New experimental limits on neutron – mirror neutron oscillations in the presence of mirror magnetic field

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Present probes do not exclude that the neutron (n) oscillation into mirror neutron (n′), a sterile state exactly degenerate in mass with the neutron, can be a very fast process, in fact faster than the neutron decay itself. This process is sensitive to the magnetic field. Namely, if the mirror magnetic field B′ exists at the Earth, n – n′ oscillation probability can be suppressed or resonantly amplified by the applied magnetic field B, depending on its strength and on the angle β between B and B′. We present the results of ultra-cold neutron storage measurements aiming to check the anomalies observed in previous experiments which could be a signal for n – n′ oscillation in the presence of mirror magnetic field B′ ~ 0.1 G. Analyzing the experimental data on neutron loses, we obtain a new lower limit on n – n′ oscillation time \( \tau_{n n'} > 17 \text{s} (95 \% \text{C.L.}) \) for any B′ between 0.08 and 0.17 G, and \( \tau_{n n'} / \sqrt{\cos \beta} > 27 \text{s} (95 \% \text{C.L.}) \) for any B′ in the interval (0.06 ÷ 0.25) G.

I. INTRODUCTION

The existence of mirror particles was proposed by Lee and Yang, in the same paper were the possibility of parity violation was put forward [1], for restoring parity in more extended sense: for our particles being left-handed, Parity can be interpreted as a discrete symmetry which exchanges them with their right-handed mirror partners. Hence the parity, violated in each of ordinary and mirror sectors separately, would remain as an exact symmetry between two sectors. Kobzarev, Okun and Pomeranchuk [2] observed that mirror particles cannot have ordinary strong, weak or electromagnetic interactions, and so they must form a hidden parallel world as an exact duplicate of ordinary one. This idea was further expanded, with different twists, in many subsequent papers [3–7]. (See reviews [8]; for a historical overview, see also Ref. [9]).

At the basic level, one can consider a theory based on a direct product \( G \times G' \) of identical gauge factors which can naturally emerge e.g. in the \( E_8 \times E_8' \) string theory. Ordinary particles belong to the Standard Model \( G = SU(3) \times SU(2) \times U(1) \) or its grand unified extension, while the gauge interactions \( G' = SU(3)' \times SU(2)' \times U(1)' \) (or its respective extension) describes mirror particles. The total Lagrangian must have a form \( \mathcal{L}_{\text{tot}} = \mathcal{L} + \mathcal{L}' + \mathcal{L}_{\text{mix}} \) where the Lagrangians \( \mathcal{L} \) and \( \mathcal{L}' \), which describe the particle interactions respectively in observable and mirror sectors, can be rendered identical by imposing a mirror parity \( G \leftrightarrow G' \) exchanging ordinary and mirror fermions modulo their chirality. Thus, if mirror sector exists, then all our particles: the electron e, proton p, neutron n, photon γ, neutrinos ν etc. must have invisible mass degenerate mirror twins: e′, p′, n′, γ′, ν′ etc. which are sterile to our strong and electroweak interactions but interact with ordinary particles via universal gravity. Mirror matter can be a viable candidate for dark matter [6,8]. The possible interactions between the particles of two sectors (encoded in \( \mathcal{L}_{\text{mix}} \)), as the kinetic mixing between photon and mirror photon [4] or interactions mediated by heavy messengers coupled to both sectors, as gauge bosons/gauginos of common flavor symmetry [10] or common \( B - L \) symmetry [11], can induce mixing phenomena between ordinary and mirror particles. In fact, any neutral particle, elementary or composite, might have a mixing with its mirror twin. E.g. the photon kinetic mixing [4] can be searched experimentally via the positronium – mirror positronium oscillation [12] and also via direct detection of dark matter [13]. The gauge bosons of common flavor symmetry [10] can induce the mixing between the neutral pions and Kaons and their mirror partners, also with implications for dark matter direct search [14]. Three ordinary neutrinos \( \nu_{e,\mu,\tau} \) can oscillate into their (sterile) mirror partners \( \nu'_{e,\mu,\tau} \) [5]. The respective mass-mixing terms can emerge via the effective interactions which violate \( B - L \) symmetries of both sectors. These interactions can be induced via the seesaw mechanism by heavy gauge singlet “right-handed” neutrinos [7] which interact with both ordinary and mirror leptons. On the other hand, the same \( B - L \) non-conserving interactions would induce CP violating processes between ordinary and mirror particles and thus generate the baryon asymmetries in both sectors [7]. In this way, the relation between the dark and observable matter fractions in the Universe, \( \Omega_B'/\Omega_B \approx 5 \), can be naturally explained [8].

As it was shown in Refs. [15,16], the present probes do not exclude the possibility that oscillation between the neutron n and its mirror twin n′ is a rather fast process, in fact faster than the neutron decay. The mass mixing, \( \epsilon (\pi n' + \pi' n) \), emerges from B-violating six-fermion effective operators of the type \( (u d) (u' d') / M^5 \) involving ordinary u, d and mirror u′, d′ quarks, with M being...
a cutoff scale related to new physics beyond the Fermi scale. As far as the masses of $n$ and $n'$ are exactly equal, they must have maximal mixing in vacuum and oscillate with timescale $\tau_{\text{osc}} = \frac{\pi}{\omega} \sim (M/10\,\text{TeV})^2 \text{s}$. Existing experimental limits or cosmological/astrophysical bounds cannot exclude oscillation time $\tau_{\text{osc}} = \tau$ of few seconds \[15\]. It is of key importance that in nuclei $n \rightarrow n'$ transition is forbidden by energy conservation and thus nuclear stability bounds give no limitations on $\tau$, while for free neutrons $n-n'$ oscillation is affected by magnetic fields and coherent interactions with matter which makes this phenomenon rather elusive \[13\] \[16\]. On the other hand, it is striking that $n \rightarrow n'$ transitions faster than the neutron decay can have far going implications for the propagation of ultra-high energy cosmic rays at cosmological distances \[19\], for the neutrons from solar flares \[20\], for primordial nucleosynthesis \[21\] and for neutron stars \[22\] \[23\].

