Possible Observation of Nuclear Reactor Neutrinos Near the Oscillation Absolute Minimum.

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1 Introduction

In this note we would like to investigate a possible way to observe the $\bar{\nu}_e$ oscillations near the absolute minimum of the survival probability $P(\bar{\nu}_e \to \bar{\nu}_e)$. If one uses the $\nu_e$ oscillation parameters deduced from a global analysis of the SNO solar neutrino events \cite{1} combined with the reactor antineutrino events observed with the KamLAND detector \cite{2}, then the absolute minimum of $P(\bar{\nu}_e \to \bar{\nu}_e) \simeq 0.2$ is reached for a reactor-detector distance $\simeq 70 \text{ km}$. In comparison, the average distance $\simeq 180 \text{ km}$ in the KamLAND experiment leads to a survival probability $P(\bar{\nu}_e \to \bar{\nu}_e) \simeq 0.6$.

2 Basic Neutrino Oscillation Formalism

The neutrino oscillations are described \cite{3,4} by the energy eigenstate $|\nu_k E z\rangle$ associated with neutrinos propagating along the $z$ axis and satisfying the boundary
condition: $|\nu E z = 0\rangle = |\nu E\rangle$, where $|\nu E\rangle$ is the neutrino state emitted at $z = 0$ by the charged lepton $\ell$ with $\ell = e, \mu, \tau$. The state $|\nu E z\rangle$ is then written as a superposition of the mass matrix eigenstates $|\nu_i E\rangle$ relative to the mass $m_i$:

$$|\nu E z\rangle = \sum_{i=1}^{3} |\nu_i E\rangle \exp( i p_{iz} z) U_{\ell,i}^*$$  \hspace{1cm} (1)

where $p_{iz} \simeq E - m_i^2/(2E)$ and $U$ the $3 \times 3$ mixing matrix, which is usually written as follows:

$$U = U_1 \cdot U_2 \cdot U_3$$  \hspace{1cm} (2)

$$U_3 = \begin{pmatrix}
\cos(\theta_{12}) & \sin(\theta_{12}) & 0 \\
-\sin(\theta_{12}) & \cos(\theta_{12}) & 0 \\
0 & 0 & 1
\end{pmatrix}$$  \hspace{1cm} (3)

$$U_1 = \begin{pmatrix}
1 & 0 & 0 \\
0 & \cos(\theta_{23}) & \sin(\theta_{23}) \\
0 & -\sin(\theta_{23}) & \cos(\theta_{23})
\end{pmatrix}$$  \hspace{1cm} (4)

$$U_2 = \begin{pmatrix}
\cos(\theta_{13}) & 0 & \sin(\theta_{13}) \\
0 & 1 & 0 \\
-\sin(\theta_{13}) & 0 & \cos(\theta_{13})
\end{pmatrix}$$  \hspace{1cm} (5)

(Note we have ignored, for the moment, the possibility of CP violation.) In the particular case of two neutrino oscillations, it is of interest to note the correspondence with the propagation of photons with energy $E$ in a birefringent medium where the indices associated to the linear polarizations taken along the two optical axes are given by: $n_i \simeq 1 - m_i^2/(2E^2)$ ($i = 1, 2$). The polarization eigenstates correspond to the mass matrix eigenstates $|\nu_i\rangle$. It is of convenience to introduce the oscillation length $L_{osc}$ which is defined as:

$$L_{osc}(E, \Delta m^2) = \frac{4\hbar cE}{\Delta m^2}$$  \hspace{1cm} (6)

Assuming no CP violation, the antineutrino survival probability at distance $L$ from the detector $P(\bar{\nu}_e \rightarrow \bar{\nu}_e, L) = \langle \nu E L|\nu E 0\rangle$ can be written under the form:

$$P(3\nu|\bar{\nu}_e \rightarrow \bar{\nu}_e, E, L) = 1 - 4 \left( \cos^2(\theta_{12})\cos^4(\theta_{13}) \sin^2\left(\frac{L}{L_{osc}(E, \Delta_{12})}\right) \sin^2(\theta_{12}) \right)$$

$$-4 \left( \cos^2(\theta_{12})\cos^2(\theta_{13}) \sin^2\left(\frac{L}{L_{osc}(E, \Delta_{13})}\right) \sin^2(\theta_{13}) \right)$$

$$-4 \left( \cos^2(\theta_{13}) \sin^2\left(\frac{L}{L_{osc}(E, \Delta_{23})}\right) \sin^2(\theta_{12}) \sin^2(\theta_{13}) \right)$$  \hspace{1cm} (7)
In the above expression $\Delta_{i_1 i_2}$ stands for the mass square difference $m_{i_2}^2 - m_{i_1}^2$.

