Reinterpreting Neutrino Oscillations

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Abstract This letter proposes an alternative quantum mechanical picture for the observed phenomena of neutrino oscillations. It is assumed in the following that neutrinos interact via diabatic (or localised) interactions with a new particle field, which changes their flavor. Furthermore, it is assumed that each neutrino flavor state can only have a single associated mass thereby making them fundamental particles of nature. The effective masses associated with matter interactions replace the concept of neutrino mixing angles. Preliminary evidence that left-handed neutrinos and right-handed antineutrinos oscillate differently is presented, implying charge-parity violation. Given the apparent anomalous observations of some neutrino oscillation experiments, which have led to speculations about the existence of a fourth (sterile) neutrino, it is worth examining the oscillation behavior predicted by alternative mechanisms to determine if they more naturally explain the available data.

Contrary to charged leptons, neutral leptons are thought to be produced as a quantum superposition of at least three mass states [1,2]. Over the last 20 years, the community has made great progress in measuring the oscillation properties of the Pontecorvo Nakagawa Maki Sakata (PNMS) system [3,4]. Flavor oscillations are assumed to occur due to an energy difference in the mass states leading to oscillations in the interaction states as a function of time. However, experimental tensions have arisen in multiple neutrino sectors in the last 20 years. For example, the SAGE/GALLEX [5,6] results are outside of the predicted oscillation expectation and are in conflict with the Borexino results at similar energies [7]. More recently, new reactor antineutrino spectra and a re-evaluation of the neutron lifetime highlighted that short-baseline reactor-antineutrino results were systematically lower than expected—by 6%—implying potential oscillations at short baselines [8]. Recent re-evaluation of the spectral conversion of electron to electron antineutrinos have resulted in an upward shift of 3% (Φ_corr), partly alleviating the problem [2]. Spectral features at 5 MeV [9,10] are present in the reactor data, though these same oscillation features cannot be confirmed by recent searches [11] and this anomaly is still an open question. Finally, the LSND and MiniBoone experiments [12,13] observed an excess of electron neutrinos at lower energies, this excess is not in agreement with the accepted model of oscillations [14,15]. While errors in the flux models, cross-section models, interaction effects, or other effects are possible, this letter investigates whether a different neutrino oscillation interpretation might resolve these tensions.

Non-standard interaction (NSI) models have been proposed for lepton flavor violation effects that should be investigated in conjunction with the PNMS model. A model proposed by Ge and Murayama [16] predicts that a lepton violating process can occur through interactions with dark matter, thus leading to second order oscillation effects observable by the next generation of neutrino experiments. De Gouvea et al [17] have reviewed non-standard interactions that could result in charged lepton flavor violation. In this letter we explore the idea that flavor oscillations occur as a consequence of perturbative interactions with vector bosons, rather than neutrino state superposition as assumed in the PNMS model. Furthermore, as neutrinos do not interact with regular matter strongly it is assumed that NSI are dominant and that these vector bosons are spread uniformly in space.

While the Higgs mechanism provides a way for particles to acquire mass, it is not well understood under what conditions the mechanism applies. Is the pertur-

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Fig. 1, but at no time is the neutrino a superposition
change back to its original quantum state with another
with localized non-standard field and this neutrino can
change to acquire a single mass
The relativistic Schrödinger equation:
where
and can be interpreted as a massless spin 1/2 particle
energy p that undergoes a handness spin flip in the
presence of a field potential term (m = mL = mRL)
where LR and RL are introduce to denote transition
energy from left to right states and vice-versa. The
energy states of this system as the solution,
which result in the right- and left-handed Dirac particle
of flavor α to acquire a single mass mα, and is consistent
with the energy-momentum relation. If we assume that
individual flavor state interact with varying strength
with the surrounding matter interaction points then a
three flavor extension would have the form,
for a system that conserve flavor and for a particle of
total momentum p.

Diabatic flavor interactions imply that a neutrino
will change flavor along its path with an interaction
with localized non-standard field and this neutrino can
change back to its original quantum state with another
such interaction at a later time as is illustrated on
Fig. 1, but at no time is the neutrino a superposition
of other neutrinos. These individual interactions are
referred to as flavon interactions in this letter. We note
that if standard interactions are also diabatic then
energy is conserved as p is conserved by construction.

