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Signal of neutrino magnetic moments from a galactic supernova burst at upcoming detectors

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The neutronization burst phase of a core-collapse supernova, which lasts for a few tens of milliseconds post-bounce, is dominated by electron neutrinos and can offer exceptional discovery potential for neutrino transition magnetic moments. We simulate the neutrino spectra from the burst phase in forthcoming neutrino experiments like the Deep Underground Neutrino Experiment, and the Hyper-Kamiokande, by taking into account spin-flavour conversions of supernova neutrinos caused by interactions with ambient magnetic fields. We find that the sensitivities to neutrino transition magnetic moments are an order to several orders of magnitude better than the current terrestrial and astrophysical limits. We also discuss how this realization might provide light on the Dirac/Majorana nature and the neutrino mass-generation mechanism.

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1. Introduction

The discovery of neutrino oscillations, driven by non-zero neutrino masses and mixing, provided the first robust evidence of physics beyond the Standard Model (SM). In order to account for the tiny neutrino masses and mixing, the SM must be extended. In these extensions, a generic outcome is the existence of a non-zero neutrino magnetic moment (μ_ν) through quantum loop corrections.

Neutrino magnetic moments can either be flavour-diagonal and/or flavour off-diagonal, depending on the neutrino nature. Dirac neutrinos can have an intrinsic magnetic moment (IMM) that gives rise to spin precession for a given flavour α, i.e. $\nu_{\alpha L} \to \nu_{\alpha R}$ in the presence of sufficiently strong magnetic fields [1], as well as a transition magnetic moment (TMM) that induces flavour precession in addition to rotation of the spin, i.e., $\nu_{\alpha L} \to \nu_{\beta R}$ [2]. On the other hand, Majorana neutrinos can have only transition moments [2].

Furthermore, coherent forward scattering of neutrinos off the surrounding matter background can resonantly enhance these spin-flavour conversions, thereby termed as the resonant spin-flavour precession (RSFP) [3]. This is very similar to matter enhancement of neutrino oscillations due to the Mikheyev-Smirnov-Wolfenstein (MSW) effect [4].

2. Neutrinos from supernova neutronization burst phase

The dense matter environment, coupled with strong magnetic fields, makes a supernova (SN) ideal for studying neutrino flavour transitions due to RSFP [3].

A simple, effective two-flavour analysis of neutrino flavour evolution in SN in the presence of non-zero TMMs identifies, in addition to the usual MSW resonances, two extra resonances: (i) the RSFP-H, associated with the atmospheric mass-squared difference (Δm^2_{31}), occurring at high densities, and (ii) the RSFP-L, associated with the solar mass-squared difference (Δm^2_{21}), occurring at lower densities. Ref. [5] studied the impact of such RSFP in a three-flavour setup and discussed an additional type of resonance, the RSFP-E (electron-type), which is present in a pure three-flavour analysis.

The first $O(30)$ms post-bounce is dominated by the deleptonization epoch, also known as the neutronization burst. This epoch is characterized by a pure ν_e flux, with very little contamination of $\bar{\nu}_e$ and $\nu_{\mu,\tau}$, see the left panel of Fig. 1. During the neutronization burst, any new physics mechanism that ends up converting ν_es would cause a dramatic change in the ν_e spectra. In particular, it was discussed in Ref [5, 7, 8] that a combination of MSW and RSFP transitions can result in $\nu_e \to \bar{\nu}_e$ conversions during this epoch. A smoking-gun signal of such conversion in future detectors would be a suppression of the ν_e flux in DUNE [9] while leading to an enhancement in the $\bar{\nu}_e$ channel in Hyper-Kamiokande (HK) [10], see Figs. 2 and 3.

