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Experimental search for neutron–mirror neutron oscillations using storage of ultracold neutrons

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ABSTRACT

The idea of a hidden sector of mirror partners of elementary particles has attracted considerable interest as a possible candidate for dark matter. Recently it was pointed out by Berezhiani and Bento that the present experimental data cannot exclude the possibility of a rapid oscillation of the neutron n to a mirror neutron n′ with oscillation time much smaller than the neutron lifetime. A dedicated search for vacuum transitions $n \to n'$ has to be performed at weak magnetic field, where both states are degenerate. We report the result of our experiment, which compares rates of ultracold neutrons after storage at a weak magnetic field well below 20 nT and at a magnetic field strong enough to suppress the seeked transitions. We obtain a new limit for the oscillation time of n–n′ transitions, $\tau_{\rm osc}(90\%\ {\rm C.L.}) > 414$ s. The corresponding limit for the mixing energy of the normal and mirror neutron states is $\delta m(90\%\ {\rm C.L.}) < 1.5 \times 10^{-18}$ eV.

1. Introduction

As suggested long ago there might exist a parallel sector of “mirror particles” in form of a hidden duplicate of the observable particle sector [1]. In this picture, ordinary and mirror sectors should have identical particle contents and identical microphysics, in particular the same spectra of masses and coupling constants. Each ordinary particle, i.e. electron, nucleon, etc., is supposed to have its mirror twin exactly degenerate in mass but being sterile with respect to the ordinary gauge interactions. The gravitational interactions are supposed to be universal between the two sectors. Nowadays this hypothesis becomes increasingly popular for its intriguing implications in particle physics and cosmology (for recent reviews, see [2]). Mirror matter could be a viable dark matter candidate, with a variety of interesting applications for key cosmological issues [3].

Besides gravity, the two sectors could communicate also by other means. In particular, any neutral ordinary particle, elementary or composite, could have a mixing with its mirror partner. The “ordinary-mirror” oscillation phenomenon thus possible would render the search for mirror matter amenable to terrestrial experiments. For instance, the kinetic mixing between the ordinary and mirror photons [4] can be investigated searching for a transition of positronium to mirror positronium [5]. The mass mixing between the ordinary and mirror neutrinos could be revealed in the active–sterile neutrino oscillations [6]. Also ordinary pions and kaons could have a mass mixing with their mirror partners which can be induced e.g. by some extra gauge forces between the elementary particles of the two sectors [7].

From the phenomenological viewpoint, the small mass mixing between the ordinary neutron n and its mirror partner n′ leads to the most intriguing possibility. As it was shown in Ref. [8], the existing experimental limits on n–n′ oscillations are very weak, allowing the oscillation time $\tau_{\rm osc} = 1/\delta m$ to be much smaller than the neutron decay time $\tau_n \sim 10^3$ s. This could have direct astrophysical consequences, in particular, for the propagation of

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ultra-high energy cosmic rays at cosmological distances [8] or of the neutrons from the solar flares [9]. The experimental possibilities to test the n–n′ oscillation were discussed in detail in Ref. [10].

Since mirror neutrons are invisible, the n–n′ oscillation can manifest experimentally only as a neutron disappearance. However, as shown in Ref. [8], the neutron cannot disappear from a stable nucleus and thus does not induce nuclear instabilities, which is in a drastic difference to the case of neutron–antineutron oscillations [11]. On the other hand, the n–n′ oscillation is very sensitive to external conditions: it is suppressed by matter effects and, remarkably, by the magnetic field of the earth. Clearly, the possibility of a fast oscillation process which violates baryon number conservation looks rather intriguing (for comparison, the direct experimental limit on the neutron–antineutron oscillation time is 8.6×10^7 s [12] while the limit obtained from nuclear stability is about the same, 1.3×10^8 s [13]).

