PROCEEDINGS OF SCIENCE

Statistical reach of Neutron Electric Dipole Moment Experiments to Neutron to Mirror-Neutron Oscillations

Prajwal MohanMurthy[a,*] **and Jeff A. Winger**[b]

[a] *Laboratory for Nuclear Science, Massachusetts Institute of Technology 77 Mass. Ave., Cambridge, MA 02139, USA*

[b] *Department of Physics and Astronomy, Mississippi State University Mississippi State, MS 39762, USA*

E-mail: prajwal@alum.mit.edu, j.a.winger@msstate.edu

Baryogenesis requires baryon number violation. Certain extensions to the Standard Model have proposed the existence of an exact, but parity-conjugated, copy of the ordinary elementary particles called *mirror* particles. Several experiments have been conducted to search for $n - n'$ oscillation, a baryon number violating process, and have imposed very strong constrains on its parameters. Recent analyses of some of these experiments have identified anomalies that could suggest the detection of $n - n'$ oscillation. Neutrons, owing to their large magnetic moment, precess upon the application of a magnetic field, and similarly, its mirror counterpart is also affected by the mirror magnetic field. Previous attempts to search for $n - n'$ oscillation have involved (i) disappearance experiments, which isolated the magnetic field dependent loss channel in ultracold neutron storage or transport, (ii) reappearance experiments, which have searched for magnetic field dependent regeneration of neutrons across a barrier, that could only be traversed by a state invisible to the fundamental forces of the standard model, like the mirror neutron, and (iii) by studying the variations in the precession frequency of polarized neutrons upon flipping the direction of the applied magnetic field, which is precisely measured by experiments searching for neutron electric dipole moment. In this work, we have presented the statistical sensitivity increase for neutron electric dipole moment measurement based search for $n - n'$ oscillation by over an order of magnitude compared to [Symmetry **14**, 487 (2022)], $\tau_{nn'}^{\text{(stat. sens.)}}/\sqrt{\cos(\beta)} \gtrsim 65$ s ($0.36\ \mu\text{T}' < B' < 1.01\ \mu\text{T}'$, at 95% C.L., where β is a fixed angle between the ambient mirror magnetic field and the applied magnetic field, as would be the case if the ambient mirror magnetic field has terrestrial origins. Furthermore, we have for the first time, also presented the statistical sensitivity for modulations of the difference in the precession frequency, upon flipping the direction of the magnetic field, as a means of accessing $n - n'$ oscillations, in the case of a galactic source of ambient mirror magnetic field. This has allowed us to demonstrate a 95% C.L. sensitivity of $\tau_{nn',\Omega_\oplus}^{\text{(stat. sens.)}} \gtrsim 43$ s ($0.36\ \mu\text{T}' < B' < 1.02\ \mu\text{T}'$) and $\tau_{nn',2\Omega_\oplus}^{\text{(stat. sens.)}} \gtrsim 51$ s ($0.36\ \mu\text{T}' < B' < 1.03\ \mu\text{T}'$), with existing data. These constraints could be further improved with the help of the next generation neutron electric dipole moment experiments.

25th International Spin Physics Symposium (SPIN 2023)
24-29 September 2023
Durham, NC, USA

[*] Speaker

PoS(SPIN2023)112

1. Introduction

In the Standard Model, the weak charged current, which is chiefly responsible for the β-decay, only couples to the left handed particles, leading to maximal parity violation. The discovery of parity violation in β-decay [1], strongly drove the development of the chiral (V-A) theory of β-decay [2, 3]. The possibility of parity violation in β-decay had then already been pointed out [4]; when it was also recognized that there could very well be a parity-conjugated copy of all particles involved in the weak decay. In the same work, it was also concluded that particles with opposing parity states, *viz.* a left or a right handed state, could also oscillate between each other. Following from this initial seed of an idea, the existence of parity conjugated *mirror* matter, sometimes also referred to as *shadow* matter [5–7], and oscillations between between *ordinary* matter and their *mirror* counterparts, which are degenerate in mass, has been long proposed [8, 9]. Introduction of such mirror matter was also shown to restore parity symmetry globally [10–12]. Conservation of charge and continuity of other electromagnetic moments have been remarkably well tested [13], as they are ensured by Gauge symmetry [14]. Therefore, Gauge symmetry prioritizes oscillation between ordinary matter and their mirror counterparts in neutral systems.

A consistently parity violating β-decay, Lee and Yang reasoned, would point to a predominance of one of the chiral states, forcing the oscillation lifetime between the chiral states to be very long compared to the age of the universe [4]. Owing to such a long lifetime, an oscillation between chiral states could not be governed by electromagnetic or strong interactions. However, predominance of one of the chiral states cannot be concluded in light of chiral symmetry breaking (through QCD [15–19] and the Higgs-mechanism [20–22]). In fact, fast oscillations between neutrons and mirror-neutrons, with associated lifetimes far below its β-decay lifetime, has been proposed [23, 24]. Neutron to mirror-neutron oscillation ($n-n'$) also violates the baryon number [25], which is a key ingredient of Big-bang baryogenesis, according to the Sakharov conditions [26]. It has been shown to aid in relaxing the Greisen-Zatsepin-Kuzmin (GZK) limit [24, 27], affect neutron stars [28], and have measurable consequences for neutron to anti-neutron oscillation [25, 29–33], as well as impact the measurement of the neutron lifetime [34–37]. In this paper, we have focused on $n-n'$ oscillation, the underlying theory of which may be found in *refs.* [23, 38].

Nonetheless, minuscule CP violation restricts interactions between ordinary particles and their mirror counterparts via conventional strong, weak, or electromagnetic interactions [8, 39]. Cosmic microwave background observations, which confirm the existence of 3 species of primordial neutrinos [40], also restrict the abundances of such mirror matter strongly [41, 42]. Diffuse interaction with ordinary matter, even at very high energies, coupled with extremely small densities can still manifest measurably, *eg.* as photon to mirror-photon oscillation [43–46], or as mixing between neutrino and mirror-neutrino, which could be a candidate sterile neutrino as well [47–50]. Diffuse interaction with ordinary matter also makes mirror matter good dark matter candidates [51–59]. The co-baryogenesis of mirror matter and its cosmological implications have been extensively studied [41, 60–63], including formation of large scale structure [64–73]. Further reviews of mirror matter, its genesis, and implications have been summarized in *refs.* [74–77].

