PROCEEDINGS OF SCIENCE

Neutrino quantum decoherence at reactor experiments

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Reactor experiments are well suited to probe the possible loss of coherence of neutrino oscillations due to wave-packets separation. We discuss how decoherence modifies neutrino oscillation probabilities. We focus on the reactor experiments RENO, Daya Bay and KamLAND and discuss how well these experiments can constrain decoherence effects. We also present expected sensitivities for the future experiment JUNO.

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1. Introduction

Neutrino oscillations are a consequence of nonzero neutrino masses and the fact that virtually all useful neutrino sources are coherent, i.e., neutrinos produced via charged-current weak interactions can be faithfully described as coherent superpositions of neutrinos with different masses, weighted by the elements of the leptonic mixing matrix. This is in general true because the typical energy and distance scales involved in neutrino production and detection, neutrino masses are all tiny and neutrino wave-packets are large. However, oscillation experiments can be used to constrain how coherent the different neutrino sources are. In particular, nuclear reactors are excellent laboratories to study neutrino coherence. We performed two sets of analyses. In [1], we argued that reactor neutrino experiments can be used to place interesting constraints on how coherent nuclear reactors are as sources of antineutrinos. There, we concentrated on current constraints from the km-baseline experiments Daya Bay, the Reactor Experiment for Neutrino Oscillation (RENO), and the near-future Jiangmen Underground Neutrino Observatory (JUNO) experiment. In [2] we extended our previous analysis and included data from the Kamioka Liquid Scintillator Antineutrino Detector (KamLAND). Unlike Daya Bay and RENO, KamLAND was sensitive to neutrinos from a large number of nuclear reactor sites located between, roughly, 100 km and 1000 km away and was not characterized by a single baseline. While Daya Bay and RENO are only sensitive to $\sin^2\theta_{13}$ and $|\Delta m^2_{31}|$, KamLAND is sensitive, given that $|U_{e3}|^2$ is small, only to $\sin^2 2\theta_{12}$ and $|\Delta m^2_{21}|$ so the data sets, in some sense, complement one another. The hypothesis that all reactor experiments are characterized by the same decoherence parameter allows the KamLAND and Daya Bay/RENO data sets to "inform" one another in nontrivial ways.
We explore whether high-resolution, high-statistics measurements of the flux of antineutrinos produced in nuclear reactors are sensitive to neutrino decoherence or can be used to place meaningful bounds on how coherent nuclear reactors are as neutrino sources. We also investigate how much the measurement of the different oscillation parameters is impacted, if one allows for nontrivial values of the decoherence parameters.

2. Neutrino oscillations including decoherence

Decoherence effects may stem from several different physical origins (see e.g., [3–6, 8, 9]). In this talk we focus on the possible loss of flavor-coherence of the neutrino beam that grows with the baseline (often referred to as wave-packet separation) and is parameterized through the damping parameters $\xi_{jk}(L,E) = \left(\frac{L}{L^{\rm coh}_{jk}}\right)^2$ with $j,k = 1,2,3$. If no loss of coherence occurs during neutrino propagation, $\xi_{jk}(=\xi_{kj}) = 0$. We further define the coherence lengths as $L^{\rm coh}_{jk} = \frac{4\sqrt{2}E^2}{|\Delta m^2_{jk}|}\sigma$ [1, 7–9], which depend on the neutrino energy and the mass-squared differences. We assume all decoherence effects to be encoded in a single parameter σ, which can be interpreted as the width of the neutrino wave-packet and has dimensions of length. Estimates for the typical value of σ depend on the physics responsible for neutrino production and vary by orders of magnitude.
In the presence of decoherence effects, the density matrix ρ_{jk} describing the flavor content of the reactor antineutrinos produced in nuclear power plants as a function of L and E is $\tilde{\rho}_{jk}(L,E) = \tilde{U}^*_{ej}\tilde{U}_{ek}\exp[-i\tilde{\Delta}_{jk}]\exp[-\tilde{\xi}_{jk}(L,E)]$, with $\tilde{\Delta}_{jk} \equiv 2\pi\frac{L}{\tilde{L}^{\rm osc}_{jk}} \equiv \frac{\Delta\tilde{m}^2_{jk}L}{2E}$, where we have included

