

Reply to “Comment on “Damping of neutrino oscillations, decoherence and the lengths of neutrino wave packets””

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In [arXiv:2209.00561](#) [1] our treatment [2] of effects of particles emitted together with neutrinos on neutrino wave packets is criticized on several grounds. We show here that this criticism is based on misinterpretation of our results and is invalid. Our conclusions and, in particular, the conclusion that neutrino wave packet separation effects are unobservable in reactor and neutrino source experiments, remain unchanged.

In [1] it has been claimed that our treatment of damping of neutrino oscillations in sec. 3 of [2] is inconsistent as it (i) suffers from causality violation, (ii) involves integration over non-orthogonal basis and (iii) inadequately considers the localization of the particles involved in neutrino production process. The author presumes that these points undermine our conclusion that decoherence by wave packet (WP) separation cannot be observed in reactor and neutrino source experiments. We demonstrate here that the first of the above claims is based on an incorrect interpretation of the space-time diagram serving to illustrate our treatment, the second claim criticizes a calculation we have never done and the third one stems from misinterpretation of the localization of the neutrino production process.

I. CAUSALITY

It is claimed in [1] that our analysis of damping of neutrino oscillations implies the possibility of superluminal signals and thus leads to causality violation. To illustrate this point, the author considers a two-stage thought experiment, in which initially neutrinos are produced in electron captures in a low-density gas, so that the interactions of the daughter nuclei with the surrounding particles of the medium can be neglected. This leads to relatively long neutrino WPs and no decoherence by WP separation observed in the detector. Then, at some “decision making time” t_0 , one compresses the gas in the source with a piston, leading to strong localization of the daughter nucleus N' and much shorter neutrino WPs; as a result, an observer at the detector position should see decoherence effects. However, according to the claim in [1], this happens outside the future light cone with the origin at the point of N' interaction soon after t_0 , as the light signal from this point would reach the neutrino detector after the neutrino detection process has already been over. This would mean causality violation.

The above argument is based on the incorrect space-time diagrams in Figs. 1 and 2 of [1] which do not cor-

respond to our calculations. Our analysis in [2] is based on a consideration of mean free times of the particles involved in the neutrino production process. We have demonstrated that the production time is determined by the shortest among the mean free times t_a of all the involved particles. In the cases considered in [1], these are the mean free times of either electron (Fig. 1)¹ or of the parent nucleus N (both panels of Fig. 2), but not of N' . Thus, in all the diagrams of [1] the mean free time $t_{N'}$ of the daughter nucleus corresponds to the times when the neutrino production process has already been over. In such circumstances the interactions of N' are irrelevant; they cannot (and do not) affect the outcome of the neutrino detection experiment.

Consider now the situation when $t_{N'} < t_N$ (see Fig. 1 of this Reply). In this case the scattering of N' is relevant and it determines the length σ_x of the neutrino WP: $\sigma_x = ct_{N'}$. Simple geometrical considerations then show that, for baselines L exceeding the coherence length $L_{\text{coh}} = (2E^2/\Delta m^2)\sigma_x$ (which means that the WPs of the neutrino mass eigenstates ν_1 and ν_2 have separated by more than their length σ_x before reaching the detector), the arrival of the slower neutrino mass eigenstate ν_2 at the neutrino detector position will be inside the future light cone. This means that no causality violation arises in this case.

Figure 2 of [1] actually corresponds to the situations when the duration τ of the individual processes of scattering of the daughter nucleus N' on the surrounding atoms of the source rather than mean free time of N' determines the length of the neutrino WP. (The author does not say this explicitly, but this follows from his figure). Note that such an approach is by itself fully legitimate, except that the time intervals τ have to be found rather than loosely assumed to be small or large, depending on the density of the system. This approach was mentioned in the end of sec. 3 of our paper [2] as an alternative to the approach we have elaborated. If implemented, it could in principle

¹ Note that the light cone in Fig. 1 of [1] is plotted incorrectly: since the produced electron has in this case the shortest time of free propagation, the light cone should originate from the point of interaction with the surrounding atoms of the electron and not of N' .

