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Measuring the mass of a sterile neutrino with a very short baseline reactor experiment

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An analysis of the world's neutrino oscillation data, including sterile neutrinos, [M. Sorel, C. M. Conrad, and M. H. Shaevitz, Phys. Rev. D **70**, 073004 (2004)] found a peak in the allowed region at a mass-squared difference $\Delta m^2 \cong 0.9\,\text{eV}^2$. We trace its origin to harmonic oscillations in the electron survival probability $\mathcal{P}_{ee}$ as a function of L/E, the ratio of baseline to neutrino energy, as measured in the near detector of the Bugey experiment. We find a second occurrence for $\Delta m^2 \cong 1.9\,\text{eV}^2$. We point out that the phenomenon of harmonic oscillations of $\mathcal{P}_{ee}$ as a function of L/E, as seen in the Bugey experiment, can be used to measure the mass-squared difference associated with a sterile neutrino in the range from a fraction of an eV^2 to several eV^2 (compatible with that indicated by the LSND experiment), as well as measure the amount of electron-sterile neutrino mixing. We observe that the experiment is independent, to lowest order, of the size of the reactor and suggest the possibility of a small reactor with a detector sitting at a very short baseline.

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Present data demonstrate that neutrinos change their flavor while propagating in vacuum and through matter. The evidence comes from solar neutrino experiments [1], a long baseline reactor experiment [2], atmospheric experiments [3], and a long baseline accelerator experiment [4]. These experiments, together with the constraint imposed by the CHOOZ reactor experiment [5], provide a quantitative [6] determination of the mixing parameters and mass-squared differences for three neutrino oscillations. Moreover, as the data become ever more precise, alternative explanations of the data are continually being ruled out [7].

The lone datum that does not fit into the scenario of three neutrino mixing is the appearance result from the LSND experiment [8]. An oscillation explanation of this result requires a neutrino mass-squared difference of at least 10^{-1}eV^2 while the world's remaining data are compatible with two mass-squared differences of the order of $8 \times 10^{-5}\,\text{eV}^2$ and $2 \times 10^{-3}\,\text{eV}^2$. The addition of a sterile neutrino or neutrinos [9] has been proposed in an attempt to incorporate LSND into an analysis that would be consistent with the world's data. Other physical mechanisms have also been proposed as possible explanations [10].

Restricting our discussion to sterile neutrinos (with CP and CPT conserved), the simplest extension is the inclusion of a single sterile neutrino [11]. Such models fall into one of two classes. The 3 + 1 scheme adds the fourth neutrino whose mass separation is much larger than the other three. In the 2 + 2 scheme, the LSND mass-squared difference separates two pairs of neutrinos with the smaller mass-squared differences. Current analyses indicate that neither provides a compelling explanation of the data [12,13]. As four neutrinos do not seem to be sufficient, five neutrino scenarios have been investigated [13,14].

We begin with a general discussion of the $3 + N$ scheme, where N is the number of sterile neutrinos. We then discuss a phenomenon which we identified first as a feature of the Bugey [15] data and which leads to the proposal for a new type of experiment. These discussions are carried out in the 3 + 1 scheme with the generalization to $3 + N$ to be guided by the discussion presented earlier.

The masses of the sterile neutrinos are taken to be much greater than those of the conventional neutrinos. As such, for the baselines and energies under consideration here, only the mass-squared differences involving the extra neutrinos will contribute to oscillations, as oscillation among the conventional neutrinos is negligible. Additionally, the conventional mass-squared differences are effectively degenerate with respect to the additional N neutrinos. For the case of $N = 1$, oscillations at short baselines will be governed by only one mass-squared difference Δm^2. The phenomenology is effectively that of two neutrino oscillations, and the electron neutrino survival probability can be expressed as

$$\mathcal{P}_{ee}(L/E) \cong 1 - \sin^2(2\theta_{14})\sin^2\phi, \tag{1}$$

with $\phi = 1.27\Delta m^2\, L/E$ where Δm^2 is in eV^2, the baseline L is in meters, and the energy E is in MeV. Using a standard extension of the MNS mixing matrix U, the angle θ_{14} indicates the degree of the electron neutrino's mixing with the single sterile neutrino.

