Implications of Weak-Interaction Space Deformation for Neutrino Mass Measurements

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Abstract

The negative values for the squares of both electron and muon neutrino masses obtained in recent experiments are explained as a possible consequence of a change in metric within the weak-interaction volume in the energy-momentum representation. Using a model inspired by a combination of the general theory of relativity and the theory of deformation for continuous media, it is shown that the negative value of the square of the neutrino mass can be obtained without violating allowed physical limits. The consequence is that the negative value is not necessary unphysical.

1 Introduction

There has recently been some concern over the significant negative values obtained for the square of the neutrino mass, for both the electron neutrino measured in nuclear $\beta$-decay, and the muon neutrino measured in $\pi^+ \rightarrow \mu^+ \nu_\mu$ decay. In these measurements, the probability that the square of the electron neutrino mass $m_{\nu_e}^2$ is positive is only 3% [1], while from most recent measurements the square of the muon neutrino mass $m_{\nu_\mu}^2$ is negative by 6.1 or 0.9 standard deviations, depending on the choice of the pion rest mass value [1, 2].

While it may be argued that the negative values obtained for $m_{\nu_e}^2$ and $m_{\nu_\mu}^2$ are a consequence of systematic errors in these measurements which are still not understood, we must also investigate the possibility that there is a physical underlay for the measured results. In this paper, we therefore propose a mechanism which, in principle, allows the measured square of the neutrino mass to be negative, while at the same time does not cross allowed physical mass limits. Our assumption is that the negative values of $m_{\nu_e}^2$ and $m_{\nu_\mu}^2$ are not consequences of the dynamics of the decay, but rather are the result of the geometry, or metric, of the small volume in which the weak interaction drives the decay.

The large masses of the intermediate vector bosons $W^+$, $W^-$ and $Z^0$ result in a very short range for the weak interaction. The interaction volume is small enough to ensure the success of the Fermi $\beta$-decay theory, in which the interaction is assumed to be a four-particle coupling. One may expect that the metric valid in vacuum is not necessarily valid in a volume with such a small dimension, especially considering that we already have a change in vacuum metric in the presence of mass, in accordance with the general theory of relativity.

In this paper we study the consequence of the change of metric within the weak-interaction volume on the measured value of the square of the neutrino mass. In our model, we make minimal changes to the metric, in a manner which is as simple as possible, and only as much as necessary to make it different from the vacuum metric, yet at the same time have clear physical consequences.

2 General basis for the model

The basic idea of this model is essentially the same as that of the general theory of relativity. Translated for the purpose of this paper, it means that the metric of space deforms at the distance scale comparable to the range of the weak interaction. The majority of the necessary mathematical formalism can be taken from the theory of the deformation of continuous media, and extended to 4-dimensional Minkowski space. We can explore the consequences of this space

\footnote{We will refer to both neutrino and antineutrino just as neutrino.}
deformation without having the necessity to propose the exact mechanism which causes the deformation.

We define two 4-dimensional Minkowski spaces, an undeformed space $C$ and a deformed space $C^*$. Let us choose a point $P(\xi^0, \xi^1, \xi^2, \xi^3)$ in the undeformed space $C$. Under the deformation of the space $C$, the point $P(\xi^0, \xi^1, \xi^2, \xi^3)$ from the undeformed space is mapped into the point $P^*(\xi^{0*}, \xi^{1*}, \xi^{2*}, \xi^{3*})$ of the deformed space $C^*$. The space deformation is defined by the equations analogous to the Lagrangian coordinate point of view \[4, 5\]:

\[
\begin{align*}
\xi^{0*} &= \xi^{0*}(\xi^0, \xi^1, \xi^2, \xi^3); & \xi^{1*} &= \xi^{1*}(\xi^0, \xi^1, \xi^2, \xi^3); \\
\xi^{2*} &= \xi^{2*}(\xi^0, \xi^1, \xi^2, \xi^3); & \xi^{3*} &= \xi^{3*}(\xi^0, \xi^1, \xi^2, \xi^3),
\end{align*}
\]

or the equations analogous to the Euler coordinate point of view:

\[
\begin{align*}
\xi^0 &= \xi^0(\xi^{0*}, \xi^{1*}, \xi^{2*}, \xi^{3*}); & \xi^1 &= \xi^1(\xi^{0*}, \xi^{1*}, \xi^{2*}, \xi^{3*}); \\
\xi^2 &= \xi^2(\xi^{0*}, \xi^{1*}, \xi^{2*}, \xi^{3*}); & \xi^3 &= \xi^3(\xi^{0*}, \xi^{1*}, \xi^{2*}, \xi^{3*}).
\end{align*}
\]

