Light Sterile Neutrino Search Experiments with Reactor Neutrinos

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In the Standard Model of particle physics, three active neutrinos participate in the electroweak interaction. The active neutrino mixing framework has made a successful explanation of neutrino oscillation. Despite this great progress, there is still possibility of existence of sterile neutrinos, which do not participate in the standard model interactions. At the reactor experiment, anomalous phenomena have been observed. These phenomena may be hints of the existence of eV scale sterile neutrinos.

**NEUTRINO IN THE STANDARD MODEL**

In the standard model of particle physics, a neutrino is a massless fermion. Pauli hypothesized this particle to explain how beta decay conserves energy, momentum, and angular momentum. A neutrino is neutral, and only interacting with weak force among three fundamental forces; electromagnetic force, strong force, and weak force. Unlike other fermions which are quarks and charged leptons, at present, only left-handed neutrinos and right-handed anti-neutrino are found. Neutrinos have three flavors corresponding to electron, muon, and tau which are $\nu_e$, $\nu_\mu$, $\nu_\tau$. The number of neutrinos which participate weak interaction has been determined with high precision to be close to three by LEP Experiments.

**NEUTRINO OSCILLATION**

Neutrino oscillation is a phenomenon in which a neutrino was created with a specific lepton flavor (electron, muon, or tau) and later measured to have a different flavor. The existence of neutrino oscillation was observed by many experiments in the last decades. Neutrino oscillation is explained by the unitary mixing matrix, PMNS matrix. This matrix correlates between the mass eigenstates of the neutrino and the weak eigenstates as described by

$$
\begin{bmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{bmatrix} =
\begin{bmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\
U_{\tau 1} & U_{\tau 2} & U_{\tau 3}
\end{bmatrix}
\begin{bmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{bmatrix},
$$

where $\nu_\alpha$ ($\alpha = e, \mu, \tau$) are the weak eigenstates, $\nu_i$ ($i = 1, 2, 3$) are the mass eigenstates, and $U_{\alpha i}$ is the element of the PMNS matrix.

In $3 \times 3$ unitary matrix, there are nine degrees of freedom. However, the PMNS matrix can be described by four free parameters because five parameters can be absorbed as phases of the lepton fields. The PMNS matrix is generally parameterized by three mixing angles ($\theta_{12}$, $\theta_{23}$, and $\theta_{13}$) and a single phase ($\delta$). The matrix can be written as

$$
U_{PMNS} = R_{23}(\theta_{23})R_{13}(\theta_{13}, \delta_{CP})R_{12}(\theta_{12})
$$

$$
= \begin{bmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{bmatrix}
\begin{bmatrix}
c_{13} & 0 & s_{13}e^{-i\delta} \\
0 & 1 & 0 \\
-s_{13}e^{i\delta} & 0 & c_{13}
\end{bmatrix}
\begin{bmatrix}
c_{12} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{bmatrix},
$$

where $s_{ij}$ are sin $\theta_{ij}$, and $c_{ij}$ are cos $\theta_{ij}$. The mixing angles have been measured by many experiments using atmospheric, solar, reactor, and long-accelerator neutrino.

The single phase $\delta$ has not been measured directly. The survival probability can be calculated using the relation between mass and weak eigenstates of neutrinos, $|\nu_k\rangle = \sum_\alpha U_{\alpha k}|\nu_\alpha\rangle$, $|\nu_\alpha\rangle = \sum_k U^*_{\alpha k}|\nu_k\rangle$, where $|\nu_k\rangle$ are massive orthonormal eigenstates, and $|\nu_\alpha\rangle$ are weak orthonormal eigenstate. The massive neutrino state evolve in time as phase waves:

$$
|\nu_k(t)\rangle = e^{-iE_k t} |\nu_k\rangle.
$$

The evolution of the weak eigenstate are as follows:

$$
|\nu_\alpha(t)\rangle = \sum_k U^*_{\alpha k} e^{-iE_k t} |\nu_k\rangle.
$$

In the neutrino mixing framework, the survival probability of $\nu_\alpha \rightarrow \nu_\beta$ can be written as

$$
P_{\nu_\alpha \rightarrow \nu_\beta}(t) = |\langle \nu_\beta | \nu_\alpha(t) \rangle|^2 = \sum_{k,i,j} U^*_{\alpha k}U_{\beta k}U_{\alpha j}U^*_{\beta j}e^{-i(E_k - E_j)t}.
$$

Energy difference can be approximated by $E_k - E_j \approx \Delta m^2_{kj}/E$ where $E$ (eV) is the energy of neutrino, and $\Delta m^2_{kj}$ (eV$^2$) is the mass-squared difference between neutrino flavor $k$ and $j$. Neutrino mass is very small, so neutrino propagates with speed of light. We can set $t = L$.
where, $L (eV^{-1})$ is the baseline of the neutrino traveled [9]. Therefore, survival probability of neutrino oscillation can be approximated by

$$P_{\nu_e \rightarrow \bar{\nu}_e} (L, E) = \frac{1}{2} \sum_{k,j} U_{\alpha k}^* U_{\beta j} U_{\nu e k}^* U_{\nu e j} \exp \left(-i \frac{\Delta m_{kj}^2 L}{2E} \right).$$

This formula generally used in neutrino oscillation experiments.

