Nonmaximal θ_{23} Mixing at NOvA from Neutrino Decoherence

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(Received 26 February 2017; published 30 May 2017)

In a study of a muon-neutrino disappearance at 810 km, the NOvA experiment finds flavor mixing of the atmospheric sector to deviate from maximal ($\sin^2\theta_{23} = 0.5$) by 2.6σ. The result is in tension with the 295-km baseline measurements of T2K, which are consistent with maximal mixing. We propose that θ_{23} is in fact maximal, and that the disagreement is a harbinger of environmentally induced decoherence. The departure from maximal mixing can be accounted for by an energy-independent decoherence of strength $\Gamma = (2.3 \pm 1.1) \times 10^{-23}$ GeV.

DOI: 10.1103/PhysRevLett.118.221801

For nearly two decades, experimental investigations of atmospheric and accelerator-beam ν_μ and $\bar{\nu}_\mu$ neutrinos have indicated the θ_{23} mixing angle to be compatible with 45° (i.e., $\sin^2\theta_{23} = 0.5$), implying the ν_3 mass eigenstate to be composed of ν_μ and ν_τ flavors in nearly equal amounts. This trend has been taken as evidence for a μ-τ flavor symmetry that may underwrite the pattern exhibited by the 3×3 Pontecorvo-Maki-Nakagawa-Sakata lepton-flavor mixing matrix [1]. At present, experimental analyses of muon-neutrino disappearance by T2K, MINOS, Super-Kamiokande, and IceCube continue to report $\sin^2\theta_{23}$ allowed regions that are consistent with maximal mixing—see, for example, Ref. [2]. The new measurement reported by NOvA, however, breaks the trend. Using a 14-kton detector equivalent exposure of 6.05×10^{20} protons on target, NOvA determines two statistically degenerate values for $\sin^2\theta_{23}$ in the normal mass hierarchy (NH) at 68% confidence level: $0.404^{+0.030}_{-0.022}$ and $0.624^{+0.022}_{-0.030}$. The results indicate departure, at 2.6σ significance, from maximal θ_{23} mixing [3].

That a flavor symmetry may be operative and partially broken is a tantalizing situation, for the amount of symmetry breaking is potentially informative about underlying structures. On the other hand, it is not particularly shocking that a current experiment might reveal a departure from maximal mixing since it is often the case that symmetries are inexact at some level. More disconcerting is that the NOvA result diverges from the findings of the other state-of-the-art experiment that uses a fixed long baseline, namely, T2K. Understandably, the tension between these measurements has drawn the attention of proponents of exotic oscillation effects. An obvious difference between the experiments is their baselines: The T2K far detector is located 295 km from the accelerator-beam site, while the NOvA baseline is 810 km. For conventional three-flavor vacuum oscillations, muon-neutrino disappearance depends on L/E_ν, and the baseline difference should be of little consequence. However, for exotic physics effects promoted by propagation through matter or merely by extended propagation through spacetime, the difference in the baselines can be relevant.

Proponents of exotic oscillation effects take the view that there may be an exact μ-τ flavor symmetry. The NOvA result is then to be understood as a harbinger of new physics. One possibility is that neutrinos propagating through Earth's crust are subjected to nonstandard interactions (NSIs). The tension between the NOvA and T2K measurements of the θ_{23} mixing angle received treatment in two recent NSI analyses [4,5]. The NSI scenarios developed by these works are quite different; each analysis invokes a different set of sizable NSI couplings, and some of the couplings are required to have strengths comparable to the Mikheyev-Smirnov-Wolfenstein (MSW) matter effect [6].

It is proposed in this Letter that a simple model of neutrino decoherence driven by weak coupling to a dissipative environment offers another way wherein μ-τ flavor symmetry remains exact while the disagreement between the NOvA and T2K ν_μ-flavor disappearance results is explained. While full-bore decoherence models were "run out of town" a decade ago, overwhelmed by the accumulation of data that showed oscillations to be the dominant effect, the possibility remains that propagating neutrinos may decohere very gradually as they oscillate. Such behavior is observed in a variety of quantum systems that are "open" to environmental influences, and the phenomenology for describing these systems is well developed. For evolving neutrino states, the pervasive environment might introduce new physics originating beyond the standard electroweak model, e.g., perturbations arising from spacetime itself and its Planck-scale dynamics [7–9].