These functions must be continuous and differentiable in the space $C$ ($C^*$), because a discontinuity in these functions would imply a “rupture” of the space $C$ ($C^*$).

Following the classical theory of elasticity \[4, 5\] we define the infinitesimal length $ds$ as a line element $PQ$ between two points $P(\xi^0, \xi^1, \xi^2, \xi^3)$ and $Q(\xi^0 + dt, \xi^1, \xi^2, \xi^3 + dt^3)$, and the infinitesimal length $ds^*$ as a line element $P^*Q^*$ between two points $P^*(\xi^{0*}, \xi^{1*}, \xi^{2*}, \xi^{3*})$ and $Q^*(\xi^{0*} + dt^{0*}, \xi^{1*} + dt^{1*}, \xi^{2*} + dt^{2*}, \xi^{3*} + dt^{3*})$. Under the deformation, the length $ds$ can either be elongated or contracted. The magnification of the deformation is defined as $\frac{ds^*}{ds}$. In the undeformed space $C$, $ds$ is defined as the square root of the invariant form

\[ds^2 = g_{\mu\nu}d\xi^\mu d\xi^\nu,\] \hspace{1cm} (3)

where $g_{\mu\nu}$ are elements of a symmetric tensor $[g_{\mu\nu}]$ defining the metric of the space $C$. The metric tensor $[g_{\mu\nu}]$,

\[
[g_{\mu\nu}] = \begin{bmatrix}
1 & 0 & 0 & 0 \\
0 & -1 & 0 & 0 \\
0 & 0 & -1 & 0 \\
0 & 0 & 0 & -1
\end{bmatrix}, \hspace{1cm} (4)
\]

defines four-dimensional Minkowski space in the orthogonal cartesian representation in the system where the speed of light $c = 1$. The distance between two points $P(t, x, y, z)$ and $Q(t + dt, x + dx, y + dy, z + dz)$, where $t$ represents time and $(x, y, z)$ space, is the square root of the invariant form

\[ds^2 = dt^2 - (dx^2 + dy^2 + dz^2).\] \hspace{1cm} (5)

In the deformed space $C^*$, $ds^*$ is the square root of the invariant form

\[ds^{*2} = g_{\mu\nu}d\xi^{*\mu}d\xi^{*\nu}.\] \hspace{1cm} (6)

In the deformed Minkowski space defined by time $t^*$ and space coordinates $(x^*, y^*, z^*)$, the distance between two points $P^*(t^*, x^*, y^*, z^*)$ and $Q^*(t^* + dt^*, x^* + dx^*, y^* + dy^*, z^* + dz^*)$ is the square root of the invariant form