1.1 Theory of shift in neutron precession frequency due to $n-n'$ oscillation

Neutrons and mirror neutrons form a simple two state system. The $n-n'$ two state system is described by a similar interaction to the $n-\bar{n}$ system [78]. Being neutral particles, the neutron and its mirror counterpart may oscillate between each other, described by [38]

$$\mathcal{H}_{nn'} = \begin{bmatrix} -\mu_n \vec{B}\cdot\vec{\sigma} & \epsilon \\ \epsilon & -\mu_{n'}\vec{B}'\cdot\vec{\sigma}' \end{bmatrix}, \tag{1}$$

where the off-diagonal terms are the mass splitting related to the inverse of the oscillation time, $\epsilon = \hbar\tau_{nn'}^{-1} = \delta m_{nn'}c^2 = (m_n - m_{n'})c^2$. The diagonal terms include the (2×2) Pauli matrices $\vec{\sigma} = \langle\sigma_x, \sigma_y, \sigma_z\rangle$. The magnetic moment associated with the neutron (mirror-neutron) is $\mu_{n^{(\prime)}}$, and naively $\mu_{n'} = \mu_n = -60.3$ neV/T

[79]. The time dependent oscillation probability linked to the $n - n'$ oscillation described in Eq. 1 is [38, 80]

$$P^{nn'}_{BB'}(t) = \frac{\sin^2[(\omega-\omega')t]}{2\tau^2_{nn'}(\omega-\omega')^2} + \frac{\sin^2[(\omega+\omega')t]}{2\tau^2_{nn'}(\omega+\omega')^2} + \left(\frac{\sin^2[(\omega-\omega')t]}{2\tau^2_{nn'}(\omega-\omega')^2} - \frac{\sin^2[(\omega+\omega')t]}{2\tau^2_{nn'}(\omega+\omega')^2}\right)\cos(\beta), \tag{2}$$

where $\omega^{(')} = |\mu_{n^{(')}} B^{(')}|/2$ is the precession frequency of the neutron (mirror-neutron), $\mu_n = 45.81\ (\mu\text{T}\cdot\text{s})^{-1}$) [79] is the magnetic moment, and β is the angle between $\vec{B}$ and $\vec{B}'$.

Neutrons and mirror-neutrons can independently experience Zeeman splitting upon the application of an ordinary magnetic and a mirror magnetic field, respectively. Neutrons clearly have a large magnetic moment, and when it oscillates into its mirror counterpart, the ordinary magnetic moment goes to zero. But the two states of neutron and mirror-neutron can still be degenerate with the application of appropriate magnetic and mirror magnetic fields [35]. Around the resonance condition, when $(\mu_n B - \mu_{n'} B') \sim 0$, it can be seen from Eq. 2, that the oscillation probability is maximized. Consequently, the oscillation probability is suppressed the further one goes from the resonance condition.

Experiments in search of $n - n'$ oscillation typically studied the *ratio* between the number of neutrons stored under the influence of a finite magnetic field to the same stored under a zero magnetic field, or the *asymmetry* between the number of neutrons stored under opposing magnetic fields [81, 82]. A third new method was demonstrated in *ref.* [83], which used the shift in precession frequency, when the neutrons are stored under the influence of opposing magnetic fields, as a means of accessing $n - n'$ oscillation. This relative frequency shift, far away from resonance condition, $|\mu_n B - \mu_{n'} B'| \gg 0$ and for $\omega' t \gg 1$, is given by [38, 83]

$$\frac{\delta\omega}{\omega} = \underbrace{\frac{1}{2\omega'^2\eta\,(\eta^2-1)}}_{f_d(\eta)} \frac{\cos(\beta)}{\tau^2_{nn'}}, \tag{3}$$

where, $\eta = B/B'$ and $f_d(\eta)$ is a scaling function purely dependent on the ambient mirror magnetic field and the applied magnetic field. Near the resonance condition, the scaling function is modified by [67, 84]

$$f_d^{|\mu_n B - \mu_{n'} B'| \approx 0}(\eta) = \frac{f_d^{|\mu_n B - \mu_{n'} B'| \gg 0}(\eta)}{2} \left[1 - \exp\left\{-2\omega^2 \left(\langle t_f^2\rangle - \langle t_f\rangle^2\right)\right\} \cos\left(2\omega\langle t_f\rangle\right)\right], \tag{4}$$

where $\langle t_f \rangle$ is the mean time of flight between two consecutive bounces of the neutrons during storage.

1.2 Current state of measurements in search of $n - n'$ oscillations

Ever since *refs.* [23, 24] pointed out that the lifetime for $n - n'$ oscillation could be measurably smaller than its β-decay lifetime, the search for $n - n'$ oscillation has been hotly pursued. Two techniques [85, 86], (i) disappearence ($n \longrightarrow n'$) and (ii) re-appearence ($n \longrightarrow n' \longrightarrow n$) of ordinary neutrons, have both been exploited to search for $n - n'$ oscillation. In the disappearance technique, usually ultracold neutrons (UCNs) are stored in material bottles under various magnetic field configurations, and counted after a specific period of time. Any correlation of the neutron counts with the applied magnetic field can be interpreted as evidence for $n - n'$ oscillation. Recently, the disappearance technique has also been applied to a beam of UCN to search for $n - n'$ oscillation [87]. On the other hand, reappearance technique based experiments typically allow a beam of cold neutrons to pass through a magnetic field before being incident on a wall which absorbs the ordinary neutrons, but allows mirror neutrons to pass through unimpeded. These mirror neutrons can oscillate back to ordinary neutrons. Similar to the experiments employing the disappearance technique, any correlation of the neutron transmission with the applied magnetic field can also be interpreted as evidence for $n - n'$ oscillation.

Since the mirror photon is uniquely different from the ordinary photon [43], mirror electromagnetic fields are also uniquely separate from the electromagnetic fields applicable in a laboratory. The first measurements in search of $n - n'$ oscillation were made using UCNs and employed the disappearance technique determining $\tau_{nn'} < 103$ s ($B' = 0$, 95% C.L.) [88], under the assumption of zero mirror magnetic field. This condition was subsequently relaxed, which then was able to constrain the $n - n'$ oscillation lifetime to $\tau_{nn'} < 12$ s ($0.4\ \mu\text{T}' < B' < 12.5\ \mu\text{T}'$, 95% C.L.) [89]. Currently the best limits upon the $n - n'$ oscillation lifetime also come from similar UCN storage experiments culminating in $\tau_{nn'} < 448$ s ($B' = 0$, 90% C.L.) [90, 91].