2. Method to search for n–n′ transitions

The probability of transition from the initial neutron state at time 0 to a mirror neutron state at time t_f of free neutron flight is given by

$$P_{\mathrm{nn'}}(t_\mathrm{f}) = \frac{\delta m^2}{\delta m^2 + \omega^2} \cdot \sin^2\bigl(t_\mathrm{f}\sqrt{\delta m^2 + \omega^2}\bigr), \tag{1}$$

where $\omega = \mu_\mathrm{n} H/2$ (here and in the following natural units are used, $c = \hbar = 1$). The expression for ω assumes the absence of significant mirror magnetic fields [8,10]. A factor $\exp(-t_\mathrm{f}/\tau_\mathrm{n})$ is neglected in Eq. (1), since we consider time intervals $t_\mathrm{f} \ll \tau_\mathrm{n}$. When the magnetic field is so weak that $\omega \ll \delta m$, the transition probability $P_{\mathrm{nn'}}(t_\mathrm{f})$ may reach unity.

Experiments are restricted to short times $t_\mathrm{f} \ll \tau_\mathrm{osc}$, which strongly reduces the requirement on the weakness of the magnetic field. Therefore, in the trap shielded from the Earth magnetic field well enough, $\omega t_\mathrm{f} \ll 1$, the n–n′ transition probability (1) is practically the same as in zero magnetic field:

$$P_{\mathrm{nn'}}(t_\mathrm{f}) = (t_\mathrm{f}/\tau_\mathrm{osc})^2, \tag{2}$$

with $\tau_\mathrm{osc} = 1/\delta m$. In particular, for the neutron free flight time between the collisions on the trap wall, $t_\mathrm{f} = 0.1$ s in our experiment, this condition is well satisfied if the magnetic field is less than 100 nT. Therefore, when the initial pure n state propagates in the trap in the form of the wave-packet, it oscillates into n′ state with the probability $P_{\mathrm{nn'}}(t_\mathrm{f})$, and upon collision on the wall it can escape from the trap in the form of mirror neutron with this small probability. With a dominant probability, it is reflected from the wall in the form of the pure n state which for a time t_f until next collision again oscillates into n′ state, and so on. Therefore, the neutron lose rate for unit time is $\Gamma_{\mathrm{nn'}} = P_{\mathrm{nn'}}(t_\mathrm{f})\nu = t_\mathrm{f}/\tau_\mathrm{osc}^2$, where $\nu = t_\mathrm{f}^{-1}$ is the neutron scattering frequency on the walls.[1]

On the other hand, in the case of large magnetic field, $\omega t_\mathrm{f} \gg 1$, the average of the oscillating term in Eq. (1) is 1/2 thus leading to

$$P_{\mathrm{nn'}}(t_\mathrm{f}) = \frac{1}{2(\omega\tau_\mathrm{osc})^2}. \tag{3}$$

A suppression factor $2(\omega t_\mathrm{f})^2 = 10$ is already obtained with a magnetic field of 0.5 μT.

The main idea of the experiment is to measure the difference of storage times of UCN in a trap with magnetic field switched on and off. If oscillations take place mirror neutrons will pass through the trap wall without interaction. As a result the storage time will be reduced. When the magnetic field is switched on, n–n′ transitions are suppressed, and the storage time is defined solely by the probability of neutron β-decay and the probability of losses in the reflection from the trap walls. In our experiment the residual magnetic field reached values down to 2 nT, corresponding to $\omega t_\mathrm{f} = 10^{-2}$. Measurements with a field of 2 μT led to a suppression factor of 1.7×10^4.

Degeneracy of the neutron and mirror neutron states requires, besides a low magnetic field, a good vacuum within the trap. A pressure of 1×10^{-5} mbar corresponds to 0.5×10^{-15} eV potential of neutron interaction with the residual gas, leading to $\omega_\mathrm{vac} t_\mathrm{f} = 0.05$.

