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Authors: Xiaoshuang Shen, Xiaoshuang Shen

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Full Text

Preamble

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Xiaoshuang Shen

School of Physical Science and Technology, Yangzhou University, Yangzhou, 225002, P. R. China

E-mail: xssh@yzu.edu.cn

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In this model, the Hamiltonian usually employed to describe neutrino oscillations is interpreted as a non-diagonal potential energy matrix in the flavor basis. The elements of the potential energy matrix are found to exhibit characteristics consistent with the background neutrino distribution predicted by the standard cosmological model. Direct measurements of neutrino mass, confirmation of potential disparities between oscillation parameters of neutrinos and antineutrinos, and further investigation into anomalous phenomena in some oscillation experiments could provide critical insights into whether neutrinos indeed possess mass.

1 Introduction

It has been experimentally confirmed for over two decades that neutrinos can undergo flavor transitions periodically as a function of the distance over energy during their propagation, a phenomenon referred to as neutrino oscillations [?]. A widely accepted viewpoint holds that neutrino oscillation provides unequivocal evidence for the existence of neutrino mass, and therefore represents a significant discovery beyond the Standard Model (SM) of elementary particles [?].

If only the left-handed neutrino states that we observe experimentally exist, neutrinos cannot acquire a so-called Dirac mass like other SM fermions; in other words, the Higgs mechanism, which is responsible for imparting mass to charged leptons and quarks, becomes inoperative in this context [?]. Alternatively, a Majorana mass for neutrinos can be generated via the seesaw mechanism, which offers a nice explanation for the smallness of neutrino masses [?, ?]. In general, the mechanism responsible for endowing neutrinos with mass requires the intro-

duction of particles or interactions that go beyond the SM [?]. Furthermore, neutrino oscillations indicate that lepton flavor conservation, which is a feature of the SM, is not strictly maintained [?, ?].

Neutrino oscillation experiments can measure the mass square differences Δm_{ij}^2 where m_i ($i = 1, 2, 3$) denotes the mass corresponding to each of the three neutrino mass eigenstates. Current neutrino oscillation experiments have not yet been able to fully determine the ordering of the three neutrino masses. There are two possibilities, which are referred to as normal ordering (NO, $m_3 > m_2 > m_1$) and inverted ordering (IO, $m_2 > m_1 > m_3$), respectively. The absolute neutrino mass scale can only be determined through other experimental data, including the squared effective electron antineutrino mass ($m_\nu^2 = \sum_i |U_{ei}|^2 m_i^2$), where U_{ei} is the element of the lepton mixing matrix \hat{U}_{PMNS} as elaborated below, constrained by β decay, the effective Majorana mass ($m_{\beta\beta} = |\sum_{i=1}^2 U_{ei} m_i|$) probed by neutrino-less double beta ($0\nu\beta\beta$) decay (if neutrinos are Majorana particles), and the sum of neutrino masses ($\sum m = m_1 + m_2 + m_3$) constrained by cosmology [?].

According to the latest results of the KATRIN experiment, an upper limit of $m_\beta < 0.45$ eV has been placed at 90% confidence level (CL), and no neutrino mass signal has been found within the uncertainties [?]. Up to now, all searched signals of $0\nu\beta\beta$ decay are compatible with null values, leading to the upper limit $m_{\beta\beta} < 0.086$ eV (2σ) [?]. Assuming the standard Λ cold dark matter (Λ CDM) model, the combination of several cosmological observational data sets pushes the best fit to $\sum m = 0$ and provides a particularly tight limit $\sum m < 0.0642$ eV at 95% CL [?]. This limit is well below the minimum allowed by oscillation experiments for IO (~ 0.10 eV) and close to the minimum for NO (~ 0.059 eV). Although the adoption of dynamic dark energy models, such as the $\omega_0\omega_a$ CDM model, can significantly relax the limit to $\sum m < 0.163$ eV (95% CL), the marginalized posterior distribution of $\sum m$ still peaks at the prior edge, $\sum m = 0$ [?].

More evidence is needed to confirm the tension between the cosmological bound and the lower limit derived from the oscillation experiments [?], but an important fact is worth noting: apart from the phenomena of neutrino flavor transitions, no other, particularly direct experimental evidence has been found to indicate that neutrinos possess mass. It may be essential to revisit the following questions: Do the neutrino oscillations indeed provide conclusive evidence for neutrino mass? Are there alternative theoretical frameworks, especially those within the SM, that could account for the neutrino flavor transitions?

2 The Rationale for Attributing Mass to Neutrinos

The opinion that neutrinos have mass is a natural outcome of a series of theoretical and experimental advancements [?]. The first idea of neutrino oscillations (between neutrino and antineutrino) was introduced by Pontecorvo in 1957, in direct analogy with kaon oscillations ($K^0 \leftrightarrow \bar{K}^0$) [?]. The mass eigenstates

of the quarks are not identical to those states that participate in interactions, which leads to the kaon oscillations. After it was confirmed that ν_e and ν_μ are different particles, Maki et al. gave neutrino a mass and foresaw that transformation between flavors might happen [?].