\[ds^{*2} = dt^{*2} - (dx^{*2} + dy^{*2} + dz^{*2}).\] \hspace{1cm} (7)
Using again general notation, we can express total differentials \((d\xi^*0, d\xi^*1, d\xi^*2, d\xi^*3)\) in terms of total differentials \((d\xi^0, d\xi^1, d\xi^2, d\xi^3)\) by the transformation
\[
d\xi^*\nu = a^{\nu\mu} d\xi^\mu, \tag{8}\]
where
\[
a^{\nu\mu} = \frac{\partial \xi^*\nu}{\partial \xi^\mu}. \tag{9}\]
The measure of deformation \(ds^*2 - ds^2\) can be then calculated as
\[
ds^*2 - ds^2 = g_{\mu\nu}(d\xi^*\mu d\xi^*\nu - d\xi^\mu d\xi^\nu) \]
\[
= (g_{\mu\nu} a^{\mu\nu} - g_{\mu\nu}) d\xi^\mu d\xi^\nu \]
\[
= \epsilon_{\mu\nu} d\xi^\mu d\xi^\nu \tag{10}\]
or
\[
ds^*2 - ds^2 = g_{\mu\nu}(d\xi^*\mu d\xi^*\nu - d\xi^\mu d\xi^\nu) \]
\[
= (g_{\mu\nu} - g_{\mu\nu} b^{\mu\nu} b^{\kappa\nu}) d\xi^*\mu d\xi^*\nu \]
\[
= \eta_{\mu\nu} d\xi^*\mu d\xi^*\nu \tag{11}\]
where
\[
b^{\mu\nu} = \frac{\partial \xi^\nu}{\partial \xi^*\mu}. \tag{12}\]
To simplify the calculation, we can rotate our coordinate system such that the coordinate axes correspond to the principal directions of the deformation tensors \(\epsilon = [\epsilon_{\mu\nu}]\) and \(\eta = [\eta_{\mu\nu}]\). The new coordinate system corresponds to orthogonal directions in the undeformed space which remain orthogonal after deformation \([\mathcal{C}, \mathcal{F}]\). In this case, the quadratic forms in Eq.’s \(10\) and \(11\) reduce to their canonical forms, and the deformation tensors have diagonal form: \(\epsilon = [\epsilon_{\mu\mu}]\) and \(\eta = [\eta_{\mu\mu}]\). The deformation \(ds^*2 - ds^2\) is now
\[
ds^*2 - ds^2 = \epsilon_{\mu\mu} d\xi^\mu d\xi^\mu \tag{13}\]
or
\[
ds^*2 - ds^2 = \eta_{\mu\mu} d\xi^*\mu d\xi^*\mu. \tag{14}\]
We are now in the same position as in the general theory of relativity where the existence of the gravitational potential changes the metric tensor \([\mathcal{C}, \mathcal{F}, \mathcal{G}, \mathcal{H}]\), whose coefficients become functions of the local coordinates and can be written in the general form
\[
[g_{\mu\nu}] = \begin{bmatrix}
    f_{00}(\xi) & 0 & 0 & 0 \\
    0 & f_{11}(\xi) & 0 & 0 \\
    0 & 0 & f_{22}(\xi) & 0 \\
    0 & 0 & 0 & f_{33}(\xi)
\end{bmatrix}. \tag{15}\]
\(f_{\mu\nu}(\xi) = f_{\mu\nu}(\xi^0, \xi^1, \xi^2, \xi^3)\) are functions generating the deformation of four-dimensional space.

In this paper we address the effect of this space deformation on the kinematics in the deformed region. Generally, we can again define two spaces, an undeformed space \(\mathcal{C}\) and a deformed space \(\mathcal{F}\)
\( C^* \). Under the deformation, the point \( P(\pi^0, \pi^1, \pi^2, \pi^3) \) in the undeformed space \( C \), is mapped into the point \( P^*(\pi^0, \pi^1, \pi^2, \pi^3) \) of the deformed space \( C^* \). The invariant form is here defined as

\[ dm^2 = g_{\mu\nu}d\pi^\mu d\pi^\nu. \]  

(16)

Translated into the orthogonal cartesian energy-momentum representation \((E, p_x, p_y, p_z)\), the distance between two points \( P(E, p_x, p_y, p_z) \) and \( Q(E + dE, p_x + dp_x, p_y + dp_y, p_z + dp_z) \) is the square root of the same form as in Eq. 5, i.e.,

\[ dm^2 = dE^2 - (dp_x^2 + dp_y^2 + dp_z^2). \]  

(17)

The effect of the space deformation is analogous to the effect in Eq.’s 13 and 14,

\[ dm^*2 - dm^2 = E_{\mu\mu}d\pi^\mu d\pi^\mu \]  

(18)

and

\[ dm^*2 - dm^2 = G_{\mu\mu}d\pi^*\mu d\pi^*\mu. \]  

(19)

