Comments on “Study of decoherence effects in neutrino oscillations at Daya Bay”

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1. This paper is rather trivial, and not quite correct as is. Even when the paper is fixed, I am skeptical that it is worthy of submission to the Physical Review.

2. The paper purports to be about “decoherence effects,” but it is mostly about misunderstandings that are all too common (some of which seem to be in the paper as well as elsewhere).

   Neutrinos can oscillate only when there is sufficient overlap between the wavefunctions of the various possible states of the neutrino. As the wavefunctions of neutrinos with different masses propagate, they do so with different velocities, so if the wavepackets are narrow, the packets of different mass states cease to overlap (after traveling some distance), and we can say that these states have decohered.[1]

   This decoherence is influenced by the initial state of the neutrino, as well as by the method of detection of the neutrino.

   It seems to me that the paper reports only the first effect, and neglects the latter, which is the more important for the Daya Bay experiment.

3. While the paper talks about decoherence, it actually reports a limit on the quantity $\sigma_{\rm rel} = \sigma_p/p$, where p is the neutrino momentum. The relation between $\sigma_{\rm rel}$ and the coherence length is given in eq. (5) of the paper.

   Since the masses of the neutrinos are $\lesssim 1$ eV, and the energy of reactor neutrinos is a few MeV, the energy E and momentum p of these neutrinos are essentially indistinguishable. As such, $\sigma_{\rm rel} \approx \sigma_E/E$, and the paper acknowledges this obliquely in lines 244-246: “The Daya Bay data allow us to provide for the first time the limits on the relative uncertainty of neutrino **energy** due its quantum nature as $2.38 \cdot 10^{-17} < \sigma_{\rm rel} < 0.232$.”

   That is, the paper really reports on σ_E/E rather than on σ_p/p as implied in the first part of the paper.

   I actually prefer reporting on σ_E/E.

4. Once it is clear that the goal of the paper is to report on σ_E/E, we should first note that the fact that the neutrinos come from a nuclear reactor tells us what is σ_E/E for the neutrinos as produced, but not yet detected.

   As discussed in Fig. 3 of our paper, Phys. Rev. Lett. **116**, 061801 (2016), the most probable prompt neutrino energy is about 4 MeV, and the FWHM of the neutrino spectrum is about 3 MeV. Hence, the $\sigma_{\rm rel}$ for reactor neutrinos as produced is $\sigma_E/E \approx (3/2.35)/4 = 0.32$.

[1] The neutrino wavefunction oscillated up to the time/distance at which the wavefunctions of different mass states ceased to overlap. Hence, “decoherence” does not imply that there are no effects of oscillations, but rather that these effects do not grow with increasing time/distance.

It appears to me that the main content of the present version of our paper is an argument that more detailed considered of $\sigma_{\rm rel}$ for neutrinos as produced in a nuclear reactor lowers the estimate of 0.32 to 0.23.

However, when we detect the neutrinos, we get a measure of their prompt energy E', which is about 3/4 of the total energy E of the neutrino on average. As such $\sigma_E/E \approx \sigma'_E/E' \approx 0.08/\sqrt{E'}$, for E' in MeV.

This is the $\sigma_{\rm rel}$ that is relevant for considerations of decoherence.

Since we observe prompt energies between about 1 and 8 MeV, the corresponding $\sigma_{\rm rel}$ varies from 0.08 to 0.03.

If we are actually going to report a result on $\sigma_{\rm rel}$, this is what it should be.

5. Of course, publishing a paper in Physical Review whose main content is to state our detector resolution seems rather trivial.

   The paper claims that this is the first time any neutrino experiment has a value of the $\sigma_{\rm rel}$ related to decoherence, which may well be correct. But, any neutrino experiment that knows its energy resolution could have published this as "the relative uncertainty of neutrino energy due its quantum nature."

   That is, our claim, once revised to note that the relevant $\sigma_{\rm rel}$ is the detector energy resolution, while technically correct, would be somewhat "overblown," in that calling measurement uncertainty an uncertainty due to the quantum nature of the neutrino only means that we live in a quantum universe, so that a neutrino is a quantum entity, and any uncertainty associated with measurement of a neutrino is thereby associated with its quantum nature.