The flavor transformation of neutrinos can be described in the flavor basis by the non-diagonal “effective Hamiltonians” valid in the ultra-relativistic limit, $\hat{H}_{0,\nu} = \frac{1}{2E} \hat{U}_{PMNS} \text{diag}(m_1^2, m_2^2, m_3^2) \hat{U}_{PMNS}^\dagger$, where \hat{U}_{PMNS} is the leptonic equivalent of the Cabibbo-Kobayashi-Maskawa (CKM) matrix of the quark sector but here it is usually referred to as the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix [?]. The most common convention of \hat{U}_{PMNS} is

$$\hat{U}_{PMNS} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{CP}} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta_{CP}} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta_{CP}} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta_{CP}} & -c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta_{CP}} & c_{13}c_{23} \end{pmatrix}, \quad (2)$$

where $s_{ij} = \sin \theta_{ij}$, $c_{ij} = \cos \theta_{ij}$, with angles $\theta_{ij} \in [0, 90^\circ]$ and the CP-violating phase $\delta_{CP} \in [0, 360^\circ)$. In the Majorana case, the \hat{U}_{PMNS} contains two additional phases, which do not enter the equation for neutrino oscillations and manifest themselves in lepton number violating processes only. The Hamiltonian $\hat{H}_{0,\nu}$ (Eq. (1)) can be obtained based on the following assumption: the flavor neutrinos $\nu_f \equiv (\nu_e, \nu_\mu, \nu_\tau)^T$ are coherent combinations of the $\nu_{mass} \equiv (\nu_1, \nu_2, \nu_3)^T$ with definite masses m_1, m_2, m_3 :

$$\nu_f = U_{PMNS} \nu_{mass}. \quad (3)$$

Note that, again in the ultra-relativistic approximation ($p \sim E$, in natural units), one can write

$$E_i = \sqrt{m_i^2 + p^2} \approx p + \frac{m_i^2}{2E}. \quad (4)$$

The first term gives rise to the diagonal matrix $\text{diag}(p, p, p)$ and this can be dropped, because it gives rise to an overall phase factor, common to all the flavor states and thus irrelevant for oscillations. The second term leads to a special relationship between $\hat{H}_{0,\nu}$ and the neutrino energy E , namely that $\hat{H}_{0,\nu} \propto 1/E$.

The flavor transformation of neutrinos described by Eq. (1) are usually referred to as vacuum neutrino oscillations. In the case of neutrino propagation in matter, the elastic forward scattering leads to refraction phenomena and can be described by the effective potential \hat{V}_e . According to the standard interactions described by the SM, the \hat{V}_e in the flavor basis is diagonal and can be written

$$\hat{V}_e = \sqrt{2}G_F n_e \text{diag}(1, 0, 0), \quad (5)$$

where G_F is the Fermi constant and n_e is the number density of electrons [?, ?]. Adding this term to $\hat{H}_{0,\nu}$ leads to two possible effects of matter on neutrinos: the resonant enhancement of the oscillation amplitude, and the adiabatic flavor conversion, called Mikheyev-Smirnov-Wolfenstein (MSW) effect [?]. After two interrelated yet distinct phenomena, namely neutrino oscillations and MSW effect had been firmly established at about the year 2000, it is widely accepted that neutrinos are massive.

The Hamiltonian $\hat{H}_{0,\nu}$ (Eq. (1)) can well describe the neutrino oscillation phenomena observed in a variety of experiments (such as atmospheric oscillation experiments, accelerator oscillation experiments and reactor oscillation experiments), and it can be extended to the case where matter exists, thereby explaining the MSW effect [?]. From a historical perspective, neutrino oscillations and the associated MSW effect were initially predicted based on the hypothesis that neutrinos possess mass, an idea inspired by quark flavor mixing. Subsequent experimental observations confirmed the phenomena of neutrino flavor conversion, thereby greatly enhancing the credibility of the initial hypothesis. If neutrino oscillations originate from the intrinsic properties of neutrinos, as has long been assumed, then assigning neutrinos small masses and assuming that the flavor eigenstates are superpositions of mass eigenstates represent the most natural and straightforward approach to deriving the Hamiltonian $\hat{H}_{0,\nu}$. However, it is important to reiterate that neutrino oscillations provide only indirect evidence for the existence of neutrino mass. The indirect evidence can become truly persuasive only when all other possible explanations have been ruled out. As mentioned above, there is a default assumption in the current explanation of neutrino oscillations that these oscillations originate from the intrinsic properties of neutrinos themselves. This default assumption artificially rules out other possibilities that are worth considering.

3 An Alternative Possibility

From a broader perspective, it is a common physical phenomenon that certain properties of a particle undergo periodic variations over time or with propagation distance. A notable example is the kaon transformation discussed earlier, which directly inspired the development of the theory of neutrino oscillations. The K^0 and \bar{K}^0 mesons carry distinct strangeness; although strangeness is conserved in strong interactions, it is not respected in weak interactions. As a result, a K^0 meson prepared at a given time may have a certain probability amplitude to transform into a \bar{K}^0 meson through weak interaction at a later time. Unlike the kaon transformation, which originates from intrinsic properties of kaons, another more prevalent class of such phenomena involves particles under the influence of external environments or fields. For example, the polarization state of a photon exhibits periodic changes when propagating through a birefringent crystal, and similarly, the spin state of an electron undergoes periodic transformation when subjected to an external magnetic field (See reference [?] for enlightening discussions on phenomena analogous to neutrino oscillations).

