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SUPERLUMINAL NEUTRINOS IN THE FRAMEWORK OF EXTENDED STANDARD MODEL

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Abstract

The concept of superluminal neutrinos originated from the first OPERA experiment is explored in light of the existence of imaginary mass, although the result of the future experiments negating such concept does not affect the model proposed in this article. It may be developed when the mass matrix of the Dirac as well as Majorana neutrino field is diagonalized. One eigenvalue of such diagonalized mass matrix is found to be imaginary, but large in magnitude; another one is obtained as very small but real. It is found that both of the resulting fields are the mixture of left handed as well as right handed fields unlike the earlier concept of seesaw mechanism. Such treatment is also carried out for all three flavors of neutrinos, which result six mass eigenstates, three imaginary and three real. The mass generation of neutrino in the framework of left-right symmetric model is examined and the suitability of SO(4) model is indicated as it is consistent in the present context. The oscillation in the OPERA experiment is considered as the two fold process in which mass eigenstates doublet having imaginary mass is dominated over that having real mass and thus the neutrinos are found to be superluminal.

Keywords and phrases: superluminal neutrinos, OPERA, special relativity, imaginary mass of neutrino, left-right symmetric model.

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1. Introduction

The first result of the OPERA experiment [1] (OPERA+[1]) has explored a new insight to the history of experimental as well as theoretical physics. An astonishing result of OPERA+ put a question mark on the feasibility of Special Theory of Relativity (STR) [4], although the phenomenon like Cherenkov radiation [5] could be an evidence of superluminicity. No doubt, it is a revolutionary observation that neutrino may run faster than light. Therefore, either one has to repair the basic tools of the STR or to give a new model which can explain the existence of the neutrino mass that is consistent with OPERA+ observation. It is worth noting that the result of OPERA– experiment has negated the possibility of the existence of superluminal neutrinos. In this article, a model is proposed which can incorporate both of the possibilities - superluminal as well as subluminal neutrinos. A series of efforts have been coming out just after publishing the result OPERA+ to address this important issue. In the $\nu_\mu \to \nu_\tau$ channel of neutrino oscillations $\text{OPERA}+$ has measured the neutrino velocity as $(v - c)/c = [2.48 \pm 0.28\,(\text{stat}) \pm 0.30\,(\text{sys})] \times 10^{-5}$, contradicting the stringent limit obtained by SN1987A data in the energy range of few MeV [6, 7, 8]. It indicates that the muon neutrinos propagate faster than light in vacuum. It is worth noting that Lingli and Ma [9] interpreted this as a signal of Lorentz violation based on theoretical attempt [10, 11]. Hannested and Sloth [12] considered the superluminal behavior as the existence of light sterile neutrinos which can propagate in the higher dimensional bulk. Kehagias [13] looks that one as a local effect caused by the scalar filed originated from the earth. He predicted the coupling of the scalar field to the neutrinos can change the background metric, resulting the superluminal effect. Such superluminosity was also explained in the framework of extra-dimension [14]. Oda and Taira [15] considered this effect due to the existence of a new gauge field sourced by the earth. The superluminal behavior of neutrinos is also tried to be explained by tachyonic behavior [16]. The idea of tachyonic neutrino has already been come into existence [17, 18, 19]. Tachyons have their superluminal velocity not due to acceleration, but because they are born with $v > c.$ There are another two kind of particles having their velocity luminal and subluminal, known as luxons and bradyons [20], respectively.

[1]Throughout the literature OPERA+ stands for the result interpreting superluminal, whereas OPERA– [2, 3] is that in which neutrinos found to be subluminal as usual case.

