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Letter

Magnetic anomaly in UCN trapping: signal for neutron oscillations to parallel world?

Zurab Berezhiani[1,2,a], **Fabrizio Nesti**[1]

[1]Dipartimento di Fisica, Università dell'Aquila, Via Vetoio, 67100 Coppito, L'Aquila, Italy
[2]INFN, Laboratori Nazionali Gran Sasso, 67010 Assergi, L'Aquila, Italy

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Abstract Present experiments do not exclude that the neutron n oscillates, with an appreciable probability, into its invisible degenerate twin from a parallel world, the so-called mirror neutron n'. These oscillations were searched experimentally by monitoring the neutron losses in ultra-cold neutron traps, where they can be revealed by the magnetic field dependence of n–n' transition probability. In this work we reanalyze the experimental data acquired by the group of A.P. Serebrov at Institute Laue–Langevin, and find a dependence at more than 5σ away from the null hypothesis. This anomaly can be interpreted as oscillation of neutrons to mirror neutrons with a timescale of few seconds, in the presence of a mirror magnetic field order 0.1 G at the Earth. This result, if confirmed by future experiments, will have deepest consequences for fundamental particle physics, astrophysics and cosmology.

1 Introduction

There may exist a hidden parallel gauge sector that exactly copies the pattern of ordinary gauge sector. Then all particles (the electron e, proton p, neutron n etc.) should have invisible twins: e', p', n', etc. which are sterile to our strong and electroweak interactions ($SU(3) \times SU(2) \times U(1)$) but have their own gauge interactions ($SU(3)' \times SU(2)' \times U(1)'$) with exactly the same couplings. A notorious example, coined as mirror world [1–6], was introduced long time ago against parity violation: for our particles being left-handed, *parity* can be interpreted as a discrete symmetry which exchanges them with their right-handed twins from mirror sector. Concerns about parity are irrelevant for our following discussions: they extend to a parallel sector (or sectors) of any chirality. Nevertheless, in the following we shall call the twin particles from the 'primed' parallel sector mirror particles.

Parallel matter can be a viable candidate for dark matter [7–9]. Certain $B - L$ and CP violating processes between ordinary and mirror particles can generate the baryon asymmetries in both sectors [10–12] which scenario can naturally explain the relation $\Omega_D/\Omega_B \simeq 5$ between the dark and visible matter fractions in the Universe [13–16]. Such interactions can be mediated by heavy messengers coupled to both sectors, as right-handed neutrinos [10–12] or extra gauge bosons/gauginos [17].[1] In the context of extra dimensions, ordinary and mirror sectors can be modeled as two parallel three-dimensional branes and particle processes between them mediated by the bulk modes or "baby branes" can be envisaged [24].

On the other hand, these interactions can induce mixing phenomena between ordinary and mirror particles. In fact, any *neutral* particle, *elementary or composite*, may oscillate into its mirror twin. E.g. three ordinary neutrinos ν_e, ν_μ, ν_τ can be mixed with their mirror partners, sterile neutrinos ν'_e, ν'_μ, ν'_τ [25, 26] (see also [27–29]). Kinetic mixing between photon and mirror photon [30] induces the positronium–mirror positronium oscillation [31] which can be searched experimentally [32, 33].[2] The possible mixing between of the neutral pions, ρ-mesons or Kaons with their mirror twins can also have interesting implications [13, 14, 35].

As regards oscillation between the neutron n and its mirror twin n', it was shown in Ref. [36] that present probes surprisingly cannot exclude the possibility that this process is rather fast, in fact faster than the neutron decay. The

[a] e-mail: zurab.berezhiani@aquila.infn.it

[1]Mirror symmetry can be spontaneously broken e.g. due to the difference of weak interaction scales or grand unification scales between two sectors. Then the mirror sector can be deformed to a shadow world with certain predictable properties. Some phenomenological and cosmological implications of such models were discussed in Refs. [18–23].

[2]Interestingly, this kinetic mixing may be responsible also for the dark matter signals observed by the DAMA, CoGeNT and CRESST experiments (see e.g. [34] and references therein).

mass mixing, $\varepsilon(\overline{n}n' + \overline{n}'n)$, emerges from B-violating six-fermion effective operators of the type $(udd)(u'd'd')/M^5$ ($\Delta B = 1$) where u, d and u', d', respectively, are the ordinary and mirror quarks, and M is a cutoff scale related to some new physics beyond the Fermi scale. Thus, without specifying the concrete Lorentz structures of these operators, one can estimate the mixing mass as $\varepsilon \sim \Lambda^6_{\rm QCD}/M^5$, $\Lambda_{\rm QCD} \sim 250$ MeV being the strong interactions scale.

