Quantum field theoretical description of neutrino oscillations and reactor antineutrino anomaly

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Abstract

We suggest a possible explanation of the reactor antineutrino anomaly derived from a covariant quantum field-theoretical approach to neutrino oscillations. Some disadvantages of the currently prevailing interpretation of the anomaly, based upon the sterile neutrino hypothesis are pointed out.

Introduction. The measured $\overline{\nu}_e$ event rates in the short baseline (SBL) reactor experiments are about 6% lower than the theoretical expectations [1]. This so-called "reactor antineutrino anomaly" (RAA) has inspired speculation on the physical features beyond the Standard Model (SM), such as $\mathcal{O}$(1eV) mass-scale sterile neutrinos. The latter do not interact with the SM particles and may only be produced by mixing with the usual (active) neutrinos. But existence of the eV-mass sterile neutrinos is in rather poor agreement with the modern cosmological observations. A much more banal reason for the RAA may be in an inaccurate prediction of the reactor $\overline{\nu}_e$ energy spectrum (see, e.g., Ref. [2]).

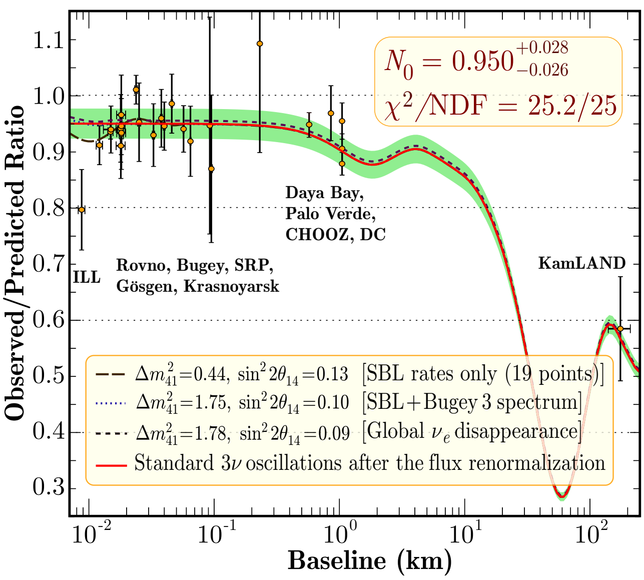

Figure 1: Comparison of the reactor data with the 3+1 mixing model and the standard 3ν model after the $\overline{\nu}_e$ flux renormalization. References to the experimental data can be found in Ref. [3].

As is shown in Ref. [3], the simplest "3+1" neutrino mixing scenarios

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could be, depending on the neutrino mixing parameters, hardly distinguishable from the standard 3ν outcome, after the proper $\overline{\nu}_e$ flux renormalization. This statement is illustrated in Fig. 1, where the solid curve represents the 3ν prediction multiplied by the best-fit factor N_0 shown in the upper legend; the 3+1 mixing parameters (see bottom legend) are taken from Ref. [4]. As one can see, the 4ν models are not preferable in comparison with the renormalized 3ν one. However, the ILL data point is below all the model predictions s under discussion. Therefore it makes sense to consider alternative explanations of the anomaly.

ISL violaton. Here we conside the explanation based on the perturbative quantum field-theoretical (QFT) approach to neutrino oscillations, which in particular predicts a small deviation of the $\nu/\overline{\nu}$ event rate, as a function of the distance L between the $\nu/\overline{\nu}$ source and detector, from the classical inverse-square law (ISL) [5]. According to the QFT approach, the neutrino oscillation phenomenon is the result of the interference of "macroscopic" Feynman diagrams with different neutrino mass eigenfields treated as propagators connecting neutrino production and absorption vertices; the external legs of such diagrams correspond to asymptotically free incoming and outgoing wave packets (see, e.g., Ref. [6] and references therein). The approach in particular predicts that at sufficiently long distances L, the neutrino event rate in the detector is proportional to the following factor [5]:

$$\frac{1}{L^2}\left[1-\frac{L_0^2}{L^2}+\mathcal{O}\left(\frac{L_0^4}{L^4}\right)\right]. \tag{1}$$

Here L_0 is the ISL violation (ISLV) spatial scale. The usual ISL behavior therefore occurs as $L \gg L_0$ but gets in general broken as $L \lesssim L_0$. The theory allows to estimate the order of magnitude of the parameter L_0 to be

$$E_\nu/\sigma_{\text{eff}}^2 \approx 20\,(E_\nu/1\text{ MeV})\,(1\text{ eV}/\sigma_{\text{eff}})^2\ \text{cm},$$

where E_ν is the neutrino energy and σ_{eff} is the scale of the neutrino transverse-momentum uncertainty defined by the masses, momenta, and momentum spreads of all external in and out wave packets in the vertices of the pertinent macrodiagrams. Hence the ISLV effect could be the real cause of RAA.

