COMMENTARY

Reply to Comment on “Neutrino Oscillations Originate from Virtual Excitation of Z Bosons” and “Neutrinos Produced from β Decays of Neutrons Cannot Be in Coherent Superpositions of Different Mass Eigenstates”

Shi-Biao Zheng[1]

1 College of Physics and Information Engineering, Fuzhou University, China

Funding: No specific funding was received for this work.

Potential competing interests: No potential competing interests to declare.

Abstract

In this reply, I point out that the comment by Cline[1] on my manusripts[2][3] has overlooked the critical fact that the quantum en- tanglement between the neutrino’s mass and other degrees of freedom would destroy the quantum coherence between the mass eigenstates.

Corresponding author: Shi-Biao Zheng, t96034@fzu.edu.cn

In a recent manuscript[3], I have proved that the electron antineutrino created by the β decay of a neutron cannot be in a coherent superposition of different mass eigenstates. In another manuscript[2], I have proposed a new mechanism, where the transformations among the neutrino’s flavors are induced by the virtual excitation of the Z bosonic field that can connect different neutrino flavors. In the comment by Cline[1], it was stated that the claims in my manuscripts are incorrect. As detailed below, the main statements of the comment are actually wrong.

Firstly, it should be pointed out that the author of the comment has seriously misinterpreted the first point of my manuscript by saying “*To prove the first point, the author assumes that the neutrino in question is in an eigenstate of momentum. If it is a superposition of different mass eigenstates, then clearly it cannot also be an eigenstate of energy. However the author believes it should be an eigenstate of energy as well.*” I have never meant that the neutrino should be in an eigenstate of energy. What I said in Ref.[2] is “**However, I find that the energy conservation law requires these mass eigenstates, if they exist, to be entangled with distinct joint energy eigenstates of the other particles produced by the same weak interaction as the neutrino.**”

Then the author commented “*In reality, a neutrino emitted in a weak interaction is a flavor state, which is a superposition of mass eigenstates. Whether the states in this superposition have exactly the same energy, momentum, or neither, is irrelevant to the fact that they will oscillate.*” This statement has actually overlooked the fact that the

entanglement between the neutrino’s mass and other degrees of freedom (e.g., momenta) is sufficient to destroy the

quantum coherence among the mass eigenstates. These degrees of freedom act as a which-path detector to encode the information about which mass eigenstate the neutrino is in. The quantum entanglement between the interfering particle and the which-path detector would inevitably deteriorate the quantum coherence of the interfering particle. In my manuscript, I have unambiguously demonstrated the three neutrino mass eigenstates, if there exist, would be left in a classical mixture when the momentum degrees of freedom are traced out. The entanglement-interference relation, which is a consequence of Bohr complementarity, has been theoretically investigated[4][5][6], and experimentally demonstrated in a number of physical systems[7][8][9][10][11][12][13]. It should be noted that the decoherence caused by entanglement with other degrees of freedom is unconditional; it does not matter that these degrees of freedom are actually not measured, as highlighted in the experimental paper of Ref.[7]. As the quantum coherence is destroyed by quantum entanglement, no oscillations can occur. It should be further pointed out that the concepts of quantum mechanics are valid even at the subatomic level, exemplified by a recent experiment, where entanglement between top quarks was observed[14]. Actually, quantum field theory is based on relativistic quantum mechanics, and certainly could not be used to negate the concepts or principles of quantum mechanics.

I agree with the statement "*This age-old issue has been discussed widely in the literature; see for example*[2][1][4][5][6][7][8][9]", but which does not mean that this issue has been adequately solved in the literature. As a matter of fact, the issue of entanglement-induced decoherence has been largely overlooked and has not been fully understood in these investigations. For example, in Ref[2] of the comment (Phys. Atom. Nucl. 72, 1363; arXiv:0905.1903), it was said "*The subsequent disentanglement, which is necessary for neutrino oscillations to occur, is assumed to be due to the interaction of these accompanying particles (such as e.g. electrons or muons produced in decays of charged pions) with medium.*" This statement correctly recognizes that the entanglement would destroy quantum coherence of the neutrino mass eigenstates necessary for oscillations. However, the claim that disentanglement can make oscillations occur is not correct. Due to quantum entanglement between the neutrino and the accompanying particles, the three mass eigenstates are essentially in a classical mixture when the degrees of freedom of the accompanying particles are traced out. There is no way to turn such a classical mixture into a quantum superposition during the neutrino's free propagation, as which would violate the principle of entropy increase. When the accompanying particles are disentangled from the neutrino by interaction with the medium, the entanglement of the accompanying particles with the neutrino is transferred to the medium, but cannot disappear.

Another main statement of the comment is "*Unfortunately he assumed an incorrect starting point, including tree- level flavor changing neutral-current interactions of Z with the neutrinos. This of course is not what nature has chosen; therefore the results found in*[3] *are incorrect." This statement seems to be quite unreasonable. What is the nature's favorite choice? According to the previous proposal, an additional element (e.g, a very heavy neutrino that is beyond the standard model, as proposed in the seesaw mechanism*[15]*) needs to be introduced to account for the tiny neutrino masses. This is unnecessary in the present proposal. According to Occam's Razor: Entities should not be multiplied unnecessarily, which proposal does nature prefer to choose? Finally, I would like to point out that the presence of off-diagonal terms in an neutral-current interaction was first proposed by Wolfenstein*[16]*, where the effective Hamiltonian was obtained for the neutrino propagating in matter. In my manuscript*[2]*, I showed that these terms can also appear in the vacuum, where the*

Z bosonic field is also present.

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