A
Appendix

In this thesis, we delve into quantum correlation measures using two key techniques: the partial trace and the partial transpose. Section A.1 explores the concept of the partial trace in detail, while section A.2 examines the partial transpose.

A.1 Partial trace

In a quantum system consisting of two subsystems, A and B, one might be interested only in the state of subsystem A. This is described using the concept of the reduced density operator. If the total system is represented by the density operator ρ_{AB}, then the state of subsystem A is described by the reduced density operator. To obtain the reduced density operator, one uses the mathematical operation known as the partial trace. The partial trace is a process used to reduce the dimension of a composite quantum system. Given the density operator ρ_{AB} for the total system, the reduced density operator for subsystem A is given by:

$$\rho_A = \mathrm{Tr}_B[\rho_{AB}]$$

where Tr_B denotes the partial trace over subsystem B. The density matrix ρ_{AB} describes the composite system, and tracing out subsystem B returns the density matrix ρ_A for subsystem A. This partial trace operation is defined for all density operators and is significant because it provides the correct measurement statistics for subsystem A, making it a unique and essential operation.

The partial trace tr_B is a mapping from the density matrices ρ_{AB} on a composite space $\mathcal{H}_A \otimes \mathcal{H}_B$ onto density matrices ρ_A on $\mathcal{H}_A$. It is defined as the linear extension of the mapping

$$tr_B : S \otimes T \mapsto tr(T)S, \tag{A.1}$$

for any matrix S on $\mathcal{H}_A$ and T on $\mathcal{H}_B$. Let $\{|a_i\rangle\}$ be a basis of $\mathcal{H}_A$, and $\{|b_i\rangle\}$ be a basis of $\mathcal{H}_B$. Any density matrix ρ_{AB} on $\mathcal{H}_A \otimes \mathcal{H}_B$ can then be decomposed as $\rho_{AB} = \sum_{ijkl} c_{ijkl} |a_i\rangle \langle a_j| \otimes |b_k\rangle \langle b_l|$ and the partial trace reads

$$tr_B \rho_{AB} = \sum_{ijkl} c_{ijkl} |a_i\rangle \langle a_j| \otimes \langle b_l \mid b_k\rangle , \tag{A.2}$$

for eg., the two qubit spin singlet $|\psi^-\rangle = \frac{1}{\sqrt{2}}(|01\rangle - |10\rangle)$ corresponds to the density matrix

$$|\psi^-\rangle \langle\psi^-| = \frac{1}{2}(|01\rangle \langle 01| - |01\rangle \langle 10| - |10\rangle \langle 01| + |10\rangle \langle 10|), \tag{A.3}$$

on which we act with the partial trace acording to the definition

$$tr_B |\psi^-\rangle \langle\psi^-| = \frac{1}{2} (|0\rangle \langle 0| \langle 1 \mid 1\rangle - |0\rangle \langle 1| \langle 0 \mid 1\rangle - |1\rangle \langle 0| \langle 1 \mid 0\rangle + |1\rangle \langle 1| \langle 0 \mid 0\rangle) = \frac{1}{2} (|0\rangle \langle 0| + |1\rangle \langle 1|) ,$$

to obtain the reduced state ρ_A.

For two flavor

A generic two-qubit state ρ_{AB} can be expanded with respect to the orthonormal basis $\{|00\rangle, |00\rangle, |00\rangle, |00\rangle\}$ as

$$\rho_{AB} = \rho_{11} |00\rangle \langle 00| + \rho_{12} |00\rangle \langle 01| + \rho_{13} |00\rangle \langle 10| + ... + \rho_{44} |11\rangle \langle 11|, \tag{A.4}$$

The partial trace is calculated according to eq. A.2

$$\rho_A = (\rho_{11} + \rho_{22}) |00\rangle \langle 00| + (\rho_{13} + \rho_{24}) |00\rangle \langle 01| + (\rho_{31} + \rho_{42}) |10\rangle \langle 00| + (\rho_{33} + \rho_{44}) |11\rangle \langle 11|, \tag{A.5}$$

The factor in front of $|1\rangle \langle 0|$, say, can be derived as follows: the preimages of $|0\rangle \langle 1|$ under the partial trace are $|10\rangle \langle 00|$ and $|11\rangle \langle 01|$ and come with factors ρ_{31} and ρ_{42} in ρ_{AB}. In matrix form the formula reads

$$tr_B \begin{pmatrix} \rho_{11} & \rho_{12} & \rho_{13} & \rho_{14} \\ \rho_{21} & \rho_{22} & \rho_{23} & \rho_{24} \\ \rho_{31} & \rho_{32} & \rho_{33} & \rho_{34} \\ \rho_{41} & \rho_{42} & \rho_{43} & \rho_{44} \end{pmatrix} = \begin{pmatrix} tr \begin{pmatrix} \rho_{11} & \rho_{12} \\ \rho_{21} & \rho_{22} \end{pmatrix} & tr \begin{pmatrix} \rho_{13} & \rho_{14} \\ \rho_{23} & \rho_{24} \end{pmatrix} \\ tr \begin{pmatrix} \rho_{31} & \rho_{32} \\ \rho_{41} & \rho_{42} \end{pmatrix} & tr \begin{pmatrix} \rho_{33} & \rho_{34} \\ \rho_{43} & \rho_{44} \end{pmatrix} \end{pmatrix} = \begin{pmatrix} \rho_{11} + \rho_{22} & \rho_{13} + \rho_{24} \\ \rho_{31} + \rho_{42} & \rho_{33} + \rho_{44} \end{pmatrix}. \tag{A.6}$$

Partial trace over A:
Finally, we mention that the partial trace tr_A over the subsystem A is defined in the obvious way and can be calculated similarly to tr_B. For convenience we state the formula for two qubits

$$tr_B \begin{pmatrix} \rho_{11} & \rho_{12} & \rho_{13} & \rho_{14} \\ \rho_{21} & \rho_{22} & \rho_{23} & \rho_{24} \\ \rho_{31} & \rho_{32} & \rho_{33} & \rho_{34} \\ \rho_{41} & \rho_{42} & \rho_{43} & \rho_{44} \end{pmatrix} = \begin{pmatrix} tr \begin{pmatrix} \rho_{11} & \rho_{13} \\ \rho_{31} & \rho_{33} \end{pmatrix} & tr \begin{pmatrix} \rho_{12} & \rho_{14} \\ \rho_{32} & \rho_{34} \end{pmatrix} \\ tr \begin{pmatrix} \rho_{21} & \rho_{23} \\ \rho_{41} & \rho_{43} \end{pmatrix} & tr \begin{pmatrix} \rho_{22} & \rho_{24} \\ \rho_{42} & \rho_{44} \end{pmatrix} \end{pmatrix} = \begin{pmatrix} \rho_{11} + \rho_{33} & \rho_{12} + \rho_{34} \\ \rho_{21} + \rho_{43} & \rho_{22} + \rho_{44} \end{pmatrix}. \tag{A.7}$$

For three flavor

A composite system consists of three subsystems: A, B, and C, then the entire system is represented by the density operator, ρ_{ABC} , then density matrix can be represented as

$$\rho_{ABC} = \begin{pmatrix} \rho_{11} & \rho_{12} & \rho_{13} & \rho_{14} & \rho_{15} & \rho_{16} & \rho_{17} & \rho_{18} \\ \rho_{21} & \rho_{22} & \rho_{23} & \rho_{24} & \rho_{25} & \rho_{26} & \rho_{27} & \rho_{28} \\ \rho_{31} & \rho_{32} & \rho_{33} & \rho_{34} & \rho_{35} & \rho_{36} & \rho_{37} & \rho_{38} \\ \rho_{41} & \rho_{42} & \rho_{43} & \rho_{44} & \rho_{45} & \rho_{46} & \rho_{47} & \rho_{48} \\ \rho_{51} & \rho_{52} & \rho_{53} & \rho_{54} & \rho_{55} & \rho_{56} & \rho_{57} & \rho_{58} \\ \rho_{61} & \rho_{62} & \rho_{63} & \rho_{64} & \rho_{65} & \rho_{66} & \rho_{67} & \rho_{68} \\ \rho_{71} & \rho_{72} & \rho_{73} & \rho_{74} & \rho_{75} & \rho_{76} & \rho_{77} & \rho_{78} \\ \rho_{81} & \rho_{82} & \rho_{83} & \rho_{84} & \rho_{85} & \rho_{86} & \rho_{87} & \rho_{88} \end{pmatrix}, \tag{A.8}$$

In a composite system relevant to neutrino oscillations, the presence of three subsystems is significant. This is primarily because there are three flavor eigenstates of neutrinos present, which can behave as modes under particular conditions. In summary, the entanglement measures EOF and concurrence are valuable tools for quantifying entanglement in quantum systems. Their computation often involves the use of the partial trace operation, which allows us to extract the reduced density matrix of a subsystem. The state of subsystem A is described by the reduced density operator where BC traces out partial trace A defined

$$\rho_A = (\rho_{11} + \rho_{22} + \rho_{33} + \rho_{44}) |0\rangle \langle 0| + (\rho_{15} + \rho_{26} + \rho_{37} + \rho_{48}) |0\rangle \langle 1| + (\rho_{51} + \rho_{62} + \rho_{73} + \rho_{84}) |1\rangle \langle 0| + (\rho_{55} + \rho_{66} + \rho_{77} + \rho_{88}) |1\rangle \langle 1| \tag{A.9}$$

The state of subsystem B is described by the reduced density operator where AC traces out partial trace B defined

$$\rho_B = (\rho_{11} + \rho_{22} + \rho_{55} + \rho_{66}) |0\rangle \langle 0| + (\rho_{13} + \rho_{24} + \rho_{57} + \rho_{68}) |0\rangle \langle 1| + (\rho_{31} + \rho_{42} + \rho_{75} + \rho_{86}) |1\rangle \langle 0| + (\rho_{33} + \rho_{44} + \rho_{77} + \rho_{88}) |1\rangle \langle 1| . \tag{A.10}$$

The state of subsystem C is described by the reduced density operator where AB traces out partial trace C defined

$$\rho_C = (\rho_{11} + \rho_{33} + \rho_{55} + \rho_{77}) |0\rangle \langle 0| + (\rho_{12} + \rho_{34} + \rho_{56} + \rho_{78}) |0\rangle \langle 1| + (\rho_{21} + \rho_{43} + \rho_{65} + \rho_{87}) |1\rangle \langle 0| + (\rho_{22} + \rho_{44} + \rho_{66} + \rho_{86}) |1\rangle \langle 1| . \tag{A.11}$$

The partial trace has a number of important properties. Many quantum correlation measures are described using partial trace function. First, it is a linear operation, meaning that it preserves the linearity of quantum mechanics. Second, it is a trace-preserving operation, meaning that the trace of the reduced density matrix is equal to the trace of the original density matrix. Third, it is a positive-operator valued measure (POVM), meaning that it produces a set of non-negative operators that sum to the identity operator. The partial trace is a very useful tool in quantum mechanics. It can be used to calculate the entanglement between subsystems, which is an important resource for quantum information processing tasks such as quantum teleportation and quantum cryptography. The partial trace is a versatile tool that has a wide range of applications in quantum physics. It is an essential tool for anyone who wants to understand the fundamental behavior of quantum systems.

