



New astrophysical limit on neutrino millicharge

Alexander I. Studenikin^{a,b}, Ilya V. Tokarev^a

^a*Department of Theoretical Physics, Faculty of Physics, Moscow State University, Moscow 119991, Russia*

^b*Joint Institute for Nuclear Research, Dubna 141980, Moscow Region, Russia*

Abstract

An impact of a nonzero neutrino millicharge in astrophysics is tested. It is shown that in astrophysical environments electromagnetic interactions of the neutrino millicharge with strong electromagnetic fields as well as weak interactions of the neutrinos with dense background matter can produce new phenomena accessible for astrophysical observations. On this basis a new limit on the neutrino millicharge $q_0 < 1.3 \times 10^{-19} e_0$ is obtained. This limit is among the strongest astrophysical constraint on the neutrino millicharge. Some other possible applications of the obtained results to astrophysics are discussed in details.

Keywords:

1. Introduction

Studies of nontrivial neutrino electromagnetic properties [1, 2] is one of the important issues of the nowadays physics beyond the Standard Model [3–6]. The updated review on the present status of neutrino electromagnetic properties is given in [6]. In this short paper we deal with a nonzero electric millicharge.

It is usually believed that the neutrino electric charge is zero. In the Standard Model neutrinos are massless and electrically neutral particles. However, the electric charge of neutrinos as massive particles is an controversial question that can open a window to “new physics”.

There are a lot of limits on the neutrino millicharge known in literature [6, 7]. The best model independent astrophysical constraint $q_0 \leq 2 \times 10^{-17} e_0$ was obtained from the analysis of the neutrino signal from SN1987A [8] (here q_0 and e_0 are the absolute values of neutrino and electron charges respectively). The most severe constraint $q_0 \lesssim 3 \times 10^{-21} e_0$ was obtained from the consideration of charge conservation law in neutron beta decay and direct measurements of the neutrality of

matter [9] and neutron itself [10]. Also note a new approach to the problem that is based on the analysis of results of reactor neutrino magnetic moment experiments and yields the limit at the level of a few $10^{-12} e_0$ [11].

In turn, recently we have focused on new astrophysical effects originated by both weak and electromagnetic interactions of millicharged neutrinos with background environment. For description of neutrinos propagation in a dense rotating matter we use the method of exact solutions of the modified Dirac equation for the neutrino wave function [12]. In particular, a new mechanism of a star rotation frequency shift due to neutrinos escaping the star (termed “Neutrino Star Turning” mechanism, νST) is predicted [13]. We have obtained a new limit on the neutrino millicharge using the estimation of the proposed νST mechanism impact on the dynamics of core-collapse of a supernova. In addition, possible applications of this and other predicted effects have been discussed in details.

2. Millicharged neutrino in dense magnetized rotating matter

In order to predict new astrophysical effects and phenomena originated by the millicharged neutrinos in as-

Email addresses: studenik@srd.sinp.msu.ru (Alexander I. Studenikin), tokarev.ilya.msu@gmail.com (Ilya V. Tokarev)

trophysical environment one should describe the neutrino behavior in such extreme background conditions.

We use in our studies of neutrinos under extreme external conditions, in particular in strong electromagnetic fields and dense matter, the method of exact solutions of modified Dirac equations [12]. Within this method, a millicharged neutrino quantum states in an external magnetic field and dense background matter is described by the modified Dirac equation

$$\left(\gamma_\mu (p^\mu + q_0 A^\mu) - \frac{1}{2} \gamma_\mu (1 + \gamma_5) f^\mu - m \right) \Psi(x) = 0, \quad (1)$$

where A^μ and f^μ are electromagnetic and matter potentials respectively (it is supposed that the neutrino millicharge is negative). In case of the neutrino propagation in the magnetized rotating matter where both matter rotation vector ω and the magnetic field \mathbf{B} are coincided with the third coordinate axis \mathbf{e}_z the solution of Eq. (1) was obtained in the following form [4, 5, 13]

$$p_0 = \sqrt{p_3^2 + 2N|q_0 B - 2Gn\omega| + m^2 + Gn}, \quad (2)$$

where $G = \frac{G_F}{\sqrt{2}}$ (G_F is the Fermi constant), ω is a matter angular velocity, n is a matter number density and $N = 0, 1, 2, \dots$ is a discrete number that numerates the modified Landau levels. The energy spectrum (2) of the millicharged neutrino in the dense magnetized rotating matter is quantized due to both electromagnetic interactions of the neutrino millicharge with the constant magnetic field and weak interactions of the neutrino with the dense rotating matter.

