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

http://dayabay.ihep.ac.cn/DocDB/0104/010403/016/DYB_Decoh_prl_v3.pdf

Kirk T. McDonald
(Version 6, May 20, 2016)

This version of my comments benefits from a 2-hour Skype phone call, and several emails, with Dmitry Naumov.

1. The topic of decoherence in neutrino oscillations in intellectually interesting, but it is not relevant to a successful neutrino-oscillation experiment such as Daya Bay, in that if oscillations were observed, then there was essentially no decoherence in the experiment. As such, little knowledge of decoherence can be extracted from the data of a successful neutrino experiment, and a discussion of decoherence based only on such data will be of limited significance. A better picture of the (non)decoherence effects in a successful neutrino-oscillation experiment should be based on more than just the nominal data of the experiment.

2. If we accept a definition of the coherence length $L_{\rm coh}$ as given by eq. (5) of the decoherence paper,

$$L_{\rm coh}(E) = \frac{L_{\rm osc}(E)}{\sqrt{2}\pi\sigma_{\rm rel}}, \tag{1}$$

where $\sigma_{\rm rel} = \sigma_E/E$, then for a reactor-neutrino experiment like Daya Bay (and JUNO), $\sigma_{\rm rel}$ is determined by the detector energy resolution, and not by "intrinsic" effects related to the source, or to the source-detector distance D.[1] A consequence of this is that if the detector resolution is sufficient to resolve oscillations in the neutrino energy spectrum, then the coherence length is automatically longer than the source-detector distance, and there will be little/no decoherence in the data.

If we approximate σ_E/E by,

$$\sigma_{\rm rel} = \frac{\sigma_E}{E} \approx \frac{\sigma_{E_{\rm prompt}}}{E_{\rm prompt}} \approx \frac{0.08}{\sqrt{E_{\rm prompt}}}, \tag{2}$$

then we arrive at a prediction of the coherence length. For example, at $E = 4$ MeV, the peak energy of the reactor antineutrino spectrum, for which $E_{\rm prompt} \approx 3$ MeV, the detector energy resolution is $\sigma_E/E \approx 0.08/\sqrt{3} \approx 0.046$, and $L_{\rm osc} \approx 2$ km $\approx D$

[1] This was perhaps first pointed out in eq. (15) of M. Beuthe, *Towards a unique formula for neutrino oscillations in vacuum*, Phys. Rev. D **66**, 013003 (2002). This insight also appeared in eq. (67) of Beuthe's lengthy review paper, ref. 2 of the decoherence paper, and was also reviewed in sec. 2.2 of my tech note,
http://kirkmcd.princeton.eduexamples/neutrino_osc.pdf
and on slide 4 of http://kirkmcd.princeton.edu/examples/neutrino_trans1.pdf

for oscillations related to neutrino-mixing angle θ_{13}, where D is the distance from the reactors to the Daya Bay Far Detector. Then, eq. (1) leads to the prediction that,

$$L_{\rm coh} \approx \frac{L_{\rm osc}}{0.046\sqrt{2}\pi} \approx 5L_{\rm osc} \approx 5D \approx 10 \text{ km} \qquad (\text{Daya Bay}, E = 4 \text{ MeV}). \tag{3}$$

However, this (simple) prediction is not mentioned in the decoherence paper.

Indeed, the word "decoherence" appears only in the title of the paper, and once in the text. That is, the paper is not about the straightforward computation of the coherence length of the experiment, but about something else: limits on the "intrinsic" value of $\sigma_{\rm rel}$ as determined by the source-detector distance D, which "intrinsic" value does not determine the coherence length in the Daya Bay experiment.

3. Limits on the "intrinsic" value of $\sigma_{\rm rel}$ can easily be calculated from the source-detector distance D, whose maximum value is ≈ 2 km.