A.2 Partial transpose

The partial transpose is a crucial operation in quantum mechanics, especially useful for studying quantum entanglement. For a composite system consisting of two subsystems, A and B, described by the density matrix ρ_{AB}, the partial transpose operation involves transposing only the part of the density matrix associated with one of the subsystems.

Formally, if ρ_{AB} is represented in a matrix form with indices m, n, k, and l, the partial transpose with respect to subsystem B is given by:

$$(\rho_{AB}^{T_B})_{mn,kl} = (\rho_{AB})_{mk,nl}, \tag{A.12}$$

where the transpose is applied only to the indices corresponding to subsystem B. Here, the transposition is applied only to the indices associated with subsystem B. The partial transpose is useful in criteria for entanglement, such as the Peres-Horodecki criterion, which states that if the partial transpose of ρ_{AB} has any negative eigenvalues, then the state is entangled. Here, we define the partial transpose for composite systems, which have three subsystems.

$$(\rho_{ABC})^{T_A} = \begin{pmatrix} \rho_{11} & \rho_{12} & \rho_{13} & \rho_{14} & \rho_{51} & \rho_{52} & \rho_{53} & \rho_{54} \\ \rho_{21} & \rho_{22} & \rho_{23} & \rho_{24} & \rho_{61} & \rho_{62} & \rho_{63} & \rho_{64} \\ \rho_{31} & \rho_{32} & \rho_{33} & \rho_{34} & \rho_{71} & \rho_{72} & \rho_{73} & \rho_{74} \\ \rho_{41} & \rho_{42} & \rho_{43} & \rho_{44} & \rho_{81} & \rho_{82} & \rho_{83} & \rho_{84} \\ \rho_{15} & \rho_{16} & \rho_{17} & \rho_{18} & \rho_{55} & \rho_{56} & \rho_{57} & \rho_{58} \\ \rho_{25} & \rho_{26} & \rho_{27} & \rho_{28} & \rho_{65} & \rho_{66} & \rho_{67} & \rho_{68} \\ \rho_{35} & \rho_{36} & \rho_{37} & \rho_{38} & \rho_{75} & \rho_{76} & \rho_{77} & \rho_{78} \\ \rho_{81} & \rho_{82} & \rho_{83} & \rho_{84} & \rho_{85} & \rho_{86} & \rho_{87} & \rho_{88} \end{pmatrix} \tag{A.13}$$

$$(\rho_{ABC})^{T_B} = \begin{pmatrix} \rho_{11} & \rho_{12} & \rho_{31} & \rho_{32} & \rho_{15} & \rho_{16} & \rho_{35} & \rho_{36} \\ \rho_{21} & \rho_{22} & \rho_{41} & \rho_{42} & \rho_{25} & \rho_{26} & \rho_{45} & \rho_{46} \\ \rho_{13} & \rho_{14} & \rho_{33} & \rho_{34} & \rho_{17} & \rho_{18} & \rho_{37} & \rho_{38} \\ \rho_{23} & \rho_{24} & \rho_{43} & \rho_{44} & \rho_{27} & \rho_{28} & \rho_{47} & \rho_{48} \\ \rho_{51} & \rho_{52} & \rho_{71} & \rho_{72} & \rho_{55} & \rho_{56} & \rho_{75} & \rho_{76} \\ \rho_{61} & \rho_{62} & \rho_{81} & \rho_{82} & \rho_{65} & \rho_{66} & \rho_{85} & \rho_{86} \\ \rho_{53} & \rho_{54} & \rho_{73} & \rho_{74} & \rho_{57} & \rho_{58} & \rho_{77} & \rho_{78} \\ \rho_{63} & \rho_{64} & \rho_{83} & \rho_{84} & \rho_{67} & \rho_{68} & \rho_{87} & \rho_{88} \end{pmatrix} \tag{A.14}$$

$$(\rho_{ABC})^{T_C} = \begin{pmatrix} \rho_{11} & \rho_{21} & \rho_{13} & \rho_{23} & \rho_{15} & \rho_{25} & \rho_{17} & \rho_{27} \\ \rho_{12} & \rho_{22} & \rho_{14} & \rho_{24} & \rho_{16} & \rho_{26} & \rho_{18} & \rho_{28} \\ \rho_{31} & \rho_{41} & \rho_{33} & \rho_{43} & \rho_{35} & \rho_{45} & \rho_{37} & \rho_{47} \\ \rho_{32} & \rho_{42} & \rho_{34} & \rho_{44} & \rho_{36} & \rho_{46} & \rho_{38} & \rho_{48} \\ \rho_{51} & \rho_{61} & \rho_{53} & \rho_{63} & \rho_{55} & \rho_{65} & \rho_{57} & \rho_{67} \\ \rho_{52} & \rho_{62} & \rho_{54} & \rho_{64} & \rho_{56} & \rho_{66} & \rho_{58} & \rho_{68} \\ \rho_{71} & \rho_{81} & \rho_{73} & \rho_{83} & \rho_{75} & \rho_{85} & \rho_{77} & \rho_{87} \\ \rho_{72} & \rho_{82} & \rho_{74} & \rho_{84} & \rho_{76} & \rho_{86} & \rho_{78} & \rho_{88} \end{pmatrix} \tag{A.15}$$

The partial transpose operation is an essential tool in quantum information theory, especially for detecting entanglement. By transposing only the part of the density matrix associated with one subsystem, we can reveal properties that are not evident in the original matrix. The presence of negative eigenvalues in the partially transposed matrix is a clear signature of entanglement. Negativity is an entanglement measure that uses partial transpose in the definition.

In summary, the partial trace is used to focus on a subsystem by eliminating the other, while the partial transpose is a tool for analyzing the entanglement properties of a quantum state.

References

[1] Steven Weinberg. A model of leptons. *Physical review letters*, 19(21):1264, 1967.

[2] Gianluca Bianco. *Study of the quantum interference between singly and doubly resonant top-quark production in proton-proton collisions at the LHC with the ATLAS detector*. PhD thesis, 12 2020.

[3] Sheldon L Glashow. Partial symmetries of weak interactions. *Nuclear physics*, 22(4):579–588, 1961.

[4] Salam Abdus. Weak and electromagnetic interactions, conf. *Proc. C*, 680519:367–377, 1968.

[5] Tom WB Kibble. Symmetry breaking in non-abelian gauge theories. *Physical Review*, 155(5):1554, 1967.

[6] Gerald S Guralnik, Carl R Hagen, and Thomas WB Kibble. Global conservation laws and massless particles. *Physical Review Letters*, 13(20):585, 1964.

[7] François Englert and Robert Brout. Broken symmetry and the mass of gauge vector mesons. *Physical review letters*, 13(9):321, 1964.

[8] Peter W Higgs. Broken symmetries and the masses of gauge bosons. *Physical review letters*, 13(16):508, 1964.

[9] Peter W Higgs. Spontaneous symmetry breakdown without massless bosons. *Physical review*, 145(4):1156, 1966.

[10] Peter Ware Higgs. Broken symmetries, massless particles and gauge fields. *Phys. Lett.*, 12:132–133, 1964.

[11] C. N. Yang and R. L. Mills. Conservation of isotopic spin and isotopic gauge invariance. *Phys. Rev.*, 96:191–195, Oct 1954.

[12] Wolfgang Pauli. Pauli letter collection: letter to Lise Meitner. Technical report, 1930.

[13] Chien-Shiung Wu, Ernest Ambler, Raymond W Hayward, Dale D Hoppes, and Ralph Percy Hudson. Experimental test of parity conservation in beta decay. *Physical review*, 105(4):1413, 1957.

[14] Yoshiyuki Fukuda, T Hayakawa, E Ichihara, K Inoue, K Ishihara, Hirokazu Ishino, Y Itow, T Kajita, J Kameda, S Kasuga, et al. Evidence for oscillation of atmospheric neutrinos. *Physical review letters*, 81(8):1562, 1998.

[15] Maurizio Acciarri, Oscar Adriani, M Aguilar-Benitez, S Ahlen, J Alcaraz, G Alemanni, J Allaby, Alberto Aloisio, MG Alviggi, G Ambrosi, et al. Determination of the number of light neutrino species from single photon production at LEP. *Physics Letters B*, 431(1-2):199–208, 1998.

[16] DELPHI Aleph. *Precision electroweak measurements on the Z resonance*. United States. Department of Energy, 2005.

[17] Vera C Rubin and W Kent Ford Jr. Rotation of the andromeda nebula from a spectroscopic survey of emission regions. *Astrophysical Journal, vol. 159, p. 379*, 159:379, 1970.

[18] Douglas Clowe, Anthony Gonzalez, and Maxim Markevitch. Weak-lensing mass reconstruction of the interacting cluster 1e 0657–558: Direct evidence for the existence of dark matter. *The Astrophysical Journal*, 604(2):596, 2004.

[19] A. D. Sakharov. Violation of CP Invariance, C asymmetry, and baryon asymmetry of the universe. *Pisma Zh. Eksp. Teor. Fiz.*, 5:32–35, 1967.

[20] Frederick Reines and Clyde L Cowan. The neutrino. *Nature*, 178(4531):446–449, 1956.

References

[21] Raymond Davis Jr, Don S Harmer, and Kenneth C Hoffman. Search for neutrinos from the sun. *Physical Review Letters*, 20(21):1205, 1968.

[22] Leslie Camilleri, Eligio Lisi, and John F Wilkerson. Neutrino masses and mixings: status and prospects. *Annual Review of Nuclear and Particle Science*, 58:343–369, 2008.

[23] K Abe, Y Haga, Y Hayato, M Ikeda, K Iyogi, J Kameda, Y Kishimoto, Ll Marti, M Miura, S Moriyama, et al. Solar neutrino measurements in super-kamiokande-iv. *Physical Review D*, 94(5):052010, 2016.

[24] B Aharmim, SN Ahmed, AE Anthony, N Barros, EW Beier, Alain Bellerive, B Beltran, M Bergevin, SD Biller, K Boudjemline, et al. Combined analysis of all three phases of solar neutrino data from the sudbury neutrino observatory. *Physical Review C*, 88(2):025501, 2013.

[25] Takeshi Araki, K Eguchi, S Enomoto, K Furuno, K Ichimura, H Ikeda, K Inoue, K Ishihara, T Iwamoto, T Kawashima, et al. Measurement of neutrino oscillation with kamland: Evidence of spectral distortion. *Physical review letters*, 94(8):081801, 2005.

[26] Z Maki. M, Nakagawa and S. Sakata. *Prog. Theor. Phys*, 28(19):6, 1962.

[27] L. Wolfenstein. Neutrino oscillations in matter. *Phys. Rev. D*, 17:2369–2374, May 1978.

[28] John N Bahcall. Solar neutrino cross sections and nuclear beta decay. *Physical Review*, 135(1B):B137, 1964.

[29] Raymond Davis Jr. Solar neutrinos. ii. experimental. *Physical Review Letters*, 12(11):303, 1964.

[30] B. Abi et al. Prospects for beyond the Standard Model physics searches at the Deep Underground Neutrino Experiment. *Eur. Phys. J. C*, 81(4):322, 2021.

[31] Yuval Grossman. Non-standard neutrino interactions and neutrino oscillation experiments. *Physics Letters B*, 359(1-2):141–147, 1995.

[32] Sven Bergmann, Yuval Grossman, and Enrico Nardi. Neutrino propagation in matter with general interactions. *Physical review D*, 60(9):093008, 1999.

