which should be cited to refer to this work.

Direct Experimental Limit on Neutron−Mirror-Neutron Oscillations

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In case a mirror world with a copy of our ordinary particle spectrum would exist, the neutron n and its degenerate partner, the mirror neutron n', could potentially mix and undergo nn' oscillations. The interaction of an ordinary magnetic field with the ordinary neutron would lift the degeneracy between the mirror partners, diminish the n' amplitude in the n wave function and, thus, suppress its observability. We report an experimental comparison of ultracold neutron storage in a trap with and without super-imposed magnetic field. No influence of the magnetic field is found and, assuming negligible mirror magnetic fields, a limit on the oscillation time $\tau_{nn'} > 103$ s (95% C.L.) is derived.

The concept of a mirror world, as an attempt to restore global parity symmetry, has attracted interest since the 1950s, started by the famous paper of Lee and Yang [1] and significantly expanded in the work of Kobzarev, Okun, and Pomeranchuk [2]. The mirror matter idea was first applied to the Standard Model of particle physics in Ref. [3]. More recent overviews can be found in Refs. [4,5]. The mirror world could hold a copy of the particle spectrum of our ordinary world. Matter and mirror matter would interact via gravity and present a viable explanation to the dark matter problem [6–10]. Besides gravity, other (new) interactions could show up in minute mixings of neutral matter particles—such as neutrinos, pions, kaons, or positronium (see Ref. [11] for e^+e^-)—and their degenerate mirror partners making oscillations between them possible. Recently it was pointed out [12] that no direct experimental limits exist on the oscillation time $\tau_{nn'}$ [13] between ordinary matter neutrons (n) and the speculative mirror neutrons (n'). An indirect limit of the order $\tau_{nn'} \gtrsim 1$ s has been derived in Ref. [12] based on the search for neutron-antineutron ($n\bar{n}$) oscillations [14]. Fast nn' oscillations with $\tau_{nn'} \sim 1$ s, or at least much shorter than the neutron β-decay lifetime, could explain [12,15] the origin of ultrahigh energy cosmic rays above the Greisen-Zatsepin-Kuzmin (GZK) cutoff [16,17]. The viability of models and implications have been further discussed in Ref. [18].

Possible approaches to nn' oscillation experiments with sensitivities of several hundred seconds have been discussed in Ref. [19]. One approach is to search for nn' oscillations by comparing the storage of ultracold neutrons

(UCN) in vacuum in a trap in the presence and the absence, respectively, of a magnetic field. The essential idea is that the neutron and mirror-neutron states would be degenerate in the absence of a magnetic field and nn' transitions could occur. (The absence of mirror magnetic fields at the location of the experiment is assumed throughout this Letter [20].) The interaction of the neutron with a magnetic field would lift the degeneracy and suppress the transition into a mirror neutron, which, of course, does not interact with the ordinary magnetic field, nor with the trap via the ordinary strong interaction. Thus, the oscillation into mirror neutrons adds a loss channel for ultracold neutron storage. If nn' transitions occurred, the storage time constant for ultracold neutrons in a trap with magnetic field would be longer than without magnetic field. One should note that this disappearance method only measures neutron loss as a function of applied magnetic field. A signal will not prove the oscillation into mirror neutrons, only that some magnetic field dependent loss channel exists. By assuming that the nn' oscillation is responsible for the loss, limits can be set on $\tau_{nn'}$. One can imagine other exotic disappearance channels for the neutron, among which only the antineutron channel is tightly constrained [14].

The formulation of the nn' oscillation is analogous to the evolution of other simple two state systems such as spin $\frac{1}{2}$, $K^0\bar{K}^0$, or $n\bar{n}$ mixing (see, e.g., Refs. [21,22]). The energy difference between neutron and mirror-neutron states due to magnetic field interaction with the neutron magnetic moment μ is μB. For convenience we adopt the notation of Refs. [19,23] and define a characteristic frequency $\omega \equiv \frac{\mu B}{2\hbar}$, which corresponds to half the energy splitting. The

probability p for an UCN to be found as a mirror neutron after a time t can then be written as

$$p(t) = \frac{\sin^2(\sqrt{1 + (\omega\tau_{nn'})^2}\, t/\tau_{nn'})}{1 + (\omega\tau_{nn'})^2}. \qquad (1)$$

The time t is limited by the free flight time t_f between two wall collisions. The wall collision frequency is determined by $\frac{1}{t_f}$. The effective transition rate of UCN into mirror neutrons is then given by

$$R = \frac{1}{t_f} \int_0^{t_f} \frac{dp}{dt} dt = \frac{1}{t_f} p(t_f). \qquad (2)$$

For a real system the factors on the right hand side of Eq. (2) must be properly averaged over the distribution of flight times between collisions during the storage time t_s:

$$R_s = \frac{1}{\langle t_f \rangle_{t_s}} \langle p(t_f) \rangle_{t_s}. \qquad (3)$$