Even though initial measurements had found no evidence for $n - n'$ oscillation and only imposed lower limits on its oscillation time, reanalysis of these data revealed two anomalies [38, 80]: a 3σ anomaly (from the data in *ref.* [88]) and a 5σ anomaly (from the data in *refs.* [90, 91]). A third additional 2.5σ anomaly was also reported in *ref.* [84]. In order to test these signals, a dedicated experiment was performed which did not confirm the anomalies but instead lead to a constraint of $\tau_{nn'} > 6$ s ($0.36\ \mu\text{T}' < B' < 25.66\ \mu\text{T}'$, 95% C.L.), and $(\tau_{nn'}/\sqrt{\cos(\beta)}) > 9$ s ($5.04\ \mu\text{T}' < B' < 25.39\ \mu\text{T}'$, 95% C.L.) [82]. The other current prevailing best constraints are $\tau_{nn'} > 17$ s ($8\ \mu\text{T}' < B' < 17\ \mu\text{T}'$, 95% C.L.) and $(\tau_{nn'}/\sqrt{\cos(\beta)}) > 27$ s ($6\ \mu\text{T}' < B' < 25\ \mu\text{T}'$, 95% C.L.) [84], and $\tau_{nn'} > 1$ s ($0.030\ m\text{T}' < B' < 1.143\ m\text{T}'$, 95% C.L.) [87]. All of the above constraints came from counting UCNs, and searching for correlations of neutron counts with the applied magnetic field, while employing the disappearance technique.

While the disappearance technique has been used to test $n - n'$ oscillation in mirror magnetic fields in the regime of $0.1\ \mu\text{T}' \lesssim B' \lesssim 1\ m\text{T}'$, cold neutron beam based experiments employing the reappearance technique have been more impactful in the high mirror magnetic field regime. The first experiment using the reappearance technique demonstrated a sensitivity of $\tau_{nn'} > 2.7$ s ($B' = 0$, 90% C.L.) using cold neutrons from the FRM2 reactor [92]. Similarly, the MURMUR and STEREO experiments, at BR2 and ILL reactors, set a constraint of $\tau_{nn'} > 2\ \mu$s ($0 < B' < 3.5$ T$'$, 95% C.L.) [93] and $\tau_{nn'} > 300\ \mu$s ($0 < B' < 5.9$ T$'$, 95% C.L.) [94], respectively. An effort at SNS in ORNL, particularly aimed at testing the possibility of $n - n'$ oscillation contributing to the neutron lifetime crisis [95], also employed the reappearance technique, and imposed a constraint of $\tau_{nn'} > 63\ \mu$s (0.16 T$' < B' < 7.08$ T$'$, 95% C.L.) [96].

In this paper, we report on a statistical analysis in the search for $n - n'$ oscillation using the precession frequency shift technique. The first measurement in search of $n - n'$ oscillation using this third technique was conducted using a meta-analysis of the neutron electric dipole moment experiment (nEDM) [97]. It did not find any evidence of $n - n'$ oscillation and thereby imposed a constraint of $(\tau_{nn'}/\sqrt{\cos(\beta)}) > 5.7$ s ($0.4\ \mu\text{T}' < B' < 1.1\ \mu\text{T}'$, 95% C.L.) [83]. The Particle Data Group maintains a comprehensive list of the most impactful measurements in search of $n - n'$ oscillation [13].

2. Statistical sensitivity of $n - n'$ oscillations to nEDM experiments

All prior efforts assumed either a zero or a terrestrial source for the ambient mirror magnetic field. In the case of a terrestrial source for the mirror magnetic field (§2.1), the relative angle between the ambient mirror magnetic field and the applied magnetic field, β, is fixed *w.r.t* time. As evident from Eq. 3, the precession frequency shift analysis yields a measure of $(\tau_{nn'}/\sqrt{\cos(\beta)})$ as a function of the ambient mirror magnetic field. The dependence of the result on the $\cos(\beta)$ term, allows searching for modulations in $\delta\omega/\omega$ arising from a galactic source of the ambient mirror magnetic field. In the case of a galactic source of the mirror magnetic field (§2.2), the relative angle between the ambient mirror magnetic field and the applied magnetic field varies *w.r.t.* time, t, leading to

$$\frac{\delta\omega}{\omega} = \frac{\delta R}{R} = \underbrace{\frac{f_d(\eta)}{\tau^2_{nn'}}}_{\mathcal{F}_{B,\Omega}} \cos(\beta = 2\pi\Omega_\oplus t), \tag{5}$$

where $\Omega_\oplus = 1/T_\oplus = (1/86164.09054)\ \text{s}^{-1}$ is the sidereal modulation frequency, and $\mathcal{F}_{B,\Omega}$ is the modulation amplitude associated with an applied magnetic field, B, and modulation frequency, Ω. The ratio of precession frequencies for the stored neutron and the cohabiting ^{199}Hg atoms [97], which are used to compensate for drifts in magnetic field, is indicated by R. Modulations in the precession frequency of the ^{199}Hg atoms is constrained by over an order of magnitude better than that of the neutrons [98]. Therefore, it is safe to neglect

PoS(SPIN2023)112

the impact of $n - n'$ oscillations upon cohabiting ^{199}Hg atoms. In this section, we will present (§2.1) a statistical improvement upon the value of $\delta R/R$ used in *ref.* [83], and also present (§2.2) the statistical reach of the modulation of $\delta R/R$ in constraining the $n - n'$ oscillation.

