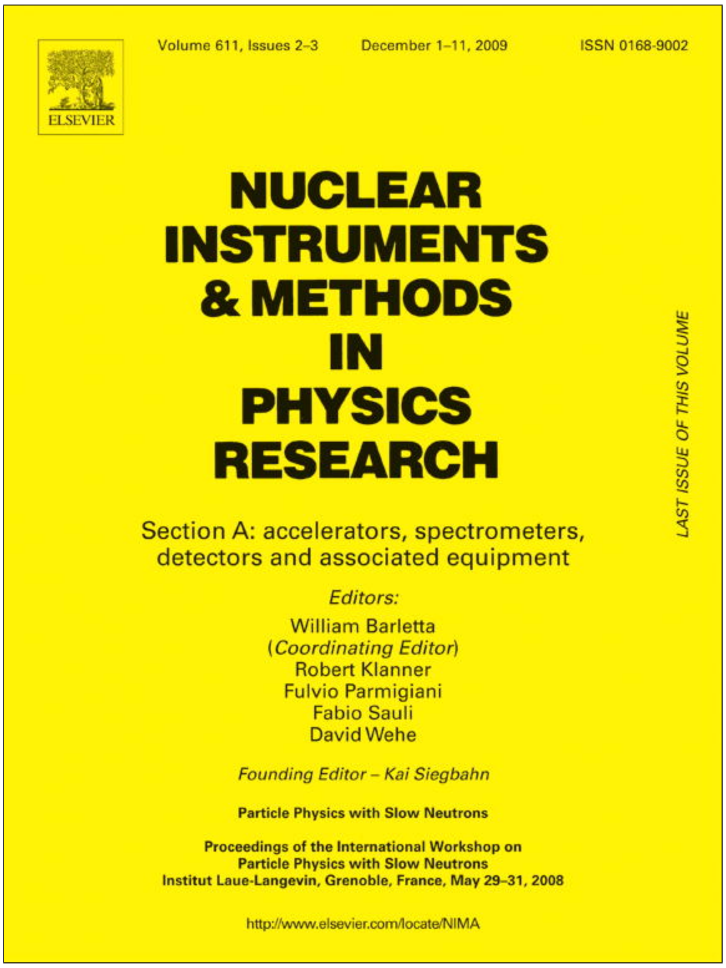
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A new project to measure the neutron lifetime using storage of ultracold neutrons and detection of inelastically scattered neutrons

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ABSTRACT

We propose to measure the neutron lifetime in a complex experiment using storage of ultracold neutrons in two traps with significantly different mean free path. The trap walls are coated with a low-temperature liquid fluorine polymer. Known possible systematic false effects will be largely reduced compared to those in preceding experiments due to corresponding setup design and measuring procedure.

1. Introduction

A large discrepancy between the world average value of the neutron lifetime [1] (PDG value $\tau_n(s) = 885.7(8)$) and the most recent neutron lifetime measurement [2] $(878.5 \pm 0.7_{st} \pm 0.3_{sys}(s))$ motivates the present project. The accuracy of the PDG value is dominated by a single experiment [3]. The contribution of each other experiment [4–8] is at least an order of magnitude smaller. Both most precise experiments use storage of ultracold neutrons (UCN) in traps with Fomblin oil wall coatings. Although a list of possible false effects in these most precise experiments is under discussion, the reason for the mentioned discrepancy is not yet understood. Besides, the neutron lifetime value could affect the condition of unitarity of the Cabibbo-Kobayashi-Maskava matrix [1]. The matrix element V_{ud} contributes the largest term in the unitarity sum $|V_{ud}|^2+|V_{us}|^2+|V_{ub}|^2 = 1$. Using the PDG neutron lifetime value [1] and the expression $|V_{ud}|^2 = (4908 \pm 4)[s]/(\tau_n[s](1+3(G_A/G_V)^2))$, where G_A and G_V are the axial and the vector weak-interaction constants, respectively, one obtains the unitarity sum $|V_{ud}|^2+|V_{us}|^2+|V_{ub}|^2 = 0.9997(40)$ in good agreement with the unitarity condition. The latest value for the term $|V_{us}|^2 = 0.2254 \pm 0.0021$ from K-decay [9–13] and the $|V_{ud}|^2$ value obtained from the recent τ_n experiment [2] result in the sum value of 1.0075(40) and that is in agreement with unity at the level of two standard deviations only.

Therefore we intend to carry out a new experiment in which possible systematic false effects would be largely reduced compared to those in preceding experiments. It would profit from advantages of preceding experiments and it would be free of their major known defects. In order to minimize the systematic uncertainties we are going to (1) keep the UCN loss probability as low as 3–5% compared to the neutron β-decay probability due to the use of low-temperature fluorine polymer wall coatings (as in Ref. [2]), (2) monitor the loss probability *experimentally* (instead of estimating it theoretically) by means measuring the inelastically scattered UCN in thermal neutron counters (as in Ref. [3]), (3) minimize any difference in UCN loss coefficients for the two traps and (4) exclude the effect of weak UCN heating [14–24] to the final result due to proper UCN spectrum shaping and monitoring.