These examples suggest a previously overlooked possibility that neutrino oscillations may also arise from the influence of a specific environment on neutrinos.

There indeed exists such an all-pervasive and unique environment for neutrinos. The Standard Cosmological Model (SCM) predicts the presence of the Cosmic Neutrino Background (C ν B) in addition to the Cosmic Microwave Background (CMB) [?, ?]. In the standard picture, the neutrinos decoupled from the thermal bath (\$ \$1s after the Big Bang) at the freeze-out temperature $T_\nu \sim 3$ MeV (for ν_μ and ν_τ) and ~ 2 MeV (for ν_e), respectively [?]. The present number density of C ν B (n_ν) is about 56 cm^{-3} per flavor. It is the largest neutrino density at Earth [?]. If neutrinos are massless, the C ν B would be blackbody radiation at $T = 1.95 \text{ K} = 0.168 \text{ meV}$, corresponding to a de Broglie wavelength (λ) of about 6 millimeters. If we simply take this wavelength ($\lambda \sim 6 \text{ mm}$) as the spatial scale of the background neutrino's wave function, a direct estimation ($6n_\nu \times 4\pi\lambda^3/3$) shows that, for a neutrino at any point in space at any moment, approximately 300 background neutrinos (plus antineutrinos) can be experienced. If, analogous to the CMB, the distribution of C ν B also approximates an ideal blackbody spectrum, then the spatial scale of the background neutrino's wave function would substantially exceed their wavelengths. Any neutrino detected in the neutrino oscillation experiments, which we might call experimental neutrino, actually travels through the background neutrino sea before being detected.

Let us now examine the influence of the C ν B on the experimental neutrinos passing through them. In this regard, a theoretical model in condensed matter physics can give us some inspiration. In some magnetic materials, a moving electron can exchange with other electrons it encounters, which is used to explain the ferromagnetism exhibited by these materials (Itinerant Electron Model) [?]. It bases on a fundamental principle of quantum mechanics—the exchange effect between identical particles. Similarly, when the wavefunctions of two neutrinos overlap in space, there must be an exchange effect between them. Compared to electrons, neutrinos possess two distinct characteristics that facilitate the occurrence of exchange effects. Firstly, neutrinos are electrically neutral, which allows their wavefunctions to overlap more readily in space due to the absence of Coulomb repulsion. Secondly, all neutrinos are left-handed, ensuring that any exchange between neutrinos does not violate the conservation of angular momentum. It is worth mentioning here that the second characteristic makes it impossible for neutrinos and right-handed antineutrinos to be exchanged unless their directions of motion happen to be exactly in a straight line. It should be emphasized that the exchange effect described here is not the neutrino-neutrino scattering mediated by the electroweak interactions. The situation here is analogous to the exchange of electrons between two hydrogen atoms in close proximity to each other when forming a hydrogen molecule. (For an insightful discussion on understanding the formation of diatomic molecules from the perspective of a two-level system, one may refer to Feynman's renowned lectures [?]).

Consider an experimental neutrino ν_α ($\alpha = e, \mu, \tau$) of energy E_1 exchanging with a background neutrino ν_α of energy E_2 when their wavefunctions overlap.

We denote the background neutrino by ν_α , which is used only for the sake of narrative convenience, and does not imply any essential difference between the background neutrinos and the experimental neutrinos. For the experimental neutrino ν_α , it can be in either the E_1 or E_2 state due to the existence of the background neutrino ν_α . This can be viewed as a two-level system. Assuming that the exchange amplitude is A , the corresponding Hamiltonian is

$$\hat{H} = \begin{pmatrix} E_1 & A \\ A & E_2 \end{pmatrix}. \quad (6)$$

Its two eigenvalues can be derived as (see Appendix A for details)

$$E'_i = \frac{E_1 + E_2 \pm \sqrt{(E_1 - E_2)^2 + 4A^2}}{2}. \quad (7)$$

Assuming $(E_1 - E_2)^2 \gg A^2$ and $E_1 \gg E_2$, we have

$$E'_1 \approx E_1 + \frac{A^2}{E_1}, \quad (8a)$$

$$E'_2 \approx E_2 - \frac{A^2}{E_1}. \quad (8b)$$

According to Eq. (8a), the experimental neutrino ν_α with energy E_1 acquires a potential energy inversely proportional to its energy by exchange with the background neutrino ν_α of the same flavor. Compared to Eq. (4), it can be seen that the fact that the neutrino has a tiny potential energy inversely proportional to its energy ($V = A^2/E_1$) is equivalent to giving the neutrino a tiny apparent mass m , as long as $m = \sqrt{2}|A|$ is taken.

As the neutrino ν_α travels through space, it can exchange with more than one ν_α at the same time. We denote the total amplitude as $A_{\alpha\alpha} \equiv A_{\alpha\alpha}$, which is expected to be proportional to the number density of ν_α . Due to the exchange with the background neutrinos of the same flavor, each experimental neutrino ν_α acquires a potential energy $V_{\alpha\alpha} = A_{\alpha\alpha}^2/E$. Next, we make an assumption that the neutrino ν_α can also exchange with ν_β ($\beta = e, \mu, \tau; \alpha \neq \beta$) in the $C\nu B$. This assumption not only enables the flavor conversion of experimental neutrinos but also makes the potential energy eigenstates different from the flavor eigenstates. We still lack a profound understanding of the essence of lepton flavor. We are unable to provide further justification for this assumption, other than by invoking the often-stated principle in quantum mechanics that anything not explicitly forbidden must exist.