2.1 $n - n'$ oscillation under the assumption of a terrestrial source of B'

The shift in precession frequency upon flipping of the direction of the magnetic field, was meta-analyzed to be $\delta R_0/R_0 = (-7 \pm 140) \times 10^{-8}$ in *ref.* [83]. This value was limited by the precision with which the value of R was known at zero magnetic field gradient, $\langle R_0 \rangle = 3.8424574(30)$ [99]. However, the data used in *refs.* [83] is statistically far more powerful than that in *ref.* [99]. The standard deviation of the measured value of R has also been presented in *ref.* [97], which was meta-analyzed in *ref.* [83], $R_0 = 3.8424546(34)$ across 54 068 cycles, making standard error a factor of $\sqrt{54\,068}$ smaller than the standard deviation. About half the data corresponds to the up direction of the applied magnetic field while the remaining half corresponds to the down direction. Therefore, the standard error associated with the difference in the value of $\langle R_0 \rangle$ obtainable from the two subsets of data is a factor of 2 larger. Furthermore, considering the relative value of the shift in frequency, additionally enlarges the standard error by another factor of $\sqrt{2}$. Ultimately, the value of $\sqrt{1/(\delta R_0/R_0)}$, which is linked to $\tau_{nn'}$ according to Eq. 3, while considering the standard deviation of R_0 in *ref.* [97], can be constrained at the 95% C.L. to be

$$\frac{\delta \langle R_0 \rangle}{\langle R_0 \rangle} < \frac{34 \times 10^{-7}}{3.8424546} \cdot \frac{2\sqrt{2}}{\sqrt{54068}} \implies \frac{\tau_{nn'}^{\text{(stat. sens.)}}}{\sqrt{\cos(\beta)}\sqrt{f_d(\eta)}} \gtrsim 6876, \tag{6}$$

where $f_d(\eta = B/B')$ is the scaling function defined in Eq. 3. The above constraint is plotted as a function of B' in Figure 1, while assuming that the angle β is fixed, as would be the case if the ambient mirror magnetic field has terrestrial origins. This sensitivity projection is over an order of magnitude better than the comparable constraint in *ref.* [83].

2.2 $n - n'$ oscillation under the assumption of a galactic source of B'

The modulation of the precession frequency of the neutron has already been studied in *refs.* [100, 101]. Due to $\tau_{nn'}$ depending on $\sqrt{\cos(\beta)}$ in Eq. 3, the relevant modulation frequencies correspond to both 1 sidereal day and 1/2 sidereal day. The modulation amplitude associated with 1 sidereal day has been constrained to $\sigma_{R_0}^{1\,\mu\text{T},\Omega_\oplus} < 8.0 \times 10^{-7}$ (95% C.L.) [100]. By comparing the constraints imposed on the modulation of nEDM in *ref.* [101] with the constraint placed upon the modulation at the frequency of $\Omega_\oplus$ in *ref.* [100], a modulation amplitude associated with 1/2 sidereal day can be constrained to $\sigma_{R_0}^{1\,\mu\text{T},2\Omega_\oplus} < 5.7 \times 10^{-7}$ (95% C.L.) [100, 101]. Similar to the previous subsection, §2.1, since roughly equal amounts of data corresponds to the two directions of the applied magnetic field, these two constraints upon the modulation amplitudes can be translated to the corresponding constraints upon the modulation of $\delta R_0/R_0$ by multiplying by $2\sqrt{2}$ and dividing by the ratio of statistical power (uncertainty) of the data in *ref.* [101], $\sigma_{d_n^{\text{(stat.)}}} = 2.7 \times 10^{-25}$ e.cm, compared to that in *ref.* [97], $\sigma_{d_n^{\text{(stat.)}}} = 1.1 \times 10^{-26}$ e.cm.. Note that while the precision of $\langle R_0 \rangle$ in Eq. 6 improves as the square root of the number of cycles, it improves linearly with the uncertainty of nEDM achieved in Eqs. 7-8, since the uncertainty of nEDM also improves as the square root of the number of cycles. The constraints upon the amplitude for the modulation of the difference in the precession frequency, upon flipping the direction of magnetic field, at the 95% C.L., is

$$\mathcal{F}_{1\,\mu\text{T},\Omega_\oplus} < \frac{8.0 \times 10^{-7}}{3.8424546} \cdot \frac{1.1 \times 10^{-26}\text{ e.cm}}{27 \times 10^{-26}\text{ e.cm}} 2\sqrt{2} \implies \frac{\tau_{nn',\Omega_\oplus}^{\text{(stat. sens.)}}}{\sqrt{f_d(\eta)}} \gtrsim 4605, \tag{7}$$

$$\mathcal{F}_{1\,\mu\text{T},2\Omega_\oplus} < \frac{5.7 \times 10^{-7}}{3.8424546} \cdot \frac{1.1 \times 10^{-26}\text{ e.cm}}{27 \times 10^{-26}\text{ e.cm}} 2\sqrt{2} \implies \frac{\tau_{nn',2\Omega_\oplus}^{\text{(stat. sens.)}}}{\sqrt{f_d(\eta)}} \gtrsim 5455. \tag{8}$$