In the present article, a theoretical model is proposed to address that superluminal issue. The motivation comes from the OPERA + result. According to the special relativity any particle having its velocity greater than that of light (Tachyon) must have purely imaginary mass, and therefore, it is not possible to detect such particle by any experiment. If the neutrinos are superluminal then they must be undetectable and should have imaginary mass contradicting the smallness of the neutrino mass, evident from various experiments. Then one can think there must be an underlying mechanism to have the neutrino velocity more than that of light in the $\nu_\mu \rightarrow \nu_\tau$ channel of OPERA + experiment. In this article, a theoretical model is proposed to explain such mechanism. First of all, it is considered that neutrino must have some imaginary mass, which makes it tachyonic in nature to exceed its speed the value of *c*. In the next section, it is explained how one mass eigenstate of the neutrino may have the imaginary mass, whereas the other one becomes real in terms of the mass. In Section 3, different mass generation mechanisms are outlined and it is mentioned that out of those which one may be consistent to the model proposed in the present article. Finally, the underlying mechanism that makes the neutrino superluminal in the OPERA + experiment is described. The present model also includes the possibility of the superluminicity being disproved by any other experiment.

2. Existence of Imaginary Mass of Neutrino

Beyond the standard model, the seesaw mechanism in favor of neutrino mass generation is well accepted theory. It is believed that through seesaw the left handed neutrino acquires a very little mass, whereas, on other side, the right handed candidate has an extremely heavy mass. But the superluminal behavior of neutrino compels us to reconsider that understanding. The neutrino mass includes the Dirac as well as Majorana mass terms. The Lagrangian of the neutrino field incorporating both of those mass terms is as follows:

$$2\mathcal{L} = \begin{pmatrix} \overline{\nu}_L & \overline{\nu}^c{}_L \end{pmatrix} \begin{pmatrix} m_L & m_D \\ m_D & m_L \end{pmatrix} \begin{pmatrix} \nu_R^c \\ \nu_R \end{pmatrix} + h.c. \tag{1}$$

The ν_L and ν_R^c are the spinors of the active neutrinos, whereas ν_R and ν_L^c are those which cannot be observed in nature. The neutrino mass matrix, given in the equation (1) can be diagonalized to obtain the following expression.

$$2\mathcal{L} = m_1\bar{\phi}_1\phi_1 + m_2\bar{\phi}_2\phi_2 \tag{2}$$

with introducing the angle θ so that

$$\tan 2\theta = \frac{2m_D}{m_R - m_L}. \tag{3}$$

The corresponding mass eigenvalues can be calculated as

$$m_{1,2} = \frac{\varepsilon_{1,2}}{2}\left[(m_L + m_R) \pm \sqrt{(m_L - m_R^2) + 4m_D^2}\right] \tag{4}$$

with $|\varepsilon_{1,2}| = 1.$

The fields ϕ_1 and ϕ_2, present in the equation (2) have the form

$$\phi_1 = \cos\theta(\nu_L + \varepsilon_1\nu_R^c) - \sin\theta(\nu_L^c + \varepsilon_1\nu_R), \tag{5}$$

$$\phi_2 = \sin\theta(\nu_L + \varepsilon_2\nu_R^c) + \cos\theta(\nu_L^c + \varepsilon_2\nu_R). \tag{6}$$

That is the basic building block of the neutrino mass model. To emerge the neutrino as a purely Dirac particle, m_L and m_R are taken to be zero, whereas purely Majorana field is evolved by considering $m_D = 0.$ The most interesting and well accepted case is seesaw mechanism, in which $m_R >> m_D$ and $m_L \to 0.$ In that case mass eigenvalues become $m_1 \approx \frac{m_D^2}{m_R}$ and $m_2 \approx m_R.$ Here case ϕ_1 is evolved as left handed neutrino and right handed antineutrino field, whereas ϕ_2 becomes right handed neutrino and left handed antineutrino field that is hard to observe in the nature. Thus according to the seesaw, the neutrino associated to ϕ_1 has a tiny mass and becomes left-handed in nature; but there suppose to exist another kind of right handed massive neutrino which is yet to found in nature, may be due to its super massive structure.

