Письма в ЭЧАЯ. 2013. Т. 10, № 3(180). С. 326–331

PROBING NEW PHYSICS SCALE WITH HIGH-ENERGY NEUTRINOS

Salah Eddine Ennadifi [1]

Laboratory of High Energy Physics, Modeling and Simulation, Faculty of Science, University Mohammed V-Agdal, Rabat, Morocco

Motivated by the new physics beyond the Standard Model through the scale at which neutrino mass has origin, we investigate its possible manifestation at low energy within the corresponding propagation of the energetic neutrino. Then, we consider the SN1987A and base on the recorded neutrino data to explore the scale range of the new physics.

Работа посвящена исследованию возможного проявления новой физики, выходящей за рамки Стандартной модели, при низких энергиях с помощью высокоэнергетических нейтрино. Для установления области расстояний, где может проявиться новая физика, были использованы данные SN1987A.

PACS: 11.10.-z; 12.60.-i; 12.10.-g

INTRODUCTION

The standard description of fundamental interactions framed by gauge theories relying on the invariance of the Lagrangian with respect to a group of local transformations provides an accurate description of particle physics phenomena [1, 2]. Particle interactions are derived from local symmetries and are explained at a fundamental level by the gauge principle. However, to most of the experimental data, some input parameters are required. Most of these undetermined parameters reflect our lack of understanding of flavor physics [3, 4]. The SM provides no explanation of why there is a mass hierarchy among the fermion masses, and with the discovery of neutrino mass, this quest has received a massive impetus towards the explanation of the existing tiny neutrino mass [5, 6]. The origin of such a small mass compared with other particles that we know has remained mysterious [6, 7]. It is then highly desirable that we should be able to observe some other effects beyond the SM. This would be typically in terms of a new pattern of the neutrino mass where it is possible to understand its mass term coupling as a new effect of a New Physics (NP) whose scale is related to the relevant higher interactions. This is however usually hard to achieve since the NP scale can easily exceed the accessibility of experiments in the predictable future.

Recently, with the progressive interest in neutrino physics, the quest of neutrino properties still receives massive impetus, and many investigations have been proposed to understand

[1] E-mail: ennadifis@gmail.com

the nature and the origin of the existing mass as well as the propagation behavior of the neutrino [8–10]. Long baseline experiments are not the only way to study NP scale in neutrino propagation. A wide variety of distant astrophysical objects are predicted to potentially produce observable fluxes of neutrinos [11, 12]. Among these prospective sources, however, only neutrinos from supernovae have been observed and used for studying the properties and interactions of neutrinos. It has therefore been suggested that the high-energy neutrinos, propagating at speeds different from the velocity of light, leave open the possibility to suspect the NP effect using the time-of-flight data.

In this Letter, motivated by the great interest in the neutrino sector of modern physics, we discuss the neutrino mass and investigate the corresponding NP scale within an effective field theory. We first view the SM as a low-energy theory below an NP scale $M_{\rm NP}$ which is characterized by the scale of the new gauge-invariant coupling generating Majorana tiny neutrino mass. Then, we consider the propagation behavior of the energetic neutrino E_ν to examine the manifestation of the NP scale in the neutrino velocity v_ν over long baselines or timescale experiments. We therefore rely on the SN1987A and base on the recorded neutrino energies and their time delays data to explore the scale of the NP.

1. MOTIVATION FOR NEW PHYSICS

In the SM, neutrinos are left-handed and massless. Hence, to generate massive neutrinos, one needs to invoke new interactions beyond the SM. It is the scale of the underlying theory producing such an effective interaction that we are interested in. Although the amount of experimental information available is still too small to motivate a particular new physics candidate, there are several ways for a particular NP to be chosen over another. The most relevant one is that enlarging the SM to allow nonzero neutrino mass. The simplest way to add neutrino mass to the SM is to lose the renormalizability of the Lagrangian. This allows one to add neutrino term consistent with the SM symmetries as

$$\zeta_{\rm eff} = \zeta_{\rm SM} + \zeta_{\nu_{\rm mass}}, \tag{1}$$

resulting in an exotic coupling correction to the low-energy SM parameters. Being electrically neutral, neutrinos allow for the possibility of Majorana masses. However, such masses are forbidden in the SM and electroweak gauge invariance $SU(2)_L \times U(1)_Y$ forbids the usual four-dimensional Yukawa interactions. So, we must call for an irrelevant operator. This could be in terms of possible invariant higher mass dimensional $d \geqslant 5$ effective operator made out of the SM fields. It parameterizes the effect of the new-physics degrees of freedom on the low-energy theory. Discarding flavor, spinor, and gauge indices, the lowest order operator is [13]