With the assumption that flavor neutrinos have
distinct effective masses, then standard interactions masses
\( m_\alpha = \langle \nu_\alpha | L_{S1} | \nu_\alpha \rangle \) and NSI (or flavon) masses
\( f_{\alpha\beta} = \langle \nu_\beta | L_{NS1} | \nu_\alpha \rangle \)1 can be expressed in the Weyl basis as
\[
\begin{bmatrix}
0 & m_{\alpha e} & f_{\alpha e} & f_{\alpha e}^\ast \\
0 & f_{e\alpha} & f_{e\alpha}^\ast & f_{e\alpha} \\
f_{\mu \alpha} & f_{\mu \alpha} & f_{\mu \alpha} & \delta_{\mu\alpha} \\
f_{\tau \alpha} & f_{\tau \alpha} & f_{\tau \alpha} & \delta_{\tau\alpha}
\end{bmatrix},
\]
where RL/LR terms are said to be Dirac and LL/RR
are said to be Majorana.

The energy states are obtained by simplifying the
Hamiltonian to,
\[
H = H_0 + H_1
\]
where,
\[
\langle \nu_1 | H_0 | \nu_m \rangle = \delta_{1m} E_{\nu m}
\]
and
\[
\langle \nu_1 | H_1 | \nu_m \rangle = (1 - \delta_{1m}) f_{1m}
\]
(7) and l or m are flavor numbers (e, μ, τ), E_{ν m}
the energy of the neutrino of flavor m, and f_{1m}
the energy width of the flavon violating interaction, δ_{1m}
the Kroenecker delta. Here the flavor interaction field is
not assumed to have a time dependent component (f_{e\mu} δ(x)).
The system energy of an electron-neutrino and a muon-
neutrino, assuming that f_{e\mu} is small enough such that
the system can be treated in a perturbative way, in the
relativistic limit is
\[
\begin{bmatrix}
p + \frac{m_\mu^2}{2p} & f_{e\mu} \\
\mu & \frac{m_\mu^2}{2p} \\
f_{e\mu} & p + \frac{m_\mu^2}{2p}
\end{bmatrix}
\]
where the perturbation is at least 18 orders of magnitudes
smaller than the particle energy. This matrix is
rewritten in the form
\[
E_{\text{sys}} = f_{e\mu} \sigma_x + \Delta E \sigma_z + E_{\text{tot}} I,
\]
where
\[
E_{\text{tot}} = p + (m_{\nu_e}^2 / 4p) + (m_{\nu_\mu}^2 / 4p), \Delta E = (m_{\nu_e}^2 / 4p) - (m_{\nu_\mu}^2 / 4p), \sigma_x \text{ and } \sigma_z \text{ are the Pauli matrices, and } I \text{ is the identity matrix. Here, } E_{\text{sys}} \text{ has the following eigenvalues:}^2
\]
\[
E_{\pm} = p + \frac{m_{\nu_e}^2}{4p} + \frac{m_{\nu_\mu}^2}{4p} \pm \delta.
\]
The relativistic Schrödinger equation:
\[
\frac{\partial}{\partial t} \psi = \left( -\frac{i}{\hbar} E_{\text{sys}} \right) \psi
\]

1 where L_{NS1} could originate from Dark Matter or Flavon interactions [16,19], however exact cause is not needed for derivation
2 \( \delta \equiv \sqrt{\Delta E^2 + \frac{f_{e\mu}^2}{4}} \) defined for reading simplicity
where $\Psi$ is the Weyl spinor and has solution $\Psi(t) = U(t)\Psi(0)$, where,

$$U(t) = e^{-i(f_{e\mu}\sigma_+ + \Delta E\sigma_+ t)/\hbar} e^{-i(E_{\nu\alpha} t)/\hbar} = U_{\text{osc}} U_{E\nu},$$