Environmentally induced neutrino decoherence is to be distinguished from neutrino wave-packet decoherence. The latter is a quantum wave effect that one may expect to occur based on known physics—no beyond-the-standard-model mechanism is needed. Neutrino wave packets have received abundant treatment from both relativistic quantum-mechanical and quantum-field theoretic perspectives [10]. In recent times the disappearance of reactor $\bar{\nu}_e$ at nine different baselines of the Daya Bay experiment has been examined for wave-packet effects; however, none were found [11]. Neglecting higher-order dispersion-effect terms, there is general agreement concerning the basic form that neutrino wave-packet decoherence would take [10,12]. For the ν_μ survival-oscillation probability, the prerequisite integration over momentum space and averaging over the time from production to detection introduces exponential damping factors that multiply each of the oscillatory terms. The damping factors have the form $\exp\{-(L/L^{\rm coh}_{ij})^2\}$, where L is the baseline length, $ij = 21$ or 31 or 32, and $L^{\rm coh}_{ij}$ is the coherence length: $L^{\rm coh}_{ij} = (4\sqrt{2}\sigma_x E^2_\nu)/|\Delta m^2_{ij}|$. Importantly, the coherence length is proportional to the width σ_x of the mass eigenstate wave packets in coordinate space and to the square of the neutrino energy, E_ν. This means that the exponential damping depends strongly on neutrino energy as well as on the baseline: $(L/L^{\rm coh}_{ij})^2 = (|\Delta m^2_{ij}|^2 L^2)/(32\sigma^2_x E^4_\nu)$. For accelerator-based long-baseline experiments such as T2K and NOvA, the processes at neutrino production at detection are nearly the same; hence, σ_x should be of similar magnitude. Moreover, in long-baseline experiments, the oscillation phase $\phi = (\Delta m^2_{32} L)/4E_\nu$ is chosen to be near unity; consequently, $(L/L^{\rm coh}_{ij})^2 \propto \phi^4/L^2$ decreases with the baseline. Thus wave-packet decoherence is not viable as an effect that could account for the emergence of apparent nonmaximal mixing with a longer baseline. On the other hand, as will be elaborated, an environmentally driven decoherence that depends only on path length can account for the emergence of apparent nonmaximal mixing at longer oscillation baselines. Furthermore, the strength of the decoherence required to do this is not contradicted by the upward-going muon data of Super-Kamiokande [7,13].

The survival probability for ν_μ flavor neutrinos propagating through the vacuum, $\nu_\mu \to \nu_\mu$, is approximately described by two-flavor mixing: $\mathcal{P}_{\mu\mu} = 1 - \sin^2 2\theta_{23} \sin^2 \phi$. A tacit assumption is that propagating neutrinos constitute a closed quantum system. Most systems, however, are inherently open to an environment and are potentially susceptible to dissipative interactions with it. The dissipative effect considered here is a decoherence effect that acts on the quantum interference and damps the oscillating terms in the neutrino oscillation probabilities.

A phenomenology that allows for dissipative interactions with an environment is provided by a density matrix formalism and the quantum analogue of Liouville's theorem in classical statistical mechanics [14,15]. Specifically, the Lindblad master equation is generally regarded as an appropriate framework for investigating neutrino decoherence [7,9,13,16–22]. The presence of weakly perturbative dynamics is parametrized by an added "dissipator" term,

$$\frac{d}{dt}\hat{\rho}_\nu(t) = -i[\hat{H}, \hat{\rho}_\nu(t)] - \mathcal{D}[\hat{\rho}_\nu(t)]. \tag{1}$$

The dissipation term $\mathcal{D}[\hat{\rho}_\nu(t)]$ is constructed using a set of $N^2 - 1$ operators, $\hat{D}_n$, where N is the dimension of the Hilbert space of interest (so that $N = 2$ for two-flavor oscillations and the $\hat{D}_n$'s are linear combinations of the Pauli spinors plus the unit matrix). Constraints can be placed on the $\hat{D}_n$ arising from mathematical considerations and from the laws of thermodynamics. For example, it may be assumed that the von Neumann entropy, $S = \mathrm{Tr}(\hat{\rho}_\nu \ln \hat{\rho}_\nu)$, increases with time, and this is enforced by requiring the $\hat{D}_n$ to be Hermitian. In addition, conservation of the average value of the energy, calculated as $\mathrm{Tr}(\hat{\rho}_\nu \hat{H})$, can be assured by requiring the $\hat{D}_n$ to commute with $\hat{H}$. For two-flavor mixing describing vacuum oscillations of the atmospheric sector, the phenomenology is reducible to a form in which decoherence is promoted by a single exponential damping term containing one free parameter, Γ_{32}. The probability for ν_μ disappearance oscillations, obtained by tracing the $|\nu_\mu\rangle$ state projector (expressed in mass basis) over the time-evolved density matrix [7,19], is