$$O_5 = (\ell h)^2, \tag{2}$$

where ℓ and h stand for the SM lepton doublets and Higgs field, respectively. The issue that we would like to address in this note is what the effective mass operators at a higher mass dimension are when the lowest dimension five operator is not available. This offers the possiblity to envisage higher dimensional operators. Indeed, using the invariant Higgs combination $(h^{\dagger}h)$, the effective neutrino mass operator can then be generally written at any mass dimension in the unique form

$$O_{2n+5} = (\ell h)^2 (h^{\dagger}h)^n, \tag{3}$$

with n a positive integer that will be involved from now on. Thus, underlying theories could then be distinguished by their different contributions to possible neutrino operator dimensions $d(n)$. In this picture, we get the possible dimensions of the neutrino mass operator

$$d(n) = 2n + 5 = 5, 7, 9 \ldots \tag{4}$$

The appearance of such an operator is more general and would be expected to occur in any theory in which lepton number was violated at some high scale [14–16]. This operator is dimensionally reduced by inverse powers of the scale of the NP, and then the new coupling correction (1) to the low-energy SM parameters reads as

$$\zeta_{\nu_{\text{mass}}} = \frac{y_\nu}{M_{\text{NP}}^{2n+1}} (\ell h)^2 (h^{\dagger}h)^n, \tag{5}$$

where $y_\nu / M_{\text{NP}}^{2n+1}$ stands now for the effective Yukawa coupling constant. This leads, after electroweak symmetry breaking: $SU(2)_L \times U(1)_Y \to U(1)_{\text{em}}$, to a suppressed Majorana neutrino mass

$$m_\nu \simeq y_\nu \frac{\langle h \rangle^{2n+2}}{M_{\text{NP}}^{2n+1}}, \tag{6}$$

where $\langle h \rangle$ is the Higgs vev. If the scale M_{NP} is huge, one may think that this operator is generated by some gravitational Planck scale effects, so that $M_{\text{NP}} \sim M_{\text{Pl}}$ and $y_\nu \sim 1$ [17]. In this case, however, there is no hope of direct observation of the relative NP and the corresponding neutrino masses $m_\nu \ll$ eV might be too small to explain the correct masses. Therefore, new scales of physics below M_{Pl} must exist to give the desired mass to neutrinos.

Although we do not have a fully consistent theory at hand, we can get a window to the NP scale M_{NP} by considering its effect that might be felt in the neutrino dynamics at low energy.

2. NEUTRINO PROPAGATION

The existence of the higher mass dimensional parameter M_{NP} behind neutrino mass is highly expected to manifest itself in the neutrino sector at low energy. In this approach, the propagation of the neutrino is not immune, unlike the other particles, to the effect of the NP. This could be considered at the neutrino dynamics where its energy E_ν depends not only on the momentum p_ν, but also on the mass scale M_{NP}. Indeed, with the neutrino mass (1), the dispersion relation for the propagating neutrino reads[1]

$$E_\nu^2 \simeq p_\nu^2 + y_\nu^2 \frac{\langle h \rangle^{4n+4}}{M_{\text{NP}}^{4n+2}}. \tag{7}$$

[1] We use natural units $c = \hbar = 1$.

With the smallness of the neutrino mass compared to its energy $y_\nu \langle h\rangle^{2n+2}/M_{\rm NP}^{2n+1} \ll E_\nu$, the corresponding effective neutrino velocity is

$$v_\nu \simeq 1 - \frac{y_\nu^2 \langle h\rangle^{4n+4}}{2E_\nu^2 M_{\rm NP}^{4n+2}}, \tag{8}$$

where now $\sim y_\nu^2 \langle h\rangle^{4n+4}/2E_\nu^2 M_{\rm NP}^{4n+2}$ is the energy-dependent retardation effect, from the speed of light, undergone by the propagating neutrino. This could then be experienced, with respect to a light ray propagating with speed $c = 1$ and emitted by the same source at a distance d from the detector, by the neutrino time delay δt_ν^c

$$\delta t_{\nu-c}(E_\nu) \simeq d \frac{y_\nu^2 \langle h\rangle^{4n+4}}{2E_\nu^2 M_{\rm NP}^{4n+2}}. \tag{9}$$

For the terrestrial long baseline experiments $d \sim R_\odot \sim 10^6$ m, the corresponding time delay values could be of submillion seconds $\delta t_{\nu-c} < 10^{-6}$ s, and an experimental time resolution at least of such an order is then required to detect such effects. Thus, it is clear that, in order to probe such conjectrued NP effects, which must be distinguished from the effects of conventional media, there is a premium on distant pulsed sources that emit neutrinos at the highest available energy, the neutrinos with their low interaction cross sections may then provide the best prospects for the highest-energy quanta from the largest distances.

3. SN1987A CONSTRAINTS

Core collapse supernovae are formidable sources of neutrinos as almost the total energy of the explosion is carried away by a burst of neutrinos. The large numbers of neutrinos produced by the nuclear processes in stellar cores are of $\sim$ MeV energies. The feeble interaction of neutrinos with matter ensures that they exit the core and star with near 100% transmission. This makes neutrinos a unique probe of stellar astrophysics. The detection of neutrinos from SN1987A has proven to be among the most fruitful experiments in the heavenly laboratory for the constraining of the possible NP effect. In principle, crossing data from sources of neutrino and gamma rays can allow one to check time coincidence or delay, due to the huge distance of the source of the neutrinos, which is in the Large Magellanic Cloud at about

$$d_{\rm SN} \simeq 50 \text{ kpc} \simeq 168{,}000 \text{ l.y.} \tag{10}$$

from the Earth, offering an opportunity to observe neutrinos over a baseline that is roughly 10^{10} times longer than that traveled by solar neutrinos. With such a far high energy neutrino emiting source, the handful of events recorded provide then a powerful tool to bound scenarios of the NP high scale $\sim M_{\rm NP}$. In particular, a total of 24 neutrinos were observed by three different detectors in the seconds following the SN1987A [18–20]. Because of the long intergalactic path (10) traveled by the energetic neutrino $E_\nu^{\rm SN}$, the resulting time delay (9) might be largely amplified due to the corresponding long time of flight

$$t_{\nu_{\rm SN}} \simeq d_{\rm SN} \left(1 + \frac{y_\nu^2 \langle h\rangle^{4n+4}}{2E_\nu^2 M_{\rm NP}^{4n+2}}\right) \simeq 168{,}000 \text{ y}, \tag{11}$$

where $d_{\rm SN}$ is the light travel time from SN1987A. This would offer the possibility to probe the scale $\sim M_{\rm NP}$ of the NP. This could be done by using the time delay difference, with respect to the speed of light $c = 1$, between the highest $E_{\nu_{\rm SN}}^{\rm high}$ and the lowest $E_{\nu_{\rm SN}}^{\rm low}$ detected neutrinos

$$\Delta t_{\nu_{\rm SN}} = \delta t_{\nu_{\rm SN}-c}^{\rm high} - \delta t_{\nu_{\rm SN}-c}^{\rm low} \simeq d_{\rm SN} \frac{y_\nu^2 \langle h \rangle^{4n+4} \left[(E_{\nu_{\rm SN}}^{\rm high})^2 - (E_{\nu_{\rm SN}}^{\rm low})^2 \right]}{2 M_{\rm NP}^{2n+2} (E_{\nu_{\rm SN}}^{\rm high})^2 (E_{\nu_{\rm SN}}^{\rm low})^2}. \tag{12}$$

Then, by referring to the essential SN1987A data and leaving out the anomalous events [21], the neutrino energies spread over a range $E_{\nu_{\rm SN}}^{\rm low} \sim 6$ MeV $< E_{\nu_{\rm SN}} < E_{\nu_{\rm SN}}^{\rm high} \sim 20$ MeV and their detection times spread around $\Delta t_\nu \simeq 10$ s. With this, the relation (12) allows us to approach the NP scale

$$M_{\rm NP} \simeq \langle h \rangle^2 \sqrt[2n+2]{d_{\rm SN} \frac{y_\nu^2 \left[(E_{\nu_{\rm SN}}^{\rm high})^2 - (E_{\nu_{\rm SN}}^{\rm low})^2 \right]}{2 \Delta t_{\nu_{\rm SN}} (E_{\nu_{\rm SN}}^{\rm high})^2 (E_{\nu_{\rm SN}}^{\rm low})^2}} \simeq 10^{\frac{4n+9}{n+1}} \text{ GeV}. \tag{13}$$

Taking $\langle h \rangle \sim 100$ GeV and $y_\nu \sim 1$, formula (13) finally allows one to explore the possible range of the NP scale

$$M_{\rm NP}(n)\Big|_{n \to +\infty} \simeq 10^4 \text{ GeV} \leqslant M_{\rm NP}(n) \leqslant M_{\rm NP}(n)\Big|_{=0} \simeq 10^9 \text{ GeV}. \tag{14}$$

Though it could be apparently above the reach of the recent experiments, seen that experiments probe higher energies and results become more precise, the chance to detect the trace of the NP, i.e., possible new heavy particles, new interactions..., remains enhanced.

CONCLUSION

We have shown that the effective field theory provides a framework where one can derive stringent bounds and effects of the NP on the low-energy theory. Since any model of NP has to recover the SM at low energy, we have required gauge invariance under the SM gauge group and studied the corresponding effective theory. In particular, we have considered the fact of the existing tiny neutrino mass to argue that NP may very well appear next in the form of higher order couplings involving neutrino with high suppressing effect. To probe the NP scale $M_{\rm NP}$, we have investigated its possible effect at low energy in the neutrino dynamics. In particular, we have considered the corresponding neutrino propagation velocity and discussed NP physics manifestation through the time delay $\delta t_{\nu-c}(E_\nu)$ with respect to the speed of light, and then mentioned its detection hardness over terrestrial long basline experiemnts because of the high scale $M_{\rm NP}$ and the need of distant astrophysical source of high-energy neutrinos. We have considered the SN1987A event where the cumulated time delay during the long time of flight $t_{\rm SN} \simeq 168{,}000$ y becomes significant. This, based on the essential recorded neutrino data, has allowed us to explore the possible range of the NP scale $10^4 \leqslant M_{\rm NP}(n) \leqslant 10^9$ GeV.

Although neutrinos have underlied much of our thinking about NP beyond the SM since it is an argument for an NP that could be felt at some particular, accessible energy scale, we still believe that neutrinos have not yet exhausted their ability to surprise us and shape our understanding of nature. More information is expected in the coming several years.

Acknowledgements. The author wishes to thank URAC 09/CNRST.

REFERENCES

1. *Quigg C.* Gauge Theories of the Strong, Weak, and Electromagnetic Interactions. N. Y.: Benjamin-Cummings Publishing Company, Inc., 1983.
2. *Cheng T. P., Li L. F.* Gauge Theories of Elementary Particle Physics. London: Oxford Univ. Press, 1984.
3. *Camilleri L., Lisi E., Wilkerson J. F.* Neutrino Masses and Mixings: Status and Prospects // Ann. Rev. Nucl. Part. Sci. 2008. V. 58. P. 343.
4. *Mohapatra R. N. et al.* Theory of Neutrinos: A White Paper // Rep. Prog. Phys. 2007. V. 70. P. 1757.
5. *Ennadifi S. E., Belhaj A., Saidi E. H.* On Fermion Mass Hierarchy from Flavor-Dependent Yukawas // J. Phys. G: Nucl. Part. Phys. 2011. V. 38.
6. *Mohapatra R. N., Senjanovic G.* Neutrino Mass and Spontaneous Parity Nonconservation // Phys. Rev. Lett. 1980. V. 44. P. 912.
7. *Minkowski P.* $\mu \to e\gamma$ at a Rate of One out of 10^9 Muon Decays // Phys. Lett. B. 1977. V. 67. P. 421.
8. *Konoplya R. A.* Superluminal Neutrinos and the Tachyon's Stability in the Rotating Universe // Phys. Lett. B. 2012. V. 706. P. 451–455.
9. *Amelino-Camelia G. et al.* Relative Locality and the Soccer Ball Problem. arXiv:hepth/1110.0521.
10. *Gubser S. S.* Superluminal Neutrinos and Extra Dimensions: Constraints from the Null Energy Condition // Phys. Lett. B. 2011. V. 705. P. 279.
11. *Halzen F., Hooper D.* High-Energy Neutrino Astronomy: The Cosmic Ray Connection // Rep. Prog. Phys. 2002. V. 65. P. 1025–1078.
12. *John Beacom F.* The Diffuse Supernova Neutrino Background // Ann. Rev. Nucl. Part. Sci. 1990. V. 40. P. 181–212.
13. *Weinberg S.* Baryon and Lepton-Nonconserving Processes // Phys. Rev. Lett. 1979. V. 43. P. 1566.
14. *Babu K. S., Nandi S., Tavartkiladze Z.* New Mechanism for Neutrino Mass Generation and Triply Charged Higgs Bosons at the LHC // Phys. Rev. D. 2009. V. 80. P. 071702.
15. *Wilczek F., Zee A.* Operator Analysis of Nucleon Decay // Phys. Rev. Lett. 1979. V. 43. P. 1571.
16. *Buchmuller W., Wyler D.* Effective Lagrangian Analysis of New Interactions and Flavor Conservation // Nucl. Phys. B. 1986. V. 268. P. 621.
17. *Barbieri R., Ellis J., Gaillard M. K.* // Phys. Lett. B. 1980. V. 90. P. 249.
18. *Hirata K. et al. (KAMIOKANDE-II Collab.)* // Phys. Rev. Lett. 1987. V. 58. P. 1490.
19. *Bionta R. M. et al. (IMB Collab.)* // Ibid. P. 1494.
20. *Alekseev E. N. et al.* // JETP Lett. 1987. V. 45. P. 589.
21. *Hari Dass N. D. et al.* // Current Science. 1987. V. 56, No. 12.

Received on July 26, 2012.