For N sterile neutrinos, the number of mass-squared differences is the number of pairs $\binom{N+1}{2}$. From the formalism found in Refs. [13] or [16], only the N mass-squared differences between the mass of the conventional neutrinos and each of the sterile neutrinos, Δm_j^2, are significant, giving for $\mathcal{P}_{ee}$

$$\mathcal{P}_{ee}(L/E) \cong 1 - 4\sum_{j=4}^{N+3} U_{ej}^2 \sin^2\phi_j, \tag{2}$$

where ϕ_j is the oscillation phase corresponding to the mass-squared difference Δm_j^2. This result follows from the restrictions imposed by CHOOZ [5] on the magnitude of the matrix elements U_{ej}^2

$$\sum_{j=4}^{N+3} U_{ej}^2 \lesssim 0.02. \tag{3}$$

Thus the magnitude of each individual U_{ej} is small. In the oscillation probability $\mathcal{P}_{ee}$, Eq. (2), we are able to neglect terms involving mass-squared differences between two sterile neutrinos as they are quartic in U_{ej}.

If there exists more than one sterile neutrino, then several scenarios can occur. Suppose one sterile neutrino is resolvable by our proposed experiment, but additional sterile neutrinos exist with a much larger mass. The oscillation phase associated with the mass-squared differences of the additional heavy sterile neutrinos, ϕ_j with $j = 5, \ldots, N$, would be large and contribute an energy independent constant to $\mathcal{P}_{ee}$. This is theoretically clean but experimentally difficult to detect. With perfect data, one could extract such a constant shift, necessarily small due to Eq. (3), in the data. However, the largest error in present experiments is the overall normalization, and thus evidence of the heavier sterile neutrinos likely would not be detectable.

Consider a second case in which two or more sterile neutrinos have mass-squared differences which lie within the sensitivity range of a single or multiple experiments. First, Eq. (3) will restrict the number of neutrinos that couple sufficiently to the electron-neutrino survival channel and that are detectable. In the case as found in [13], where the mass-squared differences associated with the possible existence of two sterile neutrinos are distinctly different and the mixing angles to each are comparable and sufficiently large, then the oscillation pattern is that of a higher frequency oscillation superimposed on a lower frequency oscillation. For [13], the two mass-squared differences were approximately $1\,\mathrm{eV}^2$ and $10\,\mathrm{eV}^2$. The pattern thus is ten cycles of the shorter wavelength oscillation riding on each individual oscillation of the longer wavelength pattern. In a $3+1$ analysis of such data both masses would be apparent, indicating the need for a two sterile neutrino analysis. However, for cases where the difference between the masses of the sterile neutrinos is not so well separated and the mixing angles not so comparable, the situation would be less straightforward.

The final case would be if the masses of the sterile neutrinos were degenerate. Determining the mass-squared difference would be standard; however, an indication of the existence of multiple sterile neutrinos could only be accomplished by measuring more than one oscillation channel. In this case, unitarity arguments, such as those proposed in [16], could become fruitful.

In order to most simply develop our proposal for a new technique of searching for sterile neutrinos, we limit the discussion in what follows to the $3+1$ case. We are motivated by the observation of a phenomenon in the analysis of Ref. [13]. In Fig. 4 of Ref. [13], there is a narrow peak in the allowed region which occurs at $\Delta m^2 \cong 0.9\,\mathrm{eV}^2$. We trace this peak to the Bugey reactor experiment [15], an electron antineutrino disappearance experiment with detector baselines of 15, 40, and 95 m. We construct a model of the aforementioned neutrino experiments. This analysis [17] produces mixing angles for three neutrino oscillations that are very similar to those of Ref. [6]. In Fig. 1, we present χ^2 versus the mass-squared difference, Δm^2, for three cases.

The horizontal solid (green) line is the result of a three-neutrino analysis of the data from Refs. [1–5], LSND [8], and KARMEN [18]. The χ^2 contains the no oscillation contribution from LSND and KARMEN. By definition the three neutrino results do not depend on Δm^2 yielding a straight line. The solid (blue) curve is the result of a $3+1$ analysis. As expected, the nonzero LSND data utilizes Δm^2 and the additional mixing angles θ_{14} and θ_{24} (the results are essentially independent of θ_{34}) to lower the χ^2. For $\Delta m^2 < 0.03\,\mathrm{eV}^2$ the fourth neutrino does not contribute to the LSND or KARMEN experiment, and the χ^2 reverts to the three neutrino result as it must. The exact values of these two curves are irrelevant for the discussion at hand. We include them to provide a reasonable background for the dashed curve in which we add the Bugey experiment [15] to the previous analysis, following exactly the analysis in Ref. [15]. For $\Delta m^2 < 0.2\,\mathrm{eV}^2$, the dashed curve merges with the solid curve as Bugey does not contribute in this region. Beyond this, the dashed curve contains fluctuations. This is because the parameters are in a region that runs along the edge of the Bugey excluded region where the χ^2 is not smooth. This phenomenon is also present in Ref. [13]. These curves do *not* indicate the existence of a sterile neutrino. The addition of the CDHS [19], CCFR84 [20], and NOMAD [21] experiments were found in Ref. [13] to largely offset the LSND indication of a sterile neutrino.