[33] Mattias Blennow, Tommy Ohlsson, and Walter Winter. Non-standard hamiltonian effects on neutrino oscillations. *The European Physical Journal C*, 49:1023–1039, 2007.

[34] André De Gouvêa and James Jenkins. Survey of lepton number violation via effective operators. *Physical Review D—Particles, Fields, Gravitation, and Cosmology*, 77(1):013008, 2008.

[35] Andre De Gouvea, Gian Francesco Giudice, Alessandro Strumia, and Kazuhiro Tobe. Phenomenological implications of neutrinos in extra dimensions. *Nuclear Physics B*, 623(1-2):395–420, 2002.

[36] Toshihiko Ota and Joe Sato. Signature of the minimal supersymmetric standard model with right-handed neutrinos in long baseline experiments. *Physical Review D—Particles, Fields, Gravitation, and Cosmology*, 71(9):096004, 2005.

[37] Minako Honda, Yee Kao, Naotoshi Okamura, Alexey Pronin, and Tatsu Takeuchi. The effect of topcolor assisted technicolor, and other models, on neutrino oscillation. In *The Origin Of Mass And Strong Coupling Gauge Theories: (SCGT 06)*, pages 278–284. World Scientific, 2008.

[38] Minako Honda, Yee Kao, Naotoshi Okamura, Alexey Pronin, and Tatsu Takeuchi. Constraints on new physics from long baseline neutrino oscillation experiments. *arXiv preprint arXiv:0707.4545*, 2007.

[39] MB Gavela, D Hernandez, T Ota, and Walter Winter. Large gauge invariant nonstandard neutrino interactions. *Physical Review D—Particles, Fields, Gravitation, and Cosmology*, 79(1):013007, 2009.

[40] Stefan Antusch, Jochen P Baumann, and Enrique Fernandez-Martinez. Non-standard neutrino interactions with matter from physics beyond the standard model. *Nuclear Physics B*, 810(1-2):369–388, 2009.

[41] Michal Malinskỳ, Tommy Ohlsson, and He Zhang. Nonstandard neutrino interactions from

a triplet seesaw model. *Physical Review D*, 79(1):011301, 2009.

[42] Carlo Giunti and Alexander Studenikin. Neutrino electromagnetic interactions: a window to new physics. *Rev. Mod. Phys.*, 87:531, 2015.

[43] C. Broggini, C. Giunti, and A. Studenikin. Electromagnetic Properties of Neutrinos. *Adv. High Energy Phys.*, 2012:459526, 2012.

[44] Ashutosh Kumar Alok, Neetu Raj Singh Chundawat, and Arindam Mandal. Cosmic neutrino flux and spin flavor oscillations in intergalactic medium. *Phys. Lett. B*, 839:137791, 2023.

[45] Roshan Mammen Abraham, Saeid Foroughi-Abari, Felix Kling, and Yu-Dai Tsai. Neutrino Electromagnetic Properties and the Weak Mixing Angle at the LHC Forward Physics Facility. 1 2023.

[46] Ashutosh Kumar Alok, Trambak Jyoti Chall, Neetu Raj Singh Chundawat, and Arindam Mandal. Spin-flavor oscillations of relic neutrinos in primordial magnetic field. *Phys. Rev. D*, 109(5):055011, 2024.

[47] Ashutosh Kumar Alok, Neetu Raj Singh Chundawat, Arindam Mandal, and Trisha Sarkar. Can neutron star discriminate between Dirac and Majorana neutrinos? 8 2022.

[48] Neetu Raj Singh Chundawat, Arindam Mandal, and Trisha Sarkar. UHE neutrinos encountering decaying and non-decaying magnetic fields of compact stars. 8 2022.

[49] Shivaramakrishna Singirala, Dinesh Kumar Singha, and Rukmani Mohanta. Correlating neutrino magnetic moment and scalar triplet dark matter to enlighten XENONnT bounds in a type II radiative seesaw model. *Phys. Rev. D*, 109(7):075031, 2024.

[50] Shivaramakrishna Singirala, Dinesh Kumar Singha, and Rukmani Mohanta. Neutrino magnetic moment and inert doublet dark matter in a Type-III radiative scenario. *Phys. Rev. D*, 108(9):095048, 2023.

[51] H. Denizli, A. Senol, and M. Köksal. Probing the electromagnetic properties of the neutrinos at future lepton colliders. *Phys. Lett. B*, 853:138648, 2024.

[52] Ashutosh Kumar Alok, Trambak Jyoti Chall, Neetu Raj Singh Chundawat, Shireen Gangal, and Gaetano Lambiase. Quantum coherence in neutrino spin-flavor oscillations. 7 2024.

[53] John N. Bahcall, N. Cabibbo, and A. Yahil. Are neutrinos stable particles? *Phys. Rev. Lett.*, 28:316–318, 1972.

[54] G Bernardi, G Carugno, J Chauveau, F Dicarlo, M Dris, J Dumarchez, M Ferro-Luzzi, J-M Levy, D Lukas, J-M Perreau, et al. Search for neutrino decay. *Physics Letters B*, 166(4):479–483, 1986.

[55] Abhijit Bandyopadhyay, Sandhya Choubey, and Srubabati Goswami. Neutrino decay confronts the SNO data. *Phys. Lett. B*, 555:33–42, 2003.

[56] Dibya S. Chattopadhyay, Kaustav Chakraborty, Amol Dighe, Srubabati Goswami, and S. M. Lakshmi. Neutrino Propagation When Mass Eigenstates and Decay Eigenstates Mismatch. *Phys. Rev. Lett.*, 129(1):011802, 2022.

[57] Khushboo Dixit, Akhila Kumar Pradhan, and S. Uma Sankar. CP violation due to a Majorana phase in two flavor neutrino oscillations with decays. *Phys. Rev. D*, 107(1):013002, 2023.

[58] Ashutosh Kumar Alok, Neetu Raj Singh Chundawat, Arindam Mandal, and Bhavya Soni. Majorana CP-violating phases and NSI effects in neutrino decay. *J. Phys. G*, 51(8):085006, 2024.

[59] Lincoln Wolfenstein. Neutrino oscillations in matter. In *Solar neutrinos*, pages 294–299. CRC Press, 2018.

[60] Ma Concepción Gonzalez-Garcia and Michele Maltoni. Atmospheric neutrino oscillations and new physics. *Physical Review D*, 70(3):033010, 2004.

[61] S Bergmann, MM Guzzo, PC De Holanda, PI Krastev, and H Nunokawa. Status of the solution to the solar neutrino problem based on nonstandard neutrino interactions. *Physical review D*, 62(7):073001, 2000.

References

[62] Marcelo M Guzzo, Pedro Cunha De Holanda, Michele Maltoni, Hiroshi Nunokawa, MA Tortola, and José WF Valle. Status of a hybrid three-neutrino interpretation of neutrino data. *Nuclear physics B*, 629(1-3):479–490, 2002.

[63] Tommy Ohlsson. Status of non-standard neutrino interactions. *Reports on Progress in Physics*, 76(4):044201, 2013.

[64] OG Miranda and H Nunokawa. Non standard neutrino interactions: current status and future prospects. *New Journal of Physics*, 17(9):095002, 2015.

[65] Yasaman Farzan and Mariam Tórtola. Neutrino oscillations and non-standard interactions. *Frontiers in Physics*, 6:10, 2018.

[66] Ivan Esteban, MC Gonzalez-Garcia, Michele Maltoni, Ivan Martinez-Soler, and Jordi Salvado. Updated constraints on non-standard interactions from global analysis of oscillation data. *Journal of High Energy Physics*, 2018(8):1–33, 2018.

[67] Ivan Esteban, MC Gonzalez-Garcia, and Michele Maltoni. On the determination of leptonic cp violation and neutrino mass ordering in presence of non-standard interactions: present status. *Journal of High Energy Physics*, 2019(6):1–24, 2019.

[68] Pilar Coloma, Ivan Esteban, MC Gonzalez-Garcia, and Michele Maltoni. Improved global fit to non-standard neutrino interactions using coherent energy and timing data. *Journal of High Energy Physics*, 2020(2):1–30, 2020.

[69] Shao-Feng Ge and Stephen J Parke. Scalar nonstandard interactions in neutrino oscillation. *Physical Review Letters*, 122(21):211801, 2019.

[70] Alexei Yu Smirnov and Xun-Jie Xu. Wolfenstein potentials for neutrinos induced by ultralight mediators. *Journal of High Energy Physics*, 2019(12):1–15, 2019.

[71] Amir N Khan, Werner Rodejohann, and Xun-Jie Xu. Borexino and general neutrino interactions. *Physical Review D*, 101(5):055047, 2020.

[72] Abinash Medhi, Debajyoti Dutta, and Moon Moon Devi. Exploring the effects of scalar non standard interactions on the cp violation sensitivity at dune. *Journal of High Energy Physics*, 2022(6):1–22, 2022.

[73] Peter B Denton, Alessio Giarnetti, and Davide Meloni. How to identify different new neutrino oscillation physics scenarios at dune. *Journal of High Energy Physics*, 2023(2):1–37, 2023.

[74] Abinash Medhi, Moon Moon Devi, and Debajyoti Dutta. Imprints of scalar nsi on the cp-violation sensitivity using synergy among dune, t2hk and t2hkk. *Journal of High Energy Physics*, 2023(1):1–25, 2023.

[75] Aman Gupta, Debasish Majumdar, and Suprabh Prakash. Neutrino oscillation measurements with juno in the presence of scalar nsi. *arXiv preprint arXiv:2306.07343*, 2023.

[76] J Aguilar, M Anastasopoulos, E Baussan, AK Bhattacharyya, A Bignami, M Blennow, M Bogomilov, B Bolling, E Bouquerel, F Bramati, et al. Study of nonstandard interactions mediated by a scalar field at the essnusb experiment. *Physical Review D*, 109(11):115010, 2024.

[77] M Agostini et al. Simultaneous precision spectroscopy of pp, be 7, and pep solar neutrinos with borexino phase-ii. *Physical Review D*, 100(8):082004, 2019.

[78] Erwin Schrödinger. Mathematical proceedings of the cambridge philosophical society. In *Mathematical Proceedings of the Cambridge Philosophical Society*, volume 31, pages 555–563, 1935.

[79] Albert Einstein, Boris Podolsky, and Nathan Rosen. Can quantum-mechanical description of physical reality be considered complete? *Physical review*, 47(10):777, 1935.

[80] John S Bell. On the einstein podolsky rosen paradox. *Physics Physique Fizika*, 1(3):195, 1964.

[81] Khushboo Dixit, Javid Naikoo, Subhashish Banerjee, and Ashutosh Kumar Alok. Quantum correlations and the neutrino mass degeneracy problem. *The European Physical Journal C*, 78:1–8, 2018.

[82] Ryszard Horodecki, Paweł Horodecki, Michał Horodecki, and Karol Horodecki. Quantum entanglement. *Reviews of modern physics*, 81(2):865–942, 2009.

[83] Harold Ollivier and Wojciech H Zurek. Quantum discord: a measure of the quantumness of correlations. *Physical review letters*, 88(1):017901, 2001.

[84] Biswajit Paul and Kaushiki Mukherjee. Shareability of quantum steering and its relation with entanglement. *Physical Review A*, 102(5):052209, 2020.