In experiments, one searches for a weak coupling, thus long $\tau_{nn'}$: so in practice $\omega\tau_{nn'} \gg 1$ in Eq. (1). Two limits are considered for Eq. (1): In the first case ("↑↓"), $\omega_{↑↓}t_f \gg 1$ (large B field), many oscillations take place and the $\sin^2(\dots)$ term of Eq. (1) is averaged to $\frac{1}{2}$ because t_f varies along UCN trajectories:

$$R_{s,↑↓} = \frac{1}{\langle t_f \rangle_{t_s}} \frac{1}{2(\omega_{↑↓}\tau_{nn'})^2}. \qquad (4)$$

In the second case ("0"), $\omega_0 t_f \ll 1$ (small B field), the n' component grows quadratically in time during the free flight:

$$R_{s,0} = \frac{1}{\langle t_f \rangle_{t_s}} \frac{\langle t_f^2 \rangle_{t_s}}{\tau_{nn'}^2}. \qquad (5)$$

Also regular losses of UCN must be considered, such as absorption and upscattering (during wall interactions or in collisions with rest gas), trap leakage, and β decay. All these loss mechanisms contribute to the UCN storage time constant τ_{store} of the system; $\lambda_{\text{store}} = 1/\tau_{\text{store}}$ is the corresponding loss rate. Generally, the loss rate depends on UCN energy and for a spectrum of stored UCN the decay curve is a sum of exponentials. The total effect can be modeled by the relative populations c_i of different velocity classes, each with its own storage loss rate $\lambda^{(i)}$. After storing an initial number $n(t = 0)$ of UCN for some time t_s in a given magnetic field one will detect the number of surviving UCN

$$n(t_s) = n(t = 0) \sum_i c_i \exp[-(\lambda_{\text{store}}^{(i)} + R_s)t_s] \qquad (6)$$

with the simple normalization condition $\sum_i c_i = 1$. For measurements in the limits ↑↓ and 0 (only the magnetic field is changed), the ratio of detected UCN becomes independent of all the regular UCN loss mechanisms

$$N_{0/↑↓} \equiv \frac{n_0(t_s)}{n_{↑↓}(t_s)} = \exp[(R_{s,↑↓} - R_{s,0})t_s]. \qquad (7)$$

In the absence of other effects, neutron—mirror-neutron oscillations lead to $N_{0/↑↓} < 1$.

We have performed UCN storage experiments at the Institut Laue-Langevin using the experimental setup of the neutron EDM experiment [24,25]. A typical measurement cycle consists of (i) a filling time of 40 s with the beam switch connecting the storage chamber to the ILL PF2 EDM beam line [26] allowing *unpolarized* UCN to enter the storage volume, (ii) different storage times t_s when the UCN isolation shutter to the storage chamber was closed, and (iii) 40 s counting time with the UCN shutter open and the beam switch connecting the storage chamber to the ^{3}He filled UCN detector [27]. The pressure inside the storage chamber was always better than 10^{-3} mbar in order to make sure that the nn' degeneracy is not lifted by the interaction of UCN with the rest gas.

The UCN storage chamber has a volume $V \sim 21$ l and a surface area of $A \sim 5400$ cm^2. The limit for stored UCN velocity is 4.1 m/s. From kinetic gas theory, the mean free path of UCN between wall collisions is $\frac{4V}{A} \approx 0.16$ m, the mean velocity is about 3 m/s [28] and, thus, $\langle t_f \rangle \approx 0.053$ s. One obtains $\omega\langle t_f \rangle \sim 1$ at a magnetic field of $B \sim 0.42$ μT; the limiting cases are obtained for magnetic fields of more than a few μT (↑↓) and of less than a hundred nT (0).

Different magnetic field configurations were used: up ($B_↑$), off ($B_0 = 0$), and down ($B_↓$). The strength of the magnetic field was adjusted by the current through the main magnetic field coil. The relevant measurements were taken at $|B_{↑↓}| \approx 6$ μT (100 mA). The magnetic field (B_z, along the main magnetic field direction) as a function of the applied current was measured using the Hg cohabiting magnetometer [29] for fields between 0.3 μT and 7 μT. For lower fields the Hg magnetometer could not be used. The Hg data set shows a perfectly linear dependence of the field on applied current and results in $|B_{z,0}| = 2.3 \pm 2.6$ nT when extrapolated to zero current. This value for the magnetic field along the main field axis indicates a residual absolute B field below 13 nT because of the absence of a preferred spatial direction. The zero field B_0 for the actual measurements was set by switching off the coil current and demagnetizing the four-layer mu-metal shield surrounding the storage chamber. We also used 3-axis fluxgate sensors directly above the storage chamber in order to verify that the residual B field was sufficiently small for the purpose of our experiment. The B-field configurations of the experiment were very well reproducible, and in particular B_0 within less than 1 nT. The direct limit on $|B_0|$ obtained from the fluxgates is, however, somewhat weaker: it was found that the connectors of the commercial devices are slightly magnetic, leading to offset fields at the location of the sensor on the order of 25 nT.