Since the masses of n and n' are exactly equal, they must have maximal mixing in vacuum and oscillate with timescale $\tau = \varepsilon^{-1} \sim (M/10\ \text{TeV})^5 \times 1$ s. It is striking that neither existing experimental limits or cosmological and astrophysical bounds can exclude the oscillation time τ as small as few seconds. The reason is that for neutrons bounded in nuclei, a $n \to n'$ transition is forbidden by energy conservation, while $\tau \sim 1$ s is compatible with the primordial nucleosynthesis bounds and the neutron stars stability bounds [36]. As for free neutrons, n–n' oscillation is affected by magnetic fields and coherent interactions with matter, which feature makes suggestive to test n–n' oscillation in 'table-top' laboratory experiments with cold and ultra-cold neutrons [36]. On the other hand, while the physics underlying $\Delta B = 1$ interactions with $M \sim 10$ TeV can be within the reach of the LHC, this physics and the fast n–n' oscillation phenomenon itself can have far going cosmological and astrophysical implications e.g. for generation of the baryon asymmetry of the Universe and dark matter, for Big Bang nucleosynthesis, for the propagation of ultra-high-energy cosmic rays at cosmological distances [36–38], for neutrons from the solar flares [39], etc. Some implications of n–n' oscillations in case of many ($\sim 10^{32}$) parallel sectors were discussed in Ref. [40].

In Refs. [36, 37] it was assumed that the mirror magnetic field vanishes at the Earth. In this case the n–n' oscillation probability in vacuum after a time t reads $P_{\boldsymbol{B}}(t) = \sin^2(\omega t)/(\omega\tau)^2$, where $\omega = \frac{1}{2}|\mu \boldsymbol{B}| = (B/1\ \text{mG}) \times 4.5\ \text{s}^{-1}$, $\mu = -6 \cdot 10^{-12}$ eV/G being the neutron magnetic moment.[3] Thus, in this case the transition probability $P_{\boldsymbol{B}}$ should not depend on the direction the applied magnetic field $\boldsymbol{B}$ but only on its strength $B = |\boldsymbol{B}|$. Under this assumption, the first limit on the n–n' oscillation time, $\tau > 1$ s, was set using the beam monitoring data from the famous experiment [41], which provided the strongest limit $\tau_{n\bar{n}} > 0.9 \times 10^8$ s on the neutron–antineutron oscillation [42, 43].

In ultra-cold neutron (UCN) traps the n–n' oscillation can be tested via magnetic field dependence of the neutron losses. With a neutron flight time between wall collisions of the order of $t \sim 0.1$ s, the experimental sensitivity can reach $\tau \sim 500$ s [44].[4] Several dedicated experiments [47–51] were performed by comparing the UCN losses in *large* ($B > 10$ mG) and *small* ($b < 1$ mG) magnetic fields. For *small* fields one has $\omega t < 1$ so that $P_{\boldsymbol{b}} = (t/\tau)^2$, while for *large* fields one has $\omega t \gg 1$ and oscillations are suppressed, $P_{\boldsymbol{B}} < (1/\tau\omega)^2 \ll (t/\tau)^2$. In this way, lower bounds on the oscillation time were obtained, which were adopted by the Particle Data Group [52]. The strongest bound, again under the *no-mirror-field* hypothesis, is $\tau > 414$ s at 90 % CL [48, 52].

However, the above limits become invalid in the presence of a mirror matter or mirror magnetic field [38] (or in the presence of many democratically mixed parallel sectors [40]). In particular, in the background of both ordinary $\boldsymbol{B}$ and mirror $\boldsymbol{B}'$ magnetic fields the n–n' oscillation is described by the Hamiltonian

$$H_{nn'} = \begin{pmatrix} \mu \boldsymbol{B}\boldsymbol{\sigma} & \varepsilon \\ \varepsilon & \mu \boldsymbol{B}'\boldsymbol{\sigma} \end{pmatrix}, \tag{1}$$

where $\boldsymbol{\sigma} = (\sigma_x, \sigma_y, \sigma_z)$ are the Pauli matrices. The probability of n–n' transition after flight time t was calculated in Ref. [38]. It depends on the magnetic field orientation and can be conveniently presented as

$$P_{\boldsymbol{B}}(t) = \mathcal{P}_B(t) + \mathcal{D}_{\boldsymbol{B}}(t) = \mathcal{P}_B(t) + D_B(t)\cos\beta, \tag{2}$$

where β is the angle between the vectors $\boldsymbol{B}$ and $\boldsymbol{B}'$ and

$$\begin{aligned} \mathcal{P}_B(t) &= \frac{\sin^2[(\omega-\omega')t]}{2\tau^2(\omega-\omega')^2} + \frac{\sin^2[(\omega+\omega')t]}{2\tau^2(\omega+\omega')^2}, \\ D_B(t) &= \frac{\sin^2[(\omega-\omega')t]}{2\tau^2(\omega-\omega')^2} - \frac{\sin^2[(\omega+\omega')t]}{2\tau^2(\omega+\omega')^2}, \end{aligned} \tag{3}$$

with $\omega = \frac{1}{2}|\mu B|$ and $\omega' = \frac{1}{2}|\mu B'|$. By reversing the magnetic field direction the probability becomes $P_{-\boldsymbol{B}}(t) = \mathcal{P}_B(t) - D_B(t)\cos\beta$. It is thus convenient to study the asymmetry $P_{\boldsymbol{B}} - P_{-\boldsymbol{B}} = 2D_{\boldsymbol{B}}\cos\beta$ in the neutron losses.