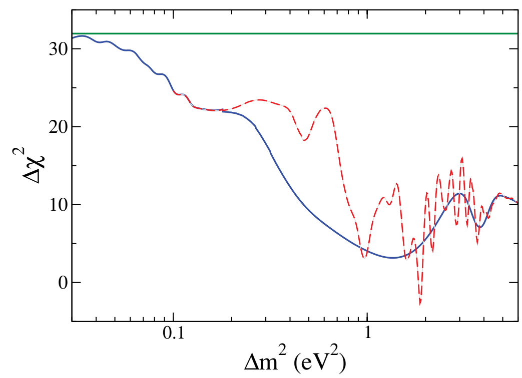

FIG. 1. (Color online) The value of $\Delta\chi^2 = \chi^2 - \chi^2_{\min}$ versus Δm^2. The solid (green) straight line is the result for a three-neutrino fit to data from Refs. [1–5,8,18]. The solid (blue) curve is the result of a four-neutrino fit to this data, and the dashed (red) curve is the result if, in addition, we add Bugey [15]. The zero for the vertical scale ($\chi^2_{\min}$) is arbitrary.

The first important feature of the dashed curve is the narrow dip near $0.9\,\mathrm{eV}^2$. This corresponds to the peak in the allowed region found in Fig. 4 of Ref. [13]. Note that we also find a second narrow dip near $1.9\,\mathrm{eV}^2$. This larger mass-squared difference is also present in Ref. [13]; however, in their analysis, the inclusion of other null result short baseline experiments [19–21] almost completely suppresses this dip's significance. Clearly the narrow dip in the χ^2 here and the narrow peak in the allowed region in Ref. [13] originates from the Bugey experiment.

To understand the source of this dip, we turn to the *in vacuo* neutrino oscillation probability for the single sterile neutrino in Eq. (1). We can use this to determine which data in the Bugey experiment yield the dips in χ^2. Figure 2 contains a plot of $\mathcal{P}_{ee}$ versus L/E from the Bugey near detector located at $L =$

15 m. The solid (red) curve is for the best fit parameters with a mass-squared difference of $\Delta m^2 = 0.9\,\mathrm{eV}^2$ and the dashed (violet) curve for $\Delta m^2 = 1.9\,\mathrm{eV}^2$. Although the statistics are poor, one can see that there is an harmonic oscillation in the data at frequencies which generate the dips in the χ^2. The dips correspond roughly to a change in χ^2 of ten. Whether these dips are real or statistical fluctuations is not the question. The point is that with improved statistics the existence of a sterile neutrino with Δm^2 in the appropriate range would produce a measurable narrow minimum in the χ^2. The Bugey experiment is an existence proof for the validity of such an experiment.

For a reactor, the neutrino spectrum and technology set the range of detectable neutrino energies to be from 1 to 5 MeV. At a baseline of 15 m, the ratio L/E ranges from 3 to 15 m/MeV. Oscillations have undergone one cycle when $\phi = \pi$. For a Δm^2 of $0.9(1.9)\,\mathrm{eV}^2$, the oscillation length is 2.7 (1.3) m/MeV which results in approximately 5 (10) cycles in the allowed range.

The amplitude of the oscillations in the Bugey data is 1.25%. The peak to trough distance is somewhat less than the average error bar, producing the low statistical significance to these dips. If the statistical error bars were one fourth this (16 times the data), an oscillation pattern of this same magnitude would be very significant. This could be achieved by running longer and/or building a larger detector and/or using a more powerful reactor.

