Physics Letters B 728 (2014) 634–638

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

The high energy neutrino nuisance at a medium baseline reactor experiment

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ARTICLE INFO

Article history:
Received 9 May 2013
Received in revised form 14 December 2013
Accepted 17 December 2013
Available online 27 December 2013
Editor: G.F. Giudice

ABSTRACT

10 years from now medium baseline reactor experiments will attempt to determine the neutrino mass hierarchy from quantities associated to the Fourier transformed neutrino spectra. Recently Qian et al. have claimed that this goal may be impeded by the strong dependence of these quantities on the reactor neutrino flux and on slight variations of $|\Delta M^2_{32}|$. We demonstrate that this effect results from a spurious dependence of the quantities on the very high energy (8+ MeV) tail of the reactor neutrino spectrum. This dependence is spurious because the high energy tail depends upon decays of exotic isotopes and is insensitive to the mass hierarchy. An energy-dependent weight in the Fourier transform eliminates this spurious dependence without decreasing the chance of correctly determining the hierarchy.

Last year the Daya Bay [1,2] and RENO [3] experiments demonstrated beyond any reasonable doubt that θ_{13} is as much as an order of magnitude larger than had been suspected several years ago, a discovery recently confirmed by T2K [4]. This large value of θ_{13} implies that 1–3 reactor neutrino oscillations may be observed at medium baselines, which we define to be 40–80 km. The medium baseline neutrino spectrum may then be used to determine the neutrino mass hierarchy [5]. Such experiments are now not only practical but indeed they will be performed within the next decade [6–8].

How does this determination work? With each fission chain, a nuclear reactor emits on average $6\bar{\nu}_e$'s in essentially random and isotropically distributed directions. The $\bar{\nu}_e$'s are detected via inverse beta decay upon their interaction with free (not bound to other nucleons) protons in a detector. Some of the $\bar{\nu}_e$'s oscillate into other flavors, providing an energy-dependent reduction of the flux which depends on the leptonic mixing angles θ_{12} and θ_{13}, on the neutrino mass differences and in particular on the neutrino mass hierarchy. In all, the $\bar{\nu}_e$ survival probability is

$$P_{ee} = \sin^4(\theta_{13}) + \cos^4(\theta_{12})\cos^4(\theta_{13}) + \sin^4(\theta_{12})\cos^4(\theta_{13}) + \frac{1}{2}(P_{12} + P_{13} + P_{23}),$$

$$P_{12} = \sin^2(2\theta_{12})\cos^4(\theta_{13})\cos\left(\frac{\Delta M^2_{21}L}{2E}\right),$$
$$P_{13} = \cos^2(\theta_{12})\sin^2(2\theta_{13})\cos\left(\frac{|\Delta M^2_{31}|L}{2E}\right),$$
$$P_{23} = \sin^2(\theta_{12})\sin^2(2\theta_{13})\cos\left(\frac{|\Delta M^2_{32}|L}{2E}\right). \quad (1)$$

The largest contribution to the depletion is caused by the P_{12} term in Eq. (1). At a medium baseline this corresponds to a single, broad dip in the measured neutrino spectra. On the other hand P_{13} and P_{23}, which we refer to collectively as 1–3 oscillations, provide a fine structure of small oscillations in the observed spectrum. Of these, the amplitude of P_{13} is greater than that of P_{23} by a factor of $\cot^2(\theta_{12}) \sim 2$, so P_{23} provides a perturbation to the P_{13} oscillations, which on their own would have been periodic in $1/E$. As the frequencies of P_{23} and P_{13} are slightly different, the fine structure, which consists of the sum of these two oscillations, is not quite periodic in $1/E$ [9]. On the contrary as the fine structure is the sum of two similar frequencies it exhibits a beating pattern, with a single beat visible in the spectrum at a medium baseline. It is the direction of the beating[1] which determines which frequency is greater. As one frequency is proportional to $|\Delta M^2_{31}|$ and the other to $|\Delta M^2_{32}|$, this direction determines whether $|\Delta M^2_{31}|$ is greater

[1] The direction of the beating corresponds to be whether, in each period, the intermediate peaks of $P_{13} + P_{23}$ are systematically at higher or lower energies than the peaks of P_{13}.