Using the equations presented above one can relate τ_osc to the difference of UCN storage times with the magnetic field switched on and off. The probability of UCN loss per second for vanishing magnetic field is given by

$$\tau_{\mathrm{st},0}^{-1} = \tau_\mathrm{n}^{-1} + \mu\nu + \frac{\langle t_\mathrm{f}^2\rangle}{\tau_\mathrm{osc}^2}\nu, \tag{4}$$

where $\tau_{\mathrm{st},0}$ is the storage time of UCN, μ is the loss probability per single collision with trap walls, ν is the average frequency of collisions, and $\langle t_\mathrm{f}^2\rangle$ is the mean square time of the neutron's free flight. With magnetic field H the loss probability is given by

$$\tau_{\mathrm{st},H}^{-1} = \tau_\mathrm{n}^{-1} + \mu\nu, \tag{5}$$

and thus the difference by

$$\tau_{\mathrm{st},0}^{-1} - \tau_{\mathrm{st},H}^{-1} = \frac{\langle t_\mathrm{f}^2\rangle}{\tau_\mathrm{osc}^2}\nu. \tag{6}$$

The determination of storage time requires counting the number N_1 of UCN in the trap after a short holding time t_1 and N_2 after a longer holding time t_2,

$$\tau_\mathrm{st} = (t_2 - t_1)/\ln(N_1/N_2). \tag{7}$$

For optimal counting statistics, t_2 is chosen about $2\tau_\mathrm{st}$.

A first method to determine τ_osc consists in measuring the difference $\theta = \tau_{\mathrm{st},H} - \tau_{\mathrm{st},0}$. From Eq. (6) we obtain

$$\tau_\mathrm{osc}^{-2} = \frac{\theta}{\langle t_\mathrm{f}^2\rangle\nu} \cdot \tau_\mathrm{st}^{-2}. \tag{8}$$

In a second method one measures the ratio R of the registered neutrons N_0 and N_H without and with magnetic field after the holding time t_h,

$$\begin{aligned} R \equiv N_0/N_H &= e^{-\langle t_\mathrm{f}^2\rangle\nu(t_\mathrm{h}+\tau_\mathrm{fill}+\tau_\mathrm{emp})/\tau_\mathrm{osc}^2} \\ &= 1 - \langle t_\mathrm{f}^2\rangle\nu(t_\mathrm{h} + \tau_\mathrm{fill} + \tau_\mathrm{emp})/\tau_\mathrm{osc}^2. \end{aligned} \tag{9}$$

Since the n–n′ transitions may also happen during filling and emptying the trap, the effective holding time $t_\mathrm{h} + \tau_\mathrm{fill} + \tau_\mathrm{emp}$ enters instead of t_h. Defining $r = 1 - R$ the oscillation time is given by

$$\tau_\mathrm{osc}^{-2} = \frac{r}{\langle t_\mathrm{f}^2\rangle\nu(t_\mathrm{h} + \tau_\mathrm{fill} + \tau_\mathrm{emp})}. \tag{10}$$

This way to determine τ_osc is more sensitive than via θ, since measurements both at $t_{\mathrm{h}1} \equiv t_1$ and $t_{\mathrm{h}2} \equiv t_2$ can be used separately to calculate the ratio R.

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[1] In other words, we consider each collision on the wall as a measurement process that reduces the neutron wave function to pure n or n′ states. One could question that for a storage time much larger than t_f and thus for big number of collisions, the wave-packet is dispersed and the neutron wave function is spread over whole trap. However, this will not affect significantly our estimation for $\Gamma_{\mathrm{nn'}}$. In fact, the same expression can be obtained by calculating the n–n′ transition probability from the stationary neutron state corresponding to a discrete energy level E_n in the rectangular potential well of the size a and with the height U by means of the perturbation theory, considering the n–n′ mass mixing δm as a small periodic perturbation with zero frequency. This approximation is valid as far as for the trap with dimensions < 1 m the splitting between the neighboring energy levels is larger than $\delta m < 10^{-15}$ eV. Then, in the limit $U \to \infty$, one gets $\Gamma_{\mathrm{nn'}} = a(m/2E_n)^{1/2}\delta m^2 = t_\mathrm{f}/\tau_\mathrm{osc}^2$. Taking into account a finite height of the potential well, $U = 3 \times 10^{-7}$ eV for our trap, one obtains a small relative correction $\sim (1/a\sqrt{m(U - E_n)}) < 10^{-5}$.