Another consideration is the energy resolution, or the minimum size of the bin in E. In order to cleanly define the oscillation length in L/E, four data points per cycle are needed, or a resolution of 0.7 (0.33) m/MeV for $\Delta m^2 = 0.9(1.9)\,\mathrm{eV}^2$. This corresponds to an energy resolution of 10% (5%). For $\Delta m^2 = 0.9\,\mathrm{eV}^2$, this resolution is less stringent than that of the Bugey experiment by about 25%. For $\Delta m^2 = 1.9\,\mathrm{eV}^2$, the needed resolution is about double that in the Bugey experiment thus requiring a total 32 fold increase in counts.

We estimated the energy resolution requirement for an average energy neutrino. The result will approximately hold for smaller L/E as can be seen in Fig. 2. Focusing on an L/E below 5 m/MeV, one could combine two bins into one wider bin, reducing the error bars so that they become comparable

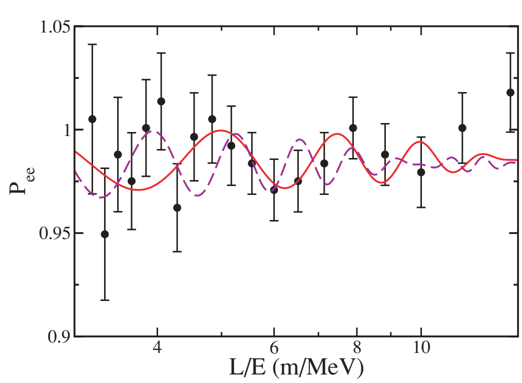

FIG. 2. (Color online) The electron survival probability $\mathcal{P}_{ee}$ versus L/E. The data are from the near detector, $L = 15$ m, of the Bugey [15] experiment. The solid (red) curve results from a sterile neutrino associated with $\Delta m^2 = 0.9\ \mathrm{eV}^2$ and the dashed (violet) curve results from $\Delta m^2 = 1.9\ \mathrm{eV}^2$.

to the other error bars, while retaining the requisite number of data points per oscillation. However, for the larger values of L/E equal spacing in E yields wider spacing in L/E, and the ideal spacing is not achieved.

There is an absolute maximum mass-squared difference that can be reached by this type of experiment. This is set by the physical size of the reactor. If one gets to a region where the length of a single oscillation is comparable to the dimensions of the reactor core, then neutrinos from the back of the reactor are incoherent with the neutrinos from the front of the reactor. For the Bugey [15] experiment, the reactor core is a cylinder of radius 2 m and height 5 m. The detector is 7 m horizontally from the center line of the core and 10 m below the base of the core. We integrated over the volume of the core, compared this to treating the core as a point source, and found for the latter that oscillation probabilities were accurate to a small fraction of a percent. If we use a scale factor for the reactor core of 3 m and an average energy of 3.5 MeV, we find the maximum achievable mass-squared difference to be roughly $3\,\mathrm{eV}^2$. An advantage of a smaller reactor is that this limit would increase. This number depends on the shape of the reactor core, the location of the detector with respect to the orientation of the cylindrical core, and the power distribution within the core. A straightforward calculation for a given experiment is necessary to get more than a crude estimate. Unfortunately, this number is smaller than the $10\,\mathrm{eV}^2$ that is the lower end of a presently allowed region found in Ref. [13]. To reach this maximum sensitivity, an energy resolution of 3% is required.

There arises a similar question concerning the size of the detector. Present experiments have both the size of the reactor core and the size of the detector to be much smaller than the baseline and the oscillation length and thus can be treated as a point. The limit on the size of the detector enters when the oscillation length becomes comparable to the dimension of the detector along the line of flight. For $\Delta m^2 = 10\,\mathrm{eV}^2$, the oscillation length is 0.9 m. To probe this region of Δm^2, either horizontally thin detectors would be required or a new technology that would include spatial resolution in addition to energy resolution would be required.

To determine the lower limit on the measurable mass-squared difference, we require that the oscillation phase reach at least $\phi = \pi/4$. The mass-squared difference would be well determined but the mixing angle would be dependent on the knowledge of the flux. This gives a lower limit of $\Delta m^2 = 0.05\,\mathrm{eV}^2$ for $L = 15$ m.

The measurement of Δm^2 is insensitive to the absolute normalization of the data; the oscillation length derived from the harmonic oscillations in the data determines Δm^2. The amplitude of these oscillations determines directly $\sin^2(2\theta_{14})$ which is also independent of the absolute flux if several oscillation cycles are measured. How this works out in the data analysis can be seen in Fig. 2. For small values of L/E, the data are coherent and thus the peak is quite near $\mathcal{P}_{ee} = 1$. The uncertainty in the norm of the data will necessarily be sufficient to allow the data to be uniformly adjusted such that the fit curve will have the peak for small L/E also quite near $\mathcal{P}_{ee} = 1$, the required physical value. A great advantage of the proposed experiment is that the normalization of the data, usually the largest systematic error in a neutrino oscillation experiment, is nearly irrelevant.