(12)

and the oscillation term can be rewritten in matrix form in the $\nu_e, \nu_\mu$ basis of Eqn. 8 as,

$$U_{\text{osc}} = \begin{bmatrix} \cos(\delta t) - i \frac{\Delta E}{\hbar} \sin(\delta t) & -i \frac{E_{\nu\alpha}}{\hbar} \sin(\delta t) \\ -i \frac{E_{\nu\alpha}}{\hbar} \sin(\delta t) & \cos(\delta t) + i \frac{\Delta E}{\hbar} \sin(\delta t) \end{bmatrix}.$$  

(13)

The probability that the neutrino has not changed flavor state after a time $t$ becomes,

$$P_{ee} \equiv P(\nu_e \neq \nu_\mu) = \left| \begin{bmatrix} 1 & 0 \end{bmatrix} U(t) \begin{bmatrix} 1 \\ 0 \end{bmatrix} \right|^2$$

(14)

The final form of the neutrino oscillation probability is therefore,

$$P_{ee} = 1 - \frac{f_{e\mu}^2}{(\Delta m_{\nu\alpha}^2/4E_\nu)^2} \sin^2 \left( t \sqrt{\frac{\Delta m_{\nu\alpha}^2}{4E_\nu}} + f_{e\mu}^2 \right).$$

(15)

This formula should be compared to the standard two-neutrino PNMS oscillation formula, which has the form,

$$P_{ee} = 1 - \sin^2(2\theta_{12}) \sin^2 \left( \frac{\Delta m_{\nu\alpha}^2}{4E_\nu} t \right).$$

(16)

Each formulas has the same number of physical constants and as such the flavon model is not more complex than the PNMS model. If one wishes, an energy-dependent mixing angle term for the flavon formula could be define as:

$$\theta_{e\mu}(E_\nu; \Delta m_{e\mu}^2, f_{e\mu}) = \frac{1}{2} \sin^{-1} \left( \frac{f_{e\mu}^2}{\left( \frac{\Delta m_{e\mu}^2}{4E_\nu} \right)^2 + f_{e\mu}^2} \right),$$

(17)

leading Eqn. 15 to be re-written as,

$$P_{ee} = 1 - \sin^2(2\theta_{e\mu}) \sin^2 \left( t \sqrt{\frac{\Delta m_{e\mu}^2}{4E_\nu}} + f_{e\mu}^2 \right).$$

(18)

For experiments at very short or very long ranges, the neutrino gains non-standard oscillation properties. At the very short range, Eqn. 15 simplifies to $(1 - f_{e\mu}^2 t^2)$. While at very long range and at sufficient energy, Eqn. 15 simplifies to $0.5 \left( 1 + (\Delta m_{\nu\alpha}^2/4E_\nu f_{\alpha\beta})^2 \right)$, leading to low-energy excess that do not follow the expected PNMS oscillation predictions.

**Testing the model**

A global fit using a simple $\Delta \chi^2$ method between this model and published experimental data is made in order to study neutrino and antineutrino data across multiple experimental conditions. Generally, oscillations are observed using sources of (anti)neutrinos of a specific flavor (i.e., reactor electron antineutrinos, solar electron neutrinos, beam muon neutrinos) and measuring how neutrinos transform (or do not transform) into other flavors as a function of baseline and energy. This observation is made by either measuring how many neutrinos are lost—in the case of a disappearance experiment—or

![Fig. 1 (top) Potential Feynman diagram for flavon interaction (19) and (bottom) oscillation picture using diabatic (fast) interactions, denoted by x, with the higgs and flavon boson assumption (diagram adapted from (20)). A ground state neutrino that has undergone a flavon interaction is assumed to be in an excited state, interaction of this excited neutrino with the Higgs boson lead to a different vacuum expectation than the original ground state neutrino which is not proportional to the absorbed energy.](image-url)
Fig. 2 Performance of the flavon model against a selection of electron neutrino and antineutrino experimental data. The data point in red is from the SAGE/GALLEX experiments and is considered anomalous. For PROSPECT and NEOS the 4-neutrino PNMS best fit value for NEOS ($\sin^2 \theta_{14} = 0.05, \Delta m_{14}^2 = 1.73 \text{ eV}^2$) is also included.

how many neutrinos of a different flavor are created—in the case of an appearance experiment. It is assumed as a first order approximation that the extension to the three neutrino survival probability for an electron neutrino is simply:

$$P_{ee} \approx P_{\nu_e \rightarrow \nu_e} P_{\nu_e \rightarrow \nu_{\mu}}$$

for the disappearance experiments relevant to this paper.