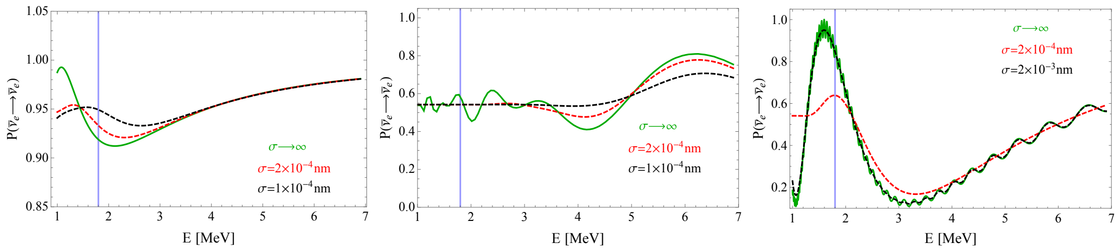

Figure 1: The electron antineutrino oscillation probability as a function of the neutrino energy for $L = 1$ km (left), KamLAND (centre), JUNO (right). The threshold for inverse beta-decay detection is in light blue.

matter effects (assuming the antineutrinos propagate through a medium with constant density) [7]. The electron antineutrino survival probability in presence of decoherence effects is given by the ee diagonal element of the density matrix: $P^{\rm dec}(\overline{\nu}_e \to \overline{\nu}_e) = \sum_{j,k} |\tilde{U}_{ej}|^2 |\tilde{U}_{ek}|^2 \exp[-i\tilde{\Delta}_{jk} - \tilde{\xi}_{jk}]$. When the damping factors $\tilde{\xi}_{jk} \to 0$ or, equivalently, when $\tilde{L}^{\rm coh}_{jk} \to \infty$ ($\sigma \to \infty$), we recover the standard oscillation probability. To illustrate the impact of decoherence on reactor antineutrino oscillations at the different reactor experiments, we depict in Fig. 1 the expected electron antineutrinos survival probability for $L = 1$ km (left), representative of the baselines of the Daya Bay and RENO experiment, while in Fig. 1 (centre) we depict the average electron antineutrino survival probability at KamLAND and in the right panel we show the probability expected at JUNO. The green, solid curve corresponds to the standard neutrino oscillation scenario without decoherence, while the red and black dashed ones are obtained assuming non-trivial decoherence effects associated to $\sigma = 2 \times 10^{-4}$ nm and $\sigma = 1 \times 10^{-4}$ nm, respectively. These values are consistent with the lower limits obtained in [2] and in [1], respectively. Decoherence "erases" the oscillatory behavior of the survival probability and its impact is more pronounced at relatively smaller energies.

3. Results

We perform the analysis for four different experiments: RENO [10], Daya Bay [11], KamLAND [12] and JUNO [13]. Fig. 2 depicts the $\sin^2\theta_{12}$-Δm^2_{21} (left) and $\sin^2\theta_{13}$-Δm^2_{31} (centre) regions of parameter space consistent with the combined data sets (filled regions in orange at 90% CL, blue at 95% CL, green at 99% CL). In all plots, we marginalize over all absent parameters, including σ when decoherence effects are allowed in the fit. The figure also depicts the allowed contours corresponding to the analysis performed assuming a perfectly coherent source (black empty curves, dot-dashed at 90% CL, dashed at 95% CL, solid at 99% CL). In [1], relying only on RENO + Daya Bay data, we found a relatively stronger correlation among the parameters. In [2], the combination of data from short-baseline experiments together with those from KamLAND significantly reduces the allowed region in the $\sin^2\theta_{13}$-Δm^2_{31} as a consequence of the fact that KamLAND is more sensitive to nontrivial σ effects that RENO and Daya Bay. We show in fig. 2 (right panel) the reduced $\chi^2(\sigma)$ profile, obtained upon marginalizing over all oscillation parameters, for all reactor experiments under consideration. We obtain the following best-fit value for the reactor-antineutrino-wave-packet width: $\sigma = 3.35 \times 10^{-4}$ nm. The no-decoherence hypothesis, $\sigma \to \infty$, however, is safely allowed at 90% CL and we can infer a lower bound on σ: $\sigma > 2.08 \times 10^{-4}$ nm at