In this work we analyze in detail the data acquired in experiment [51] and find a dependence of the neutron losses on the magnetic field direction, with more than 5σ deviation from the null hypothesis. This anomaly cannot be explained by standard physics, but can be interpreted in terms of n–n' oscillations in the background of a mirror magnetic field. Needless to say, the possible presence of the latter is striking in the light of mirror matter as dark matter, with strong implications for its direct search and its possible accumulation in the Earth.

2 Experiment and data analysis

The experiment [51] was carried out at the ILL, Grenoble, using the well-known UCN facility PF2. The trap of 190 l volume capable of storing about half a million neutrons was located inside a shield screening the Earth magnetic field and a controlled magnetic field was induced by a system

[3] In this paper we use natural units, $\hbar = c = 1$.

[4] See Ref. [45] for a recent review on the cold and ultra-cold neutrons. For the quantum mechanical treatment of n–n' transition taking into account the finite size of the UCN traps see Ref. [46].

of solenoids. Unfortunately, its strength was not measured all over the trap and its exact profile was not studied. The reference magnetic field was evaluated approximately as $B \approx 0.2$ G, but due to possible inhomogeneities its effective value could have up to 25 % uncertainty.

Each measurement, taking about 10 min, consisted of three steps: filling of the trap during 130 s by *unpolarized* UCN through the basic neutron guide; closing of the entrance valve and the UCN storing in the trap for 300 s; opening of the exit valves and counting the survived neutrons during 130 s by two independent detectors. The incident neutron flux during the filling was monitored by another detector located in the neutron guide.

The results of all measurements are reported in [51]. Here we concentrate on measurements in *vertical* magnetic fields directed up (+) and down (−), which were performed in three series. In the first series *small* ($b < 1$ mG) and *large* ($B \simeq 0.2$ G) magnetic fields were used, repeating the sequences $\{\boldsymbol{b} \mid \boldsymbol{B}\} = \{+\boldsymbol{b}, +\boldsymbol{B}, -\boldsymbol{B}, -\boldsymbol{b}; -\boldsymbol{b}, -\boldsymbol{B}, +\boldsymbol{B}, +\boldsymbol{b}\}$. Unfortunately, the neutron flux was strongly unstable, counts randomly fluctuated and soon the reactor was stopped for technical reasons. Due to this, only a small part of the data records, consisting of $\mathcal{N} = 100$ measurements for each of the $\pm\boldsymbol{B}$ and $\pm\boldsymbol{b}$ configurations, could be selected as acceptable for analysis.[5] In a second series, only the *large* magnetic field $B \simeq 0.2$ G was employed, repeating 50 times the cycle $\{\boldsymbol{B}\} = \{-\boldsymbol{B}, +\boldsymbol{B}, +\boldsymbol{B}, -\boldsymbol{B}; +\boldsymbol{B}, -\boldsymbol{B}, -\boldsymbol{B}, +\boldsymbol{B}\}$, for a total of $\mathcal{N} = 400$ measurements in 72 hours of operation. The next 24 hours were devoted to the calibration tests in the UCN flow regime, totaling $\mathcal{N} = 216$ measurements (see below). The experiment was concluded by a third series of 16 cycles $\{2\boldsymbol{B}\}$ ($\mathcal{N} = 128$) under a magnetic field $2B \simeq 0.4$ G.

