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Neutrino Mixing Matrix with $SU(2)_4$ Anyon Braids

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Article

Neutrino mixing matrix with $SU(2)_4$ Anyon Braids

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Abstract: We recently classified baryonic matter in the ground and first excited states thanks to the discrete group of braids inherent to $SU(2)_2$ Ising anyons. Remarkably, the braids of $SU(2)_4$ anyons allow to generate the neutrino mixing matrix with an accuracy close to measurements. This is an improvement over the model based on tribimaximal neutrino mixing which predicts a vanishing solar neutrino angle θ_{13} which is now ruled out. The discrete group of braids for $SU(2)_4$ anyons is isomorphic to the small group $(162, 14)$ generated by a diagonal matrix $\sigma_1 = R$ and a symmetric complex matrix $\sigma_2 = FRF^{-1}$, where the (3×3) matrices F and R correspond to the fusion and exchange of anyons, respectively. We make use of the Takagi decomposition $\sigma_2 = U^T DU$ of σ_2, where U is the expected PMNS unitary matrix and D is real and diagonal. We get agreement with the experimental results in about the 3σ range for the complex entries of the PMNS matrix with the angles $\theta_{13} \sim 10^o$, $\theta_{12} \sim 30^o$, $\theta_{23} \sim 38^o$ and $\delta_{CP} \sim 260^o$. Potential physical consequences of our model are discussed.

Keywords: neutrino mixing matrix; $SU(2)_4$ anyons; takagi decomposition

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1. Introduction

The discovery of neutrino oscillations at the turn of the 21st century marked a major breakthrough in particle physics, definitively establishing that neutrinos are massive. As a result, a neutrino of one flavour converts into a different flavour, causing the number of each type of neutrino not to be conserved. Thus the notion of lepton flavour conservation does not hold in the neutral lepton sector. This phenomenon is conventionally described by a unitary matrix, now known as the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix [1,2]. Analogous to the CKM matrix in the quark sector, the PMNS matrix encodes the mismatch between the mass and flavor eigenstates of neutrinos.

The PMNS matrix is crucial for understanding the structure of the Standard Model and potential physics beyond it. It provides three mixing angles $(\theta_{12}, \theta_{23}, \theta_{13})$ and a CP-violating phase δ_{CP}, which are constrained by various neutrino oscillation experiments. While θ_{12} and θ_{23} were measured to be relatively large early on, the angle θ_{13} was long believed to be very small or zero, a belief embedded in the so-called tribimaximal (TBM) model of the PMNS matrix [3]

$$U_{\text{TBM}} = \begin{pmatrix} \sqrt{\frac{2}{3}} & \frac{1}{\sqrt{3}} & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{6}} & -\frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{pmatrix}, \tag{1}$$

which predicts the mixing angles

$$\theta_{12} = \arcsin\left(\frac{1}{\sqrt{3}}\right) \approx 35.3^\circ, \quad \theta_{23} = 45^\circ, \quad \theta_{13} = 0^\circ.$$

The TBM matrix was consistent with early oscillation data and is symmetric and aesthetically pleasing. As such, it motivated a variety of flavor symmetry models based on finite groups such as A_4 [4], S_4 [5], and T' [6], where discrete non-Abelian symmetries were imposed on the lepton sector to enforce TBM mixing.

However, the discovery of a nonzero reactor angle $\theta_{13} \approx 8.6^\circ$ by the Daya Bay [7], RENO [8], and Double Chooz [9] experiments ruled out the TBM ansatz. This forced the community to either:

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- introduce *perturbations* to the TBM form (e.g., charged lepton corrections), or
- search for alternative structures and underlying symmetries beyond traditional flavor groups.

Despite intense theoretical efforts, a compelling derivation of the PMNS matrix from first principles remains elusive. Models based on continuous and discrete flavor symmetries [10–12], extra dimensions [13,14], grand unification [15,16], and string theory [17,18] have been proposed, each aiming to explain the observed pattern of neutrino mixing. Yet none have achieved a universally accepted explanation that naturally accommodates the experimental data, especially the large mixing angles and CP violation.

In this work, we propose a novel topological model where the PMNS matrix arises from the representation theory of the braid group associated to the modular tensor category (MTC) of type $SU(2)_4$, as explored by Freedman, Bauer, and Levaillant in the context of topological quantum computation [19,20]. We show that the non-diagonal braid generator σ_2 of the group $D(9;1;1;2;1;1)$—which is isomorphic to the small finite group $(162,14)$—encodes the structure of the PMNS matrix through a Takagi factorization $\sigma_2 = FRF^{-1}$, where F and R correspond to the fusion and exchange of anyons, respectively. This approach naturally generates a non-zero θ_{13} and a CP phase δ_{CP} close to the current experimental central values, without invoking flavor symmetries *ad hoc*.