### NEUTRINO MASS AND STERILE NEUTRINO

The discovery of neutrino oscillation revealed the difference of mass and weak eigenstate of neutrino. This means that the neutrino has mass. There are two types of fermion mass, which are Dirac, and Majorana. If the neutrino is a Dirac fermion, the neutrino will have exactly the same structure as charged leptons and quarks. Then, there must be right-handed neutrino (left-handed anti-neutrino) corresponding each left-handed neutrino (right-handed anti-neutrino). The terms of the Dirac neutrino are represented by Lagrangian as follows :

$$L^D_{mass} = -m_D \bar{\nu}_R \nu_L + h.c.,$$

where $m_D$ is Dirac mass and $\nu_i (i = R, L)$ is the chiral state of neutrino.

By the way, Majorana discovered the condition of Majorana fermion which implies the equality of particle and anti-particle. The Majorana condition is described by

$$\psi_L = \psi_R^C = C \psi_R^T, \quad \text{or} \quad \psi = \psi_R + \psi_R^C = \psi^C,$$

where $\psi$ is the Majorana spinor. If particle is not neutral, particle and anti-particle have opposite charge. Therefore, a charged particle cannot be a Majorana fermion. On the other hand, neutrino is a neutral fermion, there is a possibility that the neutrino and the anti-neutrino are same. This mean that neutrino can be Majorana fermion. Then the left-handed neutrino mass Lagrangina can be written as follows

$$L^L_{mass} = \frac{1}{2} m_L \nu_L^T C^\dagger \nu_L + h.c.,$$

and right-handed neutrino are not needed to explain neutrino mass. However, the right-handed neutrino are well-motivated. The Lagrangian of the right-handed neutrino with Majorana mass can be written as follows

$$L^R_{mass} = \frac{1}{2} m_R \nu_R^T C^\dagger \nu_R + h.c..$$

Left-handed neutrinos are also called active neutrinos because they are interacting weakly. The search of right-handed neutrino is strongly motivated because only left-handed neutrinos were found and mass of neutrinos exists. The right-handed neutrino do not interact with electromagnetic, weak, and strong forces without gravity. Due to noninteracting characteristic, it is referred the sterile neutrino. Therefore, it is important to find the right-handed neutrino corresponding to the left-handed neutrino each three flavors.

The sterile neutrino does not interact with any particles in the Standard Model, so it can only be measured by the neutrino oscillation. While recent neutrino oscillation results are understood in the framework of 3 active neutrino mixing, there is not completely exclude admixture of sterile neutrinos. The sterile neutrino has not been discovered yet, but several phenomena have recently been discovered [10].

### 3+1 NEUTRINO OSCILLATION MODEL

The theoretical motivation is to predict the right sterile neutrino of 3 flavors, but if the number of unknown variables increases, the experiment becomes impossible. Thus, a sterile neutrino of low mass, which is called light sterile neutrino, was proposed, consequently a model was created under the assumption that there is a sterile neutrino. If one sterile neutrino is added to the three-neutrino mixing framework, three-neutrino mixing model is changed so-called 3(active) + 1(sterile) neutrino mixing model [11]. If there is one sterile neutrino $\nu_s$, then we can extend the PMNS matrix to a $4 \times 4$ matrix described by

$$[\nu_e \quad \nu_\mu \quad \nu_\tau \quad \nu_s] = [U_{e3} \ U_{e2} \ U_{e1} \ U_{e4} \ U_{\mu3} \ U_{\mu2} \ U_{\mu1} \ U_{\mu4} \ U_{\tau3} \ U_{\tau2} \ U_{\tau1} \ U_{\tau4} \ U_{s1} \ U_{s2} \ U_{s3} \ U_{s4}] [\nu_1 \ \nu_2 \ \nu_3 \ \nu_4].$$