The well accepted seesaw mechanism fails to explain the superluminal nature of neutrinos. Therefore, a new theory is to be proposed which will be able to interpret the OPERA + result. The basic assumption of the theoretical model proposed in this article is that the field ν_L and ν_R are symmetric in every respect; which follows the mass $m_L = m_R = m_M$ (say). In fact there is no good reason to assume that the neutrino mass associated with right handed neutrino is much heavier than that of left handed neutrino, which is a foundation of seesaw mechanism. This is quite comfortable to consider both of those masses are same. In this circumstance equation (4) gives us

$$m_{1,2} = \varepsilon_{1,2}(m_M \pm m_D). \tag{7}$$

We are strongly motivated by the result of the OPERA + experiment and we must incorporate the possibility of the existence of imaginary mass of the neutrino in this model. The special theory of relativity reveals that any kind of superluminal particle must have imaginary mass and vice versa. That is also true that the neutrino is not superluminal all the time, rather only one experiment shows the superluminal nature of neutrino and hence the imaginary mass; but there are several instants where the neutrinos are found to be subluminal having tiny mass. To fit such criteria in this model it is assumed $\varepsilon_1 = i$, $\varepsilon_2 = 1$ and $m_D < m_M$ (but approximately equal), which result

$$m_1 = i(m_M + m_D), \qquad m_2 = m_M - m_D \to 0. \tag{8}$$

This assumption readily makes $\theta = \frac{\pi}{4}$. The ϕ_1 and ϕ_2 fields become

$$\phi_1 = \phi_{Im} = [(\nu_L - \nu_L^c) + i(\nu_R + \nu_R^c)], \tag{9}$$

$$\phi_2 = \phi_{Re} = \frac{1}{2}[\nu + \nu^c]. \tag{10}$$

ϕ_{Re} is the real neutrino field having tiny mass. This is not necessarily left handed, the right hand field is also included here. Such field is, therefore, clearly subluminal. But, the field ϕ_{Im} bears imaginary mass and becomes superluminal nature. The neutrino mass evolved in that sense is also seesaw in nature, although the $|m_1|$ may not be high enough. Of course this is a new kind of seesaw mechanism, which is essentially different from the earlier concept of seesaw mechanisms. Therefore, throughout the literature, we shall mention it as a new seesaw, whereas Type-I, Type-II and Type-III will be collectively mentioned as old seesaw.

The above discussion was framed in the perspective of neutrino with single flavor. In the nature three kinds of neutrinos flavor have been observed. Therefore, in the general considerations the mass m_D, m_L and m_R will be replaced by the 3×3

mass matrices M_D, M_L and M_R. The general symmetric mass matrices then become

$$M = \begin{pmatrix} M_L & M_D \\ M_D^T & M_R \end{pmatrix} \quad (11)$$

with $M_L \equiv M_R$.

Diagonalizing the M, we can obtain 6 mass eigenstates ϕ_{Im}^k and ϕ_{Re}^k $(k = 1, 2, 3)$ with associated 6 mass eigenvalues, alternatively imaginary and real. Thus each flavor eigenstate of neutrinos corresponds an imaginary mass eigenvalue along with a real one. Therefore, it may be said that a flavor of neutrino forms a doublet of mass eigenstates ϕ_{Re}^k, ϕ_{Im}^k. The ϕ_{Re}^k is bradyonic in nature and ϕ_{Im}^k becomes tachyon; thus as a whole neutrino may be considered as elvisebrions [20].

3. Generation of Neutrino Mass

In the earlier days of the development of particle physics, the neutrino was supposed to be massless. Therefore, in the framework of standard model there is no room for the generation of neutrino mass as $SU(2)_L \times U(1)_Y$ symmetry is broken down spontaneously. The concept of neutrino mass came into existence when Pontecorvo proposed the neutrino oscillation phenomena would lead to the existence of tiny neutrino mass [21]. Then there was need of a theoretical model which could explain the generation of neutrino mass as well as that of other elementary particles. The effort was started to extend the standard model of electro-weak interaction theory. There are several models describing the generation of neutrino mass by extending the standard model. The neutrino mass generation may be incorporated with a minimal extension of the standard model [22, 23]. Neutrino mass could also be generated in the extended standard model without including the right handed neutrino in the theory [24]. An elegant way to generate the neutrino mass is to include the right handed neutrinos in the model which leads to the left right symmetric model [25, 26, 27]. When the right handed neutrino is included in the standard model the global $B - L$ symmetry becomes gaugable and the $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ becomes the gauge group of the left right symmetric model [28, 29]. The old seesaw structure of neutrino mass [30] emerges in this left-right symmetric model.