To quantify the QFT prediction with the currently available data of reactor experiments we use the theoretical model in the leading order of the $1/L^2$ expansion (1),

$$T(L;N_0,L_0)=N_0\left(1-\frac{L_0^2}{L^2}\right)\frac{\int_0^\infty dE_\nu\sum_k f_k P_{\text{surv}}^{3\nu}(L,E_\nu)\sigma(E_\nu)S_k(E_\nu)}{\int_0^\infty dE_\nu\sum_k f_k\sigma(E_\nu)S_k(E_\nu)}, \tag{2}$$

in which L_0 and N_0 are the fitting parameters, f_k represents the fissile isotope fraction, $\sigma(E_\nu)$ is the inverse β decay cross section, $S_k(E_\nu)$ is the $\overline{\nu}_e$ energy spectrum, and $P^{3\nu}_{\rm surv}$ is the survival probability in the standard 3ν mixing scheme. The standard χ^2 method is used to extract the best-fit values of L_0 and N_0 (see Ref. [3] for more details) .

Figure 2 represents an example of our analysis adopted the SBL data only. The solid curve is the theoretical prediction (2). It is seen that the ISLV hypothesis is in quite good agreement with the experimental data. For better understand, we compare in Fig. 3 the 68% C.L. error contours obtained with two different $\overline{\nu}_e$ energy spectra models from Refs. [7] and [8] and with different reactor data sets. It is seen from Fig. 2 that both the spectum models

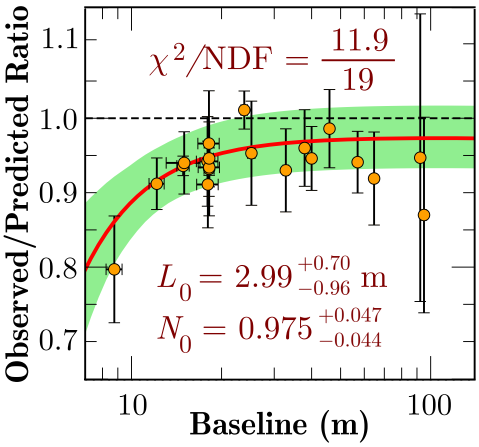

Figure 2: The result of the two-parameter fit performed with the SBL data only ($L < 100$ m). The $\overline{\nu}_e$ energy spectrum is taken from Ref. [7].

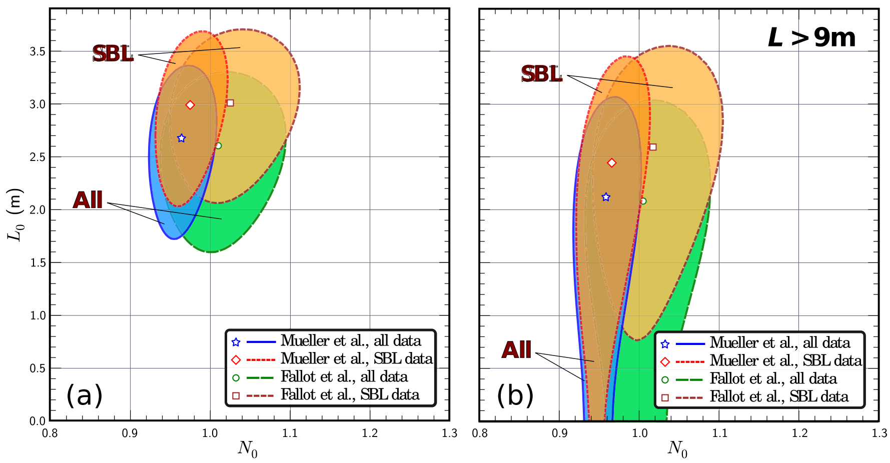

Figure 3: (a) The 68% C.L. error contours for the parameters N_0 and L_0 obtained with the two $\overline{\nu}_e$ energy spectrum models and included either SBL ($L < 300$ m) reactor data subset or the full data set shown in Fig. 1 (excluding the Data Bay data point at the effective baseline of 573 m). (b) the same as in (a) but with the ILL data point (the leftmost point in Figs. 1 and 2) excluded from the analysis.

and long baseline data ($L \gg 100$ m) insignificantly affect the best-fit values of the parameters L_0 and N_0. On the other hand, the very short baseline data (like the ILL result) are crucial to confirm or refute the ISLV effect.

Conclusions. The sterile neutrino hypothesis is not the only possible explanation of RAA. Our analysis shows that the QFT-inspired violation of the inverse-square law together with a minor renormalization of the predicted $\overline{\nu}_e$ flux may also be responsible for the observed anomaly. New high-precision short baseline experiments are needed to check the ISLV effect.

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