[85] Roope Uola, Ana CS Costa, H Chau Nguyen, and Otfried Gühne. Quantum steering. *Reviews of Modern Physics*, 92(1):015001, 2020.

[86] John F Clauser, Michael A Horne, Abner Shimony, and Richard A Holt. Proposed experiment to test local hidden-variable theories. *Physical review letters*, 23(15):880, 1969.

[87] Anthony J Leggett and Anupam Garg. Quantum mechanics versus macroscopic realism: Is the flux there when nobody looks? *Physical Review Letters*, 54(9):857, 1985.

[88] Clive Emary, Neill Lambert, and Franco Nori. Leggett–garg inequalities. *Reports on Progress in Physics*, 77(1):016001, 2013.

[89] Massimo Blasone, Fabio Dell'Anno, Silvio De Siena, and Fabrizio Illuminati. Entanglement in neutrino oscillations. *Europhysics Letters*, 85(5):50002, 2009.

[90] Massimo Blasone, Fabio Dell'Anno, Silvio De Siena, and Fabrizio Illuminati. Flavor entanglement in neutrino oscillations in the wave packet description. *Europhysics Letters*, 112(2):20007, 2015.

[91] Xue-Ke Song, Yanqi Huang, Jiajie Ling, and Man-Hong Yung. Quantifying quantum coherence in experimentally observed neutrino oscillations. *Physical Review A*, 98(5):050302, 2018.

[92] Dong Wang, Fei Ming, Xue-Ke Song, Liu Ye, and Jing-Ling Chen. Entropic uncertainty relation in neutrino oscillations. *The European Physical Journal C*, 80:1–9, 2020.

[93] MM Ettefaghi, ZS Tabatabaei Lotfi, and R Ramezani Arani. Quantum correlations in neutrino oscillation: Coherence and entanglement. *Europhysics Letters*, 132(3):31002, 2020.

[94] Li-Juan Li, Fei Ming, Xue-Ke Song, Liu Ye, and Dong Wang. Characterizing entanglement and measurement's uncertainty in neutrino oscillations. *The European Physical Journal C*, 81(8):728, 2021.

[95] Massimo Blasone, Silvio De Siena, and Cristina Matrella. Wave packet approach to quantum correlations in neutrino oscillations. *The European Physical Journal C*, 81(7):660, 2021.

[96] Massimo Blasone, Fabrizio Illuminati, Luciano Petruzziello, and Luca Smaldone. Leggett-garg inequalities in the quantum field theory of neutrino oscillations. *Physical Review A*, 108(3):032210, 2023.

[97] JA Formaggio, DI Kaiser, MM Murskyj, and TE Weiss. Violation of the leggett-garg inequality in neutrino oscillations. *Physical review letters*, 117(5):050402, 2016.

[98] Javid Naikoo, Ashutosh Kumar Alok, Subhashish Banerjee, S Uma Sankar, Giacomo Guarnieri, Christiane Schultze, and Beatrix C Hiesmayr. A quantum information theoretic quantity sensitive to the neutrino mass-hierarchy. *Nuclear Physics B*, 951:114872, 2020.

[99] Javid Naikoo, Ashutosh Kumar Alok, Subhashish Banerjee, and S Uma Sankar. Leggett-garg inequality in the context of three flavor neutrino oscillation. *Physical Review D*, 99(9):095001, 2019.

[100] Khushboo Dixit and Ashutosh Kumar Alok. New physics effects on quantum coherence in neutrino oscillations. *Eur. Phys. J. Plus*, 136(3):334, 2021.

[101] Trisha Sarkar and Khushboo Dixit. Effects of nonstandard interaction on temporal and spatial correlations in neutrino oscillations. *The European Physical Journal C*, 81:1–10, 2021.

[102] Sheeba Shafaq and Poonam Mehta. Enhanced violation of leggett–garg inequality in three flavour neutrino oscillations via non-standard interactions. *Journal of Physics G: Nuclear and Particle Physics*, 48(8):085002, 2021.

References

[103] Massimo Blasone, Fabio Dell'Anno, Silvio De Siena, M Di Mauro, and Fabrizio Illuminati. Multipartite entangled states in particle mixing. *Physical Review D*, 77(9):096002, 2008.

[104] Subhashish Banerjee, Ashutosh Kumar Alok, and Richard MacKenzie. Quantum correlations in b and k meson systems. *The European Physical Journal Plus*, 131(5):129, 2016.

[105] Ashutosh Kumar Alok, Subhashish Banerjee, and S. Uma Sankar. Quantum correlations in terms of neutrino oscillation probabilities. *Nucl. Phys. B*, 909:65–72, 2016.

[106] Subhashish Banerjee, Ashutosh Kumar Alok, R Srikanth, and Beatrix C Hiesmayr. A quantum-information theoretic analysis of three-flavor neutrino oscillations: Quantum entanglement, nonlocal and nonclassical features of neutrinos. *The European Physical Journal C*, 75:1–9, 2015.

[107] Qiang Fu and Xurong Chen. Testing violation of the leggett–garg-type inequality in neutrino oscillations of the daya bay experiment. *The European Physical Journal C*, 77(11):1–6, 2017.

[108] Javid Naikoo, Ashutosh Kumar Alok, and Subhashish Banerjee. Study of temporal quantum correlations in decohering b and k meson systems. *Physical Review D*, 97(5):053008, 2018.

[109] Fei Ming, Xue-Ke Song, Jiajie Ling, Liu Ye, and Dong Wang. Quantification of quantumness in neutrino oscillations. *The European Physical Journal C*, 80:1–9, 2020.

[110] Massimo Blasone, Fabrizio Illuminati, Luciano Petruzziello, Kyrylo Simonov, and Luca Smaldone. No-signaling-in-time as a condition for macrorealism: the case of neutrino oscillations. *The European Physical Journal C*, 83(8):688, 2023.

[111] Dibya S Chattopadhyay and Amol Dighe. Quantum mismatch: A powerful measure of quantumness in neutrino oscillations. *Physical Review D*, 108(11):112013, 2023.

[112] Massimo Blasone, Silvio De Siena, and Cristina Matrella. Complete complementarity relations for three-flavor neutrino oscillations. *arXiv preprint arXiv:2305.06095*, 2023.

[113] Songbo Xie and Joseph H Eberly. Triangle measure of tripartite entanglement. *Physical Review Letters*, 127(4):040403, 2021.

[114] Abhishek Kumar Jha, Supratik Mukherjee, and Bindu A Bambah. Tri-partite entanglement in neutrino oscillations. *Modern Physics Letters A*, 36(09):2150056, 2021.

[115] Abhishek Kumar Jha, Akshay Chatla, and Bindu A Bambah. Neutrinos as qubits and qutrits. *The European Physical Journal Plus*, 139(1):1–16, 2024.

[116] MM Ettefaghi and Z Askaripour Ravari. Quantum coherence and entanglement in neutral-current neutrino oscillation in matter. *The European Physical Journal C*, 83(5):1–11, 2023.

[117] Bhavya Soni, Sheeba Shafaq, and Poonam Mehta. Distinguishing between dirac and majorana neutrinos using temporal correlations. *arXiv preprint arXiv:2307.04496*, 2023.

[118] Debashis Gangopadhyay and Animesh Sinha Roy. Three-flavoured neutrino oscillations and the leggett–garg inequality. *The European Physical Journal C*, 77:1–7, 2017.

[119] Ming-Liang Hu, Xiao-Min Wang, and Heng Fan. Hierarchy of the nonlocal advantage of quantum coherence and bell nonlocality. *Physical Review A*, 98(3):032317, 2018.

[120] Yu-Wen Li, Li-Juan Li, Xue-Ke Song, Dong Wang, and Liu Ye. Geuine tripartite entanglement in three-flavor neutrino oscillations. *The European Physical Journal C*, 82(9):799, 2022.

[121] Debasis Mondal, Tanumoy Pramanik, and Arun Kumar Pati. Nonlocal advantage of quantum coherence. *Physical Review A*, 95(1):010301, 2017.

[122] Zhi-Yong Ding, Huan Yang, Hao Yuan, Dong Wang, Jie Yang, and Liu Ye. Experimental investigation of the nonlocal advantage of quantum coherence. *Physical Review A*, 100(2):022308, 2019.

[123] R Acciarri, MA Acero, M Adamowski, C Adams, P Adamson, S Adhikari, Z Ahmad, CH Albright, T Alion, E Amador, et al. Long-baseline neutrino facility (lbnf) and deep underground neutrino experiment (dune) conceptual design report, volume 4 the dune detectors at lbnf. *arXiv preprint arXiv:1601.02984*, 2016.

[124] Babak Abi, Roberto Acciarri, MA Acero, George Adamov, David Adams, Marco Adinolfi,

Z Ahmad, J Ahmed, T Alion, S Alonso Monsalve, et al. Long-baseline neutrino oscillation physics potential of the dune experiment. *The European Physical Journal C*, 80(10):1–34, 2020.

[125] DG Michael, P Adamson, T Alexopoulos, WWM Allison, GJ Alner, K Anderson, C Andreopoulos, M Andrews, R Andrews, KE Arms, et al. Observation of muon neutrino disappearance with the minos detectors in the numi neutrino beam. *Physical review letters*, 97(19):191801, 2006.

[126] K Abe, N Abgrall, H Aihara, Y Ajima, JB Albert, D Allan, P-A Amaudruz, C Andreopoulos, B Andrieu, MD Anerella, et al. The t2k experiment. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 659(1):106–135, 2011.

[127] Kou Abe, J Adam, H Aihara, T Akiri, C Andreopoulos, S Aoki, A Ariga, T Ariga, S Assylbekov, D Autiero, et al. Measurement of neutrino oscillation parameters from muon neutrino disappearance with an off-axis beam. *Physical review letters*, 111(21):211803, 2013.

[128] Fengpeng An, Guangpeng An, Qi An, Vito Antonelli, Eric Baussan, John Beacom, Leonid Bezrukov, Simon Blyth, Riccardo Brugnera, Margherita Buizza Avanzini, et al. Neutrino physics with juno. *Journal of Physics G: Nuclear and Particle Physics*, 43(3):030401, 2016.

[129] Angel Abusleme, Thomas Adam, Shakeel Ahmad, Rizwan Ahmed, Sebastiano Aiello, Muhammad Akram, Fengpeng An, Guangpeng An, Qi An, Giuseppe Andronico, et al. Juno physics and detector. *arXiv preprint arXiv:2104.02565*, 2021.

[130] FP An, JZ Bai, AB Balantekin, HR Band, D Beavis, W Beriguete, M Bishai, S Blyth, K Boddy, RL Brown, et al. Observation of electron-antineutrino disappearance at daya bay. *Physical Review Letters*, 108(17):171803, 2012.

[131] Bedřich Roskovec et al. Latest reactor neutrino oscillation results from the daya bay experiment. In *40th International Conference on High Energy Physics*, page 170, 2021.

[132] Charles H Bennett, David P DiVincenzo, John A Smolin, and William K Wootters. Mixed-state entanglement and quantum error correction. *Physical Review A*, 54(5):3824, 1996.

[133] Yu Guo and Lin Zhang. Multipartite entanglement measure and complete monogamy relation. *Physical Review A*, 101(3):032301, 2020.

[134] William K Wootters. Entanglement of formation of an arbitrary state of two qubits. *Physical Review Letters*, 80(10):2245, 1998.