This matrix can be pramatrized by

$$\tilde{U}_F = R_{34} (\theta_{34}) R_{24} (\theta_{24}, \delta_2) R_{14} (\theta_{14}) \times R_{23} (\theta_{23}) R_{13} (\theta_{13}, \delta_1) R_{12} (\theta_{12}, \delta_3),$$

where three mixing angles $(\theta_{14}, \theta_{24}$ and, $\theta_{34})$ and two phase $(\delta_2, \delta_3)$ are added. From this model, the survival probability of $\bar{\nu}_e \rightarrow \bar{\nu}_e$ can be expressed as

$$P_{\bar{\nu}_e \rightarrow \bar{\nu}_e} = 1 - 4 \sum_{i=1}^{3} \sum_{\substack{j=i+1 \quad j \leq 4}} U_{ei}^2 |U_{ej}|^2 \sin^2(1.27 \frac{\Delta m_{ji}^2 L}{E}).$$

It is evident from this equation that a sterile neutrino would have modification in the measured neutrino flux if the associated mixing parameter $\sin^2 2\theta_{14}$ is not too small and the mass difference is the relevant range. This survival probability can be used to search the sterile neutrino at the reactor antineutrino experiments.
**REACTOR ANTINEUTRINO EXPERIMENT**

\( \bar{\nu}_e \rightarrow \bar{\nu}_e \) disappearance

A reactor can be a source of neutrinos, so it is generally used in neutrino experiments. The reactors are obtained energy mainly through the beta decay of each isotope \( ^{235}U, ^{238}U, ^{239}Pu, \) and \( ^{241}Pu \). In the reactor, electron antineutrino comes out through \( \beta^- \) decay:

\[
n \rightarrow p + e^- + \bar{\nu}_e
\]  

(16)

If about 200 MeV of energy is produced in one fission, \( 2 \times 10^{20} \) \( s^{-1} \) neutrino is generated per GWth. The number of neutrons from the reactor is proportional to the thermal power and can be measured by the power plant operator with an accuracy of 1%. Also, the ratio of each isotope in the reactor can be measured with high accuracy [12]. Flux of reactor neutrino propagates isotropic. Depending on the distance, the neutrino flux is reduced proportional to \( 1/R^2 \).

The reactor neutrino has energy about MeV, so it has a relatively short oscillation length. Reactors do not have enough energy and cannot generate \( \nu_e \) and \( \nu_{\mu} \). Thus, the disappearance of the neutrino electron can be measured immediately. Also, the reactor shut down every 12 ~ 24 months, so it is good to measure the background.

The reactor neutrino is usually measured through Inverse Beta Decay (IBD):

\[
\bar{\nu}_e + p \rightarrow e^+ + n
\]  

(17)

When IBD occurs, the positron and neutron come out. This two coincidence particle can confirm the occurrence of IBD. Neutrinos can be distinguished from coincidence of prompt signal and delayed signal measured with a scintillation detector. This is also the way Reines and Cowan first discovered neutrino. The cross section of this reaction is as follows

\[
\sigma_{e^+} = \frac{2\pi^2 \hbar^3}{m_e^2 f \tau_n} p_{e^+} E_{e^+},
\]  

(18)

where \( p_{e^+}, E_{e^+} \), and \( m_e \) are the momentum, energy, and mass of the positron, respectively, \( \tau_n \) is the lifetime of a neutron, \( \pi \) is the circular constant, \( \hbar \) is the Dirac’s constant, and \( f = 1.7152 \) is the free neutrino decay phase space factor. In addition, since IBD generates positron with high mass, it has threshold energy and its value is as follows

\[
E_{th}^\nu = \frac{(m_n + m_e)^2 - m_n^2}{2m_p^2} \simeq 1.806 \text{ MeV}
\]  

(19)

This means that neutrino can be detected only 25% of total generated neutrinos from the reactor. Also, If IBD reactions are used to measure the neutrinos, low energy neutrino cannot be measured.

Because neutrino does not interact very much, a very large detector is needed. Therefore, it is not easy to move the position of the detector. As a result, many experiments were conducted on each baseline of reactor and detector. The expected number of reactor anti-neutrinos observed in the detector is calculated by following form

\[
N_\nu = \frac{1}{4\pi R^2} \times N_p \sum_i \alpha_i(t) \bar{\sigma}_i \times \frac{P_{th}(t)}{\sum_i \alpha_i(t) E_i},
\]  

(20)

where, \( N_p \) is the number of target protons in the detector, \( R \) is the distance between the detector and reactor, \( \alpha_i \) is the fission fraction of the isotope \( i \), \( E_i \) is the averaged released energy per fission, and \( P_{th} \) is reactor thermal power [13].

**REACTOR ANTINEUTRINO ANOMALY**

Many reactor neutrino experiments measuring neutrino oscillations have given successful observation of three neutrino mixing framework. Despite of the great success of the three neutrino mixing framework, anomalous phenomena have been observed. Many reactor neutrino experiments have found that the ratio between measured and expected \( \bar{\nu}_e \) flux from reactor is \( R = 0.934 \pm 0.024 \) less than 1. Fig. 1 shows the ratio of measured and expected number of neutrinos at different distances. These