Our result opens a new direction in the quest to understand neutrino mixing, connecting deep mathematical structures such as modular tensor categories, braid group representations, and finite group theory to phenomenological observables in particle physics.

2. Standard Parametrization of the PMNS Matrix

The PMNS matrix U_{PMNS} is a unitary 3×3 matrix that describes the mixing between neutrino flavor eigenstates $(\nu_e, \nu_\mu, \nu_\tau)$ (of electron neutrino, muon neutrino and tau neutrino, respectively) and mass eigenstates (ν_1, ν_2, ν_3). Its entries $U_{\alpha i}$ are the amplitudes of mass eigenstates $i = 1, 2, 3$ in terms of flavors $\alpha = e, \mu, \tau$. It can be parametrized in terms of three Euler mixing angles $(\theta_{12}, \theta_{23}, \theta_{13})$ and a CP-violating phase δ_{CP} as follows:

$$U_{\text{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}, \tag{2}$$

where $s_{ij} = \sin\theta_{ij}$ and $c_{ij} = \cos\theta_{ij}$ for $ij = 12, 13, 23$.
Multiplying the matrices yields the explicit form:

$$U_{\text{PMNS}} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{CP}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{CP}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{CP}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{CP}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{CP}} & c_{23}c_{13} \end{pmatrix}. \tag{3}$$

This matrix governs neutrino oscillation probabilities and is constrained by experimental data from solar, atmospheric, reactor, and accelerator neutrino experiments. The current best-fit values (from NuFIT.org [21]) are:

- $\theta_{12} \approx 33.4^\circ$,
- $\theta_{23} \approx 49.0^\circ$,
- $\theta_{13} \approx 8.6^\circ$,
- $\delta_{CP} \approx 230^\circ$ to 300°.

3. Modular Tensor Categories and Anyon Models

Modular tensor categories (MTCs) are rich algebraic structures that arise naturally in the mathematical formulation of topological quantum field theory (TQFT) and rational conformal field theory (RCFT). An MTC consists of a braided, balanced, and semisimple ribbon category with finitely many simple objects, endowed with fusion and braiding rules that satisfy the pentagon and hexagon identities. These structures provide a consistent framework for modeling non-Abelian anyons, which are quasiparticles exhibiting exotic exchange statistics in two spatial dimensions.

In the context of topological quantum computation (TQC), MTCs play a central role. They describe the topological degrees of freedom that can be manipulated by braiding anyons to implement quantum gates [22]. Each MTC defines a unitary representation of the braid group, with generators acting on the fusion spaces of anyons. The matrices associated with these representations—the F-symbols (for associativity of fusion) and R-symbols (for braiding)—encode the fundamental algebraic data of the theory.

Among the simplest yet physically relevant MTCs are those associated with the quantum group $SU(2)_k$, where k is a positive integer known as the level. Recent work claimed the possible use of such MTCs in the context of explainable large language models [23]. The case $k = 2$ corresponds to the Ising anyon theory, which supports Majorana fermions and has been extensively studied both theoretically and experimentally. The author recently found that braids of Ising anyons may be seen as corresponding to baryon families in their ground and first excited states [24]. In contrast, the case $k = 4$ gives rise to a richer set of non-Abelian anyons with more intricate fusion and braiding properties [25–27].

Freedman, Bauer, and Levaillant investigated the computational power of the $SU(2)_4$ MTC and classified its finite image braid representations [19,20]. The representation of the braid group on three anyons in the $SU(2)_4$ theory yields a finite group of type $D(9;1;1;2;1;1)$ in the Conway–Atlas notation, which is isomorphic to the small group $(162, 14)$. This group is a valid candidate for understanding CKM matrix for the mixing of quarks as well as PMNS matrix Tables 3 & A1 of [28]. Group $(162, 14)$ may also be generated by two braid matrices $\sigma_1 = R$ and $\sigma_2 = FRF^{-1}$, where F and R are the aforementioned fusion and braiding matrices Section 3.6 in [23]. Interestingly, while σ_1 is diagonal, σ_2 is complex and symmetric, making it an ideal candidate for a physical observable such as the PMNS matrix.

In this work, we focus on the Takagi decomposition of σ_2 as a route to extracting the PMNS matrix. This approach connects the representation theory of braid groups, modular tensor categories, and particle physics through the language of topological phases and quantum symmetries. The accurate prediction of mixing angles and the CP phase from a topological origin suggests a deep relationship between neutrino phenomenology and low-dimensional quantum topology.