[135] Yu Guo and Gilad Gour. Monogamy of the entanglement of formation. *Physical Review A*, 99(4):042305, 2019.

[136] Carlos Sabín and Guillermo García-Alcaine. A classification of entanglement in three-qubit systems. *The european physical journal D*, 48:435–442, 2008.

[137] Guifré Vidal and Reinhard F Werner. Computable measure of entanglement. *Physical Review A*, 65(3):032314, 2002.

[138] Bhavna Yadav, Trisha Sarkar, Khushboo Dixit, and Ashutosh Kumar Alok. Can nsi affect non-local correlations in neutrino oscillations? *The European Physical Journal C*, 82(5):446, 2022.

[139] Lekhashri Konwar and Bhavna Yadav. Nsi effects on tripartite entanglement in neutrino oscillations. *Nuclear Physics B*, 1002:116544, 2024.

[140] Lekhashri Konwar, Juhi Vardani, and Bhavna Yadav. Violation of lgti inequalities in the light of noνa and t2k anomaly. *The European Physical Journal C*, 84(10):1–7, 2024.

[141] Bhavna Yadav and Ashutosh Kumar Alok. Impact of scalar nsi on spatial and temporal correlations in neutrino oscillations. *arXiv preprint arXiv:2411.17503*, 2024.

[142] Henri Becquerel. Sur les radiations émises par phosphorescence. *Comptes rendus de 1'Academie des Sciences, Paris*, 122:420–421, 1896.

[143] Ernest Rutherford and Frederick Soddy. Xxxiii.—the radioactivity of thorium compounds. i. an investigation of the radioactive emanation. *Journal of the Chemical Society, Transactions*, 81:321–350, 1902.

References

[144] Marie Curie. Radium and radioactivity. *The Century Magazine*, 67(S 462), 1904.

[145] J Chadwick. Distribution in intensity in the magnetic spectrum of the β-rays of radium. *Ver. Dtsch. Physik. Ges*, 16(383-391):3, 1914.

[146] Charles Drummond Ellis and William A Wooster. The average energy of disintegration of radium e. *Proceedings of the Royal Society of London. Series A, Containing Papers of a Mathematical and Physical Character*, 117(776):109–123, 1927.

[147] Niels Bohr. Faraday lecture. chemistry and the quantum theory of atomic constitution. *Journal of the Chemical Society (Resumed)*, pages 349–384, 1932.

[148] Wolfgang Pauli. Letter to the physical society of tubingen. *Reproduced in [2]*, 1930.

[149] James Chadwick. Possible existence of a neutron. *Nature*, 129(3252):312–312, 1932.

[150] Enrico Fermi. Versuch einer theorie der β-strahlen. i. *Zeitschrift für Physik*, 88(3):161–177, 1934.

[151] Carl D. Anderson. The positive electron. *Phys. Rev.*, 43:491–494, Mar 1933.

[152] Hans Bethe and Rudolph Peierls. The "neutrino". *Nature*, 133(3362):532–532, 1934.

[153] J Curry Street and EC Stevenson. New evidence for the existence of a particle of mass intermediate between the proton and electron. *Physical Review*, 52(9):1003, 1937.

[154] CF Powell, PH Fowler, DH Perkins, and MW Friedlander. The study of elementary particles by the photographic method. *Physics Today*, 13(9):45–45, 1960.

[155] Clyde L Cowan Jr, Frederick Reines, FB Harrison, HW Kruse, and AD McGuire. Detection of the free neutrino: a confirmation. *Science*, 124(3212):103–104, 1956.

[156] B Pontecorvo. Chalk river laboratory pd-205 report. 1946.

[157] Raymond Davis and Don S Harmer. Attempt to observe the cl37 (ν, e-) ar37 reaction induced by reactor antineutrinos. *Bull. Am. Phys. Soc*, 4:217, 1959.

[158] Maurice Goldhaber, Lee Grodzins, and Andrew W Sunyar. Helicity of neutrinos. *Physical review*, 109(3):1015, 1958.

[159] Emil J Konopinski and Hormoz M Mahmoud. The universal fermi interaction. *Physical Review*, 92(4):1045, 1953.

[160] Gaillard Danby, Jean Maurice Gaillard, Konstantin Goulianos, Leon M Lederman, Nariman Mistry, Melvin Schwartz, and Jack Steinberger. Observation of high-energy neutrino reactions and the existence of two kinds of neutrinos. *Physical Review Letters*, 9(1):36, 1962.

[161] Martin L Perl, GS Abrams, AM Boyarski, Martin Breidenbach, DD Briggs, F Bulos, William Chinowsky, JT Dakin, GJ Feldman, CE Friedberg, et al. Evidence for anomalous lepton production in e+- e- annihilation. *Physical Review Letters*, 35(22):1489, 1975.

[162] K Kodama, N Ushida, C Andreopoulos, N Saoulidou, G Tzanakos, P Yager, B Baller, D Boehnlein, Walter Freeman, B Lundberg, et al. Observation of tau neutrino interactions. *Physics Letters B*, 504(3):218–224, 2001.

[163] John N Bahcall and Roger K Ulrich. Solar models, neutrino experiments, and helioseismology. *Reviews of Modern Physics*, 60(2):297, 1988.

[164] John N Bahcall, Neta A Bahcall, and Giora Shaviv. Present status of the theoretical predictions for the cl 37 solar-neutrino experiment. *Physical Review Letters*, 20(21):1209, 1968.

[165] Bruno Pontecorvo. Mesonium and antimesonium. *Soviet Journal of Experimental and Theoretical Physics*, 6:429, 1958.

[166] Bruno Pontecorvo. Inverse β processes and nonconservation of lepton charge. *Zhur. Eksptl'. i Teoret. Fiz.*, 34, 1958.

[167] Murray Gell-Mann and Abraham Pais. Behavior of neutral particles under charge conjugation. *Physical Review*, 97(5):1387, 1955.

[168] Ziro Maki, Masami Nakagawa, and Shoichi Sakata. Remarks on the unified model of elementary particles. *Progress of Theoretical Physics*, 28(5):870–880, 1962.

[169] Bruno Pontecorvo. Neutrino experiments and the problem of conservation of leptonic charge. *Sov. Phys. JETP*, 26(984-988):165, 1968.

[170] K. Hirata, T. Kajita, M. Koshiba, M. Nakahata, Y. Oyama, N. Sato, A. Suzuki, M. Takita, Y. Totsuka, T. Kifune, T. Suda, K. Takahashi, T. Tanimori, K. Miyano, M. Yamada, E. W. Beier, L. R. Feldscher, S. B. Kim, A. K. Mann, F. M. Newcomer, R. Van, W. Zhang, and B. G. Cortez. Observation of a neutrino burst from the supernova sn1987a. *Phys. Rev. Lett.*, 58:1490–1493, Apr 1987.

[171] Q Retal Ahmad, RC Allen, TC Andersen, JD Anglin, JC Barton, EW Beier, M Bercovitch, J Bigu, SD Biller, RA Black, et al. Direct evidence for neutrino flavor transformation from neutral-current interactions in the sudbury neutrino observatory. *Physical review letters*, 89(1):011301, 2002.

[172] Masatoshi Koshiba. Observational neutrino astrophysics. *Physics Reports*, 220(5-6):229–381, 1992.

[173] Y Fukuda, T Hayakawa, K Inoue, K Ishihara, Hirokazu Ishino, S Joukou, T Kajita, S Kasuga, Yusuke Koshio, T Kumita, et al. Solar neutrino data covering solar cycle 22. *Physical Review Letters*, 77(9):1683, 1996.

[174] Sage Collaboration et al. Measurement of the solar neutrino capture rate by sage and implications for neutrino oscillations in vacuum. *arXiv preprint astro-ph/9907131*, 1999.

[175] Wolfgang Hampel, J Handt, G Heusser, J Kiko, T Kirsten, M Laubenstein, E Pernicka, W Rau, M Wojcik, Yu Zakharov, et al. Gallex solar neutrino observations: Results for gallex iv. *Physics Letters B*, 447(1-2):127–133, 1999.

[176] KS Hirata, K Inoue, T Ishida, T Kajita, K Kihara, M Nakahata, K Nakamura, S Ohara, N Sato, Y Suzuki, et al. Real-time, directional measurement of b 8 solar neutrinos in the kamiokande ii detector. *Physical Review D*, 44(8):2241, 1991.

[177] John N Bahcall, MH Pinsonneault, and Sarbani Basu. Solar models: Current epoch and time dependences, neutrinos, and helioseismological properties. *The Astrophysical Journal*, 555(2):990, 2001.

[178] Matthew Walker. *Calibration Hardware Research and Development for SNO+*. PhD thesis, 05 2014.

[179] Bruce T Cleveland, Timothy Daily, Raymond Davis Jr, James R Distel, Kenneth Lande, CK Lee, Paul S Wildenhain, and Jack Ullman. Measurement of the solar electron neutrino flux with the homestake chlorine detector. *The Astrophysical Journal*, 496(1):505, 1998.

[180] John Bahcall. Solving the mystery of the missing neutrinos. *arXiv preprint physics/0406040*, 2004.

[181] Neutrinos from the primary proton–proton fusion process in the sun. *Nature*, 512(7515):383–386, 2014.

[182] Stephen R Dennis. *Muon antineutrino disappearance and non-standard interactions at the T2K experiment*. PhD thesis, University of Warwick, 2015.

[183] Kohji S Hirata, Takaaki Kajita, T Kifune, K Kihara, Masayuki Nakahata, K Nakamura, S Ohara, Y Oyama, N Sato, M Takita, et al. Observation of b 8 solar neutrinos in the kamiokande-ii detector. *Physical review letters*, 63(1):16, 1989.

[184] Herbert H Chen. Direct approach to resolve the solar-neutrino problem. In *Solar Neutrinos*, pages 120–122. CRC Press, 2018.

[185] QR Ahmad, RC Allen, TC Andersen, JD Anglin, G Buhler, et al. Measurement of the rate of $\nu_e + d \rightarrow p + p + e^- interactions produced by \mathrm{b}^8$ solar neutrinos at the sudbury neutrino observatory. *Phys. Rev. Lett*, 87:071301, 2001.

[186] Sno Collaboration et al. Measurement of the rate of nu_e+ d–¿ p+ p+ eˆ-interactions produced by 8b solar neutrinos at the sudbury neutrino observatory. *arXiv preprint nucl-ex/0106015*, 2001.

[187] KamLAND& Eguchi, S Enomoto, K Furuno, J Goldman, H Hanada, H Ikeda, K Ikeda, K Inoue, K Ishihara, W Itoh, et al. First results from kamland: evidence for reactor antineutrino disappearance. *Physical review letters*, 90(2):021802, 2003.

[188] J. Beringer, J. F. Arguin, R. M. Barnett, K. Copic, O. Dahl, D. E. Groom, C. J. Lin, J. Lys,

H. Murayama, C. G. Wohl, et al. Review of particle physics. *Phys. Rev. D*, 86:010001, Jul 2012.

[189] CV Achar, MGK Menon, VS Narasimham, PV Ramana Murthy, BV Sreekantan, K Hinotani, S Miyake, DR Creed, JL Osborne, JBM Pattison, et al. Detection of muons produced by cosmic ray neutrinos deep underground. *Physics Letters B*, 18(2), 1965.