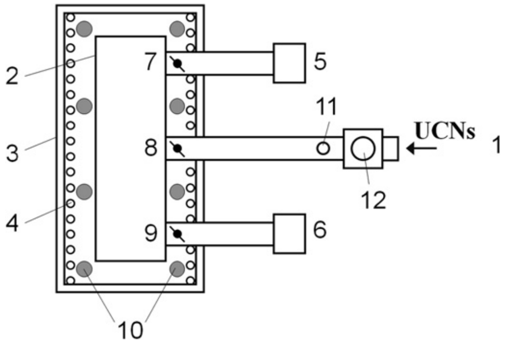

Fig. 1. Experimental setup (top view). 1: UCN input guide; 2: UCN storage chamber; 3: magnetic shielding; 4: solenoid; 5–6: UCN detectors; 7–9: valves; 10: Cs-magnetometers, 11: monitor detector, 12: entrance valve.

In the θ-measurement we search for a change of storage time, in the r-measurement we search for a change of the ratio R. In principle the measurement of R is enough to obtain a limit on n–n′ transitions. However, in case of a positive signal a confirmation by means of a θ-measurement is obligatory to demonstrate that the effect also shows up as a change of storage time and is not connected with changing the number of trapped UCN for different magnetic fields. For higher reliability of the final result we decided to perform most measurements with two different holding times in order to be able to analyse the data using both methods.

It should be mentioned that the realization of an experiment with storage of UCN seems much easier than a beam experiment. The installation is compact, and does not require a voluminous magnetic shield on a long flight base. Also the stability of neutron beam intensity is not as severe an issue as in a beam experiment. In UCN storage each neutron is used a few thousand times and the effect is proportional to $n(t_f/\tau_{osc})^2$ where n is the number of free flights between wall collisions. A simple analysis shows that for storage times less than the neutron lifetime the sensitivity of the experiment is proportional to $L^{3/2}\mu^{-1/4}\rho^{1/4}T^{1/4}$, where L is a representative linear trap size, μ is the loss factor per collision, ρ is the UCN density, and T is the total time of measurements. Thus the decisive role plays the trap size. It was therefore chosen as large as possible.

3. Experiment

The experiment has been carried out using the well-known UCN facility PF2 of the ILL reactor. It employs the vacuum chamber of the new PNPI spectrometer to search for the electric dipole moment of the neutron [14], which for this purpose was adapted to the search for n–n′ transitions. The scheme of installation is shown in Fig. 1.

The apparatus consists of a UCN storage trap with valves for filling and emptying, a neutron guide system, UCN detectors and a magnetic shielding. UCN enter the trap (2) through the input UCN guide (1), with the valves (7) and (9) closed. After filling the trap during 100 s, the valve (8) is closed and UCN are kept in the trap during the given holding time t_1 or t_2. Then the valves (7) and (9) are opened and neutrons reach UCN detectors (5 and 6). Count rates recorded by these detectors during the whole process are shown in Fig. 2. The two UCN detectors offer the possibility for cross checking the detector stability. In the data analysis the summed counts of both detectors were used.

The whole process (filling, holding, emptying and background measurement) is controlled by means of the UCN detectors (5 and 6). Although the valves (7 and 9) are closed during filling and holding times, this is facilitated due to small slits with effective area of about 0.2 mm, which does not significantly deteriorate the storage time. The stability of the incident UCN beam during filling was measured by means of a monitor detector (11), to which the other UCN count rates were normalized.