$$\mathcal{P}^{(2\nu)}_{\mu\mu} = 1 - \frac{1}{2}\sin^2 2\theta_{23}\left[1 - e^{-\Gamma_{32}L}\cos\left(\frac{\Delta m^2_{32}}{2E_\nu}L\right)\right]. \tag{2}$$

Equation (2) resembles expectations for ν_μ survival in the presence of neutrino decay [23,24]; however, there are differences. For oscillations with decay, the decay rate gives the damping constant and, due to the Lorentz boost, the damping carries an E^{-1}_ν dependence. Moreover, neutrino decay models lead to the damping of constant terms as well as oscillatory terms in the survival probability, while damping from decoherence is limited to oscillatory terms.

The interaction of neutrinos with their environment need not be constant—it could depend upon E_ν. Previous investigations of neutrino decoherence models explored this possibility using integer power-law forms for the decoherence parameter [7,13,21]: $\Gamma_{32} = \Gamma_0(E_\nu/[\mathrm{GeV}])^n$. In the absence of a model for environmental influence, many researchers have focused on the $n = 0$ case; however, power-law forms with $n = 0, \pm1, \pm2$ have been regarded as possibilities. The case n = 2 is strongly constrained by the Super-Kamiokande atmospheric data [7]; these constraints become weaker with a slower rate of energy increase or with a decreasing energy dependence. For neutrino mixing in the solar sector, the decoherence parameter Γ_{21} with $n = -1$ (and presumably $n = -2$) is strongly constrained by the solar plus KamLAND data [13]. In any event, the negative integer power-law forms do not work for the scenario considered here. This leaves $n = 0$ as the simplest choice for the scenario proposed. Support for this choice is given by the decoherence model fit results of Oliveira *et al.* [21] to the ν_μ and $\bar{\nu}_\mu$ disappearance oscillation data of the MINOS experiment at 735-km baseline. For the $n = 0$ power law, their best fit with conventional two-flavor oscillations gives $\sin^2(2\theta_{23}) = 0.92^{+0.06}_{-0.07}$, while the decoherence model yields $\sin^2(2\theta_{23}) = 0.98_{-0.08}$, with $\Gamma_{32} = 3.10^{+2.37}_{-2.49} \times 10^{-23}$ GeV.

The NOvA measurement is based on data analysis using 3ν oscillations with the MSW matter effect and so, for an accurate evaluation of decoherence, it is necessary to extend the phenomenology to a comparable framework. The Hermitian operators of the Lindblad equation, namely,

$\hat{H}$, $\hat{\rho}_\nu(t)$ and the eight $\hat{D}_n$ operators, can be expanded in terms of the Gell-Mann SU(3) basis matrices and the 3×3 unit matrix. This enables a reformulation of the evolution equation that includes an 8×8 matrix of parameters, $\mathcal{D}_{kl}$ [25,26]. The requirement $[\hat{H}, \hat{D}_n] = 0$ constrains the $\mathcal{D}_{kl}$ matrix to be diagonal, with elements involving only three positive, real-valued parameters: Γ_{21}, Γ_{31}, and Γ_{32} [26]. The time evolution of the density matrix for three-neutrino oscillations in vacuum has been solved and the oscillation probabilities with inclusion of decoherence obtained [see Eqs. (2.4) and (2.6) in Ref. [27]]. Here, we proceed by replacing the mixing angles and mass splittings with their corresponding matter effective values:

$$\mathcal{P}_{\mu\mu}^{(3\nu)} = 1 - 2\sum_{j>k}\{|\tilde{U}_{\mu j}|^2|\tilde{U}_{\mu k}|^2(1 - e^{-\Gamma_{jk}L}\cos\tilde{\Delta}_{jk}L)\},$$

where $\tilde{U}_{\mu i}$ represents the elements of an effective mixing matrix and $\tilde{\Delta}_{jk}$ the mass-splitting forms $(\Delta m_{jk}^2/2E_\nu)$ augmented by factors arising from matter effects.