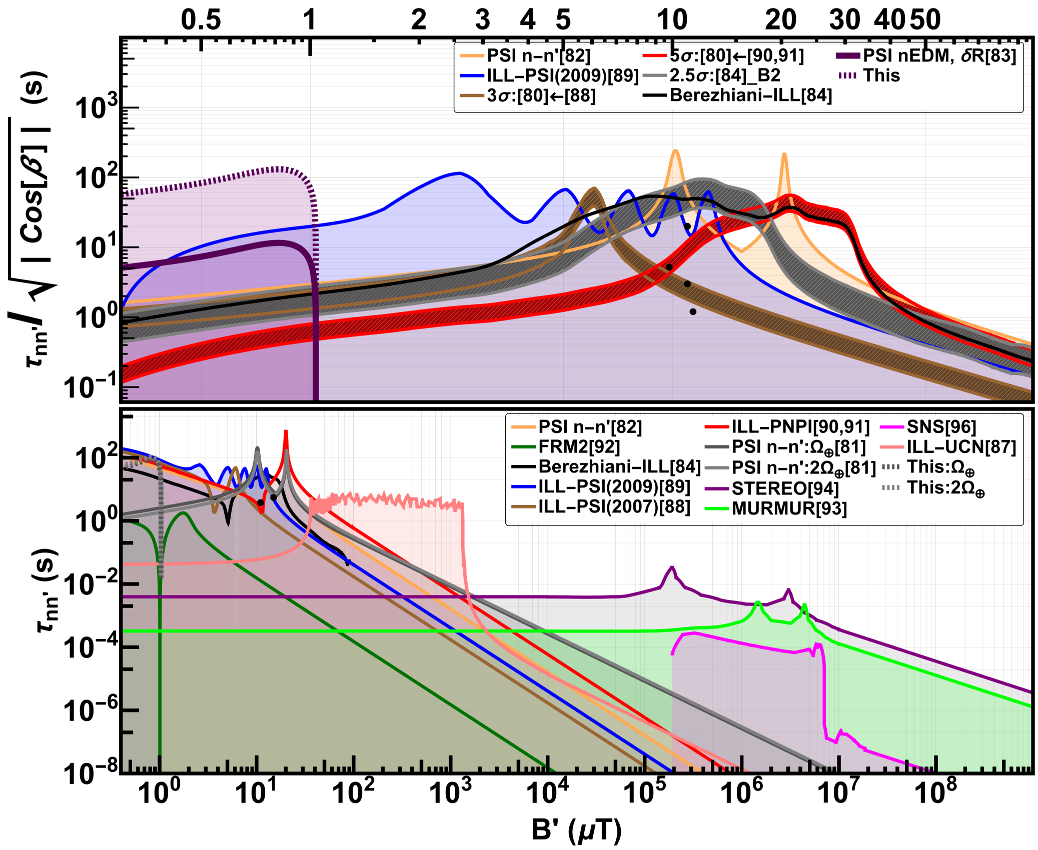

Figure 1: The 95% C.L. lower limits on the $n - n'$ oscillation parameters. The solid curves are from previous efforts, while the dashed curves are the sensitivities demonstrated in this work. The black dots indicate the solution consistent with the statistically significant signals as reported in *ref.* [38]. **(Top)** The lower limit of $\tau_{nn'}/\sqrt{\cos(\beta)}$ as a function of B'. This work has been shown as a dashed purple curve, which is an improvement over *ref.* [83], shown as a solid purple curve. Other previously imposed constraints are (a) the black curve [84], which is a weighted lower limit using data from *refs.* [84, 88–91], (b) the blue curve [89], which was an ILL-PSI effort that also reported modulation data, and (c) the orange curve [82], which was a dedicated $n - n'$ oscillation search using the nEDM apparatus at PSI. The three hatched regions are the anomalies (95% C.I.): (i) the red region [80], from the 5σ anomaly in *refs.* [90, 91]; (ii) the brown region [80], from the 3σ anomaly in *ref.* [88]; and (iii) the gray region comes from the 2.5σ anomaly in the B2 series of *ref.* [84]. **(Bottom)** The lower limit of $\tau_{nn'}$ as a function of an expanded range of B'. This work has been shown as two dashed gray curves, each corresponding to modulations with a time period of $\{1, 1/2\}$ sidereal day, as indicated. Similarly, modulation constraints from *ref.* [81] for the two indicated frequencies are shown as solid gray curves. Other previously imposed constraints are (a) the blue curve [89], from an ILL-PSI effort, (b) the black curve [84], using the same method as in the above figure, (c) the brown curve [88], which is the first ever $n - n'$ oscillation search conducted by ILL-PSI, (d) the orange curve [82], (e) the red curve [90, 91], which is an ILL-PNPI effort, (f) the purple curve [94] from STEREO, (g) the green curve [93] from MURMUR, (h) the magenta curve [96] from SNS, (i) the dark-green curve [92] from an effort at FRM2, and (j) the pink curve [87], which is an $n - n'$ oscillation search effort using a beam of UCNs at ILL.

The above constraints are plotted in Figure 1 as a function of B', while assuming that the angle varies as $\beta = 2\pi\Omega t$, as would be the case if the ambient mirror magnetic field has galactic origins. This sensitivity projection is the first of its kind available.

3. Discussion and Conclusion

Both types of constraints presented in Figure 1 use the same data, *i.e.* the shift in precession frequency of the neutrons upon flipping the direction of the applied magnetic field. In Figure 1 (Top), all the previous efforts which have searched for $n - n'$ oscillation and reported a constraint or an anomaly *w.r.t.* $(\tau_{nn'}/\sqrt{\cos(\beta)})$, under the assumption of a terrestrial source of the ambient mirror magnetic field, ensuring a constant value of $\cos(\beta)$ over time, *viz.* from *refs.* [82–84, 88–91], have been plotted. While, experiments in *refs.* [84, 88–91] were performed near Grenoble, France, and *refs.* [82, 83] were performed at Villigen-PSI, Switzerland. Between Grenoble and Villigen-PSI, there is a longitudinal difference of up to $\sim 3^o$ [81], which results in a small variation of up to $\sim 5\%$ in the constraints on $(\tau_{nn'}/\sqrt{\cos(\beta)})$, entering through β [82]. In Figure 1 (Bottom), we have plotted the result from this work, which involves searching for $n - n'$ oscillation under the assumption of a galactic source of the ambient mirror magnetic field, *viz.* based on *refs.* [100, 101], but since the modulation absorbs dependence on $\cos(\beta)$, we have also plotted other experiments which have directly constrained $\tau_{nn'}$ [82, 84, 87–94, 96]. It is important to note that the experiments that directly constrain $\tau_{nn'}$, also assume a constant ambient mirror magnetic field, but they do not need to make any additional assumptions regarding the origins of such a field.

The applied magnetic field used by *ref.* [97] was $\langle B\rangle = 1.035\ \mu\text{T}'$. Following from *ref.* [83], the above constraint is only valid in the range, $B' > 0.36\ \mu\text{T}'$ dictated by the condition $\omega'\langle t_f\rangle > 1$, under which Eq. 3 is valid, and where the value of $\langle t_f\rangle = 0.0628(27)$ s is the mean time between two consecutive bounces during storage for $t_s^* = 180$ s long [81, 82, 102]. The constraints in Figure 1 can be summarized at 95% C.L. as,

$$\tau_{nn'}^{(\text{stat. sens.})}/\sqrt{\cos(\beta)} \gtrsim 65\text{ s } (0.36\ \mu\text{T}' < B' < 1.01\ \mu\text{T}'), \tag{9}$$

$$\tau_{nn',\Omega_\oplus}^{(\text{stat. sens.})} \gtrsim 43\text{ s } (0.36\ \mu\text{T}' < B' < 1.02\ \mu\text{T}'), \tag{10}$$

$$\tau_{nn',2\Omega_\oplus}^{(\text{stat. sens.})} \gtrsim 51\text{ s } (0.36\ \mu\text{T}' < B' < 1.03\ \mu\text{T}'). \tag{11}$$

The best constraints achieved for each of the three curves summarized in Eqs. 9-11 are 131 s, 88 s, and 104 s, all at $B' = 0.82\ \mu\text{T}'$, respectively. The ambient mirror magnetic field can be non-zero and cannot be experimentally shielded [38, 80]. Therefore, it could affect the measurement. Local mirror magnetic fields, can have terrestrial [80, 103] or galactic [68, 104] origins. A terrestrial mirror magnetic field maybe generated similar to Earth's magnetic field [80] while a galactic source of mirror magnetic field maybe a relic field generated before hydrogen recombination after the big bang [104]. Such fields could be as large as the Earth's magnetic field, and so previous efforts [82–84] were focused on a mirror magnetic field typically in the range of $B' < 100\ \mu\text{T}'$, as shown in Figure 1 (Top). But recent $n - n'$ oscillation searches [87, 93, 94, 96] have also considered fields in relatively higher ranges of $B' < 7$ T$'$.

