Neutrino Oscillations mediated by the Higgs field

W. Schmidt-Parzefall
Universität Hamburg

August 17, 2021

Abstract

Neutrino oscillations occur within the frame of the Standard Model, assuming that a neutrino is composed of a left handed and a right handed mass less fermion. Neutrino oscillations proceed via the 4-component Higgs field as intermediate state.

PACS 12.10 Dm
Neutrino oscillations; Standard Model; Higgs field

Oscillations between quantum states may proceed via a mechanism involving an intermediate state. For example $B\bar{B}$ meson oscillations [1] proceed via a box graph dominated by the exchange of the $t$ quark. It is shown by the present paper that also neutrino oscillations [2] proceed via a particular graph occurring within the frame of the Standard Model after a minor modification of the description of neutrinos.

The Lagrangian $\mathcal{L}$ of the Standard Model for the observable particles [3] can be derived from a primary form of the Lagrangian [4], containing mass less fermions, mass less gauge bosons and the 4-component Higgs field [5]. A summary of this derivation is given by [6]. Neutrino oscillations are implied by the primary form of the Lagrangian. It consists of the following terms

$$\mathcal{L} = L_\psi + L_\chi + L_\phi + L_Y + L_W + L_B.$$  (1)
The terms of the primary form of $\mathcal{L}$ are

$$
L_\psi = \sum_i \overline{\psi}_i R \gamma^\mu (\partial_\mu - U_\psi^{-1} \partial_\mu U_\psi) \psi_i R
$$

$$
L_X = \sum_i \overline{\chi}_i L \gamma^\mu (\partial_\mu - U_X^{-1} \partial_\mu U_X) \chi_i L
$$

$$
L_\phi = \frac{1}{2} \left( (\partial_\mu - U_\phi^{-1} \partial_\mu U_\phi) \phi \right)^\dagger (\partial_\mu - U_\phi^{-1} \partial_\mu U_\phi) \phi + \frac{m^2_\phi}{2} \phi^\dagger \phi - \frac{m^2_H}{4v^2} (\phi^\dagger \phi)^2
$$

$$
L_Y = -\sum_i C_i \left( \overline{\psi}_i R \phi^\dagger \chi_i L + \overline{\chi}_i L \phi \psi_i R \right)
$$

$$
L_{\mathcal{W}} = -\frac{1}{4} W_{\mu\nu} W^{\mu\nu}
$$

$$
L_B = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}.
$$

$\psi_i R$ is a mass less right handed fermion turning into the right handed component of an observable fermion with mass. It carries the weak isospin $t_3 = 0$ and the $U(1)$ charge $g t_y \psi$. It has $U(1)$ symmetry and interacts with the $U(1)$ potential $B_\mu$ by the interaction transformation

$$
U_\psi = \exp \left( -i \int g t_y \psi B_\mu dx^\mu \right). \quad (3)
$$

$\chi_i L$ is a mass less left handed fermion turning into the left-handed component of an observable fermion with mass. It carries the weak isospin $t_3 = \pm \frac{1}{2}$ and the $U(1)$ charge $g t_y \chi$. It has $SU(2) \times U(1)$ symmetry and interacts with the three $W_\mu$ potentials and the $B_\mu$ potential by the interaction transformation

$$
U_\chi = \exp \left( -i \int \left( \frac{g}{\sqrt{2}} (T_+ W_\mu^+ + T_- W_\mu^-) + g t_3 W_\mu^3 + g t_y \chi B_\mu \right) dx^\mu \right), \quad (4)
$$

where the $T_\pm$ are the weak isospin rising or lowering operators, and $g$ is the universal $SO(3)$ charge.

$\phi$ is a 4-component scalar field. $m_H \approx 125 \text{ GeV}$ is the mass of the observable 1-component Higgs particle, but the sign of the mass term of $\phi$ is opposite to the sign describing an observable particle. $v \approx 246 \text{ GeV}$ is the electroweak scale.