[190] F Reines, MF Crouch, TL Jenkins, WR Kropp, HS Gurr, GR Smith, JPF Sellschop, and B Meyer. Evidence for high-energy cosmic-ray neutrino interactions. *Physical Review Letters*, 15(9):429, 1965.

[191] KS Hirata, T Kajita, M Koshiba, M Nakahata, S Ohara, Y Oyama, N Sato, A Suzuki, M Takita, Y Totsuka, et al. Experimental study of the atmospheric neutrino flux. *Physics Letters B*, 205(2-3):416–420, 1988.

[192] D Casper, R Becker-Szendy, CB Bratton, DR Cady, R Claus, ST Dye, W Gajewski, M Goldhaber, TJ Haines, PG Halverson, et al. Measurement of atmospheric neutrino composition with the imb-3 detector. *Physical Review Letters*, 66(20):2561, 1991.

[193] Maury C Goodman. The atmospheric neutrino anomaly in soudan-2. *Nuclear Physics B Proceedings Supplements*, 38:337, 1994.

[194] Y Fukuda, T Hayakawa, E Ichihara, K Inoue, K Ishihara, H Ishino, Y Itow, T Kajita, J Kameda, S Kasuga, et al. Study of the atmospheric neutrino flux in the multi-gev energy range. *Physics Letters B*, 436(1-2):33–41, 1998.

[195] Takaaki Kajita, Edward Kearns, Masato Shiozawa, Super-Kamiokande Collaboration, et al. Establishing atmospheric neutrino oscillations with super-kamiokande. *Nuclear Physics B*, 908:14–29, 2016.

[196] Olga Mena. Getting the most from NOvA and T2K. In *22nd International Conference on Neutrino Physics and Astrophysics*, 9 2006.

[197] Christoph A. Ternes, Stefano Gariazzo, Rasmi Hajjar, Olga Mena, Michel Sorel, and Mariam Tórtola. Neutrino mass ordering at DUNE: An extra ν bonus. *Phys. Rev. D*, 100(9):093004, 2019.

[198] Kenichi Fuki and Masaki Yasue. What does μ-τ symmetry imply about neutrino mixings? *Physical Review D—Particles, Fields, Gravitation, and Cosmology*, 73(5):055014, 2006.

[199] S. P. Mikheyev and A. Yu. Smirnov. Resonance Amplification of Oscillations in Matter and Spectroscopy of Solar Neutrinos. *Sov. J. Nucl. Phys.*, 42:913–917, 1985.

[200] SP Mikheyev and A Yu Smirnov. Resonant amplification of ν oscillations in matter and solar-neutrino spectroscopy. *Il Nuovo Cimento C*, 9:17–26, 1986.

[201] A Yu Smirnov. The msw effect and solar neutrinos. *arXiv preprint hep-ph/0305106*, 2003.

[202] Tommy Ohlsson and Håkan Snellman. Three flavor neutrino oscillations in matter. *Journal of Mathematical Physics*, 41(5):2768–2788, 2000.

[203] Tommy Ohlsson and Håkan Snellman. Neutrino oscillations with three flavors in matter: Applications to neutrinos traversing the earth. *Physics Letters B*, 474(1-2):153–162, 2000.

[204] José WF Valle. Resonant oscillations of massless neutrinos in matter. *Physics Letters B*, 199(3):432–436, 1987.

[205] MM Guzzo, A Masiero, and ST Petcov. On the msw effect with massless neutrinos and no mixing in the vacuum. *Physics Letters B*, 260(1-2):154–160, 1991.

[206] Esteban Roulet. Mikheyev-smirnov-wolfenstein effect with flavor-changing neutrino interactions. *Physical Review D*, 44(4):R935, 1991.

[207] Yasaman Farzan and Ian M. Shoemaker. Lepton Flavor Violating Non-Standard Interactions via Light Mediators. *JHEP*, 07:033, 2016.

[208] Nicolás Bernal and Yasaman Farzan. Neutrino nonstandard interactions with arbitrary couplings to u and d quarks. *Phys. Rev. D*, 107(3):035007, 2023.

[209] S. Abbaslu and Yasaman Farzan. A model for Axial Non-Standard Interactions of neutrinos with quarks. 7 2024.

[210] Zurab Berezhiani, RS Raghavan, and Anna Rossi. Probing non-standard couplings of neu-

trinos at the borexino detector. *Nuclear Physics B*, 638(1-2):62–80, 2002.

[211] Alexander Friedland, Cecilia Lunardini, and Carlos Pena-Garay. Solar neutrinos as probes of neutrino–matter interactions. *Physics Letters B*, 594(3-4):347–354, 2004.

[212] Omar G Miranda, Maria Amparo Tórtola, and Jose WF Valle. Are solar neutrino oscillations robust? *Journal of High Energy Physics*, 2006(10):008, 2006.

[213] Azucena Bolaños, OG Miranda, Antonio Palazzo, María Amparo Tórtola, and José WF Valle. Probing nonstandard neutrino-electron interactions with solar and reactor neutrinos. *Physical Review D—Particles, Fields, Gravitation, and Cosmology*, 79(11):113012, 2009.

[214] Tommy Ohlsson and He Zhang. Non-standard interaction effects at reactor neutrino experiments. *Physics Letters B*, 671(1):99–104, 2009.

[215] Maria Concepcion Gonzalez-Garcia, Marcelo M Guzzo, PI Krastev, Hiroshi Nunokawa, OLG Peres, V Pleitez, José Wagner Furtado Valle, and R Zukanovich Funchal. Atmospheric neutrino observations and flavor changing interactions. *Physical Review Letters*, 82(16):3202, 1999.

[216] Sven Bergmann, Yuval Grossman, and Damien M Pierce. Can lepton flavor violating interactions explain the atmospheric neutrino problem? *Physical review D*, 61(5):053005, 2000.

[217] N Fornengo, M Maltoni, R Tomas Bayo, and JWF Valle. Probing neutrino nonstandard interactions with atmospheric neutrino data. *Physical Review D*, 65(1):013010, 2001.

[218] Alexander Friedland, Cecilia Lunardini, and Michele Maltoni. Atmospheric neutrinos as probes of neutrino-matter interactions. *Physical Review D—Particles, Fields, Gravitation, and Cosmology*, 70(11):111301, 2004.

[219] C. Soumya, Monojit Ghosh, Sushant K. Raut, Nita Sinha, and Poonam Mehta. Probing muonic charged current nonstandard interactions at decay-at-rest facilities in conjunction with T2HK. *Phys. Rev. D*, 101(5):055009, 2020.

[220] Anil Kumar, Amina Khatun, Sanjib Kumar Agarwalla, and Amol Dighe. Probing NSI in Atmospheric Neutrino Experiments Using Oscillation Dip and Valley. *Springer Proc. Phys.*, 277:525–529, 2022.

[221] Anil Kumar, Amina Khatun, Sanjib Kumar Agarwalla, and Amol Dighe. A New Approach to Probe Non-Standard Interactions in Atmospheric Neutrino Experiments. *JHEP*, 04:159, 2021.

[222] Alexander Friedland and Cecilia Lunardini. Test of tau neutrino interactions with atmospheric neutrinos and k2k data. *Physical Review D—Particles, Fields, Gravitation, and Cosmology*, 72(5):053009, 2005.

[223] Sven Bergmann and Yuval Grossman. Can lepton flavor violating interactions explain the lsnd results? *Physical review D*, 59(9):093005, 1999.

[224] Toshihiko Ota, Joe Sato, and Nao-aki Yamashita. Oscillation enhanced search for new interactions with neutrinos. *Physical Review D*, 65(9):093015, 2002.

[225] Noriaki Kitazawa, Hiroaki Sugiyama, and Osamu Yasuda. Will minos see new physics? *arXiv preprint hep-ph/0606013*, 2006.

[226] Alexander Friedland and Cecilia Lunardini. Two modes of searching for new neutrino interactions at minos. *Physical Review D—Particles, Fields, Gravitation, and Cosmology*, 74(3):033012, 2006.

[227] Mattias Blennow, Tommy Ohlsson, and Julian Skrotzki. Effects of non-standard interactions in the minos experiment. *Physics Letters B*, 660(5):522–528, 2008.

[228] Joachim Kopp, Manfred Lindner, Toshihiko Ota, and Joe Sato. Nonstandard neutrino interactions in reactor and superbeam experiments. *Physical Review D—Particles, Fields, Gravitation, and Cosmology*, 77(1):013007, 2008.

[229] Nei Cipriano Ribeiro, Hiroshi Nunokawa, Takaaki Kajita, Shoei Nakayama, Pyungwon Ko, and Hisakazu Minakata. Probing nonstandard neutrino physics by two identical detectors with different baselines. *Physical Review D—Particles, Fields, Gravitation, and Cosmology*,

77(7):073007, 2008.

[230] Sanjib Kumar Agarwalla, Francesco Lombardi, and Tatsu Takeuchi. Constraining Non-Standard Interactions of the Neutrino with Borexino. *JHEP*, 12:079, 2012.

[231] Sanjib Kumar Agarwalla, Partha Bagchi, David V. Forero, and Mariam Tórtola. Probing Non-Standard Interactions at Daya Bay. *JHEP*, 07:060, 2015.

[232] Antonio Bueno, Mario Campanelli, Javier Rico, André Rubbia, and Marco Laveder. The flavor of neutrinos in muon decays at a neutrino factory and the lsnd puzzle. *Journal of High Energy Physics*, 2001(06):032, 2001.

[233] Ma Concepción Gonzalez-Garcia, Yuval Grossman, A Gusso, and Yosef Nir. New cp violation in neutrino oscillations. *Physical review D*, 64(9):096006, 2001.

[234] Patrick Huber and JWF Valle. Non-standard interactions: Atmospheric versus neutrino factory experiments. *Physics Letters B*, 523(1-2):151–160, 2001.

[235] AM Gago, MM Guzzo, H Nunokawa, WJC Teves, and R Zukanovich Funchal. Probing flavor changing neutrino interactions using neutrino beams from a muon storage ring. *Physical Review D*, 64(7):073003, 2001.

[236] Patrick Huber, Thomas Schwetz, and JWF Valle. Confusing nonstandard neutrino interactions with oscillations at a neutrino factory. *Physical Review D*, 66(1):013006, 2002.

[237] Mario Campanelli and Andrea Romanino. Effects of new physics in neutrino oscillations in matter. *Physical Review D*, 66(11):113001, 2002.

[238] Joachim Kopp, Manfred Lindner, and Toshihiko Ota. Discovery reach for nonstandard interactions in a neutrino factory. *Physical Review D—Particles, Fields, Gravitation, and Cosmology*, 76(1):013001, 2007.

[239] N Cipriano Ribeiro, H Minakata, H Nunokawa, S Uchinami, and R Zukanovich Funchal. Probing non-standard neutrino interactions with neutrino factories. *Journal of High Energy Physics*, 2007(12):002, 2007.

[240] Amina Khatun, Sabya Sachi Chatterjee, Tarak Thakore, and Sanjib Kumar Agarwalla. Constraining Non-Standard Interactions of Neutrino Using ICAL Detector at INO. *Springer Proc. Phys.*, 203:289–292, 2018.

[241] Joachim Kopp, Toshihiko Ota, and Walter Winter. Neutrino factory optimization for non-standard interactions. *Physical Review D—Particles, Fields, Gravitation, and Cosmology*, 78(5):053007, 2008.