In this work we have presented the statistical sensitivity increase for nEDM experiments to $n - n'$ oscillation, particularly the constraint on $(\tau_{nn'}/\sqrt{\cos(\beta)})$, by over an order of magnitude. Primarily, the projection of improvement comes from the more precise measurement of the value of the ratio of precession frequencies of neutrons to co-habiting ^{199}Hg atoms from existing data. This constraint imposed on $n - n'$ oscillation using nEDM measurement is already the best constraint in the range of $B' < 0.4\ \mu$T, which through this work is projected to become the best measurement in the range of $B' < 1.01\ \mu$T. All but a couple of the existing constraints upon $n - n'$ oscillation in literature now assume a zero or a non-zero terrestrial source of ambient mirror magnetic field. The only other modulation studies of $n - n'$ oscillation in *ref.* [81, 89], which considers galactic origins of ambient mirror magnetic field, do not use the nEDM data. So, we have here for the first time, presented the statistical sensitivity for modulations of the difference in the precession frequency, upon flipping the direction of the magnetic field, as a means of accessing $n - n'$ oscillations under the assumption of a galactic source of ambient mirror magnetic field. These sensitivities could be further improved by another order of magnitude with the help of the upcoming next generation nEDM experiments [105–111]. Since regions of the three anomalies remain untested [82, 83], it is vital to perform more experiments to test these anomalies thoroughly.

Acknowledgments

One of the authors, P.M., would like to acknowledge support from Sigma Xi grants # G2017100190747806 and # G2019100190747806, US-Dept. of Education grant # F-19124368008, and US-Dept. of Energy grant #DE-SC0019768. P.M. and J.A.W. are supported by US-Dept. of Energy grant #DE-SC0014448. We would like to thank G. Zsigmond for useful discussions and insights.

References

[1] C. S. Wu et al., Phys. Rev. **105**, 1413 (1957). DOI: 10.1103/PhysRev.105.1413.

[2] E. C. G. Sudarshan and R. E. Marshak, Phys. Rev. **109**, 1860 (1958). DOI: 10.1103/PhysRev.109.1860.2.

[3] R. P. Feynman and M. Gell-Mann, Phys. Rev. **109**, 193 (1958). DOI: 10.1103/PhysRev.109.193.

[4] T. D. Lee and C.-N. Yang, Phys. Rev. **104**, 254 (1956). DOI: 10.1103/PhysRev.104.254.

[5] K. Nishijima and M. H. Saffouri, Phys. Rev. Lett. **14**, 205 (1965). DOI: 10.1103/PhysRevLett.14.205.

[6] E. W. Kolb et al., Nature **314**, 415 (1985). DOI: 10.1038/314415a0.

[7] C. R. Das et al., Euro. Phys. J. C **66**, 307 (2010). DOI: 10.1140/epjc/s10052-009-1229-2.

[8] I. Kobzarev et al., Sov. J. Nucl. Phys. *3*, 837 (1966). URL: inspirehep.net/record/1351288.

[9] M. Pavšič, Int. J. Theor. Phys. **9**, 229 (1974). DOI: 10.1007/BF01810695.

[10] R. Foot et al., Phys. Lett. B **272**, 67 (1991). DOI: 10.1016/0370-2693(91)91013-L.

[11] R. Foot et al., Mod. Phys. Lett. A **07**, 2567 (1992). DOI: 10.1142/S0217732392004031.

[12] R. Foot, Phys. Rev. D **49**, 3617 (1994). DOI: 10.1103/physrevd.49.3617.

[13] R. L. Workman et al. (PDG), Prog. Theor. Exp. Phys. **2022**, 8 (2022). DOI: 10.1093/ptep/ptac097.

[14] C. N. Yang and R. L. Mills, Phys. Rev. **96**, 191 (1954). DOI: 10.1103/PhysRev.96.191.

[15] Y. Nambu, Phys. Rev. Lett. **4**, 380 (1960). DOI: 10.1103/PhysRevLett.4.380.

[16] J. Goldstone et al., Phys. Rev. **127**, 965 (1962). DOI: 10.1103/PhysRev.127.965.

[17] Y. Nambu and G. Jona-Lasinio, Phys. Rev. **122**, 345 (1961). DOI: 10.1103/PhysRev.122.345.

[18] J. Goldstone, Il Nuovo Cimento **19**, 154 (1961). DOI: 10.1007/BF02812722.

[19] Y. Nambu, Phys. Rev. **117**, 648 (1960). DOI: 10.1103/PhysRev.117.648.

[20] G. S. Guralnik et al., Phys. Rev. Lett. **13**, 585 (1964). DOI: 10.1103/PhysRevLett.13.585.

[21] F. Englert and R. Brout, Phys. Rev. Lett. **13**, 321 (1964). DOI: 10.1103/PhysRevLett.13.321.

[22] P. W. Higgs, Phys. Rev. Lett. **13**, 508 (1964). DOI: 10.1103/PhysRevLett.13.508.

[23] Z. Berezhiani and L. Bento, Phys. Rev. Lett. **96**, 081801 (2006). DOI: 10.1103/PhysRevLett.96.081801.

[24] Z. Berezhiani and L. Bento, Phys. Lett. B **635**, 253 (2006). DOI: 10.1016/j.physletb.2006.03.008.

[25] Z. Berezhiani, Euro. Phys. J. C **76**, 705 (2016). DOI: 10.1140/epjc/s10052-016-4564-0.

[26] A. D. Sakharov, JETP Lett. **5**, 24 (1967). DOI: 10.1070/PU1991v034n05ABEH002497.

