statistical uncertainties of the past and future experiments

We expect to obtain increased accuracy of the neutron lifetime measurement because of modernization of the installation and because of more intense UCN flux.

Factors of improvement in the statistical error:

1) Increase in range of the dynamic variable $\gamma \approx 1.5$ times;

2) Increase in statistics in a "narrow" trap due to partitioning of a "wide" one ≈ 1.3 times;

3) Increase in UCN beam at the installation input (PIK, ILL reactors) ≈ 2.5 times;

4) Decrease of relative down time of the installation due to working with a new continuously cooled cryostat and a longer reactor cycle ≈ 1.4 times.

Statistical uncertainty of the neutron lifetime will be ≈ 6 times less (from ≈ 3 s to ≈ 0.5 s), in particular ≈ 2 times less because of the modernization of installation. Increasing the range of the dynamic variable γ is achieved by introducing plates with a small distance between them. The effective collision frequency grows by 2–3 times compared with the cylinder trap of the past experiment. This will allow us to measure losses on the trap walls with good accuracy. A further increase of the effective frequency γ scarely improves the precision of the lifetime determination, but can be of assistance for experimental testing of the linear extrapolation.

The possible level of systematic uncertainty for the method of size extrapolation is ≈ 1 s. This new method of experimental calibration of the losses with the help of UCN allows us to compensate main systematic uncertainty.

3.4. Comparison of the statistical uncertainties in the size extrapolation method and in the calibration of losses method

When passing from a size extrapolation method to a method of experimental loss calibration the statistical error of the lifetime measurements increases somewhat because of the necessity to carry out additional calibration measurements and due to the uncertainties of these measurements.

The optimum measurement regime is achieved in the case when the calibration measurement time (eq. (6)) is K_η times less than the time of the main measurement.

$$\frac{\Delta\gamma_n \text{ (method of direct loss calibration)}}{\Delta\gamma_n \text{ (method of size extrapolation)}} = \frac{K_\eta + 1}{K_\eta - 1}\sqrt{\frac{K_\eta^2 - K_\eta + 1}{K_\eta^2}} \qquad (15)$$

Particularly, for $K_\eta = 3$ this relation gives 1.76.

The times necessary for measurements in different regimes at optimal procedure are as follows:

$$\begin{array}{ll}
\text{–main measurements (plates up)} & K\ [\mathrm{s}], \\
\text{–calibration measurements} & \\
\quad \text{(plates up)} & \dfrac{K}{K_\gamma}\ [\mathrm{s}], \\
\text{–main measurements} & \\
\quad \text{(plates down)} & \dfrac{K\sqrt{K_N}}{K_\gamma}\ [\mathrm{s}], \\
\text{–calibration measurements} & \\
\quad \text{(plates down)} & \dfrac{K\sqrt{K_N}}{K_\gamma K_\eta}\ [\mathrm{s}]
\end{array} \qquad (16)$$

4. Conclusion

The uncertainty of the neutron lifetime measurement in the experiment [8] was determined by statistics giving $\approx$ 3s in two full months of measurements. Systematic uncertainties were evaluated as ≈ 1 s.

The statistical error from the installation can be reduced to 0.5 s during the same time due to its modernization and the use of more intense UCN beam (PIK, ILL). The method of loss calibration for the trap walls, besides its aesthetic attractiveness, has a significant merit in permitting us to reduce experimentally the main systematic uncertainties, so that their final effect will be at the level 0.3–0.5 s.

Thus an estimation that we can determine for the neutron lifetime at the 1s level seems conservative enough. A discussion of measurements with an accuracy to 0.3–0.5 s is not unreasonable.

The idea of experimental calibration of UCN losses in trap with a help of UCN might find a use in other experimental installations.

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