The top row of Fig. 2 shows the rate of reactor antineutrino disappearance$^5$ as a function of distance from creation$^6$. The central values for the antineutrino parameters are displayed in this and each other subfigure for the flavon model. The short-baseline and Double Chooz data [8, 22], the Daya Bay [23] results were adjusted for recent flux results including a 3% upward $^5$averaged over reactor energy spectra $^6$Values above 750 km are averaged over remaining baseline due to numerical computation issues.
shift. We note that the change in average disappearance value between the Daya Bay near detectors and far detector is consistent with the oscillation parameters of KamLand and is the result of the non-standard oscillation behavior of the flavon model at short baseline. In the PNMS model a third neutrino is needed to explain this deficit, which in turn require a fourth neutrino to explain the short-baseline anomaly. There is no need to extend the number of neutrinos for the case of the 3-neutrino flavon model.

The second row of Fig. 2 shows the spectral oscillations in the electron to tau neutrino conversion. Oscillations at PROSPECT [11] were evaluated using the publicly available detector response matrix. The probability prediction are further corrected by normalising to unity. Oscillation at NEOS [24] were evaluated using the data ratio NEOS/Daya Bay is presented including the best fit parameter for sterile neutrinos. Oscillations at Daya Bay for the two near detectors (EH1 and EH2) site are compared to data from [23] assuming a detector resolution of $7\%/\sqrt{E}$ and accounting for respectively thirty-six and forty-eight reactor-detector baselines over two data taking period. Data ratios were performed in order to remove uncertainties on flux and cross-section models and background were subtracted according to the best fit values prior to taking the data ratio.

The third row of Fig. 2 shows the spectral oscillation in the electron to muon conversion. Oscillations at Daya Bay using the far hall and the near hall (EH3 and EH2) are again used to remove uncertainties on flux and cross sections. The spectral feature at 5.5-6.0 MeV is due to detector resolution effects. Oscillations at KamLand were compared to data from [25], where we assumed an energy resolution of $7\%/\sqrt{E}$. The oscillation probability was evaluated based on published power information for five reactor sites${^7}$. The $^{210}$Po, accidentals and geoneutrinos were removed in the background-subtracted data for the first phase of [25]. The last figure shows the oscillation from solar neutrinos and how the flavon antineutrino-parameters do not fit the solar data well, but a set of two different flavon masses fits the data including the SAGE-GALLEX point. The MSW-LSA effect is not included here, however the MSW behavior is reproduced in the solar data, as is demonstrated by the blue band and magenta line, due to the non-standard oscillation behavior at long baseline. In all cases the flavon fit results are largely consistent with the PNMS results. Disagreements can be observed in a region below 2 MeV for some experiments such as in the NEOS experiment, KamLand, and the far Daya Bay results. It should be noted that a variety of backgrounds populate the energy region below 2 MeV and more precise treatment should be performed in lieu of the background subtraction method used in this article.

We show hints that left-handed neutrino and right-handed antineutrinos oscillate differently as the antineutrino parameters cannot reproduce the solar data, but a set of different parameters can. This in turn implies CP violation which is one of three of the Sakharov conditions proposed to explain why our universe is dominated by matter. Since the neutrino data considered here consists of only four experimental measurements no official CP-violation claim can be made.

Conclusions and Potential Impact

In this letter a new oscillation model is proposed (Eqn. 15) as a replacement to the PNMS formalism (Eqn. 16). This model recreates oscillation features measured in previous experiments using a simple $\Delta \chi^2$ method. However, more sophisticated fitting techniques and new oscillation data would be required to better test this model. Of particular interest are the accelerator and atmospheric neutrino sectors where preliminary agreements are observed (Fig. 3). A follow-up paper will discuss the sensitivity of future planned experiments to this model and explore detector observable effects in beam-line experiments. It should be already noted from Fig. 2 (top) that the AIT and JUNO experiments will be sensitive to this model as they will be respectively at an oscillation minimum and maximum and will further constrain and confirm $f_{e\mu}$ and $\Delta m^2$ current results as shown in Figure 4.