A very good approximation for $\mathcal{P}_{\mu\mu}^{(3\nu)}$ with matter effects (without decoherence) is presented in Ref. [28], obtained under the assumption that $\Delta m_{21}^2 = 0$. This approximate form [see Eq. (27) of Ref. [28]] can be rearranged to allow the decoherence factors of Eq. (3) to be included, yielding

$$\begin{aligned}\mathcal{P}_{\mu\mu}^{(3\nu)} \approx 1 &- \frac{1}{2}\sin^2\tilde{\theta}_{13}\sin^2 2\theta_{23}[1 - e^{-\Gamma_{21}L}\cos 2\tilde{\phi}_-] \\ &- \frac{1}{2}\cos^2\tilde{\theta}_{13}\sin^2 2\theta_{23}[1 - e^{-\Gamma_{32}L}\cos 2\tilde{\phi}_+] \\ &- \frac{1}{2}\sin^2 2\tilde{\theta}_{13}\sin^4\theta_{23}[1 - e^{-\Gamma_{31}L}\cos 2\tilde{\phi}_0], \end{aligned} \tag{3}$$

where

$$\tilde{\phi}_0 \equiv \phi\sqrt{(\cos 2\theta_{13} - \hat{A})^2 + \sin^2 2\theta_{13}}, \tag{4}$$

$$\tilde{\phi}_\pm \equiv \frac{1}{2}[(1 + \hat{A})\phi \pm \tilde{\phi}_0], \tag{5}$$

with the matter potential $\hat{A} = (2\sqrt{2}G_F N_e E_\nu)/\Delta m_{31}^2$ and with $\tan 2\tilde{\theta}_{13} = \sin 2\theta_{13}/(\cos 2\theta_{13} - \hat{A})$.

In Eq. (3), the first term on the right-hand side is affected by the Γ_{21} decoherence parameter. However, that parameter is assumed to be negligible here, motivated by fits to the available solar plus KamLAND neutrino data [13], which obtained for the same $n = 0$ power-law form $\Gamma_{21} < 0.67 \times 10^{-24}$ GeV at 95% C.L. The three Γ_{ij} parameters of the $\mathcal{D}_{kl}$ matrix are related by the requirement of complete positivity [15,29] in such a way that, if $\Gamma_{21} = 0$, $\Gamma_{32} = \Gamma_{31} \equiv \Gamma$ (see Ref. [26], Sec. II). With Eq. (3), it is readily seen that, in the limit of vacuum oscillations and $\theta_{13} \to 0$, the first and third terms go to zero and the second term goes over to Eq. (2).

In order to measure the θ_{23} mixing angle, experiments look for the oscillation probability in the vicinity of the first oscillation minimum. For ν_μ flavor disappearance in standard model (SM) oscillations, the survival minima in the presence of nonmaximal θ_{23} mixing will be shifted from null probability to a small probability. This effect, and the reinterpretation that is possible for it, are readily discerned in the vacuum, 2ν-oscillation formulas. In the case of no decoherence, the survival probability indicates that a nonmaximal θ_{23} can give an upward shift of $(1.0 - \sin^2 2\theta_{23}^{\mathrm{SM}})$. Equation (2) indicates that the same probability shift can arise with maximal θ_{23} if decoherence is operative; an upwards shift of $[1 - \frac{1}{2}(1 + e^{-\Gamma_{32}L})]$ is to be expected.

These same trends are predicted by the 3ν-oscillation formula of Eq. (3), which provides a more accurate venue for relating the decoherence parameter, Γ, to measurements of apparent nonmaximal θ_{23} mixing. In long-baseline experiments, the matter potential $\hat{A}$ has a small value close to the oscillation minimum: $\hat{A}^{(\mathrm{min})} \sim (0.085E_\nu^{(\mathrm{min})}/\mathrm{GeV})$. Consequently the oscillation minimum for $\mathcal{P}_{\mu\mu}^{(3\nu)}$ of Eq. (3) lies very close to the minimum for vacuum oscillations, $E_\nu^{(\mathrm{min})} = (\Delta m_{31}^2 L)/2\pi$.