From the perspective of experimental neutrinos, the transition between ν_α and ν_β ($\alpha, \beta = e, \mu, \tau; \alpha \neq \beta$) involves two opposite exchange processes: the exchange

of ν_α and ν_β , and the exchange of ν_β and ν_α . Denoting the corresponding amplitudes of these exchange processes as $A_{\alpha\beta}$ and $A_{\beta\alpha}$, respectively, the associated potential energies are $(A_{\alpha\beta})^2/E$ and $(A_{\beta\alpha})^2/E$. Consequently, the amplitude corresponding to the transition between ν_α and ν_β can be generally expressed as

$$A_{\alpha\beta}^{\text{trans}} = \frac{(A_{\alpha\beta})^2 - (A_{\beta\alpha})^2}{E}. \quad (9)$$

Based on the above analysis, we can express the neutrino potential energy matrix in flavor basis as follows

$$\hat{V} = \begin{pmatrix} V_{ee} & V_{e\mu} & V_{e\tau} \\ V_{\mu e} & V_{\mu\mu} & V_{\mu\tau} \\ V_{\tau e} & V_{\tau\mu} & V_{\tau\tau} \end{pmatrix} = \frac{1}{E} \begin{pmatrix} A_{ee}^2 & (A_{e\mu}^2 - A_{\mu e}^2)e^{i\theta_{e\mu}} & (A_{e\tau}^2 - A_{\tau e}^2)e^{i\theta_{e\tau}} \\ (A_{\mu e}^2 - A_{e\mu}^2)e^{i\theta_{\mu e}} & A_{\mu\mu}^2 & (A_{\mu\tau}^2 - A_{\tau\mu}^2)e^{i\theta_{\mu\tau}} \\ (A_{\tau e}^2 - A_{e\tau}^2)e^{i\theta_{\tau e}} & (A_{\tau\mu}^2 - A_{\mu\tau}^2)e^{i\theta_{\tau\mu}} & A_{\tau\tau}^2 \end{pmatrix}, \quad (10)$$

where E is the energy of the experimental neutrino and $V_{\alpha\beta} = V_{\beta\alpha}^*$ ($\alpha, \beta = e, \mu, \tau$).

If neutrino oscillations indeed arise from the exchange effect between experimental neutrinos and the CνB, the Hamiltonian $\hat{H}_{0,\nu}$ (Eq. (1)) essentially corresponds to the potential energy matrix \hat{V} (Eq. (10)). By utilizing the experimentally determined lepton mixing matrix U_{PMNS} , along with the values of Δm_{21}^2 and $|\Delta m_{31}^2|$, we can calculate the Hamiltonian $\hat{H}_{0,\nu}$, that is, the potential energy matrix \hat{V} . For the case of NO (IO), we take the best-fit values $\theta_{12} = 33.44^\circ$ (33.45°), $\theta_{23} = 49.0^\circ$ (49.3°), $\theta_{13} = 8.57^\circ$ (8.61°), $\delta_{CP} = 195^\circ$ (286°), $\Delta m_{21}^2 = 7.42 \times 10^{-5} \text{ eV}^2$ ($7.42 \times 10^{-5} \text{ eV}^2$), and $\Delta m_{31}^2 = 2.514 \times 10^{-3} \text{ eV}^2$ ($-2.423 \times 10^{-3} \text{ eV}^2$) [?]. The calculated matrix elements of \hat{V} , apart from the factor $1/E$, are given in Table 1 (see Appendix B for calculation details), where $\overline{A^2} \equiv (A_{ee}^2 + A_{\mu\mu}^2 + A_{\tau\tau}^2)/3$ and unit of the numerical values (excluding the phase factors) is 10^{-4} eV^2 .

Table 1 The calculated matrix elements of \hat{V} (apart from the factor $1/E$)

Mass Order	$\overline{A^2} - 3.957$	$\overline{A^2} + 3.775$	$\overline{A^2} + 2.744$
NO	$\overline{A^2} - 2.656$	$\overline{A^2} + 1.214$	$\overline{A^2} - 1.119$
IO	$A_{\mu e}^2 = A_{e\mu}^2 \times e^{i3.199}$	$A_{e\tau}^2 = A_{\tau e}^2 \times e^{i4.532}$	$A_{\mu\tau}^2 = A_{\tau\mu}^2 \times e^{i3.146}$

The results of the neutrino oscillation experiment are independent of the value of $\overline{A^2}$, thereby imposing no constraints on it. As mentioned above, we expect the value of $A_{\alpha\alpha}$ to be proportional to the number density of CνB, which enables

us to infer the possible range of $\overline{A^2}$ using the results in Table 1. Theoretical analysis suggests that background neutrinos of different flavors possess nearly identical number densities, with differences on the order of one thousandth [?]. Consequently, the corresponding differences among the $A_{\alpha\alpha}$ values are expected to be at a comparable level. As an approximation, we assume that the differences among $A_{\alpha\alpha}^2$ fall within the range of one-thousandth to one-hundredth. According to Table 1, the maximum difference among $A_{\alpha\alpha}^2$ (as well as the average $\overline{A^2}$) falls within the range of 0.06 to 6×10^{-4} eV². Consequently, the value of each $A_{\alpha\alpha}$ approximately ranges from 0.06 to 0.6 eV².