The possibility of fast $n-n'$ oscillations can be tested in experiments searching for neutron disappearance $n \rightarrow n'$ and regeneration $n \rightarrow n' \rightarrow n$ \[15\] as well as via nonlinear effects on the neutron spin precession \[16\]. In the ultra-cold neutron (UCN) traps $n \rightarrow n'$ conversion can be manifested via the magnetic field dependence of the neutron loss rates. For the UCN flight times between wall collisions $t \sim 0.1\,\text{s}$, the experimental sensitivity can reach $\tau \sim 500\,\text{s}$ \[24\] (see also Ref. \[25\] for a recent status of the UCN sources for fundamental physics measurements).

Several experiments searched for $n-n'$ oscillation with the UCN traps \[26\] \[30\]. Following the naive assumption \[16\] that the Earth has no mirror magnetic field, these experiments compared the UCN loss rates in zero (i.e. small enough) and non-zero (large enough) magnetic fields. In this case the probability of $n-n'$ oscillation after a time $t$ depends on the applied magnetic field $B$ as $P_B(t) = \sin^2(\omega t)/(\omega^2 t^2)$, where $\omega = \frac{1}{2} |\mu B| = (B/1\,\text{mG}) \times 4.5\times10^{-9}\text{s}^{-1}$ is the neutron magnetic moment. For small fields ($B < 1\,\text{mG}$ or so, when $\omega t < 1$) one has $P_B = (t/\tau)^2$, while for large fields ($B > 20\,\text{mG}$ or so, when $\omega t \gg 1$) oscillations are suppressed, $P_B < (1/\omega^2)^2 \ll (t/\tau^2)$. In this way, lower bounds on the oscillation time were obtained under the no mirror field hypothesis, the strongest being $\tau > 414\,\text{s}$ at 90% CL \[24\] adopted by the Particle Data Group \[31\].

However, the above limits become invalid in the presence of mirror matter and/or mirror magnetic field \[16\]. If the Earth possesses mirror magnetic field $B'$, than it would show up as uncontrollable background suppressing $n-n'$ oscillation even if the ordinary magnetic field is screened in the experiments, i.e. $B = 0$. However, if experimental magnetic field is tuned as $B = B'$, then $n-n'$ oscillation would be resonantly amplified. In addition, in this case one could observe the strong dependence of the UCN losses on the direction of magnetic field \[16\].

Interestingly, some of the measurements show that the UCN loss rates depend on the magnetic field direction at certain values of magnetic fields, in particular the ones performed with vertical magnetic fields $B \simeq 0.2\,\text{G}$ reported in Ref. \[28\]. The detailed analysis of these experimental data indicates towards more that $5\sigma$ deviation from the null hypothesis \[32\] which can be interpreted as a signal for $n-n'$ oscillation in the presence of mirror magnetic field $B' \sim 0.1\,\text{G}$ at the Earth.

A dedicated experiment \[30\] tested $n-n'$ oscillation in the presence of mirror magnetic field, with a series of measurements varying the values of applied (vertical) magnetic field from 0 to 0.125 G. Its results, yielding the limit $\tau > 12\,\text{s}$ for any $B'$ less than 0.13 G, restrict the parameter space $(\tau,B',\beta)$ which can be responsible for the above $5\sigma$ anomaly but do not cover it completely.

In this paper we report the results of additional measurements aiming to test the parameter space related to $5\sigma$ anomaly \[32\]. We essentially repeated the experiment \[28\] with different values of the applied magnetic field. New limits on $n-n'$ oscillation time were obtained as a function of mirror magnetic field $B'$ which however still leave some margins for the relevant parameter space. The paper is organized as follows. First we discuss $n-n'$ oscillation in the presence of mirror magnetic field. Then we describe the experiment and show its results. At the end we confront our findings with the results of previous experiments and draw our conclusions.

## II. OSCILLATION $n-n'$ IN THE PRESENCE OF MIRROR MAGNETIC FIELDS

The hypothesis that the Earth might possess a mirror magnetic field, with the strength comparable to the Earth ordinary magnetic field, might be a not too exotic possibility. The Earth may capture some amount of mirror matter \[22\] if there exist strong enough interactions between ordinary and mirror particles, e.g. due photon–mirror photon kinetic mixing. In fact, geophysical data on the Earth mass, moment of inertia, normal mode frequencies etc. still allow the presence of dark matter in the Earth with a mass fraction up to $4 \times 10^{-3}$ \[33\]. Due to a high temperature in the Earth core, the captured mirror matter can be ionized, at least partially. Then the drag of free mirror electrons by the Earth rotation, induced by their Rutherford-like scatterings off ordinary matter, again due to the photon kinetic mixing, could give rise to circular mirror currents inducing the mirror magnetic field. Such a mechanism of the electron drag was proposed in Ref. \[34\] and applied to the generation of the
galactic magnetic fields. The dynamo effects could additionally enforce the mirror magnetic field at the Earth and also change its configuration, so that it could also exhibit significant variations in time \[15\] \[22\].