The survival probability at the oscillation minimum, $\mathcal{P}_{\mu\mu}^{(\mathrm{min})}$, can then be estimated by expanding Eq. (3) about $E_\nu^{(\mathrm{min})}$ and retaining terms with any product of $\hat{A}^{(\mathrm{min})}$ and $\sin\theta_{13}$ up to third order (~0.3%). This procedure yields

$$\begin{aligned}P_{\mu\mu}^{(\mathrm{min})} &\approx 1 - (1 + e^{-\Gamma L}) \\ &\times \left[\frac{1}{2}\sin^2 2\theta_{23} - 2\sin^2\theta_{23}\cos 2\theta_{23}\sin^2\theta_{13}(1 + 2\hat{A}^{(\mathrm{min})})\right].\end{aligned} \tag{6}$$

The value of Γ predicted by the decoherence scenario can be found by equating the probabilities,

$$P_{\mu\mu}^{(\mathrm{min})}(\Gamma = 0, \sin^2\theta_{23}^{\mathrm{SM}}) = P_{\mu\mu}^{(\mathrm{min})}(\Gamma, \sin^2\theta_{23} = 0.5). \tag{7}$$

The result is

$$\begin{aligned}e^{-\Gamma L} &= 8\sin^2\theta_{23}^{\mathrm{SM}} \\ &\times [1 - \sin^2\theta_{23}^{\mathrm{SM}} - (1 + 2\hat{A}^{(\mathrm{min})})\sin^2\theta_{13}\cos 2\theta_{23}^{\mathrm{SM}}] - 1,\end{aligned} \tag{8}$$

where $\hat{A}^{(\mathrm{min})} \simeq L/5800$ km. Evaluating the above equation at an 810-km baseline using NOvA's reported NH values, $\sin^2\theta_{23}^{\mathrm{SM}} = \{0.404^{+0.030}_{-0.022}$ or $0.624^{+0.022}_{-0.030}\}$, together with $\sin^2\theta_{13} = 0.0219$, we obtain

$$\Gamma = (2.3 \pm 1.1) \times 10^{-23}\ \mathrm{GeV}. \tag{9}$$

Note that the value for the decoherence parameter is the same for either of the octant solutions for $\sin^2\theta_{23}^{\mathrm{SM}}$. Our result is compatible with the limits reported in Refs. [7,13], based upon a comparison of Super-Kamiokande lepton distributions in zenith angle to predictions for muon survival using a constant ($n = 0$) decoherence parameter: $\Gamma_{32} < 4.1(5.5) \times 10^{-23}$ GeV at 95% (99%) C.L.

Figure 1 shows ν_μ survival probabilities for the ongoing experiments T2K and NOvA, and for the 1300-km baseline of DUNE. For each baseline, the survival probability versus E_ν is displayed (i) for standard oscillations with maximal mixing (the long-dashed curve), (ii) for standard oscillations with NOvA nonmaximal mixing (the short-dashed curve), and (iii) for maximal mixing oscillations with decoherence (the solid-line curve). At the first minimum for the NOvA baseline, nonmaximal mixing is indistinguishable (by construction) from maximal mixing plus decoherence. At the first minimum for T2K, the probability curves indicate that the decoherence scenario is more difficult to distinguish from maximal mixing than is NOvA nonmaximal mixing. Thus, if decoherence rather than nonmaximal mixing is operative, this situation may explain the apparent tension between NOvA and T2K measurements of ν_μ-flavor survival oscillations. The probability curves at the first minimum of DUNE show that distinguishing among predictions of the three hypotheses becomes easier at longer baselines.

Having determined the Γ-parameter value [Eq. (9)], it becomes possible to extract from Eq. (8) the values for $\sin^2\theta_{23}^{\rm SM}$ to be expected at any long baseline from a conventional SM oscillation analysis that ignores decoherence. Upon inverting Eq. (8) for this purpose, one obtains two solutions for $\sin^2\theta_{23}^{\rm SM}$ at each baseline, one for each of the octants. The solutions as a function of increasing baseline follow two distinct trajectories, as shown in Fig. 2, with the apparent $\sin^2\theta_{23}^{\rm SM}$ value for each solution displayed on the y axis. The solution points at each baseline are not symmetrically located about $\sin^2\theta_{23}^{\rm SM} = 0.5$, reflecting the interplay of 3ν mixing with matter effects. Included in the figure are experimental data points and errors representing beam-only ν_μ disappearance results reported by NOvA [3], MINOS [30], and T2K [31].

