Contribution of $U_{e3}$ to geo-neutrino flux

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We show that a non-zero $U_{e3}$ close to the CHOOZ bound ($\sin^2 2\theta_{13} \approx 0.16$ 90% CL) can change the geo-neutrino flux by 12%. Geo-neutrino detection in Kamland with an exposure of $3 \times 10^{22}$ proton-years is sensitive to $\sin^2 2\theta_{13}$ to the level of 0.2(1σ). For the same exposure a detector close to Himalayas can probe $\sin^2 2\theta_{13}$ down to 0.15(1σ) due to higher geo-neutrino flux from the Tibetan plateau.

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The Kamland measurement [1] of geo-neutrinos [2] has shown the possibility of using this neutrino source to learn about the earth as well as to determine neutrino properties. The first step in using these measurements would be to determine the geochemical properties of earth - mainly the Uranium and Thorium distribution [3] using the known bounds on neutrino parameters. The Bulk Silicate Model of the earth predicts the neutrino flux at Kamioka $\Phi = (3.7\pm0.2) \times 10^8 cm^{-2} s^{-1}$ i.e an accuracy of 5%(1σ) [4,5]. A five kiloton detector over a period of five years can have enough statistics to measure the total geo-neutrino events with a statistical accuracy of 5% (at 1σ) [4]. With this accuracy in theory and experiment in mind it is worth investigating what neutrino properties can be tested using the geo-neutrinos.

In this paper we do a three flavour calculation of $\nu_e$ survival probability assuming a non-zero mixing angle $\theta_{13}$ close to the bounds from CHOOZ [7] and Palo Verde [8], $\sin^2 \theta_{13} < 0.16(0.25)$ at 90%CL(3σ) (assuming $\Delta m_{13}^2 = 2.0 \times 10^{-3} eV^2$). In a two flavour analysis where the neutrino oscillations are determined by the solar neutrino mass scale $\Delta_S = 7.3 \times 10^{-5} eV^2$, the oscillation length at the geo-neutrino energies is less than 100Km. So the oscillation probability for geo-neutrinos which are mostly from larger distances is well approximated by $P_{ee} = 1 - 0.5 \sin^2 \theta_{12} = 0.57$ (taking $\sin^2 2\theta = 0.86$). Full calculation of the two flavour oscillation probability reveals that the energy dependent term changes by less than (3%) [5,9] as $E_{vis}$ varies in the geo-neutrino spectrum range 1MeV - 2.5MeV. In three flavour oscillations (which in the geo-neutrino energy range is given by the formula (1) shown below), the oscillation length associated with the atmospheric neutrinos mass scale $\Delta_m \sim 2 \times 10^{-3} eV^2$ is larger than the diameter of the earth so the energy dependent term cannot be averaged 0.5 and a full three flavor calculation needs to be performed if $\sin^2 2\theta_{13} \neq 0$.

The three flavour oscillation formula relevant at geo-neutrino energies and length scales is

$$P_{ee}(E, L) = 1 - \sin^2 2\theta_{13} \sin^2 \left( \frac{\Delta_a L}{4E} \right) - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \left( \frac{\Delta_a L}{4E} \right)$$

where $\Delta_a = (m_2^2 - m_1^2) = 7.3 \times 10^{-5} eV^2$ is the solar mass scale, $\Delta_a = (m_2^2 - m_3^2) \approx (m_2^2 - m_1^2) = 2.5 \times 10^{-3} eV^2$ is the atmospheric mass scale, $\sin^2 2\theta_{23} = 1$ and $\sin^2 2\theta_{12} = 0.863$. We have taken the best fit values of these parameters and ignored the errors as we want to illustrate the effect of $\sin^2 2\theta_{13}$ on the survival probability and since the main source of error is the statistical error in the experiment because of small number of events. The spectrum of geo-neutrino events detected can be expressed by

$$\frac{dN}{dE} = N_p \sigma(E) \sum_X \left( \frac{d\nu_m}{dE} \right) \int_0^{2R_0} dL P_{ee}(E, L) \frac{n_X(L)}{\tau_x}$$

where $N_p$ is the number of protons in detector fiducial volume, $t$ the exposure time, $\sigma(E)$ the cross section of the reaction $\bar{\nu}_e + p \rightarrow e^+ + n$ [10]. Since the threshold of the reaction is $E_0 = m_n + m_e - m_p = 1.804 MeV$, this reaction detects neutrinos from the decay chain of $^{232}Th$ ($E_{max} = 2.25 MeV$) and $^{238}U$ ($E_{max} = 3.26 MeV$), whereas neutrinos from $^{40}K$ ($E_{max} = 1.31 MeV$) are below threshold. Kamiokande reports events as a function of the visible energy $E_{vis} = E - E_0 + 2m_e \approx E - 0.8 MeV$ which is the energy released on the annihilation of the positron by the ambient electrons. $\left( \frac{d\nu_e}{dE} \right)_X$ represents the number of neutrinos per energy interval produced by the decay of $X = Th, U$ [11]. The number density $n_X(L)$ of $U, Th$ as a function of distance $L$ from the detector has to be put in assuming some specific earth model. We have taken the distribution given for $n_X$ (l)/$\tau_X$ from Tables VIII and X of reference [5] for the Kamiokande detector. For the Himalayan detector we take the crustal values of $n_U(r)/\tau_U$ from Figure 1 of reference [5]. The $n/\tau$ values for Thorium is determined by taking the same ratio for $(n/\tau)_{th}/(n/\tau)_U$ as the crustal distribution for Kamioka.

The results for geo-neutrino events spectrum at Kamioka are shown in Figure 1 for different values of $\sin^2 2\theta_{13}$. The geo-neutrino events spectrum for a possible detector [12] at the Himalayas is shown in Figure 2. We find that when we change $\sin^2 2\theta_{13}$ from 0 to 0.2 the oscillation probability averaged over the energy spectrum of geo-neutrinos, $\langle P_{ee} \rangle$, decreases by 12%. To achieve a 12% experimental accuracy in the statistics a total of about 100 events are needed. This can be achieved in Kamiokande with an exposure of $3 \times 10^{22}$ proton-years. In the Himalayas the geo-neutrino flux is higher since the
Tibetan plateau is twice the thickness of the average continental crust (30 km). As a result the geoneutrino flux at the Himalayas is larger by a factor of 1.8 compared to the flux at Kamioka. The same exposure at Himalayas will result in 187 events and a statistical uncertainty of 7.3% which means that $\sin^22\theta_{13}$ at the Himalayas can be probed down to 0.15 for an exposure of $3 \times 10^{32}$ proton-years.

If a geoneutrino detector can have an exposure of $16 \times 10^{32}$ proton years (5 kiloton detector run for 4 years) then the statistical error is down to 5% and if the uncertainties in the BSE model [4] can also be brought down to 5% then there exists the possibility that one can probe $\sin^2\theta_{13}$ down to 0.06 which close to what can be achieved with proposed reactor neutrino experiments [6] (assuming that uncertainty in other neutrino parameters -mainly $\sin^2\theta_{12}$ can be brought to below 5% level as well from other experiments).

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FIG. 1: Geoneutrino event spectrum and total number of events $N$ at Kamioka for different values of $\sin^2 2\theta_{13}$. 
FIG. 2: Geoneutrino event spectrum and total number of events $N$ for a detector [12] close to Himalayas for different values of $\sin^2 2\theta_{13}$. The event spectrum at Kamioka is also shown for comparison.