SEARCHES FOR STERILE NEUTRINOS AT REACTOR

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We show that in a reactor disappearance oscillation experiment the sensitivity to the mixing parameter can be substantially improved for $(1 - 5 \cdot 10^{-4})$ eV$^2$ mass parameter range which includes both the LSND and the atmospheric neutrino oscillation regions. The objectives are: to search for the sterile neutrinos and to get a better understanding of the atmospheric neutrino oscillation mechanism. The parameters of the underground (600 m.w.e.) Krasnoyarsk reactor and data from the CHOOZ reactor oscillation experiment are used to estimate the effect and background rates.

1 Introduction

It is now 40 years since neutrino oscillations and sterile neutrinos were first considered [1]. Recent study of atmospheric neutrinos [2] and analysis of solar neutrino observations [3] have provided evidence that neutrinos really oscillate and therefore are mixed and possess non zero masses. The relevant mass parameter $\delta m^2$ ranges have been localized to $\delta m^2_{atm} = (5 \cdot 10^{-4} - 6 \cdot 10^{-3})$ eV$^2$, $\delta m^2_{sol} < 5 \cdot 10^{-6}$ eV$^2$ The available solar and atmospheric data do not restrict however the number of neutrino species involved. The sterile neutrinos can play a considerable and even a dominant part in the processes of mutual transformations responsible for the observed phenomena.

If the sterile neutrinos were found to exist in nature it would have a major impact on physics. We recall here the concept that all particles are duplicated to form a parallel mirror world suggested years ago to restore the fundamental symmetries lost as the result of P and CP violation [4,5].
The $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ events at $\delta m^2 > 0.1 \, eV^2$ reported by LSND collaboration [6] give evidence in favor of sterile neutrinos. This has stimulated a great number of new studies on the theory and phenomenology of sterile neutrinos (see publications [7,8,9] and references therein).

Here we consider a reactor disappearance oscillation experiment and show that the sensitivity to the mixing parameter can be greatly improved for $(1 - 5 \cdot 10^{-4}) \, eV^2$ mass parameter range which includes both the LSND events [6] and atmospheric neutrino oscillation regions. The main objectives we pursue are:
- to search for the sterile neutrinos and
- to get a better understanding of the atmospheric neutrino oscillations.

We plan to use relatively small neutrino detectors: the neutrino target (liquid scintillator) will not exceed by mass a few percent of the targets used in the most part of the running or projected scintillation neutrino detectors.

The parameters of the underground (600 m.w.e.) Krasnoyarsk reactor and data from the CHOOZ reactor oscillation experiment are used to estimate the effect and background rates.

2 SIGNATURE FOR STERILE NEUTRINOS

The electron neutrino flavor state $\nu_e$ is connected with the mass eigenstates $\nu_i$ by the relation

$$\nu_e = \sum_i U_{ei} \nu_i$$

The survival probability $P(\nu_e \rightarrow \nu_e)$ of $\nu_e$ at the distance R (in m) from the source is given by the expression

$$P(\nu_e \rightarrow \nu_e) = 1 - 4 \sum U_{ej}^2 U_{ei}^2 \sin^2(1.27 \delta m^2_{ji} R/E), \ (j > i),$$

where E is the neutrino energy in MeV and $\delta m^2_{ji} = m_j^2 - m_i^2$ are the mass parameters in $eV^2$ ($m_j > m_i$ for $j > i$).

In the three active neutrino mixing scheme $\nu_\alpha$, ($\alpha = e, \mu, \tau$) there are three mass states $\nu_i$, ($i = 1, 2, 3$) and three mass parameters

$\delta m^2_{21} = m_2^2 - m_1^2$, $\delta m^2_{31} = m_3^2 - m_1^2$ and $\delta m^2_{32} = m_3^2 - m_2^2$, of which two are independent ($\delta m^2_{32} = \delta m^2_{31} - \delta m^2_{21}$).
All potential vacancies available in 3 neutrino mixing scheme are however already occupied by the solar and atmospheric candidates: 
\[(\delta m_{sol}^2 < 5 \cdot 10^{-6} \text{ eV}^2, \delta m_{atm}^2 = 5 \cdot 10^{-4} - 6 \cdot 10^{-3} \text{ eV}^2)\text{ and } \delta m_{sol}^2 - \delta m_{atm}^2 \approx \delta m_{atm}^2.\]

We can therefore conclude that if in the reactor oscillation experiment a disappearance effect is found at \(\delta m^2 < \delta m_{atm}^2\) it would mean that at least four mass states and one sterile neutrino must exist in nature. In the three active and three sterile neutrino oscillation scenario there are six mass states and 15 mass parameters. This increases chances to find some of the relevant transitions in the \(\delta m^2\) range we suggest to inspect.