6. Comments like the above appear in sec. 2.2 of my tech note,
   http://kirkmcd.princeton.edu/examples/neutrino_osc.pdf
   and on slide 4 of
   http://kirkmcd.princeton.edu/examples/neutrino_trans1.pdf

7. A corollary, important for the JUNO project, is that since the "decoherence" related to $\sigma_p/p \approx \sigma_E/E$ is dominated by the detector resolution, to observe the neutrino oscillations associated with θ_{12} without these being smeared out due to "decoherence," we need much better resolution than in the Daya Bay Experiment. But, if we achieve the resolution sufficient to resolve the oscillations in the energy spectrum, then automatically the neutrinos are coherent enough for the experiment to succeed.

   If the present version of our paper were correct that the relevant $\sigma_{\rm rel}$ for decoherence is almost 10 times the detector energy resolution, then the JUNO experiment would never work!

8. To continue the theme of these comments, lines 82-115 give a misleading impression that decoherence effects are dominated by the issue of the width of the neutrino wavepacket, rather than by detector resolution.

   In my view, it would be much more appropriate to mention the 1981 paper of Boris Kayser, *On the quantum mechanics of neutrino oscillation*, Phys. Rev. D 24, 110

(1981), which was perhaps the first to emphasize the important of detector resolution on coherence effects in neutrino oscillations.

I have also found the paper M. Beuthe, *Towards a unique formula for neutrino oscillations in vacuum*, Phys. Rev. D 66, 013003 (2002), to be helpful, particularly eq. (15).

Other papers that give useful perspectives on neutrino coherence include
L. Stodolsky, *When the wavepacket is unnecessary*, Phys. Rev. D **58**, 036006 (1998);
H.J. Lipkin, *What is coherent in neutrino oscillations*, Phys. Lett. **B579**, 355 (2004);
H.J. Lipkin, *Quantum theory of neutrino oscillations for pedestrians: simple answers to confusing questions*, Phys. Lett. **B642**, 366 (2006).

9. The first sentence of the paper, line 74, mentions without reference "the standard quantum mechanical approach to neutrino oscillations."

   Is there really such a thing as THE standard approach? I think not. People are generally, but vaguely, aware that if a neutrino has both a definite energy and momentum, as for a plane wave state, then it could not oscillate. So, some people assume that it has a definite energy, but not a definite momentum (perhaps starting with J.N. Bahcall and H. Primakoff, *Neutrino-antineutrino oscillations*, Phys. Rev. D **18**, 3463 (1978)); in this approach energy, but not momentum, is conserved in neutrino oscillations. Other people assume that a neutrino has a definite momentum but not energy (perhaps starting with L. Wolfenstein, *Neutrino oscillations in matter*, Phys. Rev. D **17**, 2369 (1978)); in this approach momentum, but not energy is conserved in neutrino oscillations.

   That is, both of the "standard" approaches to neutrino oscillations violate energy-momentum conservation, which seems to be "nonstandard" in the larger sense.

   The missing insight in the "standard" approach is that oscillating neutrinos are in an entangled state, which state obeys energy-momentum conservation, and in which the neutrino does not have definite energy and momentum until it is detected. That is, it does not make sense to speak of the neutrino wavepacket, as done in our paper starting on line 82, without mention of the rest of the entangled state, and of the effect of the detector on the observation of the neutrino.

   Indeed, as noted above (particularly by Stodolsky), the concept of the neutrino wavepacket is not particularly relevant to neutrino-oscillation experiments, where effects of detector resolution, detector size, and even source size, are more important for understanding coherence effects (as first emphasized by Kayser (1981) in the reference given above). This was also a major point of the various papers of Beuthe, including ref. [2] of our paper, but which key point is omitted in the present version of our paper.

In sum, the present version of our decoherence paper is substantially off the mark, and makes a subtle issue appear more complicated than it actually is, by omitting mention of the effects of the detector (and source) on experimental observables, while giving misemphasis to the wavepacket of an neutrino (which should not be considered in a careful discussion without mention of its the entangled state).