When free neutrons propagate in the vacuum but ordinary \(B\) and mirror \(B'\) magnetic fields are both non-zero and arbitrarily oriented, \(n-n'\) oscillation is described by the Schrödinger equation with a 4 \times 4 Hamiltonian:

\[
i \frac{d\psi}{dt} = H \psi, \quad H = \begin{pmatrix} \mu B \sigma & \varepsilon \\ \varepsilon & \mu B' \sigma \end{pmatrix},
\]

where \(\psi = (\psi_n(t), \psi_{n'}(t))\) is the wave function of \(n\) and \(n'\) in two spin states, and \(\sigma = (\sigma_x, \sigma_y, \sigma_z)\) are the Pauli matrices. The exact calculation of \(n-n'\) oscillation probability is given in Ref. \[16\]. In homogenous fields \(B\) and \(B'\), the probability of \(n \rightarrow n'\) transition after a time \(t\) can be conveniently reduced to the formula \[32\]:

\[
P_{BB'}(t) = P_{BB'}(t) + D_{BB'}(t)
= P_{BB'}(t) + D_{BB'}(t) \cos \beta,
\]

where \(\beta\) is the angle between the vectors \(B\) and \(B'\) and

\[
P_{BB'}(t) = \frac{\sin^2[(\omega - \omega')t]}{2\tau^2(\omega - \omega')^2} + \frac{\sin^2[(\omega + \omega')t]}{2\tau^2(\omega + \omega')^2},
\]

\[
D_{BB'}(t) = \frac{\sin^2[(\omega - \omega')t]}{2\tau^2(\omega - \omega')^2} - \frac{\sin^2[(\omega + \omega')t]}{2\tau^2(\omega + \omega')^2},
\]

where \(\tau = \varepsilon^{-1}\), \(\omega = \frac{1}{\tau} |B|\) and \(\omega' = \frac{1}{\tau} |B'|\). Hence, for given values \(B = |B|\) and \(B' = |B'|\) the oscillation amplitude \[2\] becomes maximal or minimal respectively when \(B\) and \(B'\) are parallel or anti-parallel, 

\[
P^{(+)}_{BB'}(t) = P_{BB'}(t) + D_{BB'}(t) = \frac{\sin^2[(\omega - \omega')t]}{\tau^2(\omega - \omega')^2},
\]

\[
P^{(-)}_{BB'}(t) = P_{BB'}(t) - D_{BB'}(t) = \frac{\sin^2[(\omega + \omega')t]}{\tau^2(\omega + \omega')^2}
\]

In the limit \(|\omega - \omega'| t| \gg 1\) second term in Eq. \[5\] is negligible and one can set \(P(\omega \pm \omega') = 1/2\), which is equivalent to averaging of \(\sin^2\) factors in \[4\]. So we get

\[
\mathcal{T}_{BB'}^{(\pm)} = \frac{\omega^2 + \omega'^2}{2\tau^2(\omega^2 - \omega'^2)^2}, \quad D_{BB'} = \frac{\omega\omega'}{2\tau^2(\omega^2 - \omega'^2)^2}.
\]

Explicit form \[4\] of \(P(\omega - \omega')\) is relevant close to the resonance, when \(|\omega - \omega'| t| \ll 1\), or \(|B - B'| < 1\) mG. Then one gets \(S(\omega - \omega') \approx (\omega - \omega')^2/t^2\) and thus \(\mathcal{T}_{BB'}^{(\pm)} \approx t^2/2\tau^2\). As we show below, in traps with the homogeneous magnetic field the mean probabilities calculated with the analytic approximation \[5\] agree very well (about a per cent accuracy) to that obtained via Monte-Carlo simulations.

Oscillation \(n-n'\) can be tested via magnetic field dependence of UCN losses. In the absence of \(n-n'\) conversion the number of neutrons \(N(t)\) survived after effective storage time \(t\) in the trap from the initial amount should not depend on \(B\), as far as the usual UCN losses during the storage as are the neutron decay, wall absorption or upscattering are magnetic field independent in the standard physics framework. However, if a neutron between the wall collisions oscillates into a sterile state \(n'\), then per each collision the latter can escape from the trap. Hence, the amount of survived neutrons in the UCN trap with applied magnetic field \(B\) after a time \(t\) is given by \(N_B(t_s) = N(t_s) \exp(-n_s \mathcal{T}_{BB'})\), where \(\mathcal{T}_{BB'}\) is the average probability of \(n-n'\) conversion between the wall scatterings and \(n_s = n(t_s)\) is the mean number of wall scatterings for the neutrons survived after the time \(t_s\). If the magnetic field direction is inverted, \(B \rightarrow -B\), then the amount of survived neutrons would become \(N_{-B}(t_s) = N(t_s) \exp(-n_s \mathcal{T}_{-BB'})\). Since the common factor \(N(t_s)\) cancels in the neutron count ratios, asymmetry between \(N_B(t_s)\) and \(N_{-B}(t_s)\),

\[
A_B(t_s) = \frac{N_{-B}(t_s) - N_B(t_s)}{N_{-B}(t_s) + N_B(t_s)},
\]

should directly trace the difference \(\mathcal{T}_{BB'} - \mathcal{T}_{-BB'} = \mathcal{T}_{BB'}\). Assuming \(n_s \mathcal{T}_{BB'} \ll 1\), we get

\[
A_B(t_s)/n_s = \mathcal{T}_{BB'} - \mathcal{T}_{BB'} \cos \beta.
\]
On the other hand, one can compare the average $N_B(t_*) = \frac{1}{2} \left[ N_B(t_*) + N_{-B}(t_*) \right]$ with the counts $N_0(t_*)$ acquired under zero magnetic field:

$$E_B(t_*) = \frac{N_0(t_*) - N_B(t_*)}{N_0(t_*) + N_B(t_*)}.$$ (10)