If neutrino oscillations are described by the Hamiltonian $\hat{H}_{0,\nu}$ (Eq. (1)), the primary focus lies on the neutrino masses and the mixing patterns among neutrinos. The origin of the pattern of neutrino masses and mixings, which is part of the so-called flavor puzzle, is a hot topic in the field of neutrinos [?, ?]. Although quark mixing once inspired speculation regarding neutrino mixing, current experimental evidence demonstrates that neutrinos and quarks exhibit notable differences in both mass magnitude and mixing patterns [?]. It remains an open question as to whether the observed mixing patterns of neutrinos reflect some deeper principle such as a broken flavor symmetry, or whether the patterns are purely random [?]. If neutrino oscillations are described by the potential energy matrix \hat{V} (Eq. (10)), the primary focus lies on the matrix elements rather than the eigenvalues (corresponding to the second term in Eq. (4)) and eigenstates (corresponding to Eq. (3)) of \hat{V} .

The matrix elements of \hat{V} possess certain characteristics that are consistent with the exchange mechanism. At early stages of cosmological evolution, neutrinos follow the Fermi-Dirac distribution and the equilibrium distribution is not obviously destroyed even after decoupling if $m_\nu = 0$ is assumed. Although detailed analysis indicates that certain physical processes can distort the neutrino spectrum, it is natural to assume that the distribution functions of ν_μ and ν_τ are almost equal, while that of ν_e is slightly different [?]. We anticipate that such characteristics will be manifested in the matrix elements of \hat{V} , which depend on the distribution of background neutrinos. It can be seen from Table 1 that, whether in the NO or IO case, the diagonal elements A_{ee}^2 , $A_{\mu\mu}^2$, and $A_{\tau\tau}^2$ are all situated in proximity to their mean value $\overline{A^2}$, and among the three, the values of $A_{\mu\mu}^2$ and $A_{\tau\tau}^2$ are closer. Furthermore, all the off-diagonal matrix elements $A_{\alpha\beta}^2$ ($\alpha \neq \beta$) are of the same order of magnitude as the difference between the corresponding diagonal matrix elements, $A_{\alpha\alpha}^2 - A_{\beta\beta}^2$. If the exchange amplitudes between experimental neutrinos of different flavors and background neutrinos of the same flavor are approximately equal—that is, if the values of $A_{\alpha\alpha}$ and $A_{\beta\alpha}$ are comparable—then Eq. (9) indicates that the off-diagonal matrix elements display the aforementioned characteristics. The off-diagonal matrix elements involve the exchange of an experimental neutrino with a background neutrino of different flavor, which means that the experimental neutrino will be added as an additional particle to the background neutrinos of the same flavor. Thus,

the exact values of the off-diagonal matrix elements would be affected by the Pauli exclusion principle.

4 Comparative Analysis of the Two Models

The potential energy matrix \hat{V} and the Hamiltonian $\hat{H}_{0,\nu}$ have the same form. Thereby, the model based on \hat{V} (V-model) and the model based on $\hat{H}_{0,\nu}$ (H-model) demonstrate equivalent efficacy in interpreting neutrino oscillation phenomena and, by extension, the MSW effect. However, these two types of explanatory frameworks exhibit experimentally verifiable distinctions due to the differing underlying assumptions. The V-model does not require the existence of neutrino mass, and lepton flavor is conserved during the process of neutrino oscillations. Within this framework, neutrino oscillations are characterized as a quantum mechanism phenomenon rather than an issue of quantum field theory requiring the introduction of new particles or interactions. If cosmological observations or other experimental studies confirm that neutrinos are massless or possess a mass value below the lower limit established by neutrino oscillation experiments, it would provide strong support for the V-model. Current cosmological observations and neutrino oscillation experimental results have exhibited a mild tension. However, given that cosmological observations are contingent upon specific models employed and the degeneracy between neutrino mass and other cosmological parameters, it remains premature to draw definitive conclusions. The discovery of neutrino oscillations motivates searches for charged lepton flavor violating processes, such as $\mu^+ \rightarrow e^+\gamma$ [?]. If the existence of other lepton flavor violation processes can be confirmed, it will make the H-model more credible. So far, no relevant evidence has been found [?].

In the H-model, neutrinos and antineutrinos have the same mass and mixing pattern, and their difference is manifested through the CP-violating phase δ_{CP} . Specifically, the Hamiltonian $\hat{H}_{0,\bar{\nu}}$ of anti-neutrinos is the complex conjugate of the Hamiltonian $\hat{H}_{0,\nu}$ of neutrinos [?]. From Eqs. (1) and (2), it can be inferred that when $\delta_{CP} \neq 0$ or π , neutrinos and antineutrinos have different Hamiltonians, leading to distinct oscillation behaviors. The value of the CP-violating phase δ_{CP} determined by current neutrino oscillation experiments depends on the neutrino mass ordering: for NO the global fit is consistent with CP conservation ($\delta_{CP} \approx \pi$) within 1σ , whereas for IO CP-violating values of δ_{CP} around $3\pi/2$ are favored against CP conservation at more than 3.6σ [?].