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http://dx.doi.org/10.1016/j.physletb.2013.12.045

than $|\Delta M_{32}^2|$, corresponding to the normal hierarchy, or $|\Delta M_{32}^2|$ is greater than $|\Delta M_{31}^2|$, corresponding to the inverted hierarchy.

This deviation from periodicity in the fine structure of the observed spectrum determines the hierarchy. More quantitatively, let E_n be the energy of the peak in the oscillated neutrino spectrum corresponding to neutrinos which have oscillated n times between the reactor and the detector. Note that higher values of n correspond to lower values of energy. It was shown in Ref. [10] that the inverse energies of the first 10 peaks are indeed periodic to within experimental error and indeed are well approximated by 2 flavor neutrino oscillation with an effective mass difference of [11]

$$\Delta M_{\text{eff}}^2 = \cos^2(\theta_{12})\left|\Delta M_{31}^2\right| + \sin^2(\theta_{12})\left|\Delta M_{32}^2\right|. \tag{2}$$

On the other hand, by the 16th peak P_{13} and P_{23} are in phase, and so at energies as low as E_{16} the peak locations are instead roughly those of 2-flavor oscillation with a mass of $|\Delta M_{31}^2|$, which is greater (less) than ΔM_{eff}^2 if the hierarchy is normal (inverted). If the hierarchy is normal then $|\Delta M_{31}^2|$ will be greater than ΔM_{eff}^2 and so the energies E_n of the low energy peaks, corresponding to n well above 10, will be higher than would be obtained from a simple periodic extrapolation of the high energy ($n \leqslant 10$) peaks. For example, fixing M_{eff}^2, E_{16} would be about 2% higher in the case of the normal hierarchy.

Clearly such an experiment needs to be able to measure the energy with a precision much better than 2%. The energy of the neutrino cannot be measured directly, but the energy of the positron resulting from the inverse β decay is determined by counting photoelectrons in a photomultiplier. At low energies, not many of these photoelectrons are detected and so statistical fluctuations in the number of photoelectrons limit the energy resolution. As a result, the low energy peaks, which anyway are closer together, are smeared. Assuming about 1200 photoelectrons/MeV of prompt energy (the positron plus the electron with which it annihilates), which is about the most which can be hoped for with an organic liquid scintillator, the energy resolution will be about 3% times the square root of the prompt energy in MeV. With this resolution, our simulations indicate that for n greater than about 17, the identification of an individual peak is hopeless. The same simulations show that a determination of the hierarchy at a reactor experiment using these methods requires the observation of at least the $(|\Delta M_{31}^2|/\Delta M_{21}^2 - 1)$st peak, which with the current best fit parameters corresponds to the 14th peak. Therefore only a modest reduction of the energy resolution, an increase in $|\Delta M_{31}^2|$ or a decrease in ΔM_{21}^2 can destroy the ability to determine the hierarchy at such an experiment, as was reported in Ref. [12].

On the other hand, the high energy peaks which determine ΔM_{eff}^2 can be reliably measured. As a result, such experiments can easily measure ΔM_{eff}^2, the main difficulty in the determination of the hierarchy comes from the low energy measurement of $|\Delta M_{31}^2|$. In particular, since all of the peaks $n \leqslant 10$ measure the same quantity ΔM_{eff}^2, little is gained by considering the peaks in the high energy tail of the reactor neutrino spectrum.