The transformation from the space \( C \) into the space \( C^* \) can be found in analogy with Eq.’s 8 and 9. To relate the transformation coefficients, we postulate that the Heisenberg relations hold even if the space is deformed, and that the number of possible states cannot be increased or decreased by the mechanism causing space deformation. This means that, for each index \( \mu \),

\[ d\xi^\mu d\pi^\mu = d\xi^*\mu d\pi^*\mu. \]  

(20)

As a result, the transformation is

\[ d\xi^*\mu d\pi^*\mu = a^{\mu\mu} d\xi^\nu b^{\mu\nu} d\pi^\nu = \delta^{\mu\nu}d\xi^\nu d\pi^\nu = d\xi^\mu d\pi^\mu, \]  

(21)

obviously \( b^{\mu\mu} = (a^{\mu\mu})^{-1} \), and:

\[ d\pi^*\mu = b^{\mu\mu} d\pi^\mu; \quad d\pi^\mu = a^{\mu\mu} d\pi^*\mu. \]  

(22)

The coefficients \( a^{\mu\mu} \) and \( b^{\mu\mu} \) are defined in Eq.’s 9 and 12.

### 3 Application to the neutrino mass measurement

In this section we study the consequences of the general formalism developed in the previous section for the neutrino mass measurements. Because the claim of this paper is that the negative values of the squares of the electron and muon neutrino masses are a consequence of the change in metric in the weak-interaction volume, the same model should be applied for both types of neutrino. There are many ways to deform the volume, but for the sake of simplicity we choose a very simple model of deformation, with just one free parameter. The model is a copy of the mathematical formalism of a mechanical deformation caused by hydrostatic pressure into our geometry [8]. We also assume that the “time” (or “energy”) component is not affected. In this case, our deformation tensor is given by
\[
[\mathcal{E}_{\mu\nu}] = \begin{bmatrix}
1 & 0 & 0 & 0 \\
0 & -\epsilon & 0 & 0 \\
0 & 0 & -\epsilon & 0 \\
0 & 0 & 0 & -\epsilon \\
\end{bmatrix},
\tag{23}
\]

where \(\epsilon\) is a constant. We note here that in the limit \(\epsilon \to 1\), \([\mathcal{E}_{\mu\nu}] \to [g_{\mu\nu}]\), and the undeformed Minkowski space is recovered. This choice of transformation results in

\[
m_{\nu}^2 = E^2 - (p_x^2 + p_y^2 + p_z^2) = E^2 - \epsilon(p_x^2 + p_y^2 + p_z^2). \tag{24}
\]

The square of the neutrino masses measured in nuclear \(\beta\)-decay and in \(\pi^+ \to \mu^+\nu\mu\) decay are reconstructed using energy and momentum conservation assuming a free space metric. If space is actually deformed, but not taken into account, the free undeformed space metric can result in negative values for the squares of the neutrino masses. Because two separate experimental programs determine the electron neutrino and muon neutrino masses, while our model should describe both cases, we will use the results from the muon neutrino experiments to determine the parameter \(\epsilon\), and then use that value to see the consequences for the case of the electron neutrino measurements.

The muon neutrino mass can be measured from the decay reaction \(\pi^+ \to \mu^+\nu\mu\). For \(\pi^+\) decay at rest in undeformed space, the muon neutrino mass is determined from the kinematic relation

\[
m_\pi = \sqrt{m_{\nu_\mu}^2 + p_\mu^2} + \sqrt{m_\mu^2 + p_\mu^2}, \tag{25}
\]

where momentum conservation has been imposed. If the space is deformed, however, this relation becomes

\[
m_\pi = \sqrt{m_{\nu_\mu}^2 + p_\mu^2} + \sqrt{m_\mu^* + p_\mu^*}. \tag{26}
\]

Assuming that the "true" neutrino mass is zero, then \(m_{\nu_\mu}^2 = 0\), and using the metric tensor defined in Eq. 23, we can calculate the value of the parameter \(\epsilon\) from Eq.'s 25 and 26 via

\[
\sqrt{m_{\nu_\mu}^2 + p_\mu^2} = p_\mu^* = \epsilon p_\mu. \tag{27}
\]

One must notice that \(\sqrt{m_\mu^2 + p_\mu^2} = \sqrt{m_{\nu_\mu}^2 + p_\mu^2}\) because of Eq. 23. The value of \(\epsilon\) is thus determined by the momentum of muons from the pion decay, measured to be \(p_\mu = 29.79207 \pm 0.00024\) MeV/c.