[27] Z. Berezhiani and A. Gazizov, Euro. Phys. J. C **72**, 2111 (2012). DOI: 10.1140/epjc/s10052-012-2111-1.

[28] Z. Berezhiani et al., Euro. Phys. J. C **81**, 1036 (2021). DOI: 10.1140/epjc/s10052-021-09806-1.

[29] R. N. Mohapatra and R. E. Marshak, Phys. Rev. Lett. **44**, 1316 (1980). DOI: 10.1103/PhysRevLett.44.1316.

[30] M. Baldo-Ceolin et al., Zeit. Für Physik C **63**, 409 (1994). DOI: 10.1007/BF01580321.

[31] D. G. Phillips II et al., Phys. Rep. **612**, 1 (2016). DOI: 10.1016/j.physrep.2015.11.001.

[32] Z. Berezhiani, Euro. Phys. J. C **81**, 33 (2021). DOI: 10.1140/epjc/s10052-020-08824-9.

[33] A. Addazi et al., J. Phys. G **48**, 070501 (2021). DOI: 10.1088/1361-6471/abf429.

[34] W. Tan, Phys. Lett. B **797**, 134921 (2019). DOI: 10.1016/j.physletb.2019.134921.

[35] Z. Berezhiani et al., Physics **1**, 271 (2019). DOI: 10.3390/physics1020021.

[36] Z. Berezhiani, Lett. in High Energy Phys. **2**, 10 (2019). DOI: 10.31526/lhep.1.2019.118.

[37] Z. Berezhiani, Euro. Phys. J. C **79**, 484 (2019). DOI: 10.1140/epjc/s10052-019-6995-x.

[38] Z. Berezhiani, Euro. Phys. J. C **64**, 421 (2009). DOI: 10.1140/epjc/s10052-009-1165-1.

[39] S. I. Blinnikov and M. Y. Khlopov, Sov. J. Nucl. Phys. **36**, 472 (1982). URL: inspirehep.net/literature/177194.

[40] N. Aghanim et al., Astron. Astrophys. Suppl. Ser. **641**, A6 (2020). DOI: 10.1051/0004-6361/201833910.

[41] Z. Berezhiani et al., Phys. Lett. B **375**, 26 (1996). DOI: 10.1016/0370-2693(96)00219-5.

[42] Z. Berezhiani et al., Phys. Lett. B **503**, 362 (2001). DOI: 10.1016/S0370-2693(01)00217-9.

[43] S. L. Glashow, Phys. Lett. B **167**, 35 (1986). DOI: 10.1016/0370-2693(86)90540-X.

[44] B. Holdom, Phys. Lett. B **166**, 196 (1986). DOI: 10.1016/0370-2693(86)91377-8.

[45] R. Foot et al., Phys. Lett. B **503**, 355 (2001). DOI: 10.1016/S0370-2693(01)00228-3.

[46] R. Foot, *Are Mirror Worlds Opaque?*, Phys. Lett. B **505**, 1 (2001). DOI: 10.1016/S0370-2693(01)00361-6.

[47] E. K. Akhmedov et al., Phys. Rev. Lett. **69**, 3013 (1992). DOI: 10.1103/PhysRevLett.69.3013.

[48] Z. Berezhiani and R. N. Mohapatra, Phys. Rev. D **52**, 6607 (1995). DOI: 10.1103/PhysRevD.52.6607.

[49] Z. K. Silagadze, Phys. At. Nucl. **60**, 272 (1997). arXiv: [hep-ph/9503481].

[50] V. Berezinsky et al., Nucl. Phys. B **658**, 254 (2003). DOI: 10.1016/S0550-3213(03)00191-3.

[51] H. M. Hodges, Phys. Rev. D **47**, 456 (1993). DOI: 10.1103/PhysRevD.47.456.

[52] L. Bento and Z. Berezhiani, Fortschr. Phys. **50**, 489 (2002). DOI: 10.1002/9783527610853.ch8.

[53] R. Foot and S. Mitra, Phys. Lett. A **315**, 178 (2003). DOI: 10.1016/S0375-9601(03)01033-8.

[54] Z. Berezhiani, AIP Conf. Proc. **878**, 195 (2006). DOI: 10.1063/1.2409087.

[55] Z. Berezhiani, Eur. Phys. J. Spec. Top. **163**, 271 (2008). DOI: 10.1140/epjst/e2008-00824-6.

[56] Z. Berezhiani et al., J. High Energy Phys. **2009**, 083 (2009). DOI: 10.1088/1126-6708/2009/07/083.

[57] C. R. Das et al., Phys. Rev. D **84**, 063510 (2011). DOI: 10.1103/PhysRevD.84.063510.

[58] T. Jenke et al., Phys. Rev. Lett. **112**, 151105 (2014). DOI: 10.1103/PhysRevLett.112.151105.

[59] Z. Berezhiani, Int. J. Mod. Phys. A **33**, 1844034 (2018). DOI: 10.1142/S0217751X18440347.

[60] E. D. Carlson and S. L. Glashow, Phys. Lett. B **193**, 168 (1987). DOI: 10.1016/0370-2693(87)91216-0.

[61] A. Coc et al., Phys. Rev. D **87**, 123530 (2013). DOI: 10.1103/PhysRevD.87.123530.

[62] A. Coc et al., Phys. Rev. D **90**, 085018 (2014). DOI: 10.1103/PhysRevD.90.085018.

[63] R. Foot, Int. J. Mod. Phys. A **29**, 1430013 (2014). DOI: 10.1142/S0217751X14300130.

[64] R. N. Mohapatra and V. L. Teplitz, Astrophys. J. **478**, 29 (1997). DOI: 10.1086/303762.

[65] R. Foot, Phys. Lett. B **471**, 191 (1999). DOI: 10.1016/S0370-2693(99)01382-9.

[66] R. Foot, Phys. Lett. B **452**, 83 (1999). DOI: 10.1016/S0370-2693(99)00230-0.

[67] A. Y. Ignatiev and R. R. Volkas, Phys. Rev. D **68**, 023518 (2003). DOI: 10.1103/PhysRevD.68.023518.

[68] R. Foot and R. R. Volkas, Phys. Rev. D **70**, 123508 (2004). DOI: /10.1103/PhysRevD.70.123508.

[69] Z. Berezhiani et al., Int. J. Mod. Phys. D **14**, 107 (2005). DOI: 10.1142/S0218271805005165.