From the perspective of the V-model, the difference in oscillation phenomena between neutrinos and antineutrinos indicates that they possess distinct potential energy matrices. The potential energy matrices of neutrinos and antineutrinos are respectively dependent on the distributions of relic neutrinos and antineutrinos. It is normally assumed that cosmological lepton charge asymmetry i.e. the difference between the number densities of relic neutrinos and antineutrinos, is vanishing small [?]. In this scenario, neutrinos and antineutrinos would exhibit nearly identical potential energy matrices, resulting in similar apparent

masses and mixing patterns. If, for certain reasons (e.g., neutrinos possess a non-zero chemical potential [?]), the distribution of neutrinos and antineutrinos in the background exhibits a certain degree of asymmetry, this would result in slightly different potential energy matrices for neutrinos and antineutrinos, consequently leading to slightly different apparent masses and mixing angles. Nowadays, the measurement of neutrino masses and mixing angles has entered the sub-percentage accuracy era. A subtle discrepancy has consistently been observed between the values of Δm_{21}^2 and θ_{12} extracted from the global fit of the solar neutrino data and those measured by KamLAND (antineutrino channel), and this discrepancy has been reaffirmed by the latest analyses [?]. A pertinent research topic is whether the oscillation parameters (mass-squared differences and mixing angles) of neutrinos and antineutrinos are entirely identical. The identification of subtle systematic differences in the oscillation parameters between neutrinos and antineutrinos would provide compelling additional evidence supporting the V-model.

Anomalies observed in oscillation experiments present an additional potential avenue for distinguishing between the two models. There are four long-standing anomalies in the short-baseline neutrino experiments that still lack satisfactory explanations in the H-model [?]. Two arise from the apparent oscillatory appearance of electron (anti)neutrinos in relatively pure muon-(anti)neutrino beams [?]. The other two anomalies are associated with an overall normalization discrepancy of electron antineutrinos expected both from conventional fission reactors (the Reactor Antineutrino Anomaly, RAA) and in the radioactive decay of ^{71}Ga (the Gallium Anomaly, GA) [?]. These anomalies share several common features: firstly, they all involve high-flux neutrino sources; secondly, regardless of the different sources, baselines and energy ranges of these experiments, all of the above anomalies can be understood individually via short-baseline neutrino oscillations driven by a new mass-squared difference, $\Delta m^2 \sim 1 \text{ eV}^2$; thirdly, there are obvious tensions in the range of possible values of Δm^2 (and the mixing angle θ) obtained from different experiments; fourthly, a clear oscillatory signal dependent on L/E (L is the detector-to-neutrino-source distance, and E is the neutrino energy) has not been observed in almost all the cases (except for the Neutrino-4 experiment [?]). One of the most extensively studied theoretical frameworks proposed for interpreting these anomalies involves the addition of at least one sterile neutrino (ν_s) to the standard three-flavor neutrino mixing paradigm [?]. However, due to the third and fourth points mentioned above, this framework fails to provide a consistent explanation. Furthermore, introducing additional massive neutrinos at eV scale is in strong tension with cosmological observations [?].

The V-model offers an alternative plausible explanation for some of these anomalies, which may be validated through future experiments. In the recent BEST experiment that confirmed the GA [?], the dimension of the neutrino source, the spatial extent of the target area, and their relative positional configuration, are all clearly defined, which enables us to take it as an example for detailed analysis. The BEST experiment utilized a ^{51}Cr neutrino source of unprecedented

strength ($\sim 1.16 \times 10^{17}$ Bq). It was observed that there was approximately a $\sim 20\%$ deficiency of ν_e compared to the expected value, which is consistent with the hypothesis of $\nu_e \rightarrow \nu_s$ oscillations with a large mass difference ($\Delta m^2 \geq 0.5 \text{ eV}^2$), but no distance-dependent evidence has been identified [?]. It can be shown that in the BEST experiment, within the inner target volume, the number of background neutrinos ν_μ and ν_τ is greater than 20% of the number of experimental neutrinos ν_e , and they are of the same order of magnitude (see Appendix C for detailed analysis). Thus, in principle, it is possible that the missing ν_e may have transformed into ν_μ and/or ν_τ —undetectable by the BEST experiment—via the exchange with background neutrinos ν_μ and/or ν_τ . In addition, this exchange is expected to have a significant impact on the local background neutrino number density. The potential energy matrix \hat{V} depends on the distribution of background neutrinos, and if the distribution is perturbed by experimental neutrinos through some mechanism yet to be elucidated, a larger apparent squared mass difference may potentially emerge. For simplicity, let us consider two flavor oscillations ($\nu_\alpha \leftrightarrow \nu_\beta$). The corresponding potential energy matrix is

$$\hat{V}' = \frac{1}{E} \begin{pmatrix} A_{\alpha\alpha}^2 & (A_{\alpha\beta}^2 - A_{\beta\alpha}^2)e^{i\theta_{\alpha\beta}} \\ (A_{\beta\alpha}^2 - A_{\alpha\beta}^2)e^{i\theta_{\beta\alpha}} & A_{\beta\beta}^2 \end{pmatrix}. \quad (11)$$