The above utilized a baseline $L = 15$ m. Doubling the flux by moving to $L = 11$ m would be attractive. We repeat the analysis for this value of L. The maximum mass-squared difference which can be probed remains around $3\,\text{eV}^2$. The minimum and maximum value of L/E shift to 2.2 and 10.3 m/MeV, respectively. The midpoint for L/E moves to 5.1 m/MeV, and the measurement would cover four (seven) cycles for $\Delta m^2 = 0.9(1.9)\,\text{eV}^2$. To reach $3\,\text{eV}^2$, a resolution of 4% in the energy would be required. By lowering the maximum value of L/E the minimum sensitivity is raised, here to $0.06\,\text{eV}^2$. Going to a smaller baseline increases the flux by L^2, but the size of the reactor, hence its power, would necessarily decrease by L^3. This produces a smaller number of cycles such that the number of energy bins decreases by an additional factor of L. The overall result is that the experiment, to lowest approximation, is independent of the size of the reactor. This is true if you are searching for the existence of a sterile neutrino. Since the accuracy of the measured mass-squared difference would be increased by observing additional cycles, the last factor of L would not apply if the goal were a fixed error on Δm^2. The larger width in the energy binning also reduces the resolution needed. For $L = 11$ m, the required resolution increases to 6 (13)% for $\Delta m^2 = 0.9(1.9)\,\text{eV}^2$. For a discovery experiment, a small research reactor with a small detector sitting very near the core is an interesting option to consider. The detector might even be wrapped around the core to increase the count rate.

The argument does require that the technology for neutrino detection scales nicely as the size of the detector. The technical issues for doing this experiment and those involved with using short baseline neutrino detectors for nonproliferation monitoring [22] are related. A new technology for neutrino detection, such as proposed in [23], opens new windows for the experiments being proposed.

We have shown that a very short baseline reactor experiment can be used to measure the mass-squared difference associated with a sterile neutrino should it lie in the range of less than a tenth of an eV^2 up to several eV^2 by measuring the oscillations in the data over a number of oscillation lengths. A Fourier transform analysis of such data would be an efficient way of extracting the oscillation frequencies; however, such methods are not fundamentally different from fitting oscillation parameters to the data as a function of the mass-squared difference Δm^2. The experiment also measures $\sin^2(2\theta_{14})$ through the amplitude of the oscillations. We suggest that a small reactor with a very short baseline be investigated. The experiment is not sensitive to the absolute normalization of the data and thus holds the possibility of being more accurate than alternatives.

The MiniBooNE experiment [24] will soon confirm or contradict the LSND experiment. The experiment proposed here could play a significant role independently of that outcome. Should MiniBooNE leave the situation ambiguous, the proposed experiment could provide a cost effective, accurate, and independent way to resolve the situation. Should MiniBooNE confirm the existence of a sterile neutrino, then this experiment might provide a more accurate measurement of the mass-squared difference and of θ_{14}. Should MiniBooNE not see evidence for a sterile neutrino, it would be setting upper limits on the mixing angles. This proposed experiment might then be a way of further looking for a sterile neutrino in this range or, should a null result be found, further reducing the allowed value of θ_{14}.

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[1] J. N. Bahcall, *Neutrino Astrophysics* (Cambridge University Press, Cambridge, 1989); Homestake Collaboration, B. T. Cleveland *et al*., Astrophys. J. **496**, 505 (1998); Kamiokande Collaboration, Y. Fukuda *et al*., Phys. Rev. Lett. **77**, 1683 (1996); SAGE Collaboration, J. N. Abdurashitov *et al*., J. Exp. Theor. Phys. **95**, 181 (2002); GALLEX Collaboration, W. Hampel *et al*., Phys. Lett. **B477**, 127 (1999); GNO Collaboration, M. Altmann *et al*., *ibid.* **B616**, 174 (2005); Super-K Collaboration, S. Fukuda *et al*., Phys. Rev. Lett. **86**, 5651 (2001); **86**, 5656 (2001); Phys. Lett. **B539**, 179 (2002); M. B. Smy *et al*., Phys. Rev. D **69**, 011104 (2004); SNO Collabortion, Q. R. Ahmad *et al*., Phys. Rev. Lett. **87**, 071301 (2001); **89**, 011301 (2002); **89**, 011302 (2002); S. N. Ahmed *et al*., *ibid.* **92**, 181301 (2004); B. Aharmim *et al*., Phys. Rev. C **72**, 055502 (2005).