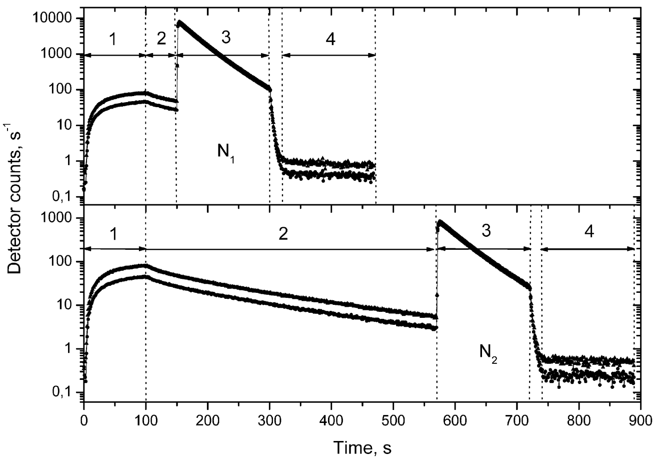

Fig. 2. Count rates of UCN detectors during measurements. The filling time is 100 s. Holding times were $t_1 = 50$ s and $t_2 = 470$ s. The time for emptying and background measurement is 150 s each. The region 3 in these plots is used to deduce the numbers N_1 and N_2. This picture was obtained after 130 cycles, with $\tau_{\text{fill}} = 35$ s and $\tau_{\text{emp}} = 30$ s after $t_h = 50$ s, and $\tau_{\text{emp}} = 38$ s after $t_h = 470$ s.

The UCN trap with volume 190 liters is a horizontal cylinder with diameter 45 cm and length 120 cm. It was made from copper with the inner surface coated by beryllium. The critical velocity of this coating is 6.8 m/s.

Using a Monte Carlo calculation we estimated the average frequency ν of collisions of UCN with trap walls, as well as $\langle t_f^2\rangle$. These values slightly differ for different holding times, e.g. $\nu = 11.11$ s^{-1} and $\langle t_f^2\rangle = 0.011$ s^2 for $t_h = 50$ s, and, $\nu = 10.43$ s^{-1} and $\langle t_f^2\rangle = 0.013$ s^2 for $t_h = 470$ s.

The UCN storage times were deduced from measurements with different holding times using Eq. (7). We obtained for instance 208 s for $t_1 = 50$ s and $t_2 = 470$ s, and 188 s for $t_1 = 50$ s and $t_2 = 250$ s. The variation is due to the spectral dependence of the storage time.

The magnetic shielding of the installation consists of four layers of permalloy. The residual field level was controlled by means of 14 Cs-magnetometers which were installed around of UCN trap [15]. For monitoring the transition-suppressing magnetic field 2 µT, two additional Cs-magnetometers were used.

4. Results of measurements

Measurements were carried out in a mode, which allows to remove the drift of incident UCN beam intensity and a possible drift of the UCN storage time. For this purpose the measurements with different holding times t_1 and t_2 were interchanged in the sequence (t_1, t_2, t_2, t_1). Such a sequence provides one value of τ_{st} at the "zero" magnetic field or at the "suppressing" magnetic field H. The measurements with magnetic field "0" and "H" were interchanged in sequence $(0, H, H, 0)$, $(H, 0, 0, H)$, $(H, 0, 0, H)$, $(0, H, H, 0)$. This allows to remove, besides a linear drift, also an eventual squared long term drift of storage time. A small part of the experiments was carried out in the mode of r-measurement, i.e. using only a single holding time.