The direct calculation yields that the difference between the two eigenvalues of matrix \hat{V}' is

$$|\lambda_1 - \lambda_2| = \frac{1}{E} \sqrt{(A_{\alpha\alpha}^2 - A_{\beta\beta}^2)^2 + 4A_{\alpha\beta}^2 A_{\beta\alpha}^2}. \quad (12)$$

Expressed in terms of the apparent mass m_i ($m_i^2 = 2E\lambda_i$), that is,

$$\Delta m^2 \equiv |m_1^2 - m_2^2| = 2\sqrt{(A_{\alpha\alpha}^2 - A_{\beta\beta}^2)^2 + 4A_{\alpha\beta}^2 A_{\beta\alpha}^2}. \quad (13)$$

Under normal circumstances, background neutrinos ν_α and ν_β have similar distributions, thus $A_{\alpha\alpha}^2$ and $A_{\beta\beta}^2$ are small, and therefore Δm^2 is small (compared to $A_{\alpha\alpha}^2$). However, perturbation of the background neutrino ν_β distribution caused by the experimental neutrino ν_α results in a significant local depletion of ν_β , thereby substantially reducing $A_{\beta\beta}^2$. Based on the preceding analysis, the possible values of $A_{\alpha\alpha}^2$ approximately range from 0.06 to 0.6 eV^2 , resulting in a squared difference of apparent mass that can reach the order of eV^2 . The perturbation of local background neutrinos depends on the specific experimental details, which leads to differences among the results of different experiments. The experimental neutrino flux is inversely proportional to the square of the propagation distance L , which leads to variations in Δm^2 (as well as in the mixing angles) as a function of distance. Consequently, anomalies tend to manifest predominantly near the neutrino source, and in this case, the oscillation

dependence on L/E becomes more complex. If future experiments can establish a clear correlation between the deficiency of ν_e and the activity of radioactive sources, it will be a strong support for the V-model.

5 Conclusion

In summary, neutrino oscillations constitute indirect evidence for the existence of neutrino mass. If neutrino oscillations originate from the intrinsic properties of neutrinos themselves, then attributing mass to neutrinos and postulating that flavor eigenstates are superpositions of mass eigenstates would likely provide the most natural and straightforward explanation for neutrino oscillations. Consequently, the phenomena of neutrino oscillation can be regarded as compelling evidence demonstrating that neutrinos possess mass. However, an alternative possibility exists wherein neutrino oscillations arise from the influence of the external environment, specifically through the exchange between neutrinos and the $C\nu B$. In this scenario, the Hamiltonian describing neutrino oscillations is interpreted as a potential matrix, thereby obviating the need to assign mass to neutrinos while maintaining lepton flavor conservation. From this perspective, the significance of neutrino oscillation phenomena lies not in demonstrating that neutrinos possess mass, but rather in serving as a probe for the $C\nu B$. If neutrinos possess mass, it would be a major breakthrough beyond the SM; precisely for this reason, it is imperative to gather more, particularly direct evidences, and to rule out alternative explanations. We anticipate that theoretical and experimental investigations in the coming years will conclusively determine whether neutrinos possess mass.

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Appendix A: Computation of eigenvalues of the Hamiltonian \hat{H}

Denoting the eigenvalues as E'_i ($i = 1, 2$), we have

$$\det \begin{pmatrix} E_1 - E'_i & A \\ A & E_2 - E'_i \end{pmatrix} = 0. \quad (A1)$$

That is

$$E_{i'}^2 - (E_1 + E_2)E'_i + E_1E_2 - A^2 = 0 \quad (A2)$$

The solutions are

$$E'_i = \frac{E_1 + E_2 \pm \sqrt{(E_1 - E_2)^2 + 4A^2}}{2}. \quad (A3)$$

If $(E_1 - E_2)^2 \gg A^2$ and $E_1 \gg E_2$, we have

$$E'_i \approx \frac{E_1 + E_2 \pm (E_1 - E_2)(1 + 2A^2/(E_1 - E_2)^2)}{2}, \quad (A4)$$

namely,

$$E'_1 \approx E_1 + \frac{A^2}{E_1 - E_2} \approx E_1 + \frac{A^2}{E_1}, \quad (A5)$$

$$E'_2 \approx E_2 - \frac{A^2}{E_1 - E_2} \approx E_2 - \frac{A^2}{E_1}. \quad (A6)$$

Appendix B: Computation of matrix elements of \hat{V}

From the analysis in the main text, if neutrino oscillation is due to the exchange of experimental neutrinos and background neutrinos, then there is $\hat{V} = \hat{H}_{0,\nu}$, that is,

$$\frac{1}{E} \begin{pmatrix} A_{ee}^2 & (A_{e\mu}^2 - A_{\mu e}^2)e^{i\theta_{e\mu}} & (A_{e\tau}^2 - A_{\tau e}^2)e^{i\theta_{e\tau}} \\ (A_{\mu e}^2 - A_{e\mu}^2)e^{i\theta_{\mu e}} & A_{\mu\mu}^2 & (A_{\mu\tau}^2 - A_{\tau\mu}^2)e^{i\theta_{\mu\tau}} \\ (A_{\tau e}^2 - A_{e\tau}^2)e^{i\theta_{\tau e}} & (A_{\tau\mu}^2 - A_{\mu\tau}^2)e^{i\theta_{\tau\mu}} & A_{\tau\tau}^2 \end{pmatrix} = \frac{1}{2E} \hat{U}_{PMNS} \text{diag}(m_1^2, m_2^2, m_3^2) \hat{U}_{PMNS}^\dagger. \quad (B1)$$