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Although the residual field is probably on the level of a few nT, we give a conservative limit of $|B_0| < 50$ nT, which is sufficient for our purpose here, i.e., for the limiting case 0.

Most of the measurements were performed repeating the sequence (a) (B_0, $B_\uparrow$, $B_\downarrow$, B_0, B_0, $B_\downarrow$, B_0, $B_\uparrow$) with field changes typically every 1.5 h during daytime. The demagnetization procedure before B_0 measurements took about half an hour. For a given B-field configuration 16 UCN cycles were measured: 4 for each storage time of $t_s = 100$ s, 50 s, 175 and again 100 s. Night runs were taken for longer periods at one B-field configuration with $t_s = 100$ s. They were used to check on the long term stability of the system. It was found that drifts of the count rates were slow and on a level below 0.3% over several hours. This agrees in magnitude with changes in the reactor power, but a direct correlation could not be established. The count rate drifts were sufficiently slow to be averaged out in the day runs with frequent changes of the B-field configuration. For $t_s = 50$ s some data was taken using another sequence (b), ($B_\uparrow$, $B_\downarrow$, B_0) while checking on an unexpected count ratio $N_{0/\uparrow\downarrow}$ (see below).

The time constant for UCN to leave the storage chamber with the shutter open was measured to be $\tau_{\rm op} = 11.4 \pm 0.6$ s. Mirror neutrons can leave the system also during filling and counting. The relevant average times t_s^* in our storage system are thus longer than the times between closing and opening the UCN shutter. One can replace t_s in Eq. (7) by t_s^* and, because R_s changes only rather weakly with t_s and $\tau_{\rm op}$ is much smaller than t_s, one finds to very good approximation $t_s^* = t_s + 2\tau_{\rm op}$. We assign a conservative systematic error of ± 3 s to t_s^*.

For data analysis, each B-field configuration was first treated separately. The distributions of single-cycle counts n were found to be consistent with Gaussians with standard deviations $\sigma \approx \sqrt{n}$ with no additional systematics. The counts per cycle for each configuration were thus statistically averaged; see Table I. The averaged n data show a presently unexplained tendency to a linear dependence on the magnetic field. The effect we wish to limit depends on

$|B|^2$ (via ω^2), so the direct average of the $+6$ and -6 μT measurement values cancels the linear systematic effect, leaving only the possible oscillation effect and any remaining quadratic systematic contributions. The averaged n data is then used to calculate the count ratios $N_{0/\uparrow\downarrow}$ according to Eq. (7). For 50 s storage time and sequence (a), the count ratio $N_{0/\uparrow\downarrow}$ is larger than 1 by 2.7 standard deviations, which led us to remeasure at this storage time [using sequence (b)] and corroborate that this deviation was a statistical fluctuation. Both ratios $N_{0/\uparrow\downarrow}$ (50 s) are given in the table along with the obtained average. The individual results for $N_{0/\uparrow\downarrow}$ show no signal within their respective sensitivities and, as they are independent, can be used in a combined analysis. Following Eq. (7), we write $N_{0/\uparrow\downarrow} = \exp[a t_s]$ with a fit parameter a. The fit gives $a = (5.38 \pm 5.78) \times 10^{-6}$ s^{-1}. We use this value at the limit of the experimentally measured range ($t_s^* = 198$ s) to set the constraint on the neutrons which may have been lost, yielding

$$N_{0/\uparrow\downarrow}(t_s^* = 198 \text{ s}) = 1.001\,06 \pm 0.001\,14. \tag{8}$$

Results with $N_{0/\uparrow\downarrow} > 1$ are unphysical for nn' oscillations. In order to derive a limit on $N_{0/\uparrow\downarrow}$ we adopt the Bayesian approach described by the Particle Data Group (page 305 of Ref. [30]; probability distribution set to zero for $N_{0/\uparrow\downarrow} > 1$) and obtain

$$N_{0/\uparrow\downarrow}(t_s^* = 198 \text{ s}) > 0.99835 \text{ s}(95\% \text{C.L.}). \tag{9}$$

In order to derive the limit on $\tau_{nn'}$, the flight time distribution averages $\langle t_f \rangle_{t_s}$ and $\langle t_f^2 \rangle_{t_s}$ are needed as additional input. A better determination than the one from the kinetic gas theory argument given above was obtained by Monte Carlo calculations using GEANT4UCN [31]. The parameters of the simulation (mainly material properties, such as Fermi pseudopotential, loss probability per wall reflection, and fraction of diffuse to specular reflection) have been tuned to reproduce measurements of the UCN beam energy spectrum and filling, storage, and emptying time curves of the apparatus. Excellent agreement with the observables is obtained, which justifies the extraction of the required flight time distributions. The averages are given in Table II. The assigned systematic uncertainties were derived by varying the material parameters of the simulation, the largest influence coming from the loss probabilities per wall collision.