2. The experimental setup and measuring procedure

The experiment uses storage of UCN in two traps with significantly different mean free path. All trap walls are coated with a low-temperature liquid fluorine polymer. The experimental setup and the measuring procedures are shown and explained in Fig. 1.

To our knowledge, the polymer layer is not damaged by cooling to $-40\,^{\circ}$C; the loss coefficient η is equal to $(5–8) \times 10^{-6}$, and the weak heating probability is less than 2×10^{-6} per wall collision [14–24].

During the UCN storage time interval t the mean value of total loss probability (per time unit)

$$\bar{\lambda} = \lambda_\beta + \bar{\lambda} = \frac{1}{t} \ln \frac{N(0)}{N(t)} \qquad (1)$$

where $N(0)$ and $N(t)$ are the mean numbers of UCN at the beginning and at the end of this interval, respectively; λ_β and λ_1 are the probabilities of β-decay and UCN loss via interaction with walls, respectively. Counting of inelastically up-scattered neutrons

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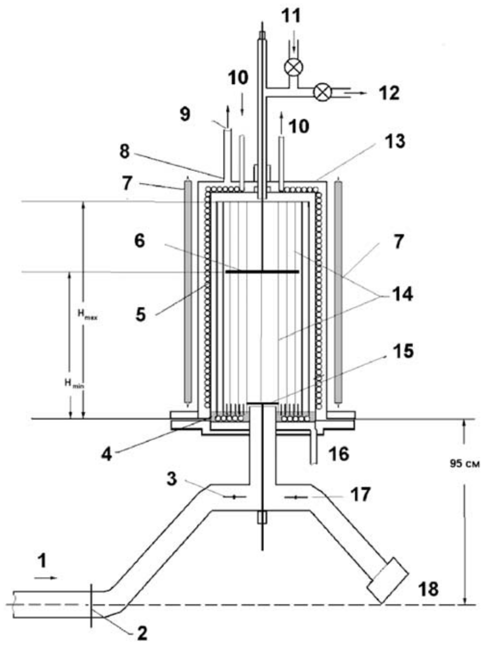

Fig. 1. The experimental setup. UCN from source (1) pass through the Al-foil (2) and fill in the neutron guide with three valves (3), (17), (15) in it, and with the UCN-detector (18) at its exit. The input valve (15) is open during filling and emptying the storage bottle (4); it is closed during the cleaning and storing time intervals. The storage bottle is placed into a double vertical cylindrical vacuum housing (13) with a cooling system (10) and pumping (9, 16). It is surrounded with 26 thermal neutron counters (7). A thick layer of a liquid fluorine polymer YH VAC 18/8 is applied to the inner volume bottom. A vertical copper cylinder (5) with height 95 cm and a diameter of 40 cm is installed on it. This cylinder and the bottom fluorine polymer layer form a storage bottle of the experiment in configuration "number 1". In configuration "number 2" thin vertical strips of copper foils (14) and spiral foils on the bottom are added with equivalent fluorine polymer coating; thus the wall area increases by a factor of 3. The upper boundary $E_{\max}$ of the spectrum of stored UCN is defined by the position of a polyethylene absorber (6), which is lifted to the height $H_{\min} = 47$ cm during the filling period. Then valves (3) and (15) close, while valve (17) opens in order to empty UCN from the neutron guide to the detector and to measure eventual leak of UCN through valve (15). After a time interval $t_{\rm cl}$ sufficiently long to remove UCN with energy $E > E_{\max}$ from the storage trap, the absorber rises to a maximum height $H_{\max} = 95$ cm and the storage period starts. The inelastically scattered neutrons during storage are counted by the detectors (7), while the UCN that were up-scattered in a weak heating process stay inside the trap, if their energy is not sufficient to reach the height of 95 cm. Valves (11, 12) serve to distribute/remove He-gas providing prompt temperature equalization in the bottle after its cooling.

in the configurations "number 1" and "number 2" during time intervals t_k (k is the configuration number, $k = 1, 2$) allows us to calculate the wall loss probability $\overline{\lambda}_{lk}$ in the configuration k averaged over the time interval t_k:

$$\overline{\lambda}_{lk} = \frac{\varepsilon_{\rm ucn}}{\varepsilon_{\rm th}}\frac{\sigma_{\rm ie}+\sigma_{\rm c}}{\sigma_{\rm ie}}\frac{J_k\overline{\lambda}_k}{N_k(0)-N_k(t_k)'} \tag{2}$$

where $\varepsilon_{\rm ucn}$ and $\varepsilon_{\rm th}$ are the detection efficiencies for UCN and thermal neutrons, respectively; $\sigma_{\rm ie}$ and $\sigma_{\rm c}$ are the inelastic and capture cross-section, J_k is the count rate in the thermal neutron detector during the interval k and $\overline{\lambda}_k$ is the total loss probability in the configuration k averaged over the time interval t_k. Thus we measure two pairs of values $(\overline{\lambda}_1, \overline{\lambda}_{l1})$ and $(\overline{\lambda}_2, \overline{\lambda}_{l2})$ in two traps with different mean free paths but other identical conditions and calculate the reciprocal neutron lifetime by

$$\lambda_\beta = \frac{\overline{\lambda}_1\xi - \overline{\lambda}_2}{\xi - 1}, \xi = \frac{\overline{\lambda}_{l2}}{\overline{\lambda}_{l1}}. \tag{3}$$