There are two solutions corresponding to two choices of the pion mass, which have been labeled Solution A and Solution B. Solution A, for which \(m_\pi = 139.56782 \pm 0.00037\) MeV and \(m_{\nu_\mu}^2 = -0.143 \pm 0.024\) MeV\(^2\) yields for the parameter \(\epsilon\) a value

\[
\epsilon = 0.999988 \pm 0.000004, \tag{28}
\]

while Solution B with \(m_\pi = 139.56995 \pm 0.00035\) MeV and \(m_{\nu_\mu}^2 = -0.016 \pm 0.023\) MeV\(^2\) yields

\[
\epsilon = 0.9999998 \pm 0.0000004. \tag{29}
\]

\(^2\)This assumption, even if not critical for the discussion in this paper, does have a basis in the experiments which deal with "free" neutrinos, such as neutrino oscillation experiments, and suggest that the neutrino mass is very close to zero [9].
As should have been expected, the value of the parameter $\epsilon$ is very close to 1, suggesting that the space deformation is not very large.

We now apply the same model to the measurement of the electron neutrino rest mass. The electron neutrino rest mass determined from tritium $\beta$-decay is obtained from the shape of the $\beta$-spectrum close to the end-point, expressed as

$$W(E) = AF p(E + m_e) \sum_i W_i(E_{0i} - E) \sqrt{(E_{0i} - E)^2 - m_{\nu_e}^2},$$

(30)

where $A$ is an amplitude, $F$ is the Fermi function, $m_e$ and $m_{\nu_e}$ are the electron and neutrino rest masses, $p$ and $E$ are the electron momentum and kinetic energy, $W_i$ is the relative transition probability to the $i$th molecular final state of corresponding end-point energy $E_{0i}$. Fitting the nuclear $\beta$-decay data with Eq. 30 produces a significant negative value for the square of the electron neutrino mass [1].

We apply the metric deformation parameter $\epsilon$ obtained from the muon neutrino mass measurement to the nuclear $\beta$-decay and electron neutrino mass measurement. We do not lose on generality, but simplify our calculation, by assuming only one molecular final state. In this case, the shape of the $\beta$-spectrum close to the end-point reduces to

$$W(E) \sim p(E + m_e)(E_0 - E) \sqrt{(E_0 - E)^2 - m_{\nu_e}^2}. $$

(31)

If the decay happens in the deformed space $C^*$, where, as in the case of the muon neutrino mass, we assume that the “true” neutrino mass $m_{\nu_e}^* = 0$, then Eq. 31 becomes

$$W(E^*) \sim p^*(E^* + m_{\nu_e}^*)(E_0 - E^*)^2. $$

(32)

All the kinematic quantities in the deformed space can be calculated from the quantities in the undeformed space using the transformation defined by the tensor in Eq. 23 and the value of the parameter $\epsilon$ as determined from the $\pi^+ \to \mu^+\nu_\mu$ decay. Thus $p^* = \epsilon p$, and, in a non-relativistic approximation, $E^* = \epsilon^2 E$, and $m_{\nu_e}^* = m_e$. We do not transform $E_0$ because it is a parameter in the distribution, and therefore a constant. Then, Eq. 32 become

$$W(E, \epsilon) \sim \epsilon p(\epsilon^2 E + m_e)(E_0 - \epsilon^2 E)^2. $$

(33)

Assuming the weak-interaction volume has deformed metrics and the “true” neutrino mass is zero, Eq. 33 represents the shape of the $\beta$-spectrum. By assuming that the parameter $\epsilon$ is constant and that the transformation affects only momentum and not the total energy, as shown by Eq. 23, we restrict ourselves to a very simple model. Even under these simplifying assumptions, there is sufficient new information contained in Eq. 33 that we can study several experimental signatures resulting from this distribution:

- We verified that the shape of the distribution represented by Eq. 33 is consistent with existing measurements. In Fig 1. we plot the deviation of this distribution for $\epsilon = 0.999988$ from the distribution for $\epsilon = 1$, corresponding to undeformed space, normalized to the undeformed distribution. It is clear that over the entire electron energy spectrum, except for the region very close to the end-point, the deviation is sufficiently small that it could not have been observed given the precision of existing experimental measurements. This is even more true for $\epsilon = 0.999998$. 