3 EXPERIMENT

3.1 We consider two identical liquid scintillation spectrometers, stationed at the distances \(R_1\) and \(R_2\) from the reactor antineutrino source. The positron energy spectra \(S(E_e)\) are measured simultaneously via the inverse beta decay reaction

\[\bar{\nu}_e + p \rightarrow e^+ + n \text{ with } E_e = E - 1.80 \text{ MeV}.\]

The usual delayed coincidence technic between the prompt \(e^+\) signal (boosted by the annihilation gamma rays) and the signal from the neutron capture 2.2 MeV gamma (no Gd is added to the scintillator).

Small deviations of the ratio \(S_1/S_2\)

\[S_1/S_2 = C \cdot (1 - \sin^2 2\theta \sin^2 \phi_1) \cdot (1 - \sin^2 2\theta \sin^2 \phi_2)^{-1}, \quad (3)\]

from a constant value are searched for the oscillation effects \((\phi_{1,2}\) stands for \(1.27 \delta m^2 R_{1,2}/E)\).

No knowledge of the constant \(C\) in Eq. (3) is needed for this analysis so that the details of the geometry, ratio of the target masses etc are excluded from the consideration.

3.2 A simplified version of the BOREXINO detector composition [10] is chosen for the design of the spectrometers (Fig.1). The target in the center of the detector (mineral oil + PPO) is viewed by the PMT’s (\(\sim 15%\) coverage, 150 photoelectrons/MeV) through sufficiently thick layer of the oil.
The expected positron energy spectrum is shown in the Fid.2 by the solid line. 

The search for oscillations in the mass parameter range as wide as \((1 - 5 \cdot 10^{-4}) \text{ eV}^2\) can be performed in two steps. First, the measurements are done at the distances of 20 m - 100m with small detectors, then larger detectors are used to cover the 100 m - 1 km region. The projected target masses and expected neutrino detection rates can be seen in the Table 1.

Table 1: Expected reactor \(\bar{\nu}_e\) detection rates \(N(e^+, n)/\text{day}\) in this experiment and in the BOREXINO [11] and KamLAND [12] projects

| Detector- reactor dist. | THIS EXPERIMENT | BOREXINO | KamLAND |
|-------------------------|-----------------|----------|---------|
| Target mass             | 3.4 t           | 50t      |         |
|                         | 20 m 100 m      | 100 m 300 m 1 km | 800 km 160 km |
| \(N(e^+, n)/\text{day}\) | 10 000 400     | 7 000 750 70 | 0.08 2 |

The rates are found with the computed \(\bar{\nu}_e\) detection efficiencies \(\epsilon = 70\%\) for the smaller detector and \(\epsilon = 85\%\) for the bigger one.

3.3 We consider two components of the background.
- The natural radioactivity of the external and internal materials such as the walls of the room, the PMT’s, the mineral oil etc.
- All sort of effects produced by cosmic muons.

The neutrino detection rate expected for the 1 km position (see Tab.1) when scaled to the same target mass is \(\sim\) three orders of magnitude higher than in the KamLAND and the BOREXINO projects. So we hope that no extraordinary efforts are needed to keep the background due to the radioactivity at a sufficiently low level.

To estimate the muon induced component we use the absolute value of the background measured in the CHOOZ experiment [13]: \(\sim\) 1 per day per 5 ton target at the depth of 300 mwe /CHOOZ/.

At Krasnoyarsk with the depth of 600 mwe the \(\sim\) 5 times lower level of the background is expected, which indicates that in the 1 km position the effect to background ratio not worse than 20 : 1 can be hoped for.

3.4 Calibrations of the detector are of crucial importance. The
difference between the energy scales of the two detectors which is difficult to avoid can give additional modulation to the ratio of the spectra (3) and thus imitate the oscillation effect.

The difference can be measured and relevant corrections found by systematic intercomparison of the scales in many energy points using the sources of γ-rays listed in the Table 2.

Table 2: Sources of γ-rays for calibrations

| Source | $^{137}$Cs | $^{65}$Zn | $^{22}$Na | (n,γ) | $^{60}$Co | $^{24}$Na |
|--------|--------|--------|--------|--------|--------|--------|
| Energy, MeV | 0.662 | 1.115 | 1.022 | 2.23 | 2.505 | 4.122 |

In addition an overall tests can be done with the use of the $^{252}$Cf spontaneous fission source which can produce in the detector a broad spectrum due to prompt γ- rays and neutron recoils (see the broken line in the Fig.2).