Figure 2 shows that long-baseline experiments using a conventional SM analysis will, at shorter baselines, tend to infer that θ_{23} mixing lies close to maximal—assuming that the mixing is indeed maximal. At the T2K baseline, a precise measurement could, in principle, discern a deviation from maximal, $\Delta\theta_{23} \simeq \pm 4°$, although, in practice, a deviation of this size would be difficult to observe. At MINOS+ and NOvA however, $\Delta\theta_{23}$ grows to $\simeq \pm 6°$, so an apparent deviation from maximal mixing is more readily obtained. At the baseline of DUNE, a conventional oscillation measurement is predicted to report a larger excursion of θ_{23} from maximal mixing than that deduced at NOvA: $\Delta\theta_{23} \simeq \pm 8°$.

The decoherence parameter value presented in Eq. (9) is inferred from the values reported by NOvA. An alternative approach could be based on a combined fit to the three long-baseline experiments. As an exploratory trial, a χ-square fit for the decoherence parameter was carried out while assuming that errors are Gaussian in the value of the probability minimum of Eq. (6), using the data points and errors displayed in Fig. 2. This fit ($\chi^2/\mathrm{d.o.f.} = 1.02$) yields a somewhat lower value for the decoherence parameter: $\Gamma = (1.8 \pm 0.9) \times 10^{-23}$ GeV. The central trajectories are very similar to those displayed in Fig. 2 but lie slightly closer to the horizontal centerline at $\sin^2\theta_{23}^{\rm SM}$; they fall at the 1σ limits of T2K and remain well within the 1σ ranges of MINOS and NOvA. A more incisive treatment requires attention to details of the experiments and is not pursued here. Further insights might be gleaned by considering the high energy ν_μ event samples ($E_\nu > 4$ GeV) that are accessible to MINOS+ and DUNE.

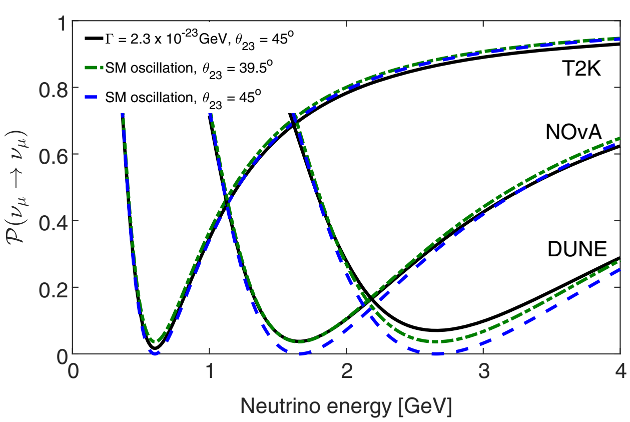

FIG. 1. Muon-neutrino survival versus E_ν at the T2K, NOvA, and DUNE baselines in the vicinity of their respective first minima. The probability distributions compare standard oscillations with maximal and nonmaximal θ_{23} mixing (the long-dashed and short-dashed curves), to oscillations with maximal mixing plus decoherence (the solid-line curve).

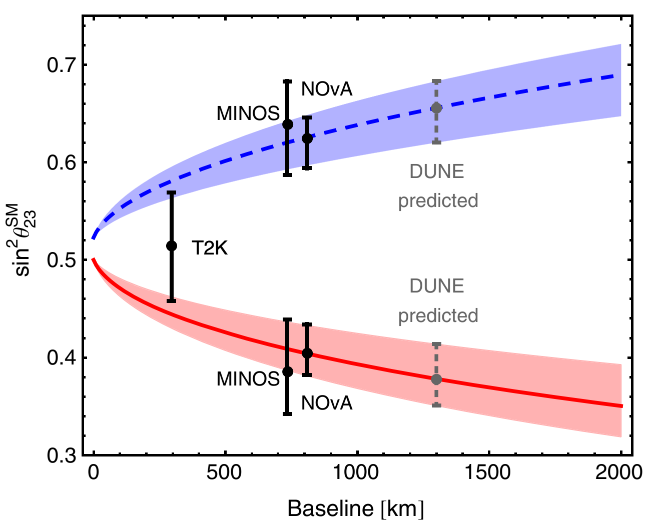

FIG. 2. Depiction of the trend toward a larger apparent deviation from maximal θ_{23} mixing with an increasing oscillation baseline, as predicted by the maximal mixing plus decoherence oscillation scenario. The predictions are double valued and asymmetric about $\sin^2\theta_{23} = 0.5$, reflecting the octant degeneracy inherent to a measurement of θ_{23} in the presence of matter effects. The curves displayed are for the normal mass hierarchy.