TABLE I. Measured total UCN counts n normalized per cycle for the day sequences [(a), (b); see text] at different storage times t_s^* (with systematic error) and magnetic field configurations. $n(B_{\uparrow\downarrow})$ is the weighted average of $n(B_\uparrow)$ and $n(B_\downarrow)$, and $N_{0/\uparrow\downarrow} = n(B_0)/n(B_{\uparrow\downarrow})$.

t_s [s]	50 (a)	50 (b)	100 (a)	175 (a)
t_s^* [s]	73 ± 3 (a)	73 ± 3 (b)	123 ± 3 (a)	198 ± 3 (a)
$n(B_0)$	$44\,317 \pm 40$	$44\,363 \pm 53$	$28\,635 \pm 21$	$17\,015 \pm 22$
$n(B_\uparrow)$	$44\,197 \pm 53$	$44\,443 \pm 53$	$28\,671 \pm 30$	$17\,047 \pm 31$
$n(B_\downarrow)$	$44\,128 \pm 53$	$44\,316 \pm 46$	$28\,596 \pm 30$	$16\,974 \pm 31$
$n(B_{\uparrow\downarrow})$	$44\,163 \pm 38$	$44\,371 \pm 35$	$28\,633 \pm 22$	$17\,011 \pm 22$
$N_{0/\uparrow\downarrow}$	1.0035(13)	0.9998(15)	1.0001(11)	1.0002(18)
		1.0019(10)		

TABLE II. Results for $\langle t_f \rangle_{t_s}$ and $\langle t_f^2 \rangle_{t_s}$ using Monte Carlo distributions of flight times between wall collisions. Variation of parameters in the simulation is used to assign systematic uncertainties.

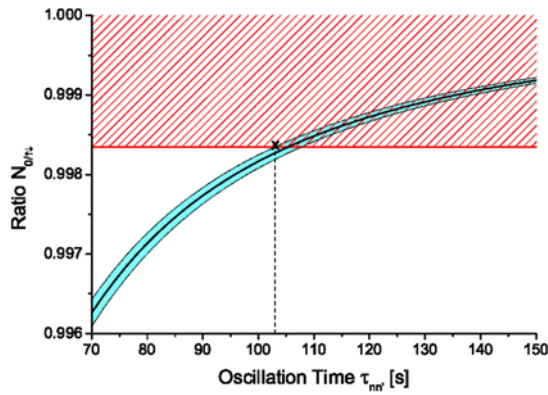| t_s [s]	50	100	175
$\langle t_f \rangle_{t_s}$ [s]	0.0498(5)	0.0515(5)	0.0543(5)
$\langle t_f^2 \rangle_{t_s}$ [s^2]	0.004\,20(8)	0.004\,50(9)	0.005\,05(10)

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FIG. 1 (color online). The count ratio $N_{0/\uparrow\downarrow}$ as a function of the oscillation time [see Eq. (7)]. The dashed region indicates the allowed region of Eq. (9). The error band of the curve displays the systematic uncertainties; see text. The x indicates the point at which the limit on $\tau_{nn'}$ is evaluated.

The limit on the oscillation time is obtained using the limit on lost neutrons, Eq. (9), and the average free flight time values (at $t_s = 175$ s, from Table II) in Eq. (7) and solving for $\tau_{nn'}$. The systematic uncertainties are taken into account for the limit on $\tau_{nn'}$ by adding (or subtracting) them simultaneously in order for them to weaken the limit, i.e., $\langle t_f \rangle_{t_s} = 0.0548$ s, $\langle t_f^2 \rangle_{t_s} = 0.00515$ s^2, and $t_s^* = 195$ s. With a reminder of the assumptions (negligible mirror magnetic field [20], no conventional strong or electromagnetic interactions of the mirror neutron n', and degeneracy of n and n' in the gravitational field) we obtain the final result

$$\tau_{nn'} > 103 \text{ s}(95\%\text{C.L.}). \tag{10}$$

Figure 1 displays the dependence of $N_{0/\uparrow\downarrow}$ on $\tau_{nn'}$ [see Eq. (7)] with the band indicating the influence of the systematic uncertainties. The 95% confidence limit of Eq. (9) is shown and the cross marks the point which determines the limit on the oscillation time.

The result impacts the role nn' oscillations can play in the transport of ultrahigh energy cosmic rays over large distances [12,15], although it may not completely rule out the nn' explanation for events above the GZK cutoff.

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