3. Evolution equation

We consider a three flavor setup, $\nu = (\nu_e, \nu_\mu, \nu_\tau)^T$ and $\bar{\nu} = (\bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}_\tau)^T$, and a finite transverse magnetic field $B_\perp = B_0\,(r_0/r)^3$, where $r_0 \approx 0.0024 R_\odot$ is the radius of the iron core for a progenitor

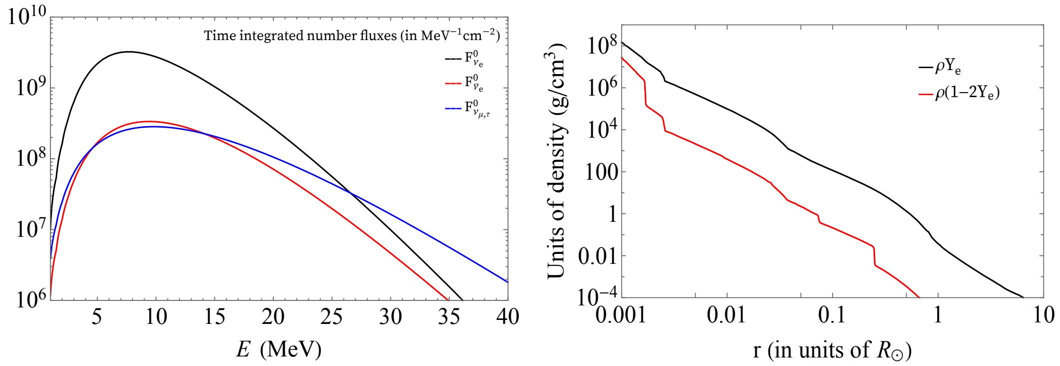

Figure 1: *Left*: Time-integrated neutrino number fluxes (upto 50 ms) for the neutronization burst epoch. Note that ν_e dominates over other flavours upto $E \lesssim 25$ MeV. *Right*: The quantities, $\rho(1-2Y_e)$ and ρY_e, relevant for RSFP and MSW transitions respectively. These are taken from the static profile of a $15M_\odot$ star with solar metallicity [6]. Here we consider $R_\odot = 696340$ Km. Note than in units of $R_\odot$, the resonances discussed in the text happens mostly for $r/R_\odot \lesssim 1$.

mass $15M_\odot$ and 10^7 G $\lesssim B_0 \lesssim 10^{10}$ G [11]. The equation of motion is

$$i\frac{d}{dr}\begin{pmatrix}\nu\\ \bar{\nu}\end{pmatrix} = \begin{pmatrix} H_\nu & B_\perp M \\ -B_\perp M & H_{\bar{\nu}}\end{pmatrix}\begin{pmatrix}\nu\\ \bar{\nu}\end{pmatrix}, \tag{1}$$

where r is the radial coordinate in the SN. The H_ν ($H_{\bar{\nu}}$) is the neutrino (anti-neutrino) Hamiltonian in matter that contains forward scattering potentials and are functions of the matter profile, ρ, and electron number fraction, Y_e [5, 7, 8]. We use the static profile model for a progenitor mass $15M_\odot$ and solar metallicity as shown in the right panel of Fig. 1 [6]. The matrix M in Eq. 1 contains the TMMs and is antisymmetric:

$$M = \begin{pmatrix} 0 & \mu_{e\mu} & \mu_{e\tau} \\ -\mu_{e\mu} & 0 & \mu_{\mu\tau} \\ -\mu_{e\tau} & -\mu_{\mu\tau} & 0 \end{pmatrix}. \tag{2}$$

4. Sensitivity in upcoming detectors

The effect of the RSFP is to reduce the ν_e flux, and increase the $\bar{\nu}_e$. Depending on the mass ordering, the effect can be quite large. We focus on the Deep Underground Neutrino Experiment (DUNE), which can detect ν_e, and the Hyper-Kamiokande (HK) which is mainly sensitive to the $\bar{\nu}_e$ flux. The number of events of species ν_α detected per unit energy is

$$\frac{dN_{\nu_\alpha}}{dE_r} = \frac{N_{\text{tar}}}{4\pi R^2}\int dE_t F_{\nu_\alpha}(E_t)\sigma_\alpha(E_t)W(E_r, E_t), \tag{3}$$

with N_{tar} the number of targets, $R = 10$ kpc the benchmark distance of the galactic supernova from the Earth, F_{ν_α} is the ν_α flux that reaches the detector, σ_α is the cross section and W is the Gaussian energy resolution function with width σ_E that depends on that experimental setup. E_t is the actual neutrino energy, while E_r is the experimentally reconstructed energy. Results are shown in Figs. 2