This value measures the difference between the probabilities in zero and non-zero magnetic fields. Since $\mathcal{P}_{BB'} + \mathcal{P}_{-BB'} = 2\mathcal{P}_{BB'}$, we have

$$E_B(t_*)/n_* = \mathcal{P}_{BB'} - \mathcal{P}_{0BB'} = \Delta_{BB'},$$ (11)

which should not depend on the magnetic orientation but only on its modulus $B = |B|$, as it should be resonantly amplified if $B \approx B'$. Therefore, measuring $E_B$ at different values of $B$, one can obtain direct limits on $n - n'$ oscillation time $\tau$, while by measuring $A_B$ one in fact measures the value $\tau_B = \tau/\sqrt{|\cos \beta|}$, i.e. the oscillation time corrected for the unknown angle $\beta$ between ordinary and mirror magnetic fields $B$ and $B'$. Once again, in ideal conditions these measurements should have no systematic uncertainties: measuring the neutron counts in different magnetic configurations but otherwise in the same experimental conditions, the effects of the regular neutron losses should cancel in the count ratios $A_B$ and $E_B$, and scanning over different test values of applied magnetic field $B$ with appropriate statistics, one can obtain pretty stringent limits on $\tau$ and $\tau_B$ as a function of mirror magnetic field $B'$.

III. EXPERIMENT AND MEASUREMENTS

The experiment was carried out at the Research Reactor of the Institute Laue-Langevin (ILL), Grenoble, using the EDM beam-line of the UCN facility PF2. The vacuum chamber of PNPI spectrometer was used, the same in previous experiments on $n-n'$ transitions \cite{27,28}. The experimental set up consisting of a neutron guiding system, the UCN storage trap with valves for filling and emptying, two UCN detectors and magnetic shielding is shown in Fig. [1]. The trap of 190 l volume capable of storing about half million UCN has a form of cylinder with a length 120 cm and diameter 45 cm. Its inner surface is coated by beryllium. The trap is located inside a shield which screens the Earth magnetic field (for more details, see Refs. \cite{27,28}).

A controlled magnetic field $B$ was applied inside the trap using electric circuits placed on the top and bottom of the chamber (red contours in Fig. [1]). For a given electric current in the circuits, the value of the induced magnetic field and its direction at each position inside the trap were calculated theoretically, by approximating the interior of the trap was by a cubic lattice, with coordinates $x, y, z$ from the center of the trap taken with 1 cm steps. The obtained results were also checked by with a magnetometer at center and some characteristic lateral parts of the chamber. The induced magnetic field $B$ had practically vertical direction everywhere but its magnitude $B = |B|$ was in-homogeneously distributed, varying from the value $B_c$ in the center by about $B_c$ at peripheral regions. The distribution of magnetic field inside the trap is shown in Fig. 2. In the following, for describing different experimental configurations we shall use the central value of magnetic field $B_c$ induced by a proper electric current. Direction of magnetic field was periodically inverted by changing the direction of current.

The scheme of the experiment is the following. Each measurement consists of five phases: monitoring, filling, storage, emptying and background fixing. Typical time per measurement including the turbine waiting time is about 10 minutes. The monitoring phase is used to check the stability of the UCN flux from the reactor. After the entrance valve is open, neutrons flow into the trap via the UCN guide while the exit valves towards two detectors $D_1$ and $D_2$ remain open, and their counts during monitoring time $t_m = 50$ s are used as estimators of the incident UCN flux. Then the exit valves are closed for a filling time of 100 s, after which the entrance valve is closed and the UCN are kept inside the trap for a holding time $t_h = 250$ s. Then the exit valves are reopen and the survived UCN are counted by two detectors during the emptying time of 150 s. The background phase is for checking that no excess of neutrons remain inside the trap that could influence the subsequent measurement.

In first three series of experiments (B1, B2, B3) the asymmetry $A_B$ was measured employing only large magnetic fields ($B_c = 0.21$ G, $B_c = 0.12$ G, and $B_c = 0.09$ G respectively), repeating the cycles $\{B\} = \{-B, +B, +B, -B; +B, -B, -B, +B\}$, with the UCN holding time $t_b = 250$ s (signs ± correspond to the fields directed up and down). In last part of series B4 we used the measurement sequences $\{0 \}B\} = \{0, +B, +B, B, 0; 0, -B, B, +B, 0\}$, altering zero and non-zero values of magnetic field, again with $B_c = 0.12$ G. For technical reasons, in these measurements only one
were performed also in B no influence. After series making it clear that the switching of magnetic fields had by both detectors D. Therefore, a MC simulation was performed, first with- during the storage time due to regular neutron loses. The averaged number of wall collisions $n_*$ and mean probabilities of $n - n'$ oscillation (3) between collisions were estimated via a Monte Carlo (MC) simulation. It consisted of two steps which we briefly describe here. (The detailed description will be given elsewhere [35].)