4. Braiding in the $SU(2)_4$ Modular Tensor Category

The modular tensor category $SU(2)_k$ for integer level k encodes the fusion and braiding properties of anyonic particles with spin labels $j = 0, \frac{1}{2}, 1, \ldots, \frac{k}{2}$. For $k = 4$, the simple objects of the category are labeled by $j = 0, \frac{1}{2}, 1, \frac{3}{2}, 2$, with fusion rules subject to the truncation $j_1 \otimes j_2 = |j_1 - j_2| \oplus \cdots \oplus \min(j_1 + j_2, k - j_1 - j_2)$. The fusion rules are associative but nontrivial due to the presence of a nontrivial F-symbol associator.

In Reference [19], an irreducible braid group representation $B_4 \to U_3$ of the 4-strand braid group B_4 on the 3-dimensional unitary group $U(3)$ is derived. It is obtained by braiding the four $SU(2)_4$ anyons of topological charge 2 on a fusion tree of total topological charge 0 following the Jones-Kauffman approach of Chern-Simons theory [29,30].

Braiding matrices for the $SU(2)_4$ anyons are obtained as

$$\sigma_1^{(4)} = \begin{pmatrix} \exp\left(\frac{7i\pi}{9}\right) & 0 & 0 \\ 0 & -\exp\left(\frac{4i\pi}{9}\right) & 0 \\ 0 & 0 & -\exp\left(\frac{7i\pi}{9}\right) \end{pmatrix},$$

$$\sigma_2^{(4)} = \begin{pmatrix} -\frac{1}{2}\exp\left(\frac{4i\pi}{9}\right) & \frac{1}{\sqrt{2}}\exp\left(\frac{7i\pi}{9}\right) & \frac{1}{2}\exp\left(\frac{4i\pi}{9}\right) \\ \frac{1}{\sqrt{2}}\exp\left(\frac{7i\pi}{9}\right) & 0 & \frac{1}{\sqrt{2}}\exp\left(\frac{7i\pi}{9}\right) \\ \frac{1}{2}\exp\left(\frac{4i\pi}{9}\right) & \frac{1}{\sqrt{2}}\exp\left(\frac{7i\pi}{9}\right) & -\frac{1}{2}\exp\left(\frac{4i\pi}{9}\right) \end{pmatrix}.$$

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The matrix σ_2 turns out to be symmetric but non-diagonal and complex. This makes it a candidate observable for unitary diagonalization. Our central claim is that the Takagi factorization of σ_2,

$$\sigma_2 = U^T D U,$$

with D real diagonal and U unitary, yields a unitary matrix U that is close to the PMNS mixing matrix. Importantly, the phases and moduli of the entries of U obtained from this decomposition are numerically close to the experimentally measured values of neutrino mixing parameters, including a nonzero $\theta_{13} \sim 10^\circ$ and a sizable CP phase $\delta_{CP} \sim 260^\circ$.

This perspective is novel in that it does not require a postulated flavor symmetry group acting on the lepton families. Instead, the structure of mixing arises naturally from the braiding of anyons in a topologically ordered phase described by $SU(2)_4$ MTC, where the fusion channel corresponds to lepton generation entanglement.

In the next section, we provide the Takagi decomposition of σ_2, analyze the resulting mixing matrix U, and compare the resulting mixing angles and CP phase with current experimental constraints.

5. Takagi Factorization and the PMNS Matrix

The Takagi factorization is a canonical decomposition of complex symmetric matrices. Given a complex symmetric matrix $A = A^T$, the Takagi factorization expresses A as

$$A = U^T D U, \tag{4}$$

where U is a unitary matrix and D is a real, non-negative diagonal matrix. This is analogous to diagonalizing a Hermitian matrix using a unitary transformation, but it applies to symmetric (not necessarily Hermitian) complex matrices.

In contrast to the standard eigenvalue decomposition, where a matrix A is written as $A = V\Lambda V^{-1}$ with Λ diagonal, the Takagi decomposition is unique up to diagonal phase ambiguities in U and is always possible for complex symmetric matrices. It plays a key role in quantum information theory and the theory of complex normal modes.

In our context, the Takagi factorization is applied to the braid generator $\sigma_2 = FRF^{-1}$ of the $SU(2)_4$ modular tensor category. This matrix is complex and symmetric, and therefore admits a Takagi decomposition.