The neutron mean free-flight time between wall collisions and its variance were estimated via Monte Carlo simulation [48, 51]. For a storage time of 300 s one has $\langle t \rangle = t_{\rm f} = 0.094$ s and $\langle t^2 \rangle - t_{\rm f}^2 = \sigma_{\rm f}^2 = 0.0036$ s^2. For estimating the mean oscillation probability $\overline{P}_{\boldsymbol{B}} = \overline{\mathcal{P}}_B + \overline{\mathcal{D}}_{\boldsymbol{B}}$, the time-dependent factors in (3) must be averaged over the UCN velocity distribution in the trap. The Monte Carlo simulated average coincides with very good accuracy (percent) with the analytic approximation $\langle \sin^2(\omega t) \rangle = S(\omega) = \frac{1}{2}[1 - \exp(-2\omega^2\sigma_{\rm f}^2)\cos(2\omega t_{\rm f})]$, which we adopt. As a result, in the limit $\omega t_{\rm f} \ll 1$ we obtain $S(\omega) = \omega^2\langle t^2 \rangle$, while for $\omega t_{\rm f} \gg 1$ the oscillations are averaged and $S(\omega) = 1/2$. In analyzing below the consequences for the mirror magnetic field B', the averages of the oscillating factors, $\langle \sin^2[(\omega \pm \omega')t] \rangle = S(\omega \pm \omega')$, might be safely set to $1/2$ unless $\omega \approx \omega'$. In fact, the explicit form of $S(\omega - \omega')$ is relevant only very close to the resonance, where $|B - B'| \sim 10^{-3}$ G. In the resonance one has $\overline{\mathcal{P}}_B$, $\overline{D}_B = \langle t^2 \rangle / 2\tau^2$. Since n–n' oscillation can take place not only during the 300 s of UCN storage but also during filling and emptying of the trap, the effective exposure time can be estimated as $t_* \approx 370$ s [51]. Hence, for an overall amount of wall scatterings we take $n_* = t_*/t_{\rm f} \simeq 4000$.

The raw data [51] can be tested for magnetic field dependence of UCN losses, as a probe for n–n' oscillation. In fact, if between the wall collisions the neutron oscillates into a sterile state n', then per each collision it can escape the trap with a mean probability $\overline{P}_{\boldsymbol{B}}$. The asymmetry in the magnetic field between the detector counts $N_{\boldsymbol{B}}(t_*) \propto \exp(-n_*\overline{P}_{\boldsymbol{B}})$ and $N_{-\boldsymbol{B}}(t_*) \propto \exp(-n_*\overline{P}_{-\boldsymbol{B}})$, directly traces the difference between the probabilities $\overline{P}_{\boldsymbol{B}} - \overline{P}_{-\boldsymbol{B}} = \overline{\mathcal{D}}_B$ [38]:

$$A_{\boldsymbol{B}}^{\rm det}(t_*) = \frac{N_{-\boldsymbol{B}}(t_*) - N_{\boldsymbol{B}}(t_*)}{N_{-\boldsymbol{B}}(t_*) + N_{\boldsymbol{B}}(t_*)} = n_*\overline{D}_B \cos\beta, \tag{4}$$

where we assume $n_*\overline{\mathcal{D}}_{\boldsymbol{B}} \ll 1$. Clearly, the neutron loss factors related to regular reasons, which are magnetic field independent, cancel out from this ratio. These are the decay, the wall absorption or upscattering due to collisions with the residual gas, etc. On the other hand, since $\overline{P}_{\boldsymbol{B}} + \overline{P}_{-\boldsymbol{B}} = 2\overline{\mathcal{P}}_B$, the value

$$E_B^{\rm det}(t_*) = \frac{N_{\boldsymbol{b}}(t_*) + N_{-\boldsymbol{b}}(t_*)}{N_{\boldsymbol{B}}(t_*) + N_{-\boldsymbol{B}}(t_*)} - 1 = n_*(\overline{\mathcal{P}}_B - \overline{\mathcal{P}}_b) \tag{5}$$

should not depend on the magnetic field orientation.

We compute then the values (4) and (5) by summing up the counts in two detectors, $N = N_1 + N_2$ (the individual counts N_1 and N_2 are used below for the stability check). For each detector we consider Poisson statistics, so that $\Delta N_{1,2} = \sqrt{N_{1,2}}$. In addition, we compute analogous asymmetries $A_{\boldsymbol{B}}^{\rm mon}$, $E_B^{\rm mon}$ for the monitor counts $M_{\boldsymbol{B}}$ and $M_{-\boldsymbol{B}}$, and for the detector-to-monitor normalized ones $A_{\boldsymbol{B}}^{\rm nor}$, $E_B^{\rm nor}$ using the ratios $(N/M)_{\boldsymbol{B}}$ and $(N/M)_{-\boldsymbol{B}}$.

The results are shown in Table 1. We see that the value of $A_{\boldsymbol{B}}^{\rm det}$, based on 400 measurements in $\{\boldsymbol{B}\}$ mode (see Fig. 1), has a 5.2σ deviation from zero.[6]

Can this anomalous dependence on the magnetic field be induced by technical factors as e.g. fluctuation of the reactor power or unstable vacuum condition in the trap? Fig. 1 shows that the detector counts N had up to 2 % drift which is, however, well traced by the monitor counts M: the con-

[5] Namely, three bands were selected in which the reactor power and the UCN flux were stable enough, with deviations no more than 10 % off the values of the normal functioning.