[70] P. Ciarcelluti, Int. J. Mod. Phys. D **14**, 187 (2005). DOI: 10.1142/S0218271805006213.

[71] P. Ciarcelluti, Int. J. Mod. Phys. D **14**, 223 (2005). DOI: 10.1142/S0218271805006225.

[72] Z. Berezhiani et al., Astropart. Phys. **24**, 495 (2006). DOI: 10.1016/j.astropartphys.2005.10.002.

[73] Z. Berezhiani, L. Pilo, and N. Rossi, Euro. Phys. J. C **70**, 305 (2010). DOI: 10.1140/epjc/s10052-010-1457-5.

[74] Z. Berezhiani, World Scientific (2005), pp. 2147-2195. DOI: 10.1142/9789812775344_0055.

[75] L. B. Okun, Phys. Usp. **50**, 380 (2007). DOI: 10.1070/PU2007v050n04ABEH006227.

[76] R. Foot, Phys. Rev. D **82**, 095001 (2010). DOI: 10.1103/PhysRevD.82.095001.

[77] D. Dubbers and M. G. Schmidt, Rev. Mod. Phys. **83**, 1111 (2011). DOI: 10.1103/RevModPhys.83.1111.

[78] R. N. Mohapatra and R. E. Marshak, Phys. Lett. B **94**, 183 (1980). DOI: 10.1016/0370-2693(80)90853-9.

[79] E. Tiesinga et al. (CODATA), Rev. Mod. Phys. **93**, 025010 (2021). DOI: 10.1103/RevModPhys.93.025010.

[80] Z. Berezhiani and F. Nesti, Euro. Phys. J. C **72**, 1974 (2012). DOI: 10.1140/epjc/s10052-012-1974-5.

[81] P. Mohanmurthy, Ph.D Thesis, ETH Zürich (2019). DOI: 10.3929/ethz-b-000417951.

[82] C. Abel et al., Phys. Lett. B **812**, 135993 (2021). DOI: 10.1016/j.physletb.2020.135993.

[83] P. Mohanmurthy et al., Symmetry **14**, 487 (2022). DOI: 10.3390/sym14030487.

[84] Z. Berezhiani et al., Euro. Phys. J. C **78**, 717 (2018). DOI: 10.1140/epjc/s10052-018-6189-y.

[85] Y. N. Pokotilovski, Phys. Lett. B **639**, 214 (2006). DOI: 10.1016/j.physletb.2006.06.005.

[86] B. Kerbikov and O. Lychkovskiy, Phys. Rev. C **77**, 065504 (2008). DOI: 10.1103/PhysRevC.77.065504.

[87] G. Ban et al., Phys. Rev. Lett. **131**, 191801 (2023). DOI: 10.1103/PhysRevLett.131.191801.

[88] G. Ban et al., Phys. Rev. Lett. **99**, 161603 (2007). DOI: 10.1103/PhysRevLett.99.161603.

[89] I. Altarev et al., Phys. Rev. D **80**, 032003 (2009). DOI: 10.1103/PhysRevD.80.032003.

[90] A. P. Serebrov et al., Phys. Lett. B **663**, 181 (2008). DOI: 10.1016/j.physletb.2008.04.014.

[91] A. P. Serebrov et al., Nucl. Instrum. Methods Phys. Res. A **611**, 137 (2009). DOI: 10.1016/j.nima.2009.07.041.

[92] U. Schmidt, Proc. of BNLV International Workshop (BNLV 2007). URL: inpa-old.lbl.gov/blnv2/files/Saturday/Session13/Schmidt.pdf.

[93] C. Stasser et al., Euro. Phys. J. C **81**, 17 (2021). DOI: 10.1140/epjc/s10052-021-08829-y.

[94] H. Almazán et al., Phys. Rev. Lett. **128**, 061801 (2022). DOI: 10.1103/PhysRevLett.128.061801.

[95] P. Mohanmurthy et al., Symmetry **15**, 1899 (2023). DOI: 10.3390/sym15101899.

[96] L. J. Broussard et al., Phys. Rev. Lett. **128**, 212503 (2022). DOI: 10.1103/PhysRevLett.128.212503.

[97] C. Abel et al., Phys. Rev. Lett. **124**, 081803 (2020). DOI: 10.1103/PhysRevLett.124.081803.

[98] S. K. Peck et al., Phys. Rev. A **86**, 012109 (2012). DOI: 10.1103/PhysRevA.86.012109.

[99] S. Afach et al., Phys. Lett. B **739**, 128 (2014). DOI: 10.1016/j.physletb.2014.10.046.

[100] I. Altarev et al., Phys. Rev. Lett. **103**, 081602 (2009). DOI: 10.1103/PhysRevLett.103.081602.

[101] I. Altarev et al., Euro. Phys. Lett. **92**, 51001 (2011). DOI: 10.1209/0295-5075/92/51001.

[102] C. Abel et al., EPJ Web Conf. **219**, 07001 (2019). DOI: 10.1051/epjconf/201921907001.

[103] A. Y. Ignatiev and R. R. Volkas, Phys. Rev. D **62**, 023508 (2000). DOI: 10.1103/PhysRevD.62.023508.

[104] Z. Berezhiani and A. D. Dolgov, Astropart. Phys. **21**, 59 (2004). DOI: 10.1016/j.astropartphys.2003.11.002.

[105] A. Serebrov, Proc. of Sci. **281**, 179 (2017). DOI: 10.22323/1.281.0179.

[106] T. M. Ito et al., Phys. Rev. C **97**, 012501 (2018). DOI: 10.1103/PhysRevC.97.012501.

[107] E. Chanel et al., EPJ Web Conf. **219**, 02004 (2019). DOI: 10.1051/epjconf/201921902004.

[108] D. Wurm et al., EPJ Web Conf. **219**, 02006 (2019). DOI: 10.1051/epjconf/201921902006.

[109] M. W. Ahmed et al., J. Instrum. **14**, P11017 (2019). DOI: 10.1088/1748-0221/14/11/P11017.

[110] N. J. Ayres et al., Euro. Phys. J. C **81**, 512 (2021). DOI: 10.1140/epjc/s10052-021-09298-z.

[111] M. McCrea (TUCAN), Proc. of Sci. **380**, 459 (2022). DOI: 10.22323/1.380.0459.

PoS(SPIN2023)112