[2] KamLAND Collaboration, K. Eguchi *et al*., Phys. Rev. Lett. **90**, 021802 (2003); T. Akari *et al*., *ibid.* **94**, 081801 (2005).

[3] Super-K Collaboration, Y. Fukuda *et al*., Phys. Rev. Lett. **81**, 1562 (1998); Y. Ashie *et al*., *ibid.* **93**, 101801 (2004); Phys. Rev. D **71**, 112005 (2005); J. Hosaka *et al*., *ibid.* **74**, 032002 (2006).

[4] K2K Collaboration, M. H. Ahn *et al*., Phys. Rev. Lett. **90**, 041801 (2003); E. Aliu *et al*., *ibid.* **94**, 081802 (2005); Minos Collaboration, D. G. Michael *et al*., *ibid.* **97**, 191801 (2006).

[5] CHOOZ Collaboration, M. Appolonio *et al*., Phys. Lett. **B466**, 415 (1999); Eur. Phys. J. C **27**, 331 (2003).

[6] G. L. Fogli, E. Lisi, A. Marrone, and A. Palazzo, Prog. Part. Nucl. Phys. **57**, 742 (2006); J. N. Bahcall, M. C. Gonzalez-Garcia, and C. Peña-Garay, J. High Energy Phys. 08 (2004) 016.

[7] M. C. Gonzalez-Garcia and M. Maltoni, Phys. Rev. D **70**, 033010 (2004).

[8] LSND Collaboration, C. Athanassopoulos *et al*., Phys. Rev. C **54**, 2685 (1996); Phys. Rev. Lett. **81**, 1774 (1998); Phys. Rev. C **58**, 2489 (1998); A. Aguilar *et al*., Phys. Rev. D **64**, 112007 (2001).

[9] J. T. Peltoniemi and J. W. F. Valle, Nucl. Phys. **B406**, 409 (1993); D. O. Caldwell and R. N. Mohapatra, Phys. Rev. D **48**, 3259 (1993); J. T. Peltoniemi, D. Tommasini, and J. W. F. Valle, Phys. Lett. **B298**, 383 (1993); E. J. Chun, A. S. Joshipura, and A. Y. Smirnov, *ibid.* **B357**, 608 (1995); N. Okada and O. Yasuda, Int. J. Mod. Phys. A **12**, 3669 (1997).

[10] A. de Gouvêa and Y. Grossman, Phys. Rev. D **74**, 093008 (2006); M. C. Gonzalez-Garcia, P. C. de Holanda, and R. Zukanovich Funchal, *ibid.* **73**, 033008 (2006); G. Barenboim, N. E. Mavromatos, S. Sarkar, and A. Waldron-Lauda, Nucl. Phys. **B758**, 90 (2006); S. Palomares-Ruiz, J. Phys. Conf. Ser. **39**, 307 (2006); H. Päs, S. Pakvasa, and T. J. Weiler, Phys. Rev.

D **72**, 095017 (2005); S. Palomares-Ruiz, S. Pascoli, and T. Schwetz, J. High Energy Phys. 09 (2005) 048; G. Barenboim and N. E. Mavromatos, *ibid.* 01 (2005) 034; V. A. Kostelecky and M. Mewes, Phys. Rev. D **70**, 076002 (2004); **69**, 016005 (2004); A. Friedland, C. Lunardini, and C. Peña-Garay, Phys. Lett. **B594**, 347 (2004); M. M. Guzzo, P. C. de Holanda, and O. L. G. Peres, *ibid.* **B591**, 1 (2004); V. Barger, D. Marfatia, and K. Whisnant, *ibid.* **B576**, 303 (2003); S. Davidson, C. Peña-Garay, N. Ruis, and A. Santamaria, J. High Energy Phys. 03 (2003) 011; G. Barenboim, L. Borissov, J. Lykken, and A. Y. Smirnov, *ibid.* 10 (2002) 001; A. M. Gago *et al.*, Phys. Rev. D **65**, 073012 (2002); H. Murayama and T. Yanagida, Phys. Lett. **B520**, 263 (2001); M. C. Gonzalez-Garcia *et al.*, Phys. Rev. Lett. **82**, 3202 (1999); J. W. F. Valle, Prog. Part. Nucl. Phys. **26**, 91 (1991); D. V. Ahluwalia, Mod. Phys. Lett. A **13**, 2249 (1998).