[6] In Ref. [51] a somewhat different fitting procedure was adopted. The data were averaged between the B and $2B$ magnetic fields and, as a result, a circa 3σ deviation was reported, which in our notation translates to $A_{(\boldsymbol{B}+2\boldsymbol{B})}^{\rm det} = (3.8 \pm 1.2) \times 10^{-4}$. However, because the probability of n–n' oscillation (3) depends resonantly on the magnetic field, one should not average between different field values. After our communication, A.P. Serebrov and A.K. Fomin reanalyzed the experimental records and confirmed the 5.2σ anomaly in the $\{\boldsymbol{B}\}$ mode data. We thank them for this cross check. For a joint proposal of new experimental series, to confirm definitely this anomaly or to exclude it, see [55].

Table 1 Results for $A_{\boldsymbol{B}}$ (and E_B, marked by †) by data fitting of three series, their statistical errors and the respective $\chi^2_{\rm dof}$ in parentheses

	$A_{\boldsymbol{B}}^{\rm det}(t_*)$ $[\times 10^{-4}]$	$A_{\boldsymbol{B}}^{\rm nor}(t_*)$ $[\times 10^{-4}]$
$\{\boldsymbol{b} \mid \boldsymbol{B}\}$	2.03 ± 2.69 *(1.45)*	4.04 ± 3.05 *(1.04)*
	-4.11 ± 3.80 *(1.36)*†	-3.23 ± 4.31 *(1.25)*†
$\{\boldsymbol{B}\}$	6.96 ± 1.34 *(0.87)*	6.02 ± 1.52 *(0.89)*
$\{\boldsymbol{2B}\}$	-0.26 ± 2.40 *(1.77)*	-0.10 ± 2.72 *(1.82)*

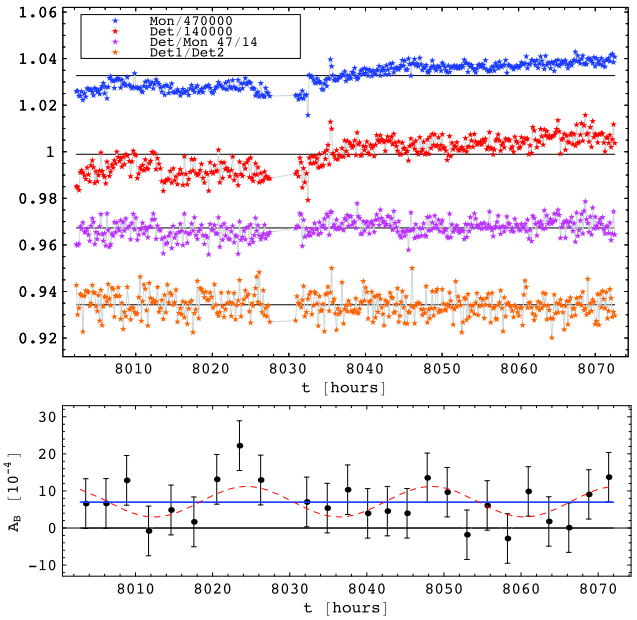

Fig. 1 The $\{\boldsymbol{B}\}$ series. *Upper Panel*: from up to down, monitor counts M and sum of detector counts $N = N_1 + N_2$, normalized, respectively, to 470000 and 140000; then ratios $N/M(\times 47/14)$ and N_1/N_2. *Lower Panel*: $A_{\boldsymbol{B}}^{\rm det}$ binned by two $\{\boldsymbol{B}\}$ cycles (16 measurements), with the constant and periodic fits

stant fit of ratios N/M gives $\chi^2_{\rm dof} = 1.55$. In addition, individual counts in two detectors are perfectly synchronous: N_1/N_2 is constant with $\chi^2_{\rm dof} = 0.98$. In fact, the two detectors separately give $A_{\boldsymbol{B}}^{\rm det1} = (8.40 \pm 1.92) \times 10^{-4}$ ($\chi^2_{\rm dof} = 0.88$) and $A_{\boldsymbol{B}}^{\rm det2} = (5.62 \pm 1.86) \times 10^{-4}$ ($\chi^2_{\rm dof} = 0.81$). It is important to note that since the measurements with switching field were taken at consecutive times, a drift in the reactor flux (or changing vacuum conditions or other factors that may affect the initial amount of neutrons in the trap) could contaminate the asymmetry itself. However, the cycles $\{\boldsymbol{B}\}$ were configured to make the asymmetry (4) insensitive to any slow drift. Clearly, a linear drift is canceled in each of the measurement quartets $(-,+,+,-)$ and $(+,-,-,+)$, while the quadratic component is canceled between two consecutive quartets. In fact, we fit $A_{\boldsymbol{B}}^{\rm det}$ as the average of (4) in each complete $\{\boldsymbol{B}\}$ cycle (8 measurements), and obtain an excellent $\chi^2_{\rm dof} = 0.87$.