Let $\Delta m_{21}^2 \equiv m_2^2 - m_1^2$, $\Delta m_{31}^2 \equiv m_3^2 - m_1^2$, and $\bar{A}^2 \equiv (A_{ee}^2 + A_{\mu\mu}^2 + A_{\tau\tau}^2)/3$. Let $(m_1^2 + m_2^2 + m_3^2)/3 \equiv \bar{m}^2$, we have

$$m_1^2 = \bar{m}^2 - \frac{\Delta m_{21}^2 + \Delta m_{31}^2}{3}, \quad (B2)$$

$$m_2^2 = \bar{m}^2 + \frac{2\Delta m_{21}^2 - \Delta m_{31}^2}{3}, \quad (B3)$$

$$m_3^2 = \bar{m}^2 + \frac{2\Delta m_{31}^2 - \Delta m_{21}^2}{3}. \quad (B4)$$

Let $\Delta m_1^2 \equiv -(\Delta m_{21}^2 + \Delta m_{31}^2)/3$, $\Delta m_2^2 \equiv (2\Delta m_{21}^2 - \Delta m_{31}^2)/3$, and $\Delta m_3^2 \equiv (2\Delta m_{31}^2 - \Delta m_{21}^2)/3$. Let $A_{ee}^2 = \bar{A}^2 + \Delta A_{ee}^2$, $A_{\mu\mu}^2 = \bar{A}^2 + \Delta A_{\mu\mu}^2$, and $A_{\tau\tau}^2 = \bar{A}^2 + \Delta A_{\tau\tau}^2$, we have

$$\bar{A}^2 \hat{I} + \begin{pmatrix} \Delta A_{ee}^2 & (A_{e\mu}^2 - A_{\mu e}^2)e^{i\theta_{e\mu}} & (A_{e\tau}^2 - A_{\tau e}^2)e^{i\theta_{e\tau}} \\ (A_{\mu e}^2 - A_{e\mu}^2)e^{i\theta_{\mu e}} & \Delta A_{\mu\mu}^2 & (A_{\mu\tau}^2 - A_{\tau\mu}^2)e^{i\theta_{\mu\tau}} \\ (A_{\tau e}^2 - A_{e\tau}^2)e^{i\theta_{\tau e}} & (A_{\tau\mu}^2 - A_{\mu\tau}^2)e^{i\theta_{\tau\mu}} & \Delta A_{\tau\tau}^2 \end{pmatrix} = \frac{\bar{m}^2}{2} \hat{I} + \hat{U}_{PMNS} \text{diag}(\Delta m_1^2, \Delta m_2^2, \Delta m_3^2) \hat{U}_{PMNS}^\dagger$$

where \hat{I} is the identity matrix. Substituting the matrix \hat{U}_{PMNS} , we have

$$\Delta m_2^2 = \frac{2\Delta m_{21}^2 - \Delta m_{31}^2}{3} = 8.62 \times 10^{-4} \text{ eV}^2, \quad (B17)$$

$$\Delta m_3^2 = \frac{2\Delta m_{31}^2 - \Delta m_{21}^2}{3} = -1.65 \times 10^{-3} \text{ eV}^2. \quad (B18)$$

By substituting the measured mixing angle θ_{ij} and Eqs. (B13)-(B18) into Eqs. (B6)-(B11), all matrix elements of \hat{V} can be calculated, with the results presented in Table 1 of the main text.

Appendix C: Analysis of the BEST experiment under the V-Model

In the BEST experiment, an inner spherical volume, with diameter 133.5 cm, contains (7.4691 ± 0.0631) t of Ga. An outer cylindrical volume (234.5 cm high, 218 cm diam.) contains (39.9593 ± 0.0024) t of Ga. The ^{51}Cr source was placed at the center irradiating both volumes simultaneously. The activity of the source is $(116.23 \pm 0.03) \times 10^{15}$ Bq. The measured production rates for the inner and the outer targets were found to be similar, but 20% - 24% lower than expected [?, ?]. We hereby demonstrate that the flux of background neutrinos ν_μ and ν_τ entering the inner sphere per unit time exceeds 20% of the number of source-generated neutrinos ν_e during the same time. The source generates 1.16×10^{17} neutrinos ν_e per second, and 20% of them, approximately 2.3×10^{16} , are missing. The number of background neutrinos ν_μ or ν_τ entering the inner sphere per second is approximately $N = ncS$, where n is the number density of ν_μ or ν_τ ($\sim 56 \text{ cm}^{-3}$), c is the propagation speed of the neutrinos ($\sim 3 \times 10^{10} \text{ cm}\cdot\text{s}^{-1}$), and S is the surface area of the inner sphere (πd^2 , $d = 133.5 \text{ cm}$). Substituting the values, we get $N \approx 9.4 \times 10^{16}$. It can be seen that $N > 2.3 \times 10^{16}$, and they are of the same order of magnitude. This means that there are enough background neutrinos within the inner target region to exchange with 20% of the experimental neutrinos, and such exchanges will have a significant impact on the local number density of background neutrinos near the source.

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