[242] Walter Winter. Testing non-standard cp violation in neutrino propagation. *Physics Letters B*, 671(1):77–81, 2009.

[243] Gian Luigi Fogli, Eligio Lisi, Alessandro Mirizzi, and Daniele Montanino. Reexamining nonstandard interaction effects on supernova neutrino flavor oscillations. *Physical Review D*, 66(1):013009, 2002.

[244] Andreu Esteban-Pretel, Ricard Tomàs, and José WF Valle. Probing nonstandard neutrino interactions with supernova neutrinos. *Physical Review D—Particles, Fields, Gravitation, and Cosmology*, 76(5):053001, 2007.

[245] Gianpiero Mangano, Gennaro Miele, Sergio Pastor, Teguayco Pinto, Ofelia Pisanti, and Pasquale D Serpico. Effects of non-standard neutrino–electron interactions on relic neutrino decoupling. *Nuclear Physics B*, 756(1-2):100–116, 2006.

[246] Mattias Blennow and Davide Meloni. Nonstandard interaction effects on astrophysical neutrino fluxes. *Physical Review D—Particles, Fields, Gravitation, and Cosmology*, 80(6):065009, 2009.

[247] Zurab Berezhiani and Anna Rossi. Limits on the non-standard interactions of neutrinos from e+ e- colliders. *Physics Letters B*, 535(1-4):207–218, 2002.

[248] J Barranco, OG Miranda, CA Moura, and JWF Valle. Constraining non-standard interactions in ν_{ee} or $\bar{\nu_{ee}}$ scattering. *arXiv preprint hep-ph/0512195*, 2005.

[249] J Barranco, OG Miranda, and TI Rashba. Sensitivity of low energy neutrino experiments to physics beyond the standard model. *Physical Review D—Particles, Fields, Gravitation, and*

Cosmology, 76(7):073008, 2007.

[250] Juan Barranco, Omar G Miranda, and Timur I Rashba. Probing new physics with coherent neutrino scattering off nuclei. *Journal of High Energy Physics*, 2005(12):021, 2005.

[251] Sacha Davidson and Veronica Sanz. Non-Standard Neutrino Interactions at Colliders. *Phys. Rev. D*, 84:113011, 2011.

[252] Pouya Bakhti and Yasaman Farzan. CP-Violation and Non-Standard Interactions at the MOMENT. *JHEP*, 07:109, 2016.

[253] Jordi Salvado, Olga Mena, Sergio Palomares-Ruiz, and Nuria Rius. Non-Standard Interactions with High-energy Atmospheric Neutrinos at IceCube. *PoS*, NuFact2017:132, 2018.

[254] Y. Farzan and M. Tortola. Neutrino oscillations and Non-Standard Interactions. *Front. in Phys.*, 6:10, 2018.

[255] Sujata Pandey, Siddhartha Karmakar, and Subhendu Rakshit. Strong constraints on non-standard neutrino interactions: LHC vs. IceCube. *JHEP*, 11:046, 2019.

[256] Saeed Abbaslu, Mehran Dehpour, Yasaman Farzan, and Sahar Safari. Searching for axial neutral current non-standard interactions of neutrinos by DUNE-like experiments. *JHEP*, 04:038, 2024.

[257] Wilfried Buchmüller and Daniel Wyler. Effective lagrangian analysis of new interactions and flavour conservation. *Nuclear Physics B*, 268(3-4):621–653, 1986.

[258] MB Krauss. Neutrino mass from higher than d= 5 effective operators with discrete symmetries. In *Journal of Physics: Conference Series*, volume 447, page 012039. IOP Publishing, 2013.

[259] KS Babu, S Nandi, and Zurab Tavartkiladze. New mechanism for neutrino mass generation and triply charged higgs bosons at the lhc. *Physical Review D—Particles, Fields, Gravitation, and Cosmology*, 80(7):071702, 2009.

[260] Davide Meloni, Tommy Ohlsson, Walter Winter, and He Zhang. Non-standard interactions versus non-unitary lepton flavor mixing at a neutrino factory. *Journal of High Energy Physics*, 2010(4):1–28, 2010.

[261] Carla Biggio, Mattias Blennow, and Enrique Fernandez-Martinez. General bounds on non-standard neutrino interactions. *Journal of High Energy Physics*, 2009(08):090, 2009.

[262] Enrique Fernández-Martínez. Non-standard neutrino interactions. In *Proceedings of the The Xth Nicola Cabibbo International Conference on Heavy Quarks and Leptons. October 11-15 2010. Laboratori Nazionali di Frascati dell'INFN*, page 56, 2010.

[263] Paul Langacker and David London. Lepton-number violation and massless nonorthogonal neutrinos. *Physical Review D*, 38(3):907, 1988.

[264] KS Babu, Garv Chauhan, and PS Bhupal Dev. Neutrino nonstandard interactions via light scalars in the earth, sun, supernovae, and the early universe. *Physical Review D*, 101(9):095029, 2020.

[265] Sacha Davidson, Nuria Rius, Arcadi Santamaria, et al. Present and future bounds on non-standard neutrino interactions. *Journal of High Energy Physics*, 2003(03):011, 2003.

[266] Carlo Giunti and Chung W Kim. *Fundamentals of neutrino physics and astrophysics*. Oxford university press, 2007.

[267] Pilar Coloma, MC Gonzalez-Garcia, Michele Maltoni, João Paulo Pinheiro, and Salvador Urrea. Global constraints on non-standard neutrino interactions with quarks and electrons. *Journal of High Energy Physics*, 2023(8):1–42, 2023.

[268] Wei Chao and He Zhang. One-loop renormalization group equations of the neutrino mass matrix¡? format?¿ in the triplet seesaw model. *Physical Review D—Particles, Fields, Gravitation, and Cosmology*, 75(3):033003, 2007.

[269] Jose F Nieves and Palash B Pal. Generalized fierz identities. *American journal of physics*, 72(8):1100–1108, 2004.

[270] Celso C Nishi. Simple derivation of general fierz-type identities. *American journal of physics*, 73(12):1160–1163, 2005.

[271] Lucien Heurtier and Yongchao Zhang. Supernova constraints on massive (pseudo) scalar coupling to neutrinos. *Journal of Cosmology and Astroparticle Physics*, 2017(02):042, 2017.

[272] PS Pasquini and OLG Peres. Bounds on neutrino-scalar yukawa coupling. *Physical Review D*, 93(5):053007, 2016.

[273] MUHAMMED Deniz, B Sevda, SAİME Kerman, A Ajjaq, L Singh, HT Wong, and MEHMET Zeyrek. Constraints on scalar-pseudoscalar and tensorial nonstandard interactions and tensorial unparticle couplings from neutrino-electron scattering. *Physical Review D*, 95(3):033008, 2017.

[274] Shao-Feng Ge, Manfred Lindner, and Werner Rodejohann. Atmospheric trident production for probing new physics. *Physics Letters B*, 772:164–168, 2017.

[275] Guo-yuan Huang, Tommy Ohlsson, and Shun Zhou. Observational constraints on secret neutrino interactions from big bang nucleosynthesis. *Physical Review D*, 97(7):075009, 2018.

[276] Yasaman Farzan, Manfred Lindner, Werner Rodejohann, and Xun-Jie Xu. Probing neutrino coupling to a light scalar with coherent neutrino scattering. *Journal of High Energy Physics*, 2018(5):1–27, 2018.

[277] Edward Hardy and Robert Lasenby. Stellar cooling bounds on new light particles: plasma mixing effects. *Journal of High Energy Physics*, 2017(2):1–37, 2017.

[278] N Bohr. Can quantum-mechanical description of physical reality be considered complete? In *Niels Bohr Collected Works*, volume 7, pages 291–298. Elsevier, 1996.

[279] Wendell H Furry. Note on the quantum-mechanical theory of measurement. *Physical Review*, 49(5):393, 1936.

[280] Stuart J Freedman and John F Clauser. Experimental test of local hidden-variable theories. *Physical review letters*, 28(14):938, 1972.

[281] Alain Aspect, Philippe Grangier, and Gérard Roger. Experimental realization of einstein-podolsky-rosen-bohm gedankenexperiment: a new violation of bell's inequalities. *Physical review letters*, 49(2):91, 1982.

[282] Artur K Ekert. Quantum cryptography based on bell's theorem. *Physical review letters*, 67(6):661, 1991.

[283] Charles H Bennett, Gilles Brassard, Claude Crépeau, Richard Jozsa, Asher Peres, and William K Wootters. Teleporting an unknown quantum state via dual classical and einstein-podolsky-rosen channels. *Physical review letters*, 70(13):1895, 1993.

[284] Reinhard F Werner. Quantum states with einstein-podolsky-rosen correlations admitting a hidden-variable model. *Physical Review A*, 40(8):4277, 1989.

[285] Charles H Bennett and Stephen J Wiesner. Communication via one-and two-particle operators on einstein-podolsky-rosen states. *Physical review letters*, 69(20):2881, 1992.

[286] Michał Horodecki, Paweł Horodecki, and Ryszard Horodecki. Mixed-state entanglement and distillation: Is there a "bound" entanglement in nature? *Physical Review Letters*, 80(24):5239, 1998.

[287] Richard Jozsa and Noah Linden. On the role of entanglement in quantum-computational speed-up. *Proceedings of the Royal Society of London. Series A: Mathematical, Physical and Engineering Sciences*, 459(2036):2011–2032, 2003.

[288] Peter W Shor. Algorithms for quantum computation: discrete logarithms and factoring. In *Proceedings 35th annual symposium on foundations of computer science*, pages 124–134. Ieee, 1994.

[289] Emanuel Knill and Raymond Laflamme. Power of one bit of quantum information. *Physical Review Letters*, 81(25):5672, 1998.

[290] Animesh Datta, Anil Shaji, and Carlton M Caves. Quantum discord and the power of one qubit. *Physical review letters*, 100(5):050502, 2008.

[291] Leah Henderson and Vlatko Vedral. Classical, quantum and total correlations. *Journal of*

physics A: mathematical and general, 34(35):6899, 2001.

[292] Bryan Eastin. Simulating concordant computations. *arXiv preprint arXiv:1006.4402*, 2010.

[293] Wojciech Hubert Zurek. Quantum discord and maxwell's demons. *Physical Review A*, 67(1):012320, 2003.

[294] Jonathan Oppenheim, Michał Horodecki, Paweł Horodecki, and Ryszard Horodecki. Thermodynamical approach to quantifying quantum correlations. *Physical review letters*, 89(18):180402, 2002.

[295] Vaibhav Madhok and Animesh Datta. Interpreting quantum discord through quantum state merging. *Physical Review A—Atomic, Molecular, and Optical Physics*, 83(3):032323, 2011.

[296] Daniel Cavalcanti, Leandro Aolita, Sergio Boixo, Kavan Modi, Marco Piani, and Andreas Winter. Operational interpretations of quantum discord. *Physical Review A—Atomic, Molecular, and Optical Physics*, 83(3):032324, 2011.

[297] Alexander Streltsov, Hermann Kampermann, and Dagmar Bruß. Quantum cost for sending entanglement. *Physical review letters*, 108(25):250501, 2012.