As a further check, the anomaly cannot be eliminated by normalizing to the monitor counts: we find a residual 4σ asymmetry also in $A_{\boldsymbol{B}}^{\rm nor}$ (see Table 1). This lower value is in agreement with the fact that this measure mildly underestimates the effect, at first by statistical reasons: accounting for the monitor fluctuations $\Delta M = \sqrt{M}$ one formally enlarges the errors; then, by dynamical reasons: during the 130 s of filling time nearly half of the neutrons counted by the monitor are neutrons that reenter the neutron guide back from the trap, where they could oscillate into n' being exposed to the magnetic field. The UCN diffusion time in the trap when the entrance valve is open is estimated as $t_{\rm dif} \simeq 60$ s. Hence, the monitor asymmetry $A_{\boldsymbol{B}}^{\rm mon}$ is expected to be one order of magnitude less than $A_{\boldsymbol{B}}^{\rm det}$. In fact, analyzing the monitor data we get $A_{\boldsymbol{B}}^{\rm mon} = (0.96 \pm 0.72) \times 10^{-4}$ ($\chi^2_{\rm dof} = 0.90$).

Finally, a series of calibration measurements were performed in order to check for possible systematic effects that could make the neutron counts sensitive to the magnetic field orientation, as for instance an influence of the alternating solenoid current on the counting electronics. Measurements were performed with high statistics in $\{\boldsymbol{B}\}$ mode, with data taken in continuous flow regime, i.e. with entrance and exit valves of the trap open during 200 s of counting simultaneously with the two detectors and the monitor. With valves open, the effective diffusion time of the UCN in the trap is estimated via MC simulations as $t_*^{\rm flow} \simeq 20$ s. Coherently, these counts show no systematic effects: we find $A_{\boldsymbol{B}}^{\rm det} = (0.01 \pm 0.39) \times 10^{-4}$ ($\chi^2_{\rm dof} = 1.23$) and $A_{\boldsymbol{B}}^{\rm mon} = (0.22 \pm 0.78) \times 10^{-4}$ ($\chi^2_{\rm dof} = 1.16$). The counts of the two detectors were stable: the ratio N_1/N_2 is fitted by a constant with $\chi^2_{\rm dof} = 0.98$.

3 Interpretation of the results

Let us now analyze the obtained results in the light of n–n' oscillations. Using (4) and (5), the values shown in Table 1 translate into

$$\overline{D}_B \cos\beta = (1.60 \pm 0.32) \times 10^{-7}, \tag{6}$$

$$\overline{\mathcal{P}}_B - \overline{\mathcal{P}}_b = -(1.03 \pm 1.11) \times 10^{-7}, \tag{7}$$

$$\overline{D}_{2B} \cos\beta = -(0.06 \pm 0.80) \times 10^{-7}, \tag{8}$$

where we have conservatively taken $A_{\boldsymbol{B}}^{\rm det} = (6.40 \pm 1.26) \times 10^{-4}$, by averaging the results of $\{\boldsymbol{B}\}$ and $\{\boldsymbol{b} \mid \boldsymbol{B}\}$) cycles.

Equations (2) and (3) show that in the presence of strong enough mirror field, $B' \gg 10$ mG, the values of $\mathcal{P}_B$ and D_B have peculiar dependence on the experimental magnetic field, so the above results can be used to put constraints in the plane (B', τ) or $(B', \tau_\beta = \tau |\cos\beta|^{-1/2})$.

Equations (6), for a given B, gives a correlation between B' and τ_β. We perform a 2-parameter fit in this plane, and

find the preferred regions which are depicted as gray areas in Fig. 2. Since the homogeneity of the vertical field $\boldsymbol{B}$ was not precisely controlled in this experiment, and its effective value averaged over the trap could vary between $B = 0.15$–0.25 G, we consider that $(B/0.2\ \mathrm{G}) = 1 \pm 0.25$ and marginalize over this range. The global fit also includes the constraint from (7), conservatively referring to the case $\cos\beta = 1$, as well the limits on τ from experiments with horizontal magnetic field [48, 51] and the limit on the neutron losses in the Earth magnetic field [53]. These latter limits are also explicitly depicted, respectively, as the yellow area peaked at 0.2 G and the blue area peaked at 0.5 G. The horizontal-field measurements of Ref. [51] (with $B = 0.2$ G) imply $\mathcal{P}_B - \mathcal{P}_b = -(3.60 \pm 1.95) \times 10^{-8}$. For $B' \gg 1$ G this gives the lower limit $\tau > 0.28\ \mathrm{s} \times (1\ \mathrm{G}/B')^2$. The measurements of neutron losses in the Earth magnetic field ($B \approx 0.5$ G) yield roughly $P_B < 2 \times 10^{-6}$ [53]. For $B' \gg 1$ G it gives the limit $\tau > 0.1\ \mathrm{s} \times (1\ \mathrm{G}/B')$.

As one can see from Fig. 2 the positive asymmetry (6) along with the constraint (7) and the limits from horizontal-field measurements [48, 51], restrict the parameter space to three regions marked (a), (b) and (c).