To summarize: It is proposed that a small decoherence effect whose strength lies just below the current upper limit can account for the nonmaximal mixing observation at NOvA while indicating why θ_{23} appears to be more nearly maximal at T2K. The decoherence effect is characterized by a single, energy-independent damping parameter, $\Gamma = (2.3 \pm 1.1) \times 10^{-23}$ GeV.

If maximal θ_{23} mixing plus decoherence is operative but θ_{23} measurements continue to be expressed in terms of standard oscillations without decoherence, certain trends in neutrino results can be anticipated. (i) NOvA will continue to report nonmaximal mixing. (ii) T2K results will gradually shift from maximal to nonmaximal θ_{23} mixing, but with a deviation from maximal that is always less than that reported by NOvA. (iii) This apparent tension will hold regardless of whether ν_μ and $\bar{\nu}_\mu$ data samples are treated separately or together at each of the baselines. (iv) At DUNE, a larger (apparent) deviation from maximal θ_{23} mixing will be observed than that reported by NOvA. Specifically, ν_μ disappearance in DUNE will appear to be governed by mixing at strength $\sin^2\theta_{23} \simeq 0.38$ for the lower octant NH solution. Sensitive tests of decoherence using atmospheric neutrinos may also be feasible; however, as Eq. (3) indicates, a careful accounting of matter effects for $\bar{\nu}_\mu$ as well as ν_μ fluxes with a consideration of mass hierarchy is required.

This work was supported by the U.S. Department of Energy under Grant No. DE-SC0007866, and by the IdEx program at Sorbonne Paris Cité (ANR-11-IDEX-0005-02).

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[1] Z. Xing and Z. Zhao, A review of $\mu - \tau$ flavor symmetry in neutrino physics, Rep. Prog. Phys. **79**, 076201 (2016).

[2] A. Yu. Smirnov, in *Proceedings of the 8th Symposium on Large TPCs for Low-Energy Rare Event Detection, Paris, 2016*, https://indico.cern.ch/event/473362/contributions/2315754/.

[3] P. Adamson *et al.* (NOvA Collaboration), Measurement of the Neutrino Mixing Angle $\theta_2 3$ in NOvA, Phys. Rev. Lett. **118**, 151802 (2017).

[4] S. Fukasawa, M. Ghosh, and O. Yasuda, Is nonstandard interaction a solution to the three neutrino tensions?, arXiv:1609.04204.

[5] J. Liao, D. Marfatia, and K. Whisnant, Nonmaximal neutrino mixing at NOvA from nonstandard interactions, Phys. Lett. B **767**, 350 (2017).

[6] L. Wolfenstein, Neutrino oscillations in matter, Phys. Rev. D **17**, 2369 (1978); S. P. Mikheyev and A. Y. Smirnov, Resonant amplification of ν oscillations in matter and solar-neutrino spectroscopy, Yad. Fiz. **42**, 1441 (1985) [Sov. J. Nucl. Phys. **42**, 913 (1985)]; Nuovo Cimento Soc. Ital. Fis. **9C**, 17 (1986).

[7] E. Lisi, A. Marrone, and D. Montanino, Probing Possible Decoherence Effects in Atmospheric Neutrino Oscillations, Phys. Rev. Lett. **85**, 1166 (2000).

[8] J. Ellis, N. E. Mavromatos, and D. V. Nanopoulos, A microscopic Liouville arrow of time, Chaos Solitons Fractals **10**, 345 (1999).

[9] G. Barenboim, N. E. Mavromatos, S. Sarker, and A. Waldon-Lauda, Quantum decoherence and neutrino data, Nucl. Phys. **B758**, 90 (2006).

[10] Y.-L. Chan, M.-C. Chu, K. M. Tsui, C. F. Wong, and J. Xu, Wave-packet treatment of reactor neutrino oscillation experiments and its implications on determining the neutrino mass hierarchy, Eur. Phys. J. C **76**, 310 (2016).