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We plot the distribution in the region close to the end-point in Fig. 2, where we show that the values corresponding to $\epsilon = 0.999988$ lay above the undeformed distribution, consistent with the distribution resulting in $m_{\nu_e}^2 < 0$.

If we assume that the electron energy distribution is described by Eq. 33, but is fitted by the distribution with a shape described by Eq. 30, there would be a mismatch at some point in the spectrum. In Fig. 3 one can easily see this mismatch close the end-point for the case when the distribution is generated by Eq. 33 with parameter $\epsilon = 0.999988$, and then fit with the distribution with shape described by Eq. 30. This mismatch results in a bump close to the end-point, as shown in Fig. 4, experimentally corresponding to an overestimation of the counting rate. This effect is observed in many electron neutrino mass measurements [1, 10, 11, 12, 13, 14, 15].

Finally, it has also been observed experimentally that $m_{\nu_e}^2$ is dragged further below the endpoint as a function of the lower limit of $E$ in the fit interval [10, 13]. The $W(E)$ distribution generated using Eq. 33 with parameter $\epsilon = 0.999988$ and then fit using the distribution with shape described Eq. 30 is plotted in Fig. 5, showing that the same effect is observed; namely that $m_{\nu_e}^2$ becomes more negative as the fit interval is increased by lowering the limit of $E$.

A more realistic deformation of space, in which there would be more than one free parameter, and whose parameters could be energy and momentum dependent (generally as in Eq. 15), would result in a different relation in the mass-energy equation, where the calculation would be more complex and harder to relate to existing experimental results. Finding the exact deformation function is far beyond the scope of this paper, and our model is made as simple as possible. Despite its simplicity, this model still results in several significant consequences which already have been or could be experimentally tested.

4 Conclusion

In this paper we have suggested, analogous to the general theory of relativity and the theory of deformation for continuous media, a simple mechanism in which the negative values for the square of the neutrino mass reported in most of the neutrino experiments [1] could be the result of a change in metrics in the small weak interaction volume in the energy-momentum representation. We constructed a simple model in which the changes in energy-momentum metrics do result in $m_{\nu_e}^2 \leq 0$, while at the same time no components of the model violated allowed physical limits. The goal of this paper was not to construct the complete theory of metric deformation, but rather to demonstrate that the negative value of the square of the neutrino mass should not immediately be discarded as unphysical, and could indicate new physical phenomena.

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Figure 1: Normalized deviation of the $\beta$-spectrum described by Eq. 33 for $\epsilon = 0.999988$ from an undeformed electron energy distribution. The deviation for $\epsilon = 0.9999998$ is much smaller.
Figure 2: Beta spectrum near the end-point. The solid line is for an undeformed spectrum, while the dashed line represents the deformed spectrum for $\epsilon = 0.999988$. The deviation for $\epsilon = 0.999998$ is less than the thickness of the line.
Figure 3: A mismatch close the end-point when the spectrum generated by Eq. $\text{[33]}$ with parameter $\epsilon = 0.999988$ (dots) is fit with the distribution with shape described by Eq. $\text{[30]}$ (solid line).
Figure 4: The bump produced close to the end-point by the fitting procedure described in the text, experimentally corresponding to an excess in counting rate close to the end-point. This is just a different presentation of the effect presented in Fig. 3.
Figure 5: Square of the neutrino rest mass $m_{\nu_e}^2$ obtained by fitting the $\beta$-spectrum generated with Eq. [33] with $\epsilon = 0.999988$ as a function of the lower limit $E$ of the fit interval.
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