The values of $\overline{D}_B$ and $\overline{\mathcal{P}}_B - \overline{\mathcal{P}}_b$ imply that the preferred region is (a), where the mirror magnetic field $B' = 0.09$ to 0.12 G at 90 % CL, and the n–n' oscillation time is in the range 2 to 10 s. The region is considerably enlarged by the B magnetic field uncertainty which is marginalized in the fit. The best fit point, visible in the figure inset, is relative to $B = 0.2$ G and corresponds to $B' = 0.11$ G, $\tau_\beta = 3$ s.

At 99 % CL the region becomes larger and also region (b) beyond the 0.2 G resonance (of the horizontal-field measurements) becomes allowed. The region extends up to $B' \simeq 0.3$ G, therefore we conclude that at 99 % CL the mirror magnetic field is constrained in the range $0.08\ \mathrm{G} < B' < 0.3$ G.

We note finally that at larger B' the horizontal-field measurements do not constrain the positive result of $\overline{D}_B$ and a third region (c) is allowed, extending from $B' = 1.5$ G to 15 G where the Earth-field constraint becomes dominant, with oscillation time in the range $0.2\ \mathrm{s} > \tau_\beta > 0.005$ s. This region has, however, a higher minimum χ^2 and in addition it is disfavored by Eq. (8). Let us remark also that the region with $\tau \ll 1$ s is disfavored by the Big Bang nucleosynthesis bounds.

The positive result that emerged from the fit points to a non-zero mirror magnetic field at the Earth. Let us then comment whether this is plausible. If mirror particles represent dark matter, they must present in the Galaxy along with the normal matter. If by chance the solar system is traveling across a mirror molecular cloud extended over few parsecs, there may exist a mirror field $\boldsymbol{B}'$, with $B' \sim 10$ to 100 mG. Then, since the experimental field $\boldsymbol{B}$ rotates together with the Earth, the angle β between $\boldsymbol{B}$ and $\boldsymbol{B}'$ and thus $P_{\boldsymbol{B}}$ would show a periodic time dependence with period of sidereal day $T = 23.94$ h. On the other hand, if there exist strong enough interactions between ordinary and mirror particles, e.g. due photon–mirror photon kinetic mixing [30] or due to pion–mirror pion mixing [35], then the Earth may cap-

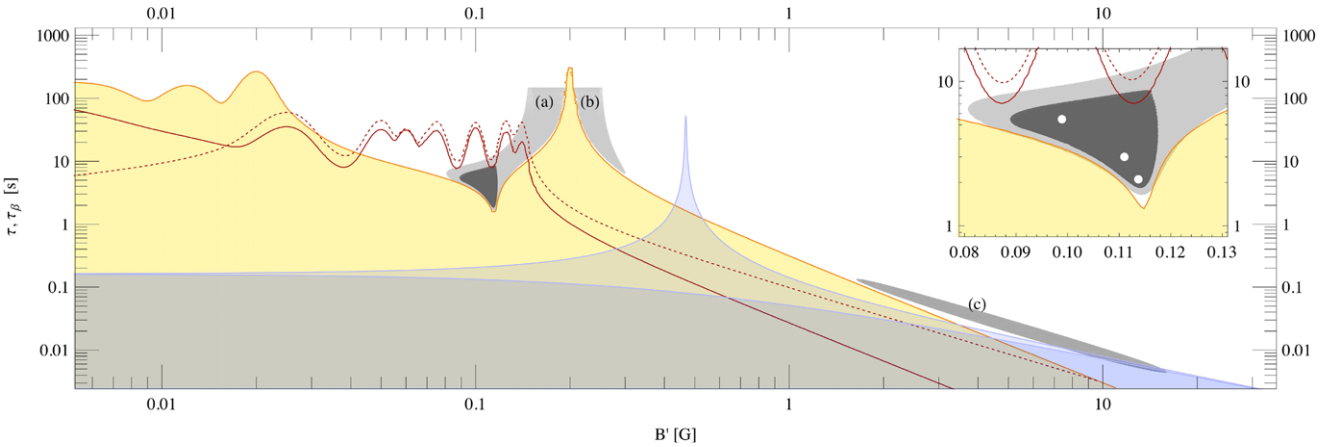

Fig. 2 Global fit in the B'-τ, τ_β plane. The positive result (anomaly) corresponds to the *gray-shaded areas*, which show the parameter space allowed at 90 % CL (*darker*) and 99 % CL (*lighter*) by the global fit of non-zero $\overline{D}_B$, (6), with magnetic field marginalized over the uncertain range $B = 0.15$–0.25 G (the zoomed inset displays the best fit points assuming a constant field $B = 0.15, 0.20, 0.25$, left to right). For comparison, available constraints from earlier measurements are also shown: the *yellow-shaded area* in the background is excluded at 99 % CL by the measurements of E_B from Refs. [48, 51]; the region of τ (τ_β) below the *wavy solid* (*dotted*) *curves* are disfavored by the measurements of Refs. [47, 49, 50] (not included in the fit). Interestingly, the data of Ref. [49] for E_B and A_B also imply a best fit value $B' = 0.11$ G, with $\tau = 14$ s and $\tau_\beta = 20$ s, respectively. The *blue-shaded* area peaked at $B' = 0.5$ G is excluded by measurements in the Earth magnetic field, illustrated for B' and B_{Earth} parallel (*lighter blue*) and antiparallel (*darker blue*) (Color figure online)