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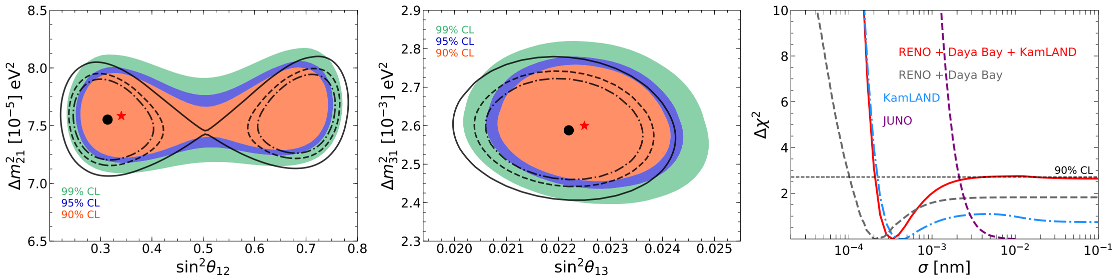

Figure 2: [Left, centre]: 90, 95 and 99% CL (2 d.o.f.) allowed regions in the $\sin^2\theta_{12}$-Δm^2_{21} and $\sin^2\theta_{13}$-Δm^2_{31} planes from our combined analysis of RENO + Daya Bay + KamLAND data including decoherence (filled regions, red stars) and assuming a perfectly coherent source (black empty contours, black dots). [Right]: The reduced χ^2 as a function of σ relative to its minimum value, obtained marginalizing over the remaining neutrino oscillation parameters.

90% CL. This is stronger by a factor 2 relative to the previous lower bound $\sigma > 1.02 \times 10^{-4}$ nm [1], obtained by combining data only from RENO and Daya Bay. We also studied the sensitivity of the future JUNO experiment [13] to constrain or measure the neutrino wave-packet width σ. We first estimated the sensitivity of JUNO to σ assuming future JUNO data are consistent with no decoherence effects, $\sigma \to \infty$. Fig. 2 (right panel) depicts the reduced $\chi^2(\sigma)$, obtained upon marginalizing over all oscillation parameters, for all reactor experiments under consideration. The sensitivity for JUNO translates into $\sigma > 2.11 \times 10^{-3}$ nm at the 90% CL. On the other hand, when simulating data consistent with the solar parameters and the best-fit value of σ obtained from the analysis of Daya Bay and RENO, we find that the impact of decoherence is very strong in JUNO. In such a case, we expect the no-decoherence hypothesis to be completely ruled out at more than ten σ. Furthermore, in that scenario, the short-wavelength oscillations are completely erased, rendering the measurements of Δm^2_{31} and Δm^2_{32} impossible. It is very clear that, under these circumstances, JUNO is completely insensitive to the mass ordering.

4. Conclusions

To summarise, we discussed the effects of wave-packet-separation decoherence on the current data on the oscillations of reactor antineutrinos, obtained for $L \sim 1$ km (Daya Bay and RENO), for $L \sim 100+$ km (KamLAND) and for $L \sim 50$ km (JUNO). We found that the current data can exclude wave-packet sizes $\sigma < 2.08 \times 10^{-4}$ nm at 90% CL, assuming that neutrinos from all nuclear-reactor cores can be characterized by the same σ. In the next few years, we expect an order-of-magnitude better sensitivity from the JUNO experiment [1]. We also showed that, given the existing reactor data, measurements of the standard oscillation parameters are robust. In the next few years, we expect an order-of-magnitude better sensitivity from the JUNO experiment [1].
We find that it is important to test the hypothesis that nuclear reactors are, for modern practical applications, a coherent source of antineutrinos, to probe how large decoherence effects could be, and to understand how these might impact our ability to measure fundamental physics parameters with reactor neutrino oscillation experiments.

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