The two mass less fermions $\psi_i R$ and $\chi_i L$ forming together a fermion with mass interact with each other via the field $\phi$ by a Yukawa interaction represented by the Lagrangian $L_Y$. The $C_i$ are coupling constants.
$L_Y$ describes the reactions

$$
\psi_{iR} + \phi \rightarrow \chi_{iL} \quad \text{and} \quad \chi_{iL} \rightarrow \psi_{iR} + \phi. \quad (5)
$$

Since weak isospin and the $U(1)$ charge are conserved by these reactions, the interaction transformation of $\phi$ is

$$
U_{\phi} = U_{\psi}^{-1} U_{\chi}. \quad (6)
$$

The mass less fermions $\chi_{iL}$ and $\psi_{iR}$ carry electric charge. The electric charge $q$ is a linear combination of the weak charge $g t_3$ and the $U(1)$ charge $g' y$, realised by a rotation about the electroweak angle $\theta_W \approx 28.6^\circ$, which is defined by the condition, that the two mass less fermions forming together a fermion with mass, carry the same electric charge,

$$
q_\chi = \sin \theta_W g t_3 + \cos \theta_W g' y_\chi = \cos \theta_W g ty_\psi = q_\psi. \quad (7)
$$

The electric charge of $\phi$ is

$$
q_\phi = q_\chi - q_\psi = 0. \quad (8)
$$

The charges of the mass less fermions forming leptons are plotted in Figure 1, including the corresponding antiparticle states.

![Figure 1: The charges of the mass less fermions forming leptons approximate an SU(3) octet. The two mass less fermions $\chi_{iL}$ and $\psi_{iR}$ forming together a lepton are connected by a dotted line.](image-url)
Deviating from the historical Standard Model, here a neutrino is assumed to be composed of a left handed and a right handed mass less fermion, like a charged lepton. The two constituents of a neutrino $\chi_L$ and $\psi_R$ interact with the Higgs field $\phi$ by a Yukawa interaction and form a massive fermion, obtaining its mass $m_i = C_i v$ by a term of the Lagrangian $L_Y$.

The interactions implied by the Lagrangian $L_Y$ are described by the Feynman diagrams Figure 2.

![Feynman diagrams](image)

**Figure 2**: The Feynman diagrams corresponding to the Lagrangian $L_Y$ for the Yukawa interaction of the constituents $\chi_L$ and $\psi_R$ of a neutrino. The arrows denote ingoing and outgoing states. The diagram 2a is explicitly implied by $L_Y$. The diagram 2b occurs due to crossing symmetry. It transforms a $\nu_j$ into a $\nu_k$, $j, k = e, \mu, \tau$ and thus represents the mechanism for neutrino oscillations.

Actually, only the reaction corresponding to the diagram 2a is explicitly implied by the Lagrangian $L_Y$. In order to describe the observed neutrino oscillations within the frame of the Standard Model, the assumption is made, that there is crossing symmetry [7], and therefore also the reaction of the rotated diagram 2b occurs. As a justification the similarity with the electromagnetic interaction is considered, where the $e^+e^-$ Bhabha scattering proceeds via two diagrams related by crossing symmetry.

Conservation of weak isospin and $U(1)$ charge requires for the reaction 2b that the interaction transformation of the field $\phi$ is

$$U_\phi = U_\psi U_\chi.$$ (9)

In addition, the relation (6) $U_\phi = U_\psi^{-1} U_\chi$ is imposed by diagram 2a. Both
conditions together result in the requirement

\[ U_\psi = 1. \]  

(10)

This is fulfilled for neutrinos, but not for charged leptons or quarks. The \( \psi_R \) component of neutrinos does not carry any charge. Therefore, the constituents of neutrinos interact not only according to diagram 2a but also according to diagram 2b.

By both reactions, 2a and 2b a neutrino is transformed into a neutrino. By reaction 2a a neutrino is only transformed into itself. However, by reaction 2b a neutrino can also be transformed into a neutrino of a different generation. This results in neutrino oscillations, proceeding via the 4-component Higgs field \( \phi \) as an intermediate state.

In summary, the observed neutrino oscillations can be explained within the frame of the Standard Model, assuming that a neutrino is composed of a left handed and a right handed mass less fermion, and assuming crossing symmetry for the reactions implied by the Yukawa interaction of the mass less fermions with the 4-component Higgs field. This picture allows to compute the neutrino oscillation rates, once the neutrino masses are known.
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