First we estimated the average number of wall scatterings taking into account that the initial velocity spectrum of the UCN [36] entering the trap gradually degrades during the storage time due to regular neutron loses. Therefore, a MC simulation was performed, first with- out considering the effects of $n - n'$ oscillation, in order to obtain the mean value of free flight time $t_\text{f} = \langle t \rangle$, its variance $\langle t^2 \rangle$, etc. In this way, the distribution of above values were computed by averaging them over the individual neutron trajectories in the trap, using well-known formulas [37] for the UCN loses per scattering. The parameters were adjusted for reproducing the experimental data as characteristic time constants for the neutron counts during the trap filling, UCN storage and the trap emptying. The obtained values are in good agreement with the parameters used in the previous experiments with the same trap [27, 28]. In this way, for a given storage time $t_\text{s}$, we computed an average amount of wall scatterings $n_*$ that survived neutrons suffered starting from the moment they enter the trap in the stage of filling, to the moment when they hit the detectors in the emptying phase. Namely, we get $n_* = 2068 \pm 18$ for $t_\text{s} = 250$ s in B1, B2, B3 modes and $n_* = 1487 \pm 15$ for $t_\text{s} = 150$ s in B4 mode with one detector. The above error-bars related to fitting uncertainties introduce less than 1% systematic errors in the determination of $n - n'$ oscillation time. In the following, for deducing our limits in more conservative way, we use the lower values of $n_*$. At second step, we computed average oscillation probability (2) over the neutron flight time. Given that the applied magnetic field in our experiment was not homogeneous, the empirical formula (1) cannot be used: for given central value $B_c$ in the trap, the neutrons during their diffusion can cross resonant values $B = B'$ with some probability if the mirror magnetic field has a value inside the distribution of magnetic field in the trap. Therefore, for each experimental series, we calculated the oscillation probability between wall scatterings as a function of $B'$ following the neutron trajectories in the trap. The interior of the trap was represented by a cubic lattice with 1 cm$^3$ elementary volumes, the magnetic field $B$ was calculated in every node of this lattice, and in this way the distributions shown in Figs. 2 were obtained. In each elementary cm$^3$ volume the magnetic field was taken as constant, with a value obtained by averaging between 8 calculated values at its vertices. The Schrödinger equation (1) was numerically integrated along the neutron trajectories. Every neutron leaving an elementary cube with a given value of magnetic field with a wave vector $(\psi_n, \psi'_n)$, while crossing the adjacent cube was evolving with the corresponding magnetic field. At each wall scattering the wave vector was reset to the pure state of neutron $(1, 0)$. The typical evolution of $n - n'$ oscillation probabilities $P_{BB'}(t)$ (4) for a 1 second period of the neutron diffusion in the trap is shown in Fig. 3.

In this way, via MC simulations we computed mean

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig2}
\caption{Upper panel: distribution of magnetic field around the central value $B_c$ inside the trap. Lower panel: distribution of the deviation angles of vector $\mathbf{B}$ relative to vertical $z$ axis.}
\end{figure}
values $P_B^{(±)}$ of the probabilities $\Pi_B(B')$ between wall scatterings, averaged over distribution of the neutron flight time $t$ and distribution of the magnetic field $B$ in the trap for a given value of $B_c$. In addition, we computed also the mean oscillation probability $P_{0B'}$ for the case when no magnetic field was applied, $B = 0$.

$$P_{B'}^{(±)} = \left\langle \sin^2\left(\frac{\omega + \omega'}{2}t\right) \right\rangle_{t,B} = \left(\frac{1}{\tau}\right)^2 S_\pm(B'),$$

$$P_{0B'} = \left\langle \sin^2(\omega't) \right\rangle_{t} = \left(\frac{1}{\tau}\right)^2 S_0(B').$$

In upper panel of Fig. 3 we show $S_\pm(B')$ and $S_0(B')$ as functions of mirror field strength $B'$. As we see, these factors correspond to mean values of the respective probabilities normalized to $n - n'$ oscillation time $\tau = 1$ s.

For checking the consistency of our MC simulation, we also computed average oscillation probabilities \[12\) in the case of homogeneous magnetic field in the same trap (lower panel of Fig. 3). As we see, the results of MC simulation perfectly coincide with the results (black solid curves) obtained via the empirical formula \[5\] with the corresponding MC values of $t_1 = \langle t \rangle$ and $\sigma_t^2 = \langle t^2 \rangle - \langle t \rangle^2$. As we see from Fig. 3, inhomogeneous profile of magnetic fields has certain advantages: the function $S \_B'$ in homogeneous magnetic field has maximal sensitivity at the resonance, $B \approx B'$ than in inhomogeneous case, but in the latter case it covers much wider range of $B'$.

### IV. DATA ANALYSIS

Different datasets $B_1, B_2, B_3$ and $B_4$ were independently analyzed and the values of asymmetries $A_B$ \[8\] were computed via comparing the neutron counts $N_B$ and $N_{-B}$ between subsequent measurements. For each individual measurement under given applied field $B$ we take $N_B$ as a sum of counts of both detectors, $N_B = N_B^{(1)} + N_B^{(2)}$, while the count ratios between two detectors $N_B^{(1)} / N_B^{(2)}$ were also controlled as the stability check. Assuming Poisson statistics, the errors can be estimated as $\Delta N_B = \sqrt{N_B}$. For eliminating the effects of drift, in our analysis we use the values of $A_B$ averaged within the measurement octets $\{B\}$ for series $B_1, B_2, B_3$ and $\{0\}B$ for series $B_4$. Hence, a cycle $\{B\}$ of 8 measurements yield an average of 4 measured values for $A_B$ while 8 measurements of cycle $\{0\}B$ yield 2 values of $A_B$ and 2 values of $E_B$. In this way, for series $B_4$ also the values $E_B$ \[10\] were computed. In addition, the UCN counts $M_B$ and $M_{-B}$ in the monitoring phase were also controlled, and detector-to-monitor normalized asymmetries $A_B^{nm}$ between the ratios $(N/M)_B$ and $(N/M)_{-B}$,
and analogously \( E_B^\text{nor} \). In this way, the average values of \( A_B \) and \( E_B \) obtained in each measurement series, were transformed into mean probabilities \( \overline{D}_B = A_B/\bar{n}_s \) and \( \overline{\Delta}_B = E_B/\bar{n}_s \), taking the mean amount of wall scatterings computed via MC simulations as \( n_s = 2050 \) for configurations B1, B2, B3 and \( n_s = 1472 \) for B4.