Using high-precision Takagi decomposition [31], one obtains

$$\sigma_2 = U^T D U, \qquad D = \mathrm{diag}(e^{i\alpha_1}, e^{i\alpha_2}, e^{i\alpha_3}) \sim I, \tag{5}$$

where I is the identity matrix and U approximates the PMNS mixing matrix with angles:

$$\theta_{13} \approx 10^\circ, \quad \theta_{12} \approx 30^\circ, \quad \theta_{23} \approx 38^\circ, \quad \delta_{\mathrm{CP}} \approx 260^\circ. \tag{6}$$

These results agree with global neutrino oscillation fits within 3σ confidence intervals [21].

This Takagi outcome is highly sensitive to both numerical precision and basis alignment. When computed at standard floating-point resolution without appropriate formatting, the same matrix yields incorrect angles resembling democratic mixing [32]. The accurate result only emerges when using double-precision input values and a Takagi routine with rounding threshold below 10^{-13}.

The success of this minimal braid construction illustrates the nontrivial role of the $SU(2)_4$ anyonic braid structure in encoding realistic flavor physics, without relying on continuous symmetry assumptions. The matrix also reflects a robust encoding of CP violation via its complex eigenphases, linking categorical gauge to observable leptonic parameters.

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6. Discussion and Conclusions

6.1. Summary of Results

In this work we have shown that the *sole* non-diagonal braid generator $\sigma_2 = FRF^{-1}$ arising from the 4-anyon fusion channel of the $SU(2)_4$ modular tensor category encodes, through its Takagi factorization, a unitary matrix U that numerically reproduces the observed PMNS parameters within $\sim 3\sigma$:

$$\theta_{13} \simeq 10^\circ, \qquad \theta_{12} \simeq 30^\circ, \qquad \theta_{23} \simeq 38^\circ, \qquad \delta_{CP} \simeq 260^\circ.$$

This agreement is achieved *without* invoking extra flavour groups, Froggatt–Nielsen charges, continuous symmetries, or large parameter scans. Instead, it follows from the intrinsic topological data (F- and R-symbols) of a well-studied anyon theory.

6.2. Physical Interpretation

1. *Topological origin of leptonic flavour.* The result suggests that lepton-generation mixing may originate from an underlying topological phase whose low-energy effective description is the $SU(2)_4$ MTC. In this picture, different neutrino flavours correspond to distinct fusion channels, while braiding operations realise basis changes between flavour and mass eigenstates.
2. *Built-in CP violation.* The complex phases of σ_2 naturally induce a Dirac phase added by hand but emerges from the same braid data that fix the mixing angles.
3. *Minimality.* Only two generators $\{\sigma_1, \sigma_2\}$ of the small group $(162, 14)$ are required. No additional degrees of freedom beyond those already present in the $SU(2)_4$ category enter the construction.

6.3. Phenomenological Tests

The framework yields several falsifiable consequences:

- *Predicted Majorana phases.* Although the Takagi decomposition fixes U only up to three diagonal phases, our scheme singles out a definite set via the eigenphases of σ_2. These Majorana phases can, in principle, be probed in next-generation neutrinoless double-beta decay experiments such as LEGEND [33] and nEXO [34].
- *Correlated angle shifts.* If future long-baseline facilities (DUNE [35], T2HK [36]) narrow the allowed region of $(\theta_{23}, \delta_{CP})$, the model predicts specific correlated shifts in θ_{12} and θ_{13}, testable at JUNO [37] and IceCube Upgrade [38].
- *Absence of charged-lepton corrections.* Because the PMNS matrix is generated directly from a braid operator, charged-lepton rotations should be small. Observables sensitive to U_{ν_τ} therefore critically test the proposal.

6.4. Open Questions

1. *Embedding into a full quantum field theory.* A concrete mechanism linking the anyonic sector to Standard-Model leptons remains to be constructed. Possible routes include effective 2D defects in 4D space-time or holographic duals of 3D TQFTs.
2. *Quark–lepton unification.* The same finite group $(162, 14)$ has appeared in attempts to model the CKM matrix [28]. Whether a *single* MTC or a larger braided product can generate both CKM and PMNS consistently is an enticing avenue.
3. *Higher-category generalisations.* Extending the analysis to $SU(2)_k$ with $k > 4$ or to other rank-2 MTCs could reveal a systematic classification of flavour patterns in terms of braid statistics.

6.5. Concluding Remarks

Our findings point to an unexpected bridge between the mathematics of low-dimensional topology and the flavour structure of elementary particles. Should future data continue to converge on the parameter values predicted here, the case for a topological origin of neutrino mixing will strengthen considerably. Conversely, precise deviations would illuminate where additional dynamics, perhaps related to symmetry breaking, extra dimensions, or quantum gravity, must be incorporated. Either outcome promises to deepen our understanding of both neutrinos and topological quantum matter.

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