4 EXPECTED RESULTS

4.1 Expected 90% CL exclusion contour is shown in Fig.3. It can be seen that in the (0.7 - 0.007) eV$^2$ mass range the sensitivity to the mixing angle better than 0.01 can be reached. For $\delta m^2 > 1$ eV$^2$ the sensitivity is decreasing because of the finite size of the $\tilde{\nu}_e$ source while the small $\delta m^2$ region is influenced by poor statistics at the 1 km position.

4.2 It is highly desirable to get more information on the $\delta m^2_{\text{atm}}$ region. According to the 1998 y. SUPERKAMIOKANDE publication [2] the allowed mass parameters for atmospheric oscillations have shifted towards smaller $\delta m^2$ values relative to the KAMIOKANDE data. The results from CHOOZ leave now a considerable freedom for the $\nu_e \rightarrow \nu_e$ atmospheric neutrino oscillations (see Fig.3)...

Eqs.(1,2) show that the $\tilde{\nu}_e$ disappearance probabilities depend only on its mass content. So some information on the issue can be expected from the data.
In three neutrino oscillation model at $\sim 1$ km from the reactor $\bar{\nu}_e$ can oscillate only if the mass state $\nu_3$ contributes to the electron neutrino flavor state: using Eq.(2) we obtain by direct calculation:

$$\sin^2 2\theta = 4U_{e3}^2(1 - U_{e3}^2) \approx 4U_{e3}^2$$ (4)

For $\delta m^2 = 0.002$ eV$^2$ (taken as the most probable value) the $\nu_3$ contribution as small as $U_{e3}^2 > 5 \cdot 10^{-3}$ can be observed in the experiment under consideration.

In six neutrino oscillation model $\sin^2 2\theta$ will depend on mass spectrum in a more specific manner. Here are two examples. Suppose that holds the mass hierarchy

$$m_6^2 \gg m_5^2 \gg m_4^2... \gg m_1^2.$$ (5)

In this case the 15 mass parameters are clustered in 5 tight groups:

$$\delta m_i^2 \approx m_i^2 \quad (i = 2, 3...6)$$ (5')

If we now assume for a moment that there exist no mass parameter greater then $\delta m_{atm}^2 \approx m_6^2$ then instead of Eq.(4) we find:

$$\sin^2 2\theta = 4U_{e6}^2(1 - U_{e6}^2)$$ (6)

If however we consider $\delta m_{LSND}^2 \approx m_6^2$ as the maximal mass parameter and use $\delta m_{atm}^2 \approx m_5^2$ then the reactor neutrino survival probability can be expressed as:

$$P(\nu_e \rightarrow \nu_e) = 1 - 4U_{e6}^2(1 - U_{e6}^2)\sin^2(1.27\delta m_{LSND}^2 R/E) - 4U_{e5}^2(1 - U_{e5} - U_{e6}^2)\sin^2(1.27\delta m_{atm}^2 R/E)$$ (7)

Some other representations can be found in Refs.[9, 15].

Note also that in the case of six neutrinos some of the mass parameters get in the solar neutrino region $\delta m_{sol}^2 < 6 \cdot 10^{-6}$ eV$^2$ which can probably influence some results of the analysis given in Ref.[3].

5 CONCLUSIONS

We have shown that with reactor neutrinos the sensitivity to the neutrino mixing can considerably be improved for $(1 - 5 \cdot 10^{-4})$ eV$^2$
mass parameter range. This gives opportunities for systematic searches
for the sterile neutrinos and opens promising perspectives for a better
understanding of the atmospheric neutrino oscillations.

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Figure 1. Sketch of the detector.
1 - The neutrino target (mineral oil+PPO), 2 - mineral oil, 3 - the transparent film, 4 - photomultipliers.
Figure 2. Expected positron energy spectrum (the solid line).
The arrows show energies of $\gamma$ rays used for calibrations (see Tab.2).
The broken line shows the spectrum due to Cf-252 spontaneous fission prompt $\gamma$s and neutrons.
Figure 3. Expected 90% CL exclusion plot.
Also are shown: constraints from previous experiments at Bugey [14] and CHOOZ [13] reactors and allowed oscillation parameters regions for LSND [6] and Super Kamiokande [2] experiments.