Further studies of the possible implications to the non-proliferation neutrino community are being investigated. As the oscillation patterns are more complex than in the standard PNMS model, one can potentially imagine leveraging the observed neutrino spectra for multiple purposes—either to make more confident pronouncements as to whether a reactor complex is complying with declared operations or to verify compliance with future treaties to verify the absence of undeclared reactors via observed changes in the energy spectra.

Neutrinos and antineutrinos are found to oscillate with different strengths in the flavon model between the solar and reactor sector, this implies charge-parity violation for neutrinos. This is a key requirement of the Sakharov conditions, which are necessary for understanding the matter-antimatter imbalance observed in our universe.

For some time, the physics community has had to contend with the uncomfortable tenet that the neutrino is not a fundamental particle of nature as it is composed

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${^7}$Kashiwazaki, Ohi, Takahama, Hamaoka, and Tsuruga.
Fig. 3 Preliminary results for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ with solar flavor $f_{e\mu}$ strength at LSND. Preliminary results for $\nu_\mu \rightarrow \nu_e$ with reactor flavor $f_{e\mu}$ strength at MiniBoone. Reasons for the order of such transitions order are not understood. The flavon prediction with the solar $f_{e\mu}$ is not in agreement with the $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ expectation (not shown here) for MiniBoone.

Fig. 4 $\Delta \chi^2$ map of the reactor antineutrino best fit from Fig. 2. $\Delta \chi^2$ for a parameter of interest is obtained by fixing the value of the best fit for the three other nuisance parameters. Future mid-baseline experiments such as AIT and JUNO will further constrain and confirm $f_{e\mu}$ and $\Delta m^2_{e\mu}$. 
of multiple mass states. At the price of assuming a simple interaction with a dark matter field, and a straightforward re-casting of the equations governing neutrino oscillations to include an energy-dependent term, this letter presents a model for oscillations with a single valued mass for each neutrino flavor. This model agrees with a diverse set of experimental results, as well as, or better than, the prevailing PMNS model.