The experimental uncertainty estimation for this value is

$$\frac{\delta\lambda_\beta}{\lambda_\beta} = \sqrt{\left(\frac{\xi}{\xi-1}\right)^2\left(\frac{\delta\overline{\lambda}_1}{\lambda_\beta}\right)^2 + \left(\frac{1}{\xi-1}\right)^2\left(\frac{\delta\overline{\lambda}_2}{\lambda_\beta}\right)^2 + \left(\frac{\overline{\lambda}_{l1}}{\lambda_\beta}\right)^2\left(\frac{\delta\xi}{\xi-1}\right)^2}, \tag{4}$$

where $\delta\overline{\lambda}_1, \delta\overline{\lambda}_2, \delta\xi$ are the experimental accuracies. For $\xi = 3$ and an expected value of the ratio $\overline{\lambda}_{l1}/\lambda_\beta$ equal to 2.5×10^{-2} the estimated final accuracy is

$$\frac{\delta\lambda_\beta}{\lambda_\beta} = \sqrt{2.25\left(\frac{\delta\overline{\lambda}_1}{\lambda_\beta}\right)^2 + 0.25\left(\frac{\delta\overline{\lambda}_2}{\lambda_\beta}\right)^2 + 6.25\times10^{-4}\left(\frac{\delta\xi}{\xi-1}\right)^2}. \tag{5}$$

Thus, for the expected experiment parameters $\varepsilon_{\rm th}\approx 0.3$, $\varepsilon_{\rm ucn}\approx 0.7$, N_1, $N_2 \approx 7\times10^{-4}$, $\eta = 5\times10^{-6}$ the statistical accuracy would be $[(\delta\tau_\beta)_{\rm st}\approx]$ 0.5 s per 20 days of measurements. This estimate assumes the thermal neutron background is significantly less than the signal. Due to small value of the ratio $\overline{\lambda}_1/\lambda_\beta$, the spectral evolution of the stored UCN in both experiments (numbers 1 and 2) is negligible. Nevertheless, we will provide equal spectrum evolution in the two experiments by the following choice of the storage time intervals (t_1) and (t_2), such that: $t_1/t_2 = \lambda_{l2}/\lambda_{l1}$. It provides equality of the detection efficiencies, $\varepsilon_{\rm ucn1} = \varepsilon_{\rm ucn2}$ and $\varepsilon_{\rm th1} = \varepsilon_{\rm th2}$, as well as the "scaling principle" for UCN spectra during UCN storage.

Let us analyze systematic uncertainties in this experiment. An uncertainty arises from the difference in the efficiencies $\varepsilon_{\rm th1}$ and $\varepsilon_{\rm th2}$ due to capture of some inelastically scattered neutrons in the material of the addition surface, as well as from minor geometry dependence of these efficiencies. We estimate that the values $\varepsilon_{\rm th1}$ and $\varepsilon_{\rm th2}$ differ by $<1\%$; so a systematic effect $(\delta\tau_\beta)_{\rm sys1}$ would be <0.3 s. The UCN scattered inelastically on residual gas molecules are detected by counters (7) and thus do not produce a sizeable false effect. Non-perfectness of the scaling principle would make a systematic uncertainty <0.1 s. An eventual temperature difference between the trap wall and the additional copper surface would result in $(\delta\tau_\beta)_{\rm sys2}<0.1$ s. A possible difference in the UCN detection efficiencies $\varepsilon_{\rm ucn1}$ and $\varepsilon_{\rm ucn2}$ would correspond to a small systematic effect $(\delta\tau_\beta)_{\rm sys3}<0.1$ s. The difference in quality of the coating layers of the surfaces in the configurations with number 1 and 2 is monitored by the counters (7) Therefore, it does not produce any noticeable effect. The "liquid valve" (15) excludes UCN leakage.

Summarizing, the total optimistic experimental accuracy is estimated: $(\delta\tau_\beta)_{\rm st}\approx 0.5$ s and $(\delta\tau_\beta)_{\rm sys}\approx 0.4$ s.

3. Conclusion

We propose a new neutron lifetime experiment using storage of UCN in two traps coated with a low-temperature fluorine polymer. Different wall surface areas of the traps result in different UCN mean free paths; the walls are kept in identical conditions. The UCN loss probability is as low as 3–5% compared to λ_β due to soft UCN spectrum ($E_{\rm UCN}\leq 50$ neV) and low trap temperature. The effect of UCN loss via weak heating is excluded from the neutron lifetime value due to the vertical extension of the trap that allows us to store UCN with an energy up to $E_{\rm UCN}<100$ neV. The experimental monitoring of the UCN loss probability is provided by measuring the flux of inelastically scattered neutrons using thermal neutron counters with known (measured) detection efficiency. Such an experiment would be free of known major possible systematic effects.

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