Note that the neutrino quantum states that also account for the electromagnetic interaction of a neutrino magnetic moment with the external magnetic field were obtained in [13–15].

Within a quasi-classical interpretation the neutrino discrete energy states (2) can be explained as a result of action of the effective force [12, 13]

$$\mathbf{F} = (q_0 B - 2Gn\omega) [\mathbf{e}_z \times \boldsymbol{\beta}], \quad (3)$$

where $\boldsymbol{\beta}$ is a neutrino velocity. Note that the force (3) is of different nature than one of the classical Lorentz force because of the presence of the impact from weak interactions with particles of the background.

3. Astrophysical applications

The force (3) seems to be very weak for any reasonable choice of background parameters, but nevertheless,

can produce new astrophysical effects that can be observed in terrestrial experiments [13]. In particular, during a supernova core collapse due to the action of the force (3) escaping neutrinos can be deflected on an angle

$$\Delta\phi \simeq \frac{R_S}{R} \sin\theta, \quad R = \sqrt{\frac{2N}{|q_0 B - 2Gn\omega|}}, \quad (4)$$

where R_S is the radius of the star, R is the radius of the neutrino trajectory and θ is an azimuthal angle of neutrino propagation. Thus, we predict that initially coincided light and neutrino beams will be spatially separated after passing through the dense rotating magnetized matter. Therefore, in terrestrial experiments joint observations of initially coincided light and neutrino signals from astrophysical transient sources should not occur due to their spatial separation $\Delta L \simeq \Delta\phi L$ (L is distance to the sources). This new effect can explain recent results of the ANTARES experiment [16].

On the other hand the feedback of the effective force (3) from the escaping neutrinos to the star should affect the star evolution. In particular, a torque produced by the escaping neutrinos shifts the star angular velocity

$$|\Delta\omega_0| = \frac{5N_\nu}{6M_S} |q_0 B - 2Gn\omega_0|, \quad (5)$$

where $\Delta\omega_0 = \omega - \omega_0$ (ω_0 is an initial star angular velocity), M_S is the star mass and N_ν is the number of the escaping neutrinos. We have termed the phenomenon as the “Neutrino Star Turning” (νST) mechanism [13]. Note that depending on the neutrino millicharge sign the star rotation due to the νST mechanism can either spin up ($\Delta\omega_0 > 0$ for $q_\nu < 0$) or spin down ($\Delta\omega_0 < 0$ for $q_\nu > 0$).

In case of zero neutrino millicharge the νST mechanism is produced only due to the weak interactions and yields

$$\frac{|\Delta\omega_0|}{\omega_0} \simeq 10^{-8}. \quad (6)$$

where we have considered the star with mass $M_S = 1.4M_\odot$ (M_\odot is the Solar mass) and $N_\nu = 10^{58}$ escaped neutrinos with energy ~ 10 MeV [17].

The value of the relative rotation frequency shift (6) is very close to a sporadic increase of a pulsar rotation frequency (a pulsar glitch, see, for instance, [18]). The obtained results are also important in light of the recently observed “anti-glitch” event [19] that is a sudden decrease of a pulsar rotation frequency. The νST mechanism can be used to explain both glitches and “anti-glitches” as well.

4. New astrophysical limit on neutrino millicharge

To obtain a new limit on the neutrino millicharge we have estimated the impact of the electromagnetic part of the νST mechanism on the dynamics of pulsar formation in a supernova explosion.

From Eq. (5) we obtain

$$\frac{|\Delta\omega_0|}{\omega_0} = \frac{7.6q_0}{e_0} \times 10^{18} \left(\frac{P_0}{10 \text{ s}} \right) \left(\frac{N_\nu}{10^{58}} \right) \left(\frac{1.4M_\odot}{M_S} \right) \left(\frac{B}{10^{14}\text{G}} \right), \quad (7)$$

where P_0 is a pulsar initial spin period.