All experimental analyses that determine the hierarchy solely from reactor neutrinos rely upon the breakdown in periodicity described above. Two kinds of analysis have been studied extensively in the literature. First, one may perform a χ^2 fit to the observed spectra assuming both hierarchies, and conclude that the hierarchy is the one which minimizes χ^2. This method suffers from the fact that there are many nuisance parameters which need to be considered in the determinations of the spectra, and it would be impractical to extremize χ^2 with respect to all of them. As a result, a simpler method has been proposed in Ref. [13], in which one considers a Fourier transform of the observed spectrum and identifies several hierarchy-dependent quantities associated to the transformed spectrum which are reasonably independent of some of these nuisance parameters. More such properties were identified in Refs. [10,14] and applied to simulated data in Ref. [15].

Which method is better? Refs. [16,17] and [12] have shown that both methods yield reasonably consistent determinations of the mass hierarchy. As has been shown in Refs. [16,18,19] much can be gained by incorporating data from other experiments. It is currently only known how to do this with the χ^2 approach. On the other hand, a χ^2 approach requires a quantification of all of the effects which enter into the spectrum, such as broad modifications to the reactor flux coming from weak magnetism, the detector's nonlinear energy response and various reasonably smooth backgrounds. At this point even the size of the errors on some of these effects cannot be reliably estimated [20] and so spurious dependences will necessarily arise.

On the other hand the Fourier approach only considers a part of the information available, eliminating these spurious dependences but at the same time leading to an inherent inefficiency. A χ^2 fit to the image of a handwritten number or to the position-space cosmic microwave background (CMB) temperature would require so many nuisance parameters that it would be useless, which is why Fourier transforms are used to truncate the useless information out of the CMB. As a result, the Fourier and χ^2 analyses are complimentary to each other. Just as the Daya Bay experiment analyzed their data with 5 different methods to be sure that their result is analysis-independent, we expect that JUNO and RENO 50 will both analyze their data using both the χ^2 and Fourier approaches. Thus it is important to understand the drawbacks of each approach and how they can be resolved.

In Ref. [17], the authors observed that, using a Fourier transform based-analysis, the hierarchy-dependent quantities, contrary to their original motivation, are extraordinarily sensitive to the neutrino mass differences and also to the model of the reactor spectrum. We will now will explain the origin of this sensitivity.

As the dependences of the various quantities are virtually indistinguishable, for brevity we will consider only [14]

$$RL = \frac{R-L}{R+L}, \tag{3}$$

which is the fractional difference between two minima R and L of the Fourier cosine transform of the neutrino spectrum

$$F_c(k) = \int d\left(\frac{L}{E}\right)\frac{E^2}{L}\frac{\Phi(E)\sigma(E)}{4\pi L^2}P_{ee}\left(\frac{L}{E}\right)\cos\left(\frac{kL}{E}\right), \tag{4}$$

where E is the neutrino's energy and the tree level neutrino inverse β decay cross section is [21]

$$\sigma(E) = 0.0952 \times 10^{-42}\ \text{cm}^2\,\frac{E_e\sqrt{E_e^2 - m_e^2}}{\text{MeV}^2},$$
$$E_e = E - m_n + m_p. \tag{5}$$

A $3\%/\sqrt{(E_e + m_e)/\text{MeV}}$ energy resolution is included by convoluting the observed energy spectrum with

$$\exp\left(-\frac{(E-E')^2}{0.0018(E_e + m_e)\ \text{MeV}}\right). \tag{6}$$

The masses of the electron, proton and neutron are m_e, m_p and m_n. We use the neutrino mass matrix parameters

$$\sin^2(2\theta_{13}) = 0.092, \qquad \sin^2(2\theta_{12}) = 0.861, \qquad \sin^2(2\theta_{32}) = 1,$$
$$\Delta M_{21}^2 = 7.59 \times 10^{-5}\ \text{eV}^2, \qquad \left|\Delta M_{32}^2\right| = 2.43 \times 10^{-3}\ \text{eV}^2, \tag{7}$$

where $\sin^2(2\theta_{13})$ is that of Ref. [1], $\sin^2(2\theta_{12})$ and ΔM_{21}^2 are taken from Ref. [22] and $|\Delta M_{32}^2|$ is that of Ref. [23]. These are not the