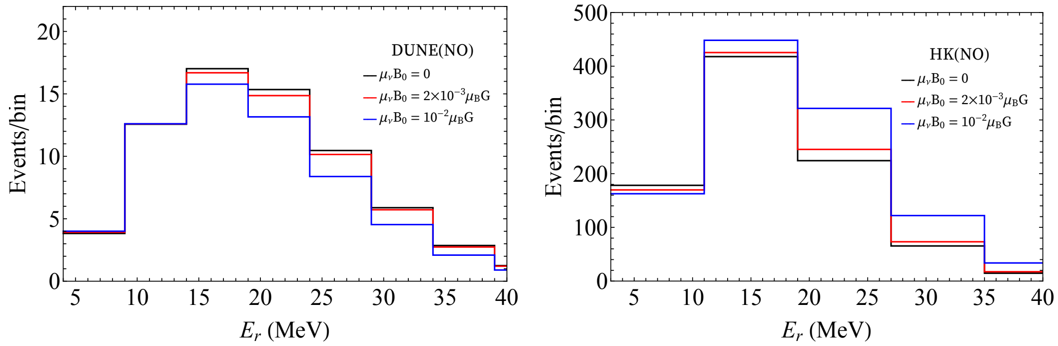

Figure 2: Expected event spectrum for a supernova explosion 10 kpc away in DUNE (left, ν_e channel) and HK (right, $\bar{\nu}_e$ channel) for distinct values of $\mu_\nu B_0$. We assume normal ordering (NO) for neutrino masses.

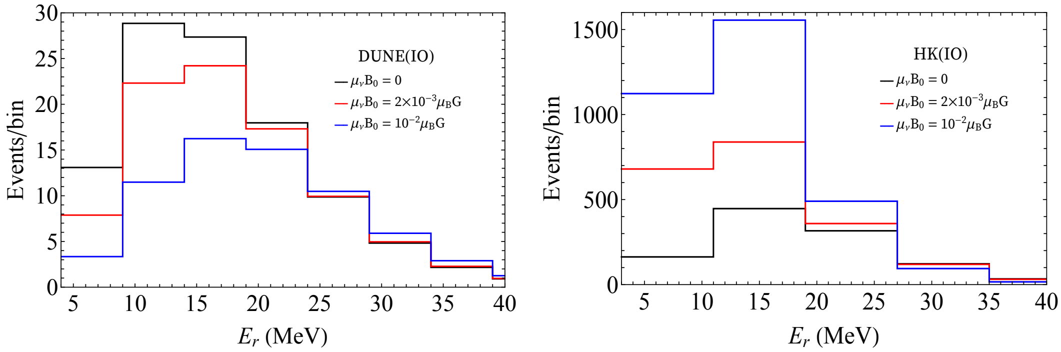

Figure 3: Same as Fig. 2, but for inverted ordering (IO).

Experiments	Sensitivities on Neutrino Magnetic Moments (in μ_B)					
	CASE 1		CASE 2		CASE 3	
	NO	IO	NO	IO	NO	IO
HK	4.5×10^{-13}	6×10^{-14}	9×10^{-13}	1.4×10^{-13}	8×10^{-13}	1.2×10^{-13}
DUNE	–	3×10^{-13}	–	7×10^{-13}	–	6×10^{-13}

Table 1: Experimental sensitivities on neutrino magnetic moments for different benchmark scenarios for a fixed value of magnetic field strength $B_0 = 10^{10}$ G. Case 1: both $\mu_{e\mu}$ and $\mu_{e\tau}$ in Eq. 1 are equal, set to μ_ν, and considered free parameters. Case 2: $\mu_{e\mu} = 0$ and $\mu_{e\tau} = \mu_\nu$ is a free parameter. Case 3: $\mu_{e\mu} = \mu_\nu$ is considered a free parameter, while $\mu_{e\tau} = 0$. The $\mu_{\mu\tau}$ is irrelevant and set to zero in all cases.

and 3 for both mass orderings. Observe that to derive constraints on μ_ν, one needs prior knowledge of B_0 from simulations and/or astrophysical observations.