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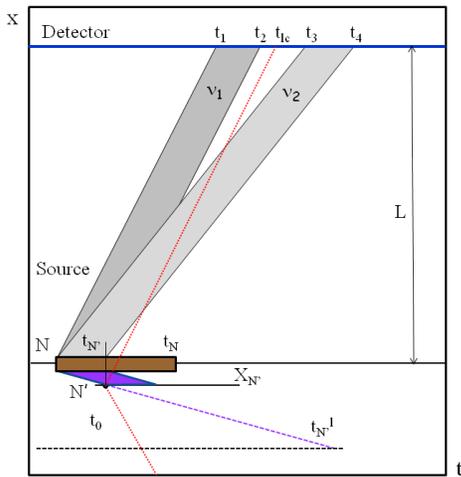


Figure 1. Space-time diagram of neutrino production, propagation and detection for neutrinos produced in e -capture in the case of compressed source gas (see text). Wave packets of the decaying nucleus N , daughter nucleus N' and mass-eigenstate components of the emitted neutrino are represented by brown, violet and gray bands, respectively. t_1 , t_2 and t_3 , t_4 are the times of arrival at the detector of the “front” and “rear ends” of the WPs of ν_1 and ν_2 , respectively. Violet dashed line corresponds to the case of uncompressed gas in the source. Red dashed lines show the borders of the future light cone from the N' interaction point. The distance of this point from the source corresponds to the mean free path of N' .

give more accurate results for the lengths of the neutrino WPs than simple order-of-magnitude estimates we have obtained. The reason we did not pursue this approach in [2] is that it would require the knowledge of the lengths of the WPs of all the particles participating in the scattering of N' (including the WPs of the scattered states), which in turn would require taking into account their interactions with the surrounding atoms, and so on. Our approach, based on the consideration of mean free times, is in fact a shortcut allowing us to avoid considering this ladder of interactions.

II. NON-ORTHOGONAL BASES

It has been hypothesized in [1] that a possible reason for the alleged violation of causality in our approach was our use of WPs for describing propagation of daughter nuclei N' , and that WPs constitute non-orthogonal bases. Using a non-orthogonal basis for summation over final states may indeed lead to wrong results. The point is, however, that we never performed such a summation, either explicitly or implicitly.

It is argued in [1] that a summation over all the possible final states of the daughter nucleus N' has to be performed, as the observer at the neutrino detector has no knowledge about these states. We disagree with this

point. The only characteristic of N' we use is the total cross-section of its interaction with particles of medium which determines the N' mean free path. We have shown in [2] that interactions of N' with medium are only important for the formation of neutrino WPs when they happen on the time scales shorter than those of the interactions of the parent nucleus N . Therefore, they constitute an important part of the neutrino production process, and the production is not over until the scattering of N' occurs. This scattering thus cannot be considered as happening “after the neutrino production”.

Notice that if one neglects the effects of N' on neutrino WPs, this would greatly increase the lengths of these WP's, as was shown in sec. 3.1.1 of [2]. This would only suppress decoherence effects and make their observation even less feasible.

In [1] several issues related to the entanglement of the particles produced at neutrino detection and its connections with the EPR paradox were discussed. These are interesting points that deserve separate consideration. However, they are not directly related to the issues discussed in our paper [2].

III. LOCALIZATION DUE TO NUCLEON INTERACTIONS WITHIN THE NUCLEUS

In [2] we assumed that the localization of the atoms of neutrino source is caused by their scattering on surrounding atoms. The author of [1] mentions as an alternative to this the localization of the decaying nucleon with respect to the other nucleons of the same parent nucleus. This would lead to much shorter neutrino WPs. However, such a localization through inter-nucleon interactions does not say anything about the absolute localization of the nucleus as a whole, and obviously only the latter is relevant for the formation of the neutrino WP. One might argue that the localization of the atom containing the unstable nucleus by its scattering on another atom does not determine the absolute position of such an atomic pair in space either [3] (note that in [2] we considered localization through atom-atom scattering). Let us clarify this issue.

Consider a source atom in a given coordinate system. The coordinate of the atom can be established (with some uncertainty) through its observable interactions with the other parts of the system. Consider first the situation when the source atom is placed in an empty box of linear size l . Then the coordinate uncertainty of the atom and of its nucleus (as well as of the constituent nucleons of the nucleus) will be given by l , not by the size of the atom or by the radius of its nucleus. This is because there is no way to find out where exactly inside the box the atom is, and its localization proceeds only through its collisions with the walls of the box. If the box is filled with a gas, the uncertainty of the coordinate of the parent nucleus will be given by the mean free path of its atom, because its scattering on the atoms of the gas will

produce measurable recoils and local gas density changes. No such recoils are produced by the interactions of the decaying nucleon with the other nucleons of the same nucleus because the daughter nucleus recoils as a whole. Thus, such inter-nucleon interactions have nothing to do with localization of the parent particle in the source.

To conclude, the criticism of our results in [1] is invalid.

We maintain the validity of our results and, in particular, stand by our conclusion that WP separation effects cannot be observed in reactor and source experiments.

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[1] B. J. P. Jones, [arXiv:2209.00561](#) [hep-ph].

[2] E. Akhmedov and A. Y. Smirnov, [arXiv:2208.03736](#) [hep-

ph].

[3] B. J. P. Jones, private communication.