   A lower limit comes from the fact that the neutrino exists only for time $\Delta t \approx D/c$, noting that since the neutrino energy is much larger than its mass, the neutrino velocity is essentially the speed of light c. Then, by the uncertainty principle,

$$\sigma_E \gtrsim \frac{\hbar}{\Delta t} \approx \frac{\hbar c}{c\Delta t} = \frac{\hbar c}{D} \approx \frac{2 \times 10^{-16} \text{ MeV-km}}{2 \text{ km}} = 10^{-16} \text{ MeV}. \tag{4}$$

   Hence, for the typical reactor-neutrino energy $E = 4$ MeV, we have that,

$$\sigma_{\rm rel} = \frac{\sigma_E}{E} > \frac{10^{-16} \text{ MeV}}{4 \text{ MeV}} = 2.5 \times 10^{-17}. \tag{5}$$

   On the other hand, the fact that oscillations are observed in the Daya Bay experiment implies that $L_{\rm coh} > D \approx L_{\rm osc}$. Hence, from eq. (1) above we infer that,

$$\sigma_{\rm rel} = \frac{\sigma_E}{E} = \frac{L_{\rm osc}}{L_{\rm coh}\sqrt{2}\pi} > \frac{1}{\sqrt{2}\pi} = 0.23. \tag{6}$$

   The decoherence paper does not mention these simple calculations, but describes a lengthy procedure whose result is,

$$2.38 \times 10^{-17} < \sigma_{\rm rel} < 0.232. \tag{7}$$

   Thus, use only of the largest Daya Bay source-detector distance reproduces the main result of the decoherence paper.

4. Hence, it seems to me that while the lengthy analysis presented in the decoherence paper is technically correct, it is readily anticipated in a few lines, and in any case it does not find the easily predicted value that $L_{\rm coh} \approx 5L_{\rm osc} \approx 10$ km in the Daya Bay experiment for $E = 4$ MeV.[2]

[2] The corresponding prediction for $\sigma_{\rm rel}$ is $\sigma_{\rm rel} = L_{\rm osc}/L_{\rm coh}\sqrt{2}\pi \approx 1/5\sqrt{2}\pi = 0.046$.

As such, I do not think that the decoherence paper is suitable for publication in its present form.

I also do not think that a paper which more or less presented these comments/calculations would be suitable for Physical Review Letters, although it would be nice if such comments began to appear in our conference talks, and perhaps also were mentioned briefly in our future analysis publications.

Some additional comments:

5. Other lower limits on the "intrinsic" value of $\sigma_{\rm rel}$ can be deduced from properties of the nuclear reactor, rather than from the detection of the neutrinos.

   For example, the typical lifetime of the beta decay that produced a reactor antineutrino is (I think) $\tau \approx 10$ s. Then $c\tau \approx 3 \times 10^4$ km, such that $\sigma_E \gtrsim \hbar c/c\tau \approx 7 \times 10^{-21}$ MeV, and for neutrino energy of 4 MeV, $\sigma_{\rm rel} > 2 \times 10^{-21}$. This is, of course, a very weak limit.

   A much stronger limit is based on the knowledge that the nucleus whose decay produced the antineutrino was localized roughly by the size of an atom, say $\sigma_x \approx 2 \times 10^{-10}$ m $= 2 \times 10^{-13}$ km. Then, $\sigma_E \approx c\sigma_p \gtrsim \hbar c/\sigma_x \approx 10^{-3}$ MeV, and for neutrino energy of 4 MeV, $\sigma_{\rm rel} > 2.5 \times 10^{-4}$.

   This latter limit is deduced in sec. 2.1.6 of the paper M. Gonchar *et al.*, *Quantum decoherence in neutrino oscillations*,
   http://dayabay.ihep.ac.cn/DocDB/0104/010403/016/dubna_decoherence_technote_v5.pdf,
   but it is not found in the decoherence paper since it is not based on the Daya Bay neutrino data.

6. I close with some comments about references for possible use in future papers.

   There are two versions of the "standard" neutrino-oscillation analyses based on the approximation of plane-wave states, which violate energy-momentum conservation when neutrinos oscillate.

   Some people assume that the oscillating neutrino 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.

One of the earliest papers to discuss decoherence in neutrino oscillations was Boris Kayser, *On the quantum mechanics of neutrino oscillation*, Phys. Rev. D **24**, 110 (1981).

Also, lines 82-115 of the decoherence paper give a misleading impression that decoherence effects are dominated by the issue of the width of the neutrino wavepacket, rather than by detector resolution. That the latter holds for reactor-neutrino experiments was perhaps first clearly enunciated in eq. (15) of M. Beuthe, *Towards a unique formula for neutrino oscillations in vacuum*, Phys. Rev. D **66**, 013003 (2002). This insight also appeared in eq. (67) of Beuthe's lengthy review paper, ref. 2 of the decoherence paper.

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).