The total numbers of neutrons registered by both detectors ranged between 5×10^5 after $t_h = 50$ s, and 0.65×10^5 after 470 s. Correspondingly the accuracy of determination of r ranged between 2×10^{-3} for 50 s and 5.5×10^{-3} for 470 s. The instability of the UCN density determined by the monitor detector during two consecutive measurements of storage time was about 2.3×10^{-3},

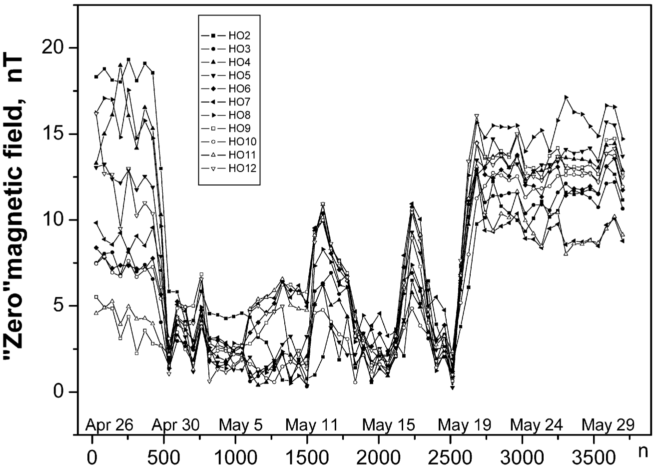

Fig. 3. Instability of the “zero” magnetic field measured with 11 Cs-magnetometers. Shown is the absolute value of the magnetic field component along the axis of spectrometer.

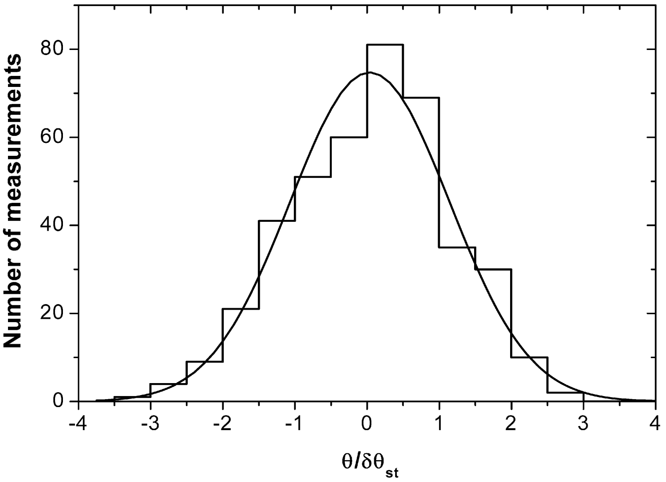

Fig. 4. Histogram of θ-measurements. The solid line shows a Gaussian fit. $\delta\theta_{\mathrm{st}}$ is the statistical error of each measurement by means both detectors for the following sequence (t_1, t_2, t_2, t_1) at “zero” magnetic field and at the “suppressing” magnetic field H. The width of distribution is $2\sigma = 2.21$, i.e. it is widened with respect to the statistical one by the factor 1.1.

i.e. it was on the level of the counting statistical accuracy of measurements.

Fig. 3 shows the instability of the “zero” magnetic field, as measured with 11 Cs-magnetometers. A level down to about 2 nT was reached by demagnetization of the shielding and electric isolation of the spectrometer from the UCN guide coming from the UCN turbine. This has allowed us to suppress both variable and constant magnetic field components inside the screen, presumably caused by leakage currents between the neutron turbine and the magnetic screen.

Jumps in the magnetic field visible in Fig. 3 were caused by changes of the magnetic conditions close to the spectrometer, such as movement of a reactor crane from steel and switching of fields in a nearby experiment. Nonetheless, during all measurements at “zero” magnetic field its actual value did not exceed 20 nT, corresponding to a value of ωt_{f} less than 0.1, which is still acceptable to perform the experimental search for neutron–mirror neutron transitions.

The distribution of values of θ is shown in Fig. 4. Deviations from the average value were normalized to the statistical error, thus enabling us to see the broadening of the distribution caused by other reasons such as for instance non-reproducibility of the effective slit area of the closed valve. The actual value of the broadening is only 1.1, determined with statistical accuracy 2.5σ, meaning that the dispersion of θ is still in reasonable agreement with a purely statistical error of the measurements.