We perform a χ^2 analysis to study the sensitivity of DUNE and HK to the presence of neutrino TMM. Table 1 summarizes the derived sensitivities to μ_ν assuming $B_0 = 10^{10}$ G.

5. Implication for neutrino properties

We summarize the experimental constraints and theoretical predictions on neutrino magnetic moments, along with our results, in Fig. 4. Existing limits on neutrino magnetic moments are shown in blue, while the red lines indicate the future sensitivities on neutrino magnetic moments

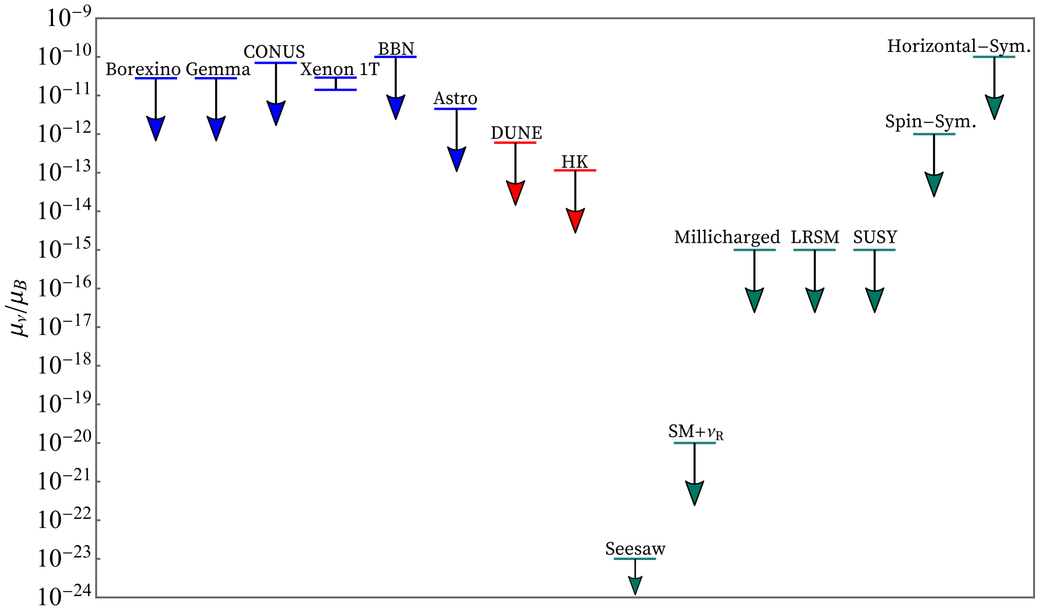

Figure 4: Summary of experimental constraints and theoretical predictions on neutrino magnetic moments. The red lines indicate the future sensitivities on neutrino magnetic moments at DUNE and HK experiments based on our analysis. Here we set magnetic field strength $B_0 = 10^{10}$ G. Theoretical predictions for maximum possible strengths of neutrino magnetic moments are summarized from Ref. [12] and references therein. See text for details.

at DUNE and HK, based on our analysis, by setting magnetic field strength $B_0 = 10^{10}$ G. Note that as compared to existing limits, the sensitivity can be upgraded by two or three orders of magnitude (from $O[10^{-11}]\ \mu_B$ to $O[10^{-14}]\ \mu_B$). This will have consequences for important unanswered questions in neutrino physics:

- *Dirac/Majorana nature of neutrinos*: Based on an Effective Field Theory (EFT) analysis, it has been shown that Dirac neutrino magnetic moments over $10^{-14}\mu_B$ would not be natural, since this would generate unacceptably large neutrino masses at higher loops [13]. Therefore, if DUNE or Hyper-Kamiokande experiment measure neutrino magnetic moments at the level of $10^{-13}\ \mu_B$, it is more likely that neutrinos are Majorana in nature.
- *Neutrino mass generation mechanism*: Due to similar chiral structure of the neutrino magnetic moment and neutrino mass operator, while removing the photon line from the loop diagram that yields the neutrino magnetic moment, a neutrino mass term is generated. A careful study of neutrino magnetic moment may shed light on the underlying neutrino mass theory.

6. Conclusion

In this work, we have studied the neutrino flavour evolution inside a SN in the presence of a finite TMM, and considered the effect it has on the spectra from the burst phase. By simulating the event spectra in upcoming neutrino experiments like as DUNE and Hyper-Kamiokande, we have found that the neutrino TMMs that may be probed by these experiments for a SN happening at

10 kpc are two or three orders of magnitude (from $O[10^{-11}]\ \mu_B$ to $O[10^{-14}]\ \mu_B$ for the allowed range of magnetic field strengths) better than the current terrestrial and astrophysical bounds. This realization can impact the understanding of the Dirac/Majorana character of the neutrino and the neutrino mass generation mechanism.

References

[1] K. Fujikawa and R.E. Shrock, *Magnetic moment of a massive neutrino and neutrino-spin rotation*, *Phys. Rev. Lett.* **45** (1980) 963.

[2] R.E. Shrock, *Electromagnetic Properties and Decays of Dirac and Majorana Neutrinos in a General Class of Gauge Theories*, *Nucl. Phys. B* **206** (1982) 359.

[3] C.-S. Lim and W.J. Marciano, *Resonant Spin - Flavor Precession of Solar and Supernova Neutrinos*, *Phys. Rev. D* **37** (1988) 1368.

[4] S.P. Mikheev and A.Y. Smirnov, *Resonance Amplification of Oscillations in Matter and Spectroscopy of Solar Neutrinos*, *Sov. J. Nucl. Phys.* **42** (1985) 913.

[5] E.K. Akhmedov and T. Fukuyama, *Supernova prompt neutronization neutrinos and neutrino magnetic moments*, *JCAP* **12** (2003) 007 [`hep-ph/0310119`].

[6] S.E. Woosley and T.A. Weaver, *The Evolution and explosion of massive stars. 2. Explosive hydrodynamics and nucleosynthesis*, *Astrophys. J. Suppl.* **101** (1995) 181.

[7] S. Ando and K. Sato, *A Comprehensive study of neutrino spin flavor conversion in supernovae and the neutrino mass hierarchy*, *JCAP* **10** (2003) 001 [`hep-ph/0309060`].

[8] A. Ahriche and J. Mimouni, *Supernova neutrino spectrum with matter and spin flavor precession effects*, *JCAP* **11** (2003) 004 [`astro-ph/0306433`].

[9] DUNE collaboration, *Supernova neutrino burst detection with the Deep Underground Neutrino Experiment*, *Eur. Phys. J. C* **81** (2021) 423 [`2008.06647`].

[10] Hyper-Kamiokande collaboration, *Hyper-Kamiokande Design Report*, `1805.04163`.

[11] T. Totani and K. Sato, *Resonant spin flavor conversion of supernova neutrinos and deformation of the anti-electron-neutrino spectrum*, *Phys. Rev. D* **54** (1996) 5975 [`astro-ph/9609035`].

[12] K.S. Babu, S. Jana and M. Lindner, *Large Neutrino Magnetic Moments in the Light of Recent Experiments*, *JHEP* **10** (2020) 040 [`2007.04291`].

[13] N.F. Bell, V. Cirigliano, M.J. Ramsey-Musolf, P. Vogel and M.B. Wise, *How magnetic is the Dirac neutrino?*, *Phys. Rev. Lett.* **95** (2005) 151802 [`hep-ph/0504134`].