[298] Tan Kok Chuan, J Maillard, Kavan Modi, Tomasz Paterek, Mauro Paternostro, and Marco Piani. Quantum discord bounds the amount of distributed entanglement. *Physical Review Letters*, 109(7):070501, 2012.

[299] Borivoje Dakić, Yannick Ole Lipp, Xiaosong Ma, Martin Ringbauer, Sebastian Kropatschek, Stefanie Barz, Tomasz Paterek, Vlatko Vedral, Anton Zeilinger, Časlav Brukner, et al. Quantum discord as resource for remote state preparation. *Nature Physics*, 8(9):666–670, 2012.

[300] Mile Gu, Helen M Chrzanowski, Syed M Assad, Thomas Symul, Kavan Modi, Timothy C Ralph, Vlatko Vedral, and Ping Koy Lam. Observing the operational significance of discord consumption. *Nature Physics*, 8(9):671–675, 2012.

[301] Kavan Modi, Aharon Brodutch, Hugo Cable, Tomasz Paterek, and Vlatko Vedral. The classical-quantum boundary for correlations:¡? format?¿ discord and related measures. *Reviews of Modern Physics*, 84(4):1655–1707, 2012.

[302] Tillmann Baumgratz, Marcus Cramer, and Martin B Plenio. Quantifying coherence. *Physical review letters*, 113(14):140401, 2014.

[303] Michael A Nielsen and Isaac L Chuang. *Quantum computation and quantum information*. Cambridge university press, 2010.

[304] Samuel L Braunstein, Ady Mann, and Michael Revzen. Maximal violation of bell inequalities for mixed states. *Physical Review Letters*, 68(22):3259, 1992.

[305] Ryszard Horodecki, Pawel Horodecki, and Michal Horodecki. Violating bell inequality by mixed spin-12 states: necessary and sufficient condition. *Physics Letters A*, 200(5):340–344, 1995.

[306] Márcio M. Cunha, Alejandro Fonseca, and Edilberto O. Silva. Tripartite entanglement: Foundations and applications. *Universe*, 5(10), 2019.

[307] N David Mermin. Extreme quantum entanglement in a superposition of macroscopically distinct states. *Physical Review Letters*, 65(15):1838, 1990.

[308] George Svetlichny. Distinguishing three-body from two-body nonseparability by a bell-type inequality. *Physical Review D*, 35(10):3066, 1987.

[309] Asad Ali, Saif Al-Kuwari, M. Rahim, Mehrdad Ghominejad, Hazrat Ali, and Saeed Haddadi. Nonclassical characteristics in spin-1/2 Heisenberg xyz model with added dm and ksea interactions under sinusoidal magnetic field: Hierarchy of quantum resources, 05 2024.

[310] Erwin Schrödinger. Discussion of probability relations between separated systems. In *Mathematical Proceedings of the Cambridge Philosophical Society*, volume 31, pages 555–563. Cambridge University Press, 1935.

[311] Eric Gama Cavalcanti, Steve J Jones, Howard M Wiseman, and Margaret D Reid. Experimental criteria for steering and the Einstein-Podolsky-Rosen paradox. *Physical Review A—Atomic, Molecular, and Optical Physics*, 80(3):032112, 2009.

[312] Howard M Wiseman, Steve James Jones, and Andrew C Doherty. Steering, entanglement, nonlocality, and the Einstein-Podolsky-Rosen paradox. *Physical review letters*, 98(14):140402, 2007.

[313] Thomas Jennewein, Gregor Weihs, Jian-Wei Pan, and Anton Zeilinger. Experimental nonlocality proof of quantum teleportation and entanglement swapping. *Physical review letters*, 88(1):017903, 2001.

[314] Shunlong Luo. Quantum discord for two-qubit systems. *Physical Review A—Atomic, Molecular, and Optical Physics*, 77(4):042303, 2008.

[315] Borivoje Dakić, Vlatko Vedral, and Časlav Brukner. Necessary and sufficient condition for nonzero quantum discord. *Physical review letters*, 105(19):190502, 2010.

[316] Alexander Streltsov, Uttam Singh, Himadri Shekhar Dhar, Manabendra Nath Bera, and Gerardo Adesso. Measuring quantum coherence with entanglement. *Physical review letters*, 115(2):020403, 2015.

[317] Uttam Singh, Manabendra Nath Bera, Himadri Shekhar Dhar, and Arun Kumar Pati. Maximally coherent mixed states: Complementarity between maximal coherence and mixedness. *Physical Review A*, 91(5):052115, 2015.

[318] Alain Aspect, Philippe Grangier, and Gérard Roger. Experimental tests of realistic local theories via bell's theorem. *Phys. Rev. Lett.*, 47:460–463, Aug 1981.

[319] Wolfgang Tittel, Jürgen Brendel, Bernard Gisin, Thomas Herzog, Hugo Zbinden, and Nicolas Gisin. Experimental demonstration of quantum correlations over more than 10 km. *Physical Review A*, 57(5):3229, 1998.

[320] BP Lanyon, P Jurcevic, C Hempel, M Gessner, V Vedral, R Blatt, and CF Roos. Experimental generation of quantum discord via noisy processes. *Physical review letters*, 111(10):100504, 2013.

[321] Paweł Caban, Jakub Rembieliński, Kordian A Smoliński, Zbigniew Walczak, and Marta Włodarczyk. An open quantum system approach to EPR correlations in k0k¯ 0 system. *Physics Letters A*, 357(1):6–11, 2006.

[322] A Bramon, R Escribano, and G Garbarino. A review of Bell inequality tests with neutral kaons, 2007.

[323] Beatrix C Hiesmayr. Nonlocality and entanglement in a strange system. *The European Physical Journal C*, 50:73–79, 2007.

[324] Massimo Blasone, Fabio Dell'Anno, Silvio De Siena, and Fabrizio Illuminati. A field-theoretical approach to entanglement in neutrino mixing and oscillations. *Europhysics Letters*, 106(3):30002, 2014.

[325] N Nikitin, V Sotnikov, and K Toms. Proposal for experimental test of the time-dependent Wigner inequalities for neutral pseudoscalar meson systems. *Physical Review D*, 92(1):016008, 2015.

[326] Alba Cervera-Lierta, Jose Ignacio Latorre, Juan Rojo, and Luca Rottoli. Maximal entanglement in high energy physics. *SciPost Physics*, 3(5):036, 2017.

[327] BO Kerbikov. Lindblad and bloch equations for conversion of a neutron into an antineutron. *Nuclear Physics A*, 975:59–72, 2018.

[328] Monika Richter-Laskowska, Marcin Łobejko, and Jerzy Dajka. Quantum contextuality of a single neutrino under interactions with matter. *New Journal of Physics*, 20(6):063040, 2018.

[329] Subhashish Banerjee, Ashutosh Kumar Alok, R. Srikanth, and Beatrix C. Hiesmayr. A quantum information theoretic analysis of three flavor neutrino oscillations. *Eur. Phys. J. C*, 75(10):487, 2015.

[330] Massimo Blasone, Silvio De Siena, and Cristina Matrella. Non-locality and entropic uncertainty relations in neutrino oscillations. *The European Physical Journal Plus*, 137(11):1272, 2022.

[331] Yu-Wen Li, Li-Juan Li, Xue-Ke Song, and Dong Wang. Trade-off relations of quantum

resource theory in neutrino oscillations. *The European Physical Journal Plus*, 137(11):1–13, 2022.

[332] Alessandro Ferraro, Leandro Aolita, Daniel Cavalcanti, Fernando M Cucchietti, and Antonio Acín. Almost all quantum states have nonclassical correlations. *Physical Review A*, 81(5):052318, 2010.

[333] André De Gouvêa, Kevin J Kelly, GV Stenico, and Pedro Pasquini. Physics with beam tau-neutrino appearance at dune. *Physical Review D*, 100(1):016004, 2019.

[334] Pedro Machado, Holger Schulz, and Jessica Turner. Tau neutrinos at dune: new strategies, new opportunities. *Physical Review D*, 102(5):053010, 2020.

[335] Pablo F de Salas, DV Forero, S Gariazzo, P Martínez-Miravé, O Mena, CA Ternes, M Tórtola, and JWF Valle. 2020 global reassessment of the neutrino oscillation picture. *Journal of High Energy Physics*, 2021(2):1–36, 2021.

[336] Oleg Victorovic Perevozchikov. Search for electron antineutrinos from the sun with kamland detector. *Doctoral Dissertations*, page 106, 2009.

[337] André de Gouvêa and Kevin J Kelly. Non-standard neutrino interactions at dune. *Nuclear Physics B*, 908:318–335, 2016.

[338] Pouya Bakhti, Amir N Khan, and Wei Wang. Sensitivities to charged-current nonstandard neutrino interactions at dune. *Journal of Physics G: Nuclear and Particle Physics*, 44(12):125001, 2017.

[339] Mehedi Masud, Samiran Roy, and Poonam Mehta. Correlations and degeneracies among the nsi parameters with tunable beams at dune. *Physical Review D*, 99(11):115032, 2019.

[340] Sabya Sachi Chatterjee, PS Dev, and Pedro AN Machado. Impact of improved energy resolution on dune sensitivity to neutrino non-standard interactions. *Journal of High Energy Physics*, 2021(8):1–25, 2021.

[341] Adriano Cherchiglia and José Santiago. Dune potential as a new physics probe. *Journal of High Energy Physics*, 2024(3):1–38, 2024.

[342] A Himmel. New oscillation results from the nova experiment, talk given at the xxix international conference on neutrino physics and astrophysics. *Chicago, USA, June*, 2020.

[343] P Dunne. Latest neutrino oscillation results from t2k, talk given at the xxix international conference on neutrino physics and astrophysics. *Chicago, USA, June*, 2020.

[344] Peter B Denton, Julia Gehrlein, and Rebekah Pestes. C p-violating neutrino nonstandard interactions in long-baseline-accelerator data. *Physical Review Letters*, 126(5):051801, 2021.

[345] Sabya Sachi Chatterjee and Antonio Palazzo. Nonstandard neutrino interactions as a solution to the noνa and t2k discrepancy. *Physical Review Letters*, 126(5):051802, 2021.

[346] Adriano Cherchiglia, Pedro Pasquini, OLG Peres, FF Rodrigues, RR Rossi, and ES Souza. Alleviating the present tension between t2k and no ν a with neutrino new physics at source. *arXiv preprint arXiv:2310.18401*, 2023.

[347] Susana F Huelga, Miguel Ferrero, and Emilio Santos. Loophole-free test of the bell inequality. *Physical Review A*, 51(6):5008, 1995.

[348] SF Huelga, TW Marshall, and E Santos. Experimental test of temporal bell inequalities at the mesoscopic level. In *Coherence and Quantum Optics VII: Proceedings of the Seventh Rochester Conference on Coherence and Quantum Optics, held at the University of Rochester, June 7–10, 1995*, pages 645–646. Springer, 1996.

[349] Francesco Capozzi, Eleonora Di Valentino, Eligio Lisi, Antonio Marrone, Alessandro Melchiorri, and Antonio Palazzo. Global constraints on absolute neutrino masses and their ordering. *Phys. Rev. D*, 95:096014, May 2017.

[350] Jorge Venzor, Abdel Pérez-Lorenzana, and Josue De-Santiago. Bounds on neutrino-scalar nonstandard interactions from big bang nucleosynthesis. *Physical Review D*, 103(4):043534, 2021.