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References

1. H. Fritsch, P. Minkowski, Physics Letters B 62(1), 72 (1976). DOI https://doi.org/10.1016/0370-2693(76)90051-4. URL https://www.sciencedirect.com/science/article/pii/0370269376900514
2. M. Tanabashi, K. Hagiwara, K. Hilasa, et al., Phys. Rev. D 98, 030001 (2018). DOI 10.1103/PhysRevD.98.030001. URL https://link.aps.org/doi/10.1103/PhysRevD.98.030001
3. T. Schwetz, M. Tórtola, J.W.F. Valle, New Journal of Physics 10(11), 113011 (2008). DOI 10.1088/1367-2630/10/11/113011. URL https://doi.org/10.1088/1367-2630/10/11/113011
4. P. Vogel, L. Wen, C. Zhang, Nature Communication p. 6:6935 (2015). DOI 10.1038/ncomms7935
5. J.N. Abdurashitov, V.N. Gavrin, V.V. Gorbachev, et al., Phys. Rev. C 80, 015807 (2009). DOI 10.1103/PhysRevC.80.015807. URL https://link.aps.org/doi/10.1103/PhysRevC.80.015807
6. V.N. Gavrin, Physics-Uspekhi 54(9), 941 (2011). DOI 10.3367/ufne.0181.201109g.0975. URL https://doi.org/10.3367/ufne.0181.201109g.0975
7. G. Bellini, J. Benziger, D. Bick, et al., Phys. Rev. D 89, 112007 (2014). DOI 10.1103/PhysRevD.89.112007. URL https://link.aps.org/doi/10.1103/PhysRevD.89.112007
8. G. Mention, M. Fechner, T. Lasserre, et al., Phys. Rev. D 83, 073006 (2011). DOI 10.1103/PhysRevD.83.073006. URL https://link.aps.org/doi/10.1103/PhysRevD.83.073006
9. D.A. Dwyer, T.J. Langford, Phys. Rev. Lett. 114, 012502 (2015). DOI 10.1103/PhysRevLett.114.012502. URL https://link.aps.org/doi/10.1103/PhysRevLett.114.012502
10. J.M. Berryman, V. Brdar, P. Huber, Phys. Rev. D 99, 055045 (2019). DOI 10.1103/PhysRevD.99.055045. URL https://link.aps.org/doi/10.1103/PhysRevD.99.055045
11. J. Ashenfelter, A.B. Balantekin, C. Baldenegro, et al., Phys. Rev. Lett. 121, 251802 (2018). DOI 10.1103/PhysRevLett.121.251802. URL https://link.aps.org/doi/10.1103/PhysRevLett.121.251802
12. C. Athanassopoulos, L. Auerbach, D. Bauer, et al., Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 388(1), 149 (1997). DOI https://doi.org/10.1016/S0168-9002(96)01155-2. URL http://www.sciencedirect.com/science/article/pii/S0168900296011552
13. A.A. Aguilar-Arevalo, B.C. Brown, L. Bugel, et al., Phys. Rev. Lett. 121, 221801 (2018). DOI 10.1103/PhysRevLett.121.221801. URL https://link.aps.org/doi/10.1103/PhysRevLett.121.221801
14. M.C. Goodman, in International Conference on History of the Neutrino: 1930-2018 Paris, France, September 5-7, 2018 (2019)
15. A. Bolshakova, I. Boyko, G. Chelkov, et al., Phys. Rev. D 85, 092008 (2012). DOI 10.1103/PhysRevD.85.092008. URL https://link.aps.org/doi/10.1103/PhysRevD.85.092008
16. S.F. Ge, H. Murayama. Apparent cpt violation in neutrino oscillation from dark non-standard interactions (2019). URL https://arxiv.org/abs/1904.02518
17. A. de Gouvêa, W.C. Huang, J. König, M. Sen, Phys. Rev. D 100, 075033 (2019). DOI 10.1103/PhysRevD.100.075033. URL https://link.aps.org/doi/10.1103/PhysRevD.100.075033
18. J.H. Noble, U.D. Jentschura, Phys. Rev. A 92, 012101 (2015). DOI 10.1103/PhysRevA.92.012101. URL https://link.aps.org/doi/10.1103/PhysRevA.92.012101
19. K. Tsumura, L. Velasco-Sevilla, Phys. Rev. D 81, 036012 (2010). DOI 10.1103/PhysRevD.81.036012. URL https://link.aps.org/doi/10.1103/PhysRevD.81.036012
20. H. Murayama, Physics World 15(5), 35 (2002). DOI 10.1088/2058-7058/15/5/36. URL https://doi.org/10.1088%2F2058-7058%2F15%2F5%2F36
21. K. Hecht, Quantum Mechanics. Graduate Texts in Contemporary Physics (Springer New York, 2000). URL https://www.springer.com/us/book/9780387989198
22. Y. Abe, C. Aberle, T. Akiri, et al., Phys. Rev. Lett. 108, 131801 (2012). DOI 10.1103/PhysRevLett.108.131801. URL https://link.aps.org/doi/10.1103/PhysRevLett.108.131801
23. F.P. An, A.B. Balantekin, H.R. Band, et al., Phys. Rev. D 95, 072006 (2017). DOI 10.1103/PhysRevD.95.072006. URL https://link.aps.org/doi/10.1103/PhysRevD.95.072006
24. Y.J. Ko, B.R. Kim, J.Y. Kim, et al., Phys. Rev. Lett. 118, 121802 (2017). DOI 10.1103/PhysRevLett.118.121802. URL https://link.aps.org/doi/10.1103/PhysRevLett.118.121802
25. A. Gando, Y. Gando, H. Hanakago, et al., Phys. Rev. D 88, 033001 (2013). DOI 10.1103/PhysRevD.88.033001. URL https://link.aps.org/doi/10.1103/PhysRevD.88.033001