Eventually we would like to discard the possibility which leads to the old seesaw structure of neutrino mass. Therefore, B - L symmetry breaking phenomena should not be taken into account. Instead, we may think about the neutrino mass generation in $SO(4)$ model [31]. According to this model no Majorana mass is created by the spontaneous breakdown of $SU(2)_L$ symmetry and most importantly, the Dirac mass generated in this model is not essentially seesaw (old) in nature. Still the Majorana mass term, which is approximately equal to the Dirac mass term according to this theory, are to be incorporated in the model. The Majorana field may be generated by introducing dimension five operator [32] in the unbroken Lagrangian. After the breaking of spontaneous symmetry, the neutrino gets Dirac as well as Majorana mass terms defined in equation (1). The discussion in the previous section reveals that the real mass of the neutrino is extremely small as the Dirac and Majorana masses are very close to each other. On the other hand the magnitude of imaginary mass may not be high enough compared to the other leptons, but much higher than the real mass, which results a new kind of seesaw.

4. Discussion

According to the old seesaw model the right handed neutrino is hardly found in nature due to its extremely high mass. But as per the model proposed in this article, one wing of a neutrino flavor cannot be found not because of its high mass, but as it has imaginary mass and thus becomes superluminal in nature. The other wing exists with its extremely small mass subject to the experimental verification of its right handed nature. In other words, the present theoretical model cannot discard the possibility of the existence of right handed neutrino even in the low energy range. In the old seesaw model, one mass eigenstate of neutrinos remains with a heavy mass, but may be sterile in nature since completely right handed. The active one having small mass consists of purely left handed state. But according to the model proposed in this article, the mass eigenstate having high but imaginary mass is undetected because of its superluminal nature. In the framework of this model, both of the mass eigenstates are mixture of left handed as well as right handed states. Therefore unlike the earlier concept the flavor eigenstates are the mixtures of all complex mass eigenstates. Let us explain the situation in more details in the view to explain the OPERA + result. In that experiment the neutrino oscillation in the $\nu_\mu \to \nu_\tau$ has been taken into account. Here the flavor eigenstates ν_μ and ν_τ are the mixtures of

$\phi^1 = \phi^1_{Re} + i\phi^1_{Im}$ and $\phi^2 = \phi^2_{Re} + i\phi^2_{Im}$. In the low energy limit, only the real part of ϕ^1 and ϕ^2 are expected to take part in the oscillation phenomena. But in the intermediate state, we cannot exclude the possibility of the participation of ϕ^1_{Im} and ϕ^2_{Im} assuming $(E^k)^2 = (p)^2 - |m_1^k|^2 (k = 1, 2)$, where $p >> |m_1^k|$ but E^k remains in the same energy range as that of initial ν_μ. Thus the neutrino oscillation may occur in two different channels, one is conventional $(\phi^1_{Re}, \phi^2_{Re})$ and the other is $(\phi^1_{Im}, \phi^2_{Im})$. In the OPERA + experiment of $\nu_\mu \to \nu_\tau$ oscillation since the masses of the $(\phi^1_{Im}, \phi^2_{Im})$ channel are imaginary, it is obvious that the neutrinos cross the luminal limit. On the other hand the OPERA – experiment [2, 3] resulted subluminal neutrinos because neutrino oscillations must take place in the $(\phi^1_{Re}, \phi^2_{Re})$ channel. Therefore, it can be considered that the neutrino oscillation is a two fold process, one occurs within our light cone and another takes place outside of it, without changing the overall energy range. If the oscillation event in the superluminal region is dominated by that of subluminal region then the overall neutrino speed due to $\nu_\mu \to \nu_\tau$ oscillation crosses the luminal barrier; in the reverse case the neutrino speed remains subluminal. The OPERA + experiment found the neutrino speed greater than that of light since here superluminal event would dominate over the subluminal one. Measuring the neutrino speed less than that of light by OPERA – experiment cannot lead to negate the revolutionary result of OPERA+, rather one can say that the subluminal event should dominate over the superluminal event in that case.

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