Fogli et al [5] and Bahcall et al [7] have performed global analysis which combines the solar neutrino SNO [1] experimental results [1] with the reactor antineutrino events observed in the KamLAND [2] liquid scintillator detector, using essentially the survival probability given in eq. (7). We quote here the “summary” of the current $3\nu$ situation, as given by Fogli et al [5]:

$$\Delta_{12} = (7.3 \pm 0.8) \times 10^{-5} \text{eV}^2,$$

$$\sin^2(\theta_{12}) = 0.315 \pm 0.035,$$

$$\sin^2(\theta_{13}) \leq 0.017$$ (8)

The quoted errors correspond to one standard deviation. It should be said that a similar bound upon $\sin^2(\theta_{13})$ has been obtained by combining the results from the Chooz reactor experiment [8] with those from the atmospheric neutrino SK observations [9].

Fogli et al [6] have also analysed recently the atmospheric neutrinos SK $\nu_\mu \rightarrow \nu_\tau$ flavor transition in combination with the preliminary results of the K2K [10] accelerator neutrino experiment. They arrive to the following determination of the relevant oscillation parameters:

$$\Delta_{23} = (2.6 \pm 0.4) \times 10^{-3} \text{eV}^2; \quad \sin^2(\theta_{23}) = 1.00^{+0.00}_{-0.05}$$ (9)

It is easy to verify that with the above values of the oscillation parameters the survival probability $P(\bar{\nu}_e \rightarrow \bar{\nu}_e)$ can be replaced, up to corrections $\leq 3\%$, by the following two neutrino approximation:

$$P(2\nu|\bar{\nu}_e \rightarrow \bar{\nu}_e, E, L) = 1 - 4 \left( \cos^2(\theta_{12}) \sin^2\left(\frac{L}{L_{osc}(E, \Delta_{12})}\right) \sin^2(\theta_{12}) \right)$$ (10)

3 Survival Probability for Rhône Reactor Neutrinos with a Detector Located under the Mont Ventoux

We would like now to compute the probability $P_D(E, L) dE$ of an antineutrino to be observed at a distance $L$ from the nuclear reactor and having its energy in the range $E, E + dE$. The detector is assumed to be of the liquid scintillator type, as in the Chooz [8] and the KamLAND [2] experiments. $P_D(E, L)$ is given as the product of three factors. The first factor is the survival probability $P(2\nu|\bar{\nu}_e \rightarrow \bar{\nu}_e, E, L)$.

The second one is the energy spectrum $S_\nu(E)$ of the antineutrino emitted by the reactor, obtained by combining with appropriate weights the spectra associated with the various $\beta^-$ decays involved in the the fission process. The third term is the cross section $\sigma_\nu(E)$ for the inverse $\beta$ decay reaction: $\bar{\nu}_e + p \rightarrow e^+ + n$. The physical quantity
measured in the detector is the prompt energy $E_{pr}$ resulting from the annihilation of the positron with the electrons of the liquid scintillator:

$$E_{pr} = E_{e^+} + m_e c^2 = E_{\bar{\nu}_e} - (m_n - m_p)c^2 + T_n + m_e c^2$$

where $T_n$ is the kinetic energy of the recoiling neutron which can be neglected in our approximate treatment. The antineutrino energy $E_{\bar{\nu}_e}$ is then given by $E_{\bar{\nu}_e} \approx E_{pr} + 0.78\text{MeV}$. We have deduced the detection probability in the absence of oscillations: $P_D(E, 0) = P_{pr}(E - 0.78\text{MeV}) \propto S_{\nu}(E) \sigma_{\nu}(E)$, from the "expected" prompt energy spectrum $P_{pr}(E_{pr})$ given in the KamLAMD paper [2]. We have kept the same cut $E_{pr} \geq 2.26\text{MeV}$, introduced in order to eliminate the events associated with the "geoantineutrinos". In our computation, the log. of the neutrino spectrum, has been approximated by a polynomial fit: $\log(P_D(E, 0)) = -2.982 + 1.141 E - 0.1611 E^2$ with $P_D(E, 0)$ normalized to unity in the interval $3.38\text{MeV} \leq E \leq 8\text{MeV}$. The energy-average survival probability is then obtained by a simple numerical quadrature:

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e, L) = \int dE P(2\nu| \bar{\nu}_e \rightarrow \bar{\nu}_e, E, L) P_D(E, 0)$$

The curve $P(\bar{\nu}_e \rightarrow \bar{\nu}_e, L)$ versus $L$ is plotted in Figure I. The parameters $\Delta_{12} \sin^2(\theta_{13})$ used in the computation have the central values given in eq. (8) and (9).

| Distance to detector | Average Electric Power |
|----------------------|------------------------|
| Bugey                | 181 km                 | 2.66 GW               |
| Saint Alban          | 145 km                 | 1.92 GW               |
| Cruas                | 73 km                  | 2.84 GW               |
| Tricastin            | 59 km                  | 2.59 GW               |

Table 1. Nuclear power plants in operation along the Rhône River with their distance to a detector supposed to be installed in the Mont Ventoux cavity and their average electric power.