All estimations of feasible initial pulsars rotation periods give the values that are very close to the present observed periods. Therefore, possible existence of a nonzero negative neutrino millicharge should not significantly speed up the rotation of a born pulsar (or speed down in case of a positive neutrino millicharge). From the straightforward demand $|\Delta\omega_0| < \omega_0$ and Eq. (7) we have obtained the upper limit on the neutrino millicharge [13]

$$q_0 < 1.3 \times 10^{-19} e_0. \quad (8)$$

That is, in fact, one of the most severe astrophysical limits on the neutrino millicharge [6, 7].

5. Acknowledgments

The work on this paper has been partially supported by the Russian Foundation for Basic Research (grants No. 14-02-31816 and 14-22-03043).

References

- [1] C. Giunti, A. Studenikin, Neutrino electromagnetic properties, *Phys.Atom.Nucl.* 72 (2009) 2089–2125.
- [2] C. Brogini, C. Giunti, A. Studenikin, Electromagnetic Properties of Neutrinos, *Adv.High Energy Phys.* 2012 (2012) 459526.
- [3] A. Studenikin, Neutrino magnetic moment: A Window to new physics, *Nucl.Phys.Proc.Suppl.* 188 (2009) 220.
- [4] A. Studenikin, I. Tokarev, New effects of nonzero neutrino electric charge, *Nucl.Phys.Proc.Suppl.* 237-238 (2013) 317–319.
- [5] A. Studenikin, I. Tokarev, Neutrino electromagnetic properties and new physics, *PoS EPS-HEP2013* (2013) 531.
- [6] C. Giunti, A. Studenikin, Neutrino electromagnetic interactions: a window to new physics, *arXiv:1403.6344*.
- [7] G. Raffelt, *Stars as laboratories for fundamental physics: The astrophysics of neutrinos, axions, and other weakly interacting particles*, University of Chicago Press, 1996.
- [8] G. Barbiellini, G. Cocconi, Electric Charge of the Neutrinos from SN1987A, *Nature* 329 (1987) 21–22.
- [9] M. Marinelli, G. Morpurgo, The electric neutrality of matter: a summary, *Phys.Lett. B* 137 (1984) 439.
- [10] J. Baumann, J. Kalus, R. Gahler, W. Mampe, Experimental limit for the charge of the free neutron, *Phys.Rev. D* 37 (1988) 3107.
- [11] A. Studenikin, New bounds on neutrino electric millicharge from limits on neutrino magnetic moment, *Europhys.Lett.* 107 (2014) 21001.
- [12] A. I. Studenikin, Method of wave equations exact solutions in studies of neutrinos and electrons interaction in dense matter, *J.Phys. A*41 (2008) 164047.
- [13] A. I. Studenikin, I. Tokarev, Millicharged neutrino with anomalous magnetic moment in rotating magnetized matter, *Nucl.Phys. B*884 (2014) 396–407.
- [14] I. Balantsev, A. Studenikin, I. Tokarev, New solutions to the Dirac equation for particles in a magnetic field and a medium, *Phys.Part.Nucl.* 43 (2012) 727–741.
- [15] I. Balantsev, A. Studenikin, I. Tokarev, Motion of a charged fermion with an anomalous magnetic moment in magnetized media, *Phys.Atom.Nucl.* 76 (2013) 489–503.
- [16] S. Adrian-Martinez, et al., Searches for Point-like and extended neutrino sources close to the Galactic Centre using the ANTARES neutrino Telescope, *Astrophys.J.* 786 (2014) L5.
- [17] K. Hirata, et al., Observation of a Neutrino Burst from the Supernova SN 1987a, *Phys.Rev.Lett.* 58 (1987) 1490–1493.
- [18] R. Rosen, et al., The Pulsar Search Collaboratory: Discovery and Timing of Five New Pulsars, *Astrophys. J.* 768 (2013) 85.
- [19] R. Archibald, et al., An Anti-Glitch in a Magnetar, *Nature* 497 (2013) 591–593.