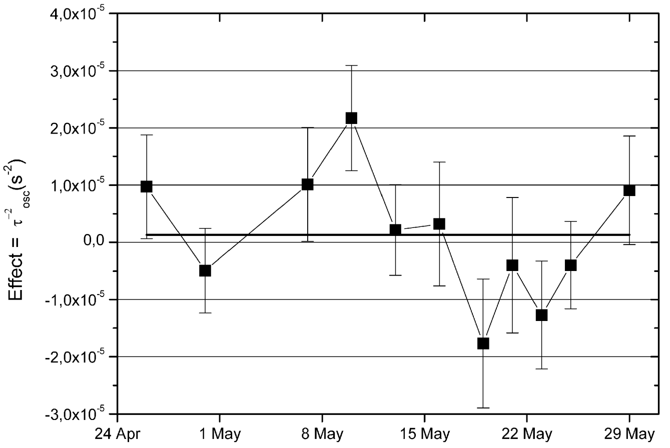

Fig. 5. Results for the value τ_{osc}^{-2} obtained from the r-measurements. Uncertainties for different runs were calculated from the dispersion of values within each run.

The final result of 10 runs of θ-measurement is:

$$\tau_{\mathrm{osc},\theta}^{-2} = (7.05 \pm 5.66) \times 10^{-6}\ \mathrm{s}^{-2}.$$

Since this result differs from zero only by 1.25 standard deviations, we interpret this result as a lower limit on the oscillation time,

$$\tau_{\mathrm{osc},\theta}(90\%\ \mathrm{C.L.}) \geqslant 247\ \mathrm{s}.$$

As already stated, the accuracy of measurements is higher for the r-values. Results for the normalized r-values are shown in Fig. 5 for the same period of measurements as in Fig. 3. A fit of this data by a constant gives the result:

$$\tau_{\mathrm{osc},r}^{-2} = (+1.29 \pm 2.76) \times 10^{-6}\ \mathrm{s}^{-2}.$$

The χ^2-value of the data distribution was equal to 1.37 which is acceptable for 11 points. Interpreted as a lower limit on the oscillation time we obtain

$$\tau_{\mathrm{osc},r}(90\%\ \mathrm{C.L.}) \geqslant 414\ \mathrm{s}.$$

Both limits are considerably better than the limit established in the work [16] $\tau_{\mathrm{osc}}(95\%\ \mathrm{C.L.}) \geqslant 103$ s, in particular if one takes into account that it depends on counting statistic as $N^{1/4}$. The sensitivity of the r-measurements to n–n′ oscillations is considerably higher than of the θ-measurements, which serve as a control measurement.

5. Conclusions

As a result of measurements carried out in this work a new lower limit for the time of neutron–mirror neutron oscillations was established:

$$\tau_{\mathrm{osc}}(90\%\ \mathrm{C.L.}) \geqslant 414\ \mathrm{s}.$$

This limit is already not too far from the neutron lifetime but might still be too low to provide restriction of the mechanism of appearance of high-energy protons above the GZK-cutoff in cosmic radiation due to n–n′ oscillations.

In this work it was shown that UCN storage is indeed a very effective experimental method to search for the n–n′ transitions. An improvement by a factor 2 may be reached due to increasing the storage volume to a trap diameter of 1 m. Another factor 3 occurs when a UCN density of 10^3 cm^{-3} will be available from new powerful UCN sources.

More substantial improvement in the search for n–n′ transitions might be realized in a new-proposed neutron–antineutron transition search proposed in Ref. [17] for the DUSEL laboratory. This project assumes a vertical path (1 km) with time of flight of cold neutrons about 1 s, with beam intensity 10^{12} s^{-1}. The same installation with small modification can be used for the n–n′ experiment. Employing a precise monitoring system and an integral method to detect the neutron intensity it might be possible to reach a sensitivity up to 10^4–10^5 s for the n–n′ oscillation time. This would represent an important progress in efforts to find mirror dark matter under laboratory conditions.

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