[11] F. P. An *et al.* (Daya Bay Collaboration), Study of wave packet treatment of neutrino oscillation at Daya Bay, arXiv:1608.01661.

[12] C. Giunti and C. W. Kim, Coherence of neutrino oscillations in the wave packet approach, Phys. Rev. D **58**, 017301 (1998).

[13] G. L. Fogli, E. Lisi, A. Marrone, D. Montanino, and A. Palazzo, Probing nonstandard decoherence effects with solar and KamLAND neutrinos, Phys. Rev. D **76**, 033006 (2007).

[14] V. Gorini, A. Frigerio, M. Verri, A. Kossakowski, and E. C. G. Sudarshan, Properties of quantum Markovian master equations, Rep. Math. Phys. **13**, 149 (1978).

[15] G. Lindblad, On the generators of quantum dynamical semigroups, Commun. Math. Phys. **48**, 119 (1976).

[16] T. Ohlsson, Equivalence between Gaussian averaged neutrino oscillations and neutrino decoherence, Phys. Lett. B **502**, 159 (2001).

[17] F. Benatti and R. Floreanini, Massless neutrino oscillations, Phys. Rev. D **64**, 085015 (2001).

[18] A. M. Gago, E. M. Santos, W. J. C. Teves, and R. Zukanovich Funchal, Quantum dissipative effects and neutrinos: Current constraints and future perspectives, Phys. Rev. D **63**, 073001 (2001).

[19] R. L. N. Oliveira and M. M. Guzzo, Quantum dissipation in vacuum neutrino oscillation, Eur. Phys. J. C **69**, 493 (2010).

[20] R. L. N. Oliveira and M. M. Guzzo, Dissipation and θ_{13} in neutrino oscillations, Eur. Phys. J. C **73**, 2434 (2013).

[21] R. L. N. Oliveira, M. M. Guzzo, and P. C. de Holanda, Quantum dissipation and CP violation in MINOS, Phys. Rev. D **89**, 053002 (2014).

[22] M. M. Guzzo, P.C de Holanda, and R. L. N. Oliveira, Quantum dissipation in a neutrino system propagating in vacuum and in matter, Nucl. Phys. **B908**, 408 (2016).

[23] R. A. Bertlmann, W. Grimus, and B. C. Hiesmayr, Open-quantum-system formulation of particle decay, Phys. Rev. A **73**, 054101 (2006).

[24] M. C. Gonzalez-Garcia and Michele Maltoni, Status of oscillation plus decay of atmospheric and long-baseline neutrinos, Phys. Lett. B **663**, 405 (2008).

[25] A. M. Gago, E. M. Santos, W. J. C. Teves, and R. Zukanovich Funchal, A study on quantum decoherence phenomena with three generations of neutrinos, arXiv: hep-ph/0208166.

[26] R. L. N. Oliveira, Dissipative effect in long baseline neutrino experiments, Eur. Phys. J. C **76**, 417 (2016).

[27] Y. Farzan, T. Schwetz, and A. Y. Smirnov, Reconciling results of LSND, MiniBooNE and other experiments with soft decoherence, J. High Energy Phys. 07 (2008) 067; P. Bakhti, Y. Farzan, and T. Schwetz, Revisiting the quantum

decoherence scenario as an explanation for the LSND anomaly, J. High Energy Phys. 05 (2015) 007.

[28] S. Choubey and P. Roy, Probing the deviation from maximal mixing of atmospheric neutrinos, Phys. Rev. D **73**, 013006 (2006).

[29] F. Benatti and R. Floreanini, Completely positive dynamical maps and the neutral kaon system, Nucl. Phys. **B488**, 335 (1997).

[30] R. Nichol (for the MINOS Collaboration), New Results from MINOS, Nucl. Phys. B, Proc. Suppl. **235–236**, 105 (2013); see also slide 18 of "Neutrino 2012," Kyoto, 2012.

[31] K. Abe *et al.* (T2K Collaboration), Precise Measurement of the Neutrino Mixing Parameter θ_{23} from Muon Neutrino Disappearance in an Off-Axis Beam, Phys. Rev. Lett. **112**, 181801 (2014); Measurements of neutrino oscillation in appearance and disappearance channels by the T2K experiment with 6.6×10^{20} protons on target, Phys. Rev. D **91**, 072010 (2015).