In each of two easily accessible sites, located in the Vaucluse Department, there exists an identical network of $3\text{km}$ subterranean galleries, which were bored for the French Ministry of Defense. They are no longer used for military purposes. They both contain the same cavity with concrete inner $2.1\text{m}$ thick walls. The inside volume has the form of a cylinder with a $8\text{m}$ diameter, terminated by the two hemispherical end-caps. The total length of the cavity is $28\text{m}$. The limestone $500\text{m}$ vertical depth is equivalent to $\sim 1500\text{m}$ of water. The first site, accessible from the Rustrel village, is occupied by the LSBB laboratory ( Le Laboratoire Souterrain Bas Bruit; www.lsbb.univ-avignon.fr ) The second site is located near the Reilhanette village in the Mont Ventoux foothills. It is presently unoccupied. Most of the equipments necessary to run a laboratory have been removed and the gallery entrance is closed by a concrete wall. So a non negligible initial investment would be necessary if one wishes to install a neutrino detector in this cavity.
Figure 1: The curve of this figure gives the average survival probability of an antineutrino detected at the distance $L$ from the reactor obtained in the $2\nu$ approximation, with the parameter values: $\Delta_{12} = 7.3 \times 10^{-5} \text{eV}^2$ and $\sin^2(\theta_{12}) = 0.315$. We have assumed that a detector is to be installed in a cylindrical horizontal cavity (diameter = 8 m with a total length = 28 m, including the two hemispherical end caps), located under the Mont Ventoux. The limestone vertical depth is equivalent to $\sim 1500$ m of water. The four points on the curve correspond to the four nuclear power stations, presently in operation along the Rhône river. Their average electric power, as given by the EDF company, is about 2.5 GW, close to that of the Chooz site, used in previous neutrino oscillation experiments.

In the following, we shall assume that an antineutrino detector has been built in the Mont Ventoux cavity. The distances $d_i$ ($1 \leq i \leq 4$) from the Rhône valley four power plants are given in Table 1. The big points appearing on the curve in Figure 1 correspond to the survival probabilities $P(\bar{\nu}_e \rightarrow \bar{\nu}_e, d_i)$. We see clearly that the two closest reactors (Tricastin and Cruas) will allow the study of $P(\bar{\nu}_e \rightarrow \bar{\nu}_e, L)$ near the oscillation absolute minimum, a region which has not been explored by the previous reactor experiments. It is also instructive to compute the survival probability averaged over the four nuclear power plants. We shall assume that the corresponding antineutrino flux is proportional to the average electric power $W_i$ delivered by each power plant, as given in Table 1. We get in this way:

$$\langle P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \rangle = \frac{\sum_{i=1}^{4} W_i \ d_i^{-2} P(\bar{\nu}_e \rightarrow \bar{\nu}_e, d_i)}{\sum_{i=1}^{4} W_i \ d_i^{-2}} = 0.3142 \quad (13)$$

We see that adding the contributions of the two far away power plants leads to an average distance which is still in the vicinity of the absolute minimum.
4 Counting Rate Estimate

We would like to end this note by giving a rough estimate of the number of neutrino events per day, assuming that the liquid scintillator is contained in an horizontal cylinder having a 6 m diameter terminated by two hemispheric end-caps. The total length is taken to be equal to be 22 m. The volume occupied by the liquid scintillator is then \( V_{Re} = 565 \text{ m}^3 \). It is about one hundred times larger than the corresponding volume in the Chooz experiment \( V_{Ch} = 5.55 \text{ m}^3 \). (Some experimenters will probably find that I am overoptimistic!) We use here the electric power instead of the thermal power so that the average signal given in the Chooz paper \( X_{Ch} = 7.56 \) counts per day per GW. We are going to assume the Mont Ventoux detector to have the same efficiency as the Chooz one; this implies that the counting rate is proportional to the liquid scintillator volume. For a given reactor, the antineutrino flux, \( \Phi_{\bar{\nu}_e} \) is given, up to a factor assumed to be the same for all the French nuclear reactors, by the ratio of the electric power \( W_i \) to the square of the distance \( d_i^2 \). The total flux is given by \( \Phi_{\bar{\nu}_e, Re} = \sum_i W_i d_i^{-2} = 0.0145 \text{ GW km}^{-2} \). The antineutrino flux leading to the counting rate \( X_{Ch} \) is equal to one if one uses the same units and remembers that the distance form the reactor is 1 km. The number of neutrino events per day \( X_{Re} \) in the absence of oscillations is then given by:

\[
X_{Re} = X_{Ch} \Phi_{\bar{\nu}_e, Re} (V_{Re}/V_{Ch}) = 1.17 \text{ d}^{-1}
\]

Our computation predicts (see eq. (13)) a counting rate about 3 times lower.

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