ture a significant amount of mirror matter.[7] Then the capture asymmetry due to the Earth rotation could give rise to circular currents that could induce a mirror magnetic field up to several Gauss [38]. If the captured mirror matter forms a compact body rotating synchronously with the Earth, then β would not vary in time. However, if it forms an extended halo around the Earth with a differential rotation, the mirror field $\boldsymbol{B}'$ and hence $P_{\boldsymbol{B}}$ may have a rather complex time variations.

Interestingly, the data of series $\{\boldsymbol{B}\}$ hint to a periodic time dependence, consistent with sidereal day period (see Fig. 1). Fitting the up-down asymmetry as $A_{\boldsymbol{B}}^{\rm det} = C + V\cos[\frac{2\pi}{T}(t - t_0)]$ (4 parameters) we obtain $C = (7.09 \pm 1.26) \times 10^{-4}$, $V = (4.10 \pm 1.71) \times 10^{-4}$, $T = 24.0 \pm 1.8$ h and $t_0 = 8000.4 \pm 1.8$ h, with $\chi^2_{\rm dof} = 0.82$. (Asymmetries in both detectors are consistent with such periodicity.) Clearly, since the constant fit already has a very good χ^2, its further improvement with the periodic fit is not very significative, and testing the time dependence requires more statistics. To our regret, the data in $\{\boldsymbol{b} \mid \boldsymbol{B}\}$ and $\{2\boldsymbol{B}\}$ were not broad and stable enough for a reliable time-dependent analysis.

4 Summary

The phenomenon of n–n' oscillation is particularly attractive, especially in the light of our findings, which clearly call for future experiments with higher precision. Namely, in this work we analyzed in detail the data acquired in experiment [51] and found that the neutron losses depend on the magnetic field orientation at more than 5σ level. This anomaly cannot be explained by standard physics but it can be interpreted in terms of n–n' oscillations assuming that the mirror sector exists and the Earth or solar system can possess a reasonable mirror magnetic field due to possible accumulation of the mirror dark matter in the Earth or its neighborhoods.

Rigorously speaking, even if our results will be confirmed by future measurements, this would mean the discovery of a new effect showing that the UCN losses depend on the magnetic field and its direction, presumably due to some yet unknown physics, but not necessarily due to the neutron transitions to a parallel world. The phenomenon of n–n' oscillations can be definitely confirmed only by the discovery of the neutron regeneration effect $n \to n' \to n$ or some other effects as e.g. deviation from a linear dependence of the neutron spin-precession frequency on the applied magnetic field [38].

The resonant character of the n–n' oscillation can greatly facilitate these searches. In particular, using the same 190 l UCN chamber with $t_{\rm f} \simeq 0.1$ s as in the experiments [48, 51] at the ILL PF2 EDM facility, these oscillations can be tested under properly controlled magnetic field profiles [55]. By tuning the magnetic field to the resonance value $B = B'$ with a precision of 1 mG, the probability of n–n' transition can be increased up to $\mathcal{P}_{\rm res}$, $D_{\rm res} \simeq (t_{\rm f}/\tau)^2$, i.e. $\sim 10^{-3}$ for $\tau = 3$ s. Then the neutron losses would be very sizable, $A_B \sim 0.1$, and also neutron regeneration $n \to n' \to n$ and resonant corrections to the neutron spin-precession [38] could be optimally tested. If the DUSEL project [56] will be realized, the neutron flight time could be increased up to few seconds which would allow to test the n–n' oscillation in an exhaustive way.

Concluding, discovery of n–n' oscillation would be a discovery of the baryon number violation ($\Delta B = 1$) but also discovery of whole parallel world which would shed light on many fundamental problems in physics and cosmology as the nature of dark matter, primordial baryogenesis and nucleosynthesis, pattern of neutron stars [36–38] and many other astrophysical issues as e.g. the origin of the pre-GZK cutoff in the cosmic ray spectrum [57] (see also [37]). In addition, the underlying physics at the scale $M \sim 10$ TeV could be testable at the LHC. The discovery of a parallel world via n–n' oscillations and of a mirror magnetic background at the Earth, striking in itself, would give crucial information on the accumulation the of dark matter in the solar system and in the Earth, due to its interaction with normal matter, with far reaching implications for physics of the sun and even for geophysics.

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