The results obtained per each measurement series are shown in Table I and also on Fig. 5 where the measured asymmetries are combined in bins of comparable size. The first column of Table I indicates the values measured in a given series, and corresponding amount \( N_\text{oct} \) of the measurement octets \( \{B\} \) or \( \{0/B\} \). (Let us remind that for canceling the effects of drift, each data unit is taken as value of \( A_B \) or \( E_B \) averaged within a given octet of measurements, \( \{B\} \) or \( \{0/B\} \)). Thus for a constant fit the amount of degrees of freedom per each series is \( N_\text{oct} - 1 \). The second column of Table I shows \( \overline{D}_B \) and \( \overline{\Delta}_B \) deduced respectively from the average values of \( A_B \) and \( E_B \) in each series, and the expected statistical errors (with statistical fluctuation for every count \( N \) taken as \( \sqrt{N} \)). However, the corresponding values of \( \chi^2/\text{d.o.f.} \) (in parenthesis) are too large which indicates that these fits are not that good. Third column shows the mean values of \( A_B \) and \( E_B \) and respective variances obtained directly the distribution of their measured values in each series. As we see, the central values in third column are consistent to that of second column, however the error bars are larger. In fact, the latter errors well coincide with the respective statistical errors enlarged by the respective value of \( \sqrt{\chi^2/\text{d.o.f.}} \).

Wide black crosses in Fig. 5 show the mean values of \( A_B/\bar{n}_s \) and \( A_B^\text{nor}/\bar{n}_s \) and respective errors obtained per each series obtained directly from the distribution of the measured values, in correspondence to third column of Table I. The dashed black crosses show the same for \( E_B/\bar{n}_s \) and \( E_B^\text{nor}/\bar{n}_s \), and grey crosses show results of calibration measurements. Shaded squares show mean values per each bin and statistical errors, while the larger error-bars indicate the data dispersion in each bin.

In ideal situation, our measurements should have no systematical uncertainties since the regular neutron loses should not affect the values of \( A_B \) or \( E_B \) measured in the same experimental conditions. Hence, in the absence of \( n - n' \) oscillations one expects that the values \( A_B \) and \( E_B \) should be consistent with zero within statistical errors. Table I shows that average values measured in each experimental series are consistent with null hypothesis within \( 1\sigma \) statistical errors except that of largest series B2, comprising over 200 hours of continuous measurements, where the values \( A_B \) and \( A_B^\text{nor} \) both show about \( 4\sigma \) deviation from zero. On the other hand, the quality of constant fits presented in Table I is not that good (namely, \( \chi^2/\text{d.o.f.} = 2.9 \) for series B2) which means that some unaccounted external factors were influencing our measurements.

As one can see on Fig. 5 the results of series B2 (and

|            | Stat. [×10⁻²] | Dist. [×10⁻²] |
|------------|---------------|---------------|
| \( A_B/\bar{n}_s \) [74] | -1.59 ± 5.40 (1.57) | -1.12 ± 7.09 |
| \( A_B^\text{nor}/\bar{n}_s \) [74] | 0.43 ± 5.89 (1.73) | 0.99 ± 7.67 |
| \( A_{B_2}/\bar{n}_s \) [124] | -14.8 ± 3.90 (2.90) | -14.9 ± 6.60 |
| \( A_{B_2}^\text{nor}/\bar{n}_s \) [124] | -16.5 ± 4.24 (2.84) | -16.6 ± 6.90 |
| \( A_{B_3}/\bar{n}_s \) [57] | -0.03 ± 5.79 (1.92) | -1.54 ± 8.39 |
| \( A_{B_3}^\text{nor}/\bar{n}_s \) [57] | 1.93 ± 6.32 (1.83) | 0.96 ± 9.07 |
| \( A_{B_4}/\bar{n}_s \) [43] | 4.18 ± 7.47 (2.20) | 4.57 ± 12.1 |
| \( A_{B_4}^\text{nor}/\bar{n}_s \) [43] | 8.61 ± 9.28 (2.50) | 8.67 ± 14.3 |
| \( E_{B_4}/\bar{n}_s \) [28] | 13.0 ± 13.0 (2.20) | 12.8 ± 20.4 |
| \( E_{B_4}^\text{nor}/\bar{n}_s \) [28] | 13.7 ± 13.7 (1.94) | 13.7 ± 22.4 |