[11] M. Cirelli *et al.*, Nucl. Phys. **B708**, 215 (2005); M. Maltoni, T. Schwetz, M. A. Tórtola, and J. W. F. Valle, Phys. Rev. D **67**, 013011 (2003); New J. Phys. **6**, 122 (2004); M. C. Gonzalez-Garcia and Y. Nir, Rev. Mod. Phys. **75**, 345 (2004); H. Pas, L. Song, and T. J. Weiler, Phys. Rev. D **67**, 073019 (2003); E. D. Church, K. Eitel, G. B. Mills, and M. Steidl, *ibid.* **66**, 013001 (2002); M. Maltoni, T. Schwetz, and J. W. F. Valle, Phys. Lett. **B518**, 252 (2001); G. L. Fogli, E. Lisi, and A. Marrone, Phys. Rev. D **63**, 053008 (2001); M. C. Gonzalez-Garcia, M. Maltoni, and C. Peña-Garay, *ibid.* **64**, 093001 (2001); O. L. G. Peres and A. Y. Smirnov, Nucl. Phys. **B599**, 3 (2001); C. Giunti and M. Laveder, J. High Energy Phys. 02 (2001) 001; V. D. Barger, B. Kayser, J. Learned, T. J. Weiler, and K. Whisnant, Phys. Lett. **B489**, 345 (2000); S. M. Bilenky, C. Giunti, W. Grimus, and T. Schwetz, Phys. Rev. D **60**, 073007 (1999).

[12] M. Maltoni, T. Schwetz, M. A. Tórtola, and J. W. F. Valle, Nucl. Phys. Proc. Suppl. **114**, 203 (2003); Nucl. Phys. **B643**, 321 (2002); M. Maltoni, T. Schwetz, and J. W. F. Valle, Phys. Rev. D **65**, 093004 (2002).

[13] M. Sorel, J. M. Conrad, and M. H. Shaevitz, Phys. Rev. D **70**, 073004 (2004).

[14] K. S. Babu and G. Seidl, Phys. Lett. **B591**, 127 (2004); K. L. McDonald, B. H. J. McKellar, and A. Mastrano, Phys. Rev. D **70**, 053012 (2004); W. Krolikowski, Acta Phys. Pol. B **35**, 1675 (2004).

[15] Bugey Collaboration, B. Achkar *et al.*, Nucl. Phys. **B434**, 505 (1995).

[16] D. C. Latimer and D. J. Ernst, Mod. Phys. Lett. A **21**, 197 (2006).

[17] J. Escamilla, D. C. Latimer, and D. J. Ernst (in preparation).

[18] KARMEN Collaboration, B. Armbruster *et al.*, Phys. Rev. D **65**, 112001 (2002).

[19] CDHS Collaboration, F. Dydak *et al.*, Phys. Lett. **B134**, 281 (1984).

[20] CCFR84 Collaboration, I. E. Stockdale *et al.*, Phys. Rev. Lett. **52**, 1384 (1984).

[21] NOMAD Collaboration, P. Astier *et al.*, Phys. Lett. **B570**, 19 (2003); D. Gibin *et al.*, Nucl. Phys. B, Proc. Suppl. **66**, 366 (1998).

[22] R. W. McKeown and D. E. Reyna, physics/0610257;B. Xin *et al.* (TEXONO Collaboration), Phys. Rev. D **72**, 012006 (2005); M. M. Nieto, A. C. Hayes, C. M. Teeter, W. B. Wilson, and W. D. Stanbro, Nucl. Sci. Eng. **149**, 270 (2005); P. Huber and T. Schwetz, Phys. Rev. D **70**, 053011 (2004); A. Bernstein, Y. F. Wang, G. Gratta, and T. West, nucl-ex/0108001.

[23] P. S. Barbeau, J. I. Collar, and O. Tench, nucl-ex/0701012.

[24] I. Stancu, Nucl. Phys. Proc. Suppl. **155**, 164 (2006); M. Sorel, J. Phys. Conf. Ser. **39**, 320 (2006).