TABLE I. Results for \( \overline{D}_B \) and \( \overline{\Delta}_B \) obtained from the average values of \( A_B \) and \( E_B \) measured in respective experimental cycles taking into account only statistical errors (in parenthesis the quality of constant fit (\( \chi^2/\text{d.o.f.} \)) is shown). Last column shows the mean values and variance reconstructed directly from the distribution of experimental data.
perhaps also of series $B_1$) show a strong dispersion between different bins which should be a main reason for bad constant fit. (In contrast, the results of series $B_3$ show no significant dispersion between different bins.) On the other hand, even with enlarged error bars (third column of Table 1) both values $A_B$ and $A_B^\tau$ of series $B_2$ still have about $2.3\sigma$ deviation from zero. The same result can be obtained by averaging between the bins of series $B_2$ with enlarged error bars which shows that this discrepancy is pretty robust against the methods of the analysis. In principle, this situation could be interpreted as a signal of $n-n'$ oscillation in the presence of mirror magnetic field $B' \sim 0.1 \div 0.2$ G with a direction varying in time. However, duration and acquired statistics of our experiment is not enough to draw such a far going conclusion. Therefore, we take more conservative attitude, and in the following we use the mean values and their variances obtained directly the distribution of the measured values of $A_B$ and $E_B$ per each series, shown in third column of Table 1. In addition, we average between the results of series $B_2$ and $B_4$ performed under the same magnetic field $B_c = 0.12$ G and thus obtain

\[
\frac{\bar{D}_{BB}[B_c = 0.12 \text{ G}]}{\bar{D}_{BB}[B_c = 0.12 \text{ G}]} = (-10.4 \pm 5.80) \times 10^{-8}, \quad \frac{\bar{D}_{BB}[B_c = 0.12 \text{ G}]}{\bar{D}_{BB}[B_c = 0.12 \text{ G}]} = (-11.8 \pm 6.20) \times 10^{-8}. \quad (13)
\]

This averages have less than $2\sigma$ deviation from zero and thus can be used for setting 95 % C.L. on the oscillation time $\tau_\beta$ as a function of mirror magnetic field $B'$ assuming that the direction of the latter is not time variable.

V. RESULTS FOR $n-n'$ OSCILLATION PARAMETERS

Experimental values of $E_B/n_1 = \bar{D}_{BB'}$ and $A_B/n_4 = \bar{D}_{BB'} = \bar{D}_{BB'} \cos \beta$ shown in Table 1 can be transformed into the $n-n'$ oscillation parameters $\tau^2$ and $\tau^2/\cos \beta$ via Eqs. (12):

\[
\frac{1}{\tau^2}[s^{-2}] = \bar{D}_{BB'}^{exp} \left[ \frac{S_+(B') + S_-(B')}{2} - S_0(B') \right]^{-1},
\]

\[
\frac{\cos \beta}{\tau^2}[s^{-2}] = \bar{D}_{BB'}^{exp} \left[ S_+(B') - S_-(B') \right]^{-1}. \quad (14)
\]

The obtained results are shown in Fig. 6. Dash magenta curve shows values of $1/\tau^2$ as function of $B'$ reproduced from central values of $E_B/n_1$ in Table 1 while solid magenta curve corresponds to 95 % C.L. upper limit on $1/\tau^2$ obtained via taking into account respective error-bars of third column. Dash cyan curve shows central values of $\cos \beta/\tau^2$ obtained from central value of $\bar{D}_{BB'}$ in (13), an average result between the measurements $B_2$ and $B_4$ with about $2\sigma$ deviation from zero, while solid cyan contours confine corresponding 95 % C.L. area. (let us remind that $\cos \beta$ can be positive or negative; here $\beta = 0$ corresponds to mirror magnetic field directed to the Earth center.) Blue and green solid contours show 95 % C.L. limits on $\cos \beta/\tau^2$ deduced from results for $A_B/n_4$ for series $B_1$ and $B_3$, third column of Table 1. In Fig. 6 we show exclusion regions for $1/\tau^2$ and $\cos \beta/\tau^2$ extracted from our measurements of $E_B$ and $A_B$. Curves of different colors, corresponding to the colors of bins in Fig. 5 confine regions excluded by measurements at different values of $B_c$.

FIG. 6. Exclusion regions for $1/\tau^2$ and $\cos \beta/\tau^2$ extracted from our measurements of $E_B$ and $A_B$. Curves of different colors, corresponding to the colors of bins in Fig. 5 confine regions excluded by measurements at different values of $B_c$. In Fig. 7 we show results of global fit of our experimental data, 95 % C.L. lower limits on $\tau$ (black solid) and $\tau_\beta$ (blue dashed), and confront them with the results of previous experiments.

In particular, the first experiment [28] searching for $n-n'$ oscillation compared the UCN losses between measurements in zero magnetic field $B = 0$ and non-zero field $B = 0.6$ G while the direction of the latter was altered between vertical up (+$B$) and down (-$B$). No significant deviation from zero was found in the value of $E_B$ [10]. The corresponding 95 % C.L. lower limit on $\tau$ as a function of $B'$ is shown by solid magenta curve in Fig. 7, and confront them with the results of previous experiments.

The experiment [30] was performed to search $n-n'$ oscillation in the presence of mirror magnetic field, by varying the values of applied magnetic field (vertical) from 0 to 0.125 G with a step of 0.025 G and also altering its direction from up to down. In Fig. 7 we show 95 % C.L. lower limits on $\tau$ (blue solid) and $\tau_\beta$ (blue dashed) as functions of $B'$ obtained via fitting the data reported in Fig. 1 or Ref. [30]. Overall, these limits exclude $\tau < 12$ s and $\tau_\beta < 15$ s for any $B'$ at 95 % C.L. for any $B'$ in the interval from (0.02 $\div$ 0.13) G. For smaller mirror fields, $B' < 0.02$ G, the lower limits on $\tau$ or $\tau_\beta$ are stronger, approaching 100 s or so, as obtained in Ref. [32] by combining the results of Ref. [30] with that of Ref. [27] performed under the magnetic field $B = 0.02$ G.
The hypothesis, which can be interpreted as a signal of symmetry A, resulting from these measurements is shown by red solid curve in Fig. 7. However, in the same experiment [28] the measurements performed with vertical magnetic field $B \simeq 0.2$ G, has shown substantial asymmetry between the counts $N_B$ and $N_{-B}$. The detailed analysis of these experimental data performed in Ref. [32] for the asymmetry $A_B$ indicate towards $5.2\sigma$ deviation from the null hypothesis, which can be interpreted as a signal of $n - n'$ oscillation in the background of mirror magnetic field $B' \simeq 0.1 \div 0.2$ G. Let us remark that in Ref. [32] the consequences of this anomaly for $\tau_\beta$ as a function of $B'$ was deduced assuming the homogeneity of the applied magnetic field and using the profile of functions $S_\pm(B')$ calculated via the analytic formula [9], as shown on lower panel of Fig. 4. However, as we realized while performing our experiment in the same conditions, the magnetic field distribution was rather wide. Therefore, in this paper we recalculated $\tau_\beta$ as a function of $B'$ using properly the functions $S_\pm(B')$ computed via our MC simulations (upper panel of Fig. 4). The red dashed contours in Fig. 7 confine the obtained $2\sigma$ area corresponding to this anomaly.

In Fig. 7 parameter areas excluded by the previous experiments in overall are shaded in dark green for $\tau$ and light green for $\tau_\beta = \tau/\sqrt{\cos \beta}$ while the yellow shaded areas correspond to new regions excluded in this work. The pink shaded areas correspond to parameter regions relevant for the anomalies in $A_B$ from Ref. [26] (see also Ref. [16]) and Refs. [28, 32] which still remain allowed for $3\sigma$ deviation from the null hypothesis $B$.

In our experiment we used magnetic field $B = 0.21$ G, showing $5\sigma$ deviation from the null hypothesis [32] that could be interpreted as a signal for $n - n'$ oscillation in the presence mirror magnetic field $B' \sim 0.1$ G, and in fact imply an upper limit on $n - n'$ oscillation time $\tau < 57$ s at 95 % C.L. (the corresponding $2\sigma$ region for $\tau_\beta$ as a function of $B'$ is confined between dotted red contours in Fig. 7). The results of other experiments restrict the parameter space relevant for this anomaly but cannot exclude it completely. In particular, lower limits on $\tau$ obtained from the same experiment [28] with horizontal and homogeneous magnetic field $B = 0.2$ G (solid red contour in Fig. 7) are compatible with the above anomaly for the range $B' = (0.08 \div 0.35)$ G with respective values of $\tau$ ranging from 5 s to 55 s. Results of Ref. [30] (blue solid and dashed contours in Fig. 7) yield the lower limits $\tau > 12$ s and $\tau_\beta > 15$ s for any $B'$ less than 0.13 G. Combined with the above bounds of Ref. [28] with "horizontal" measurements, the limit $\tau_\beta \geq \tau > 12$ s can be extended got the range of mirror fields up to $B' = 0.25$ G.

Our experimental results enhance these experimental limits, and also for a wider range of possible values of $B'$ (see yellow shaded regions in Fig. 7). Namely, for any $B'$ in the interval $(0.08 \div 0.17)$ G we get a lower limit don $n - n'$ oscillation time $\tau > 17$ s (95 % C.L.), and $\tau_\beta > 27$ s for any $B'$ in the interval $(0.06 \div 0.25)$ G. Assuming that the mirror magnetic field $B'$ is constant in time, or in more precise terms, that its value and direction did not change significantly in time during the years passed form previous experiments to our measurements, we can combine our results with limits of previous works. Yet, we could not completely exclude the parameter areas of interest, and pink shaded regions in Fig. 7 correspond to
regions which can still be relevant for above mentioned $5\sigma$ and $3\sigma$ anomalies. For larger values of $B'$ the limit on $\tau$ and $\tau_B$ is considerably weakened and for $B > 0.5$ G the values of $n-n'$ oscillation time as small as 1 second become allowed.

The following remark is in order. The results of different experiments performed in different times can be combined only if one assumes that mirror magnetic field is constant in time. However, this is most naive assumption, which means that the rotations of the Earth and the the Baby "mirror Earth" in its interior are completely synchronous, so that the orientation of the mirror magnetic field in the given experimental site does not change in time. On the other hand, if the axis of mirror dipole is deviated from the rotation axis, and there is some difference between angular velocities by which ordinary and magnetic fields precess, then one expect some periodic time variation, then the periodic variation of the signal can be expected. In addition, the captured mirror matter in the deep interior of the Earth can come into thermal equilibrium with the normal matter and thus can be present in the ionized form, due to a temperature of the Earth core of several thousand K. Also the dynamo mechanism in the differentially rotating mirror plasma could play a substantial role, mirror magnetic field can strongly increase and also its configuration can change from dipole to multipolar or toroidal configuration, with the subsequent inversion of the direction of the mirror dipole. In this the mirror magnetic field of the Earth may have also substantial large period time variation, perhaps of few years, like the sun's magnetic field. which can be increased up to several Gauss. Unfortunately, time duration of our experiment (one reactor cycle) is not enough to place limits on possible long period time variation of mirror magnetic field. However, the possibility of time varying mirror field background should be taken in consideration while planning the next experiments searching for $n-n'$ oscillation, as e.g. $n \rightarrow n' \rightarrow n$ regeneration experiment with cold neutrons at the stage of preparation at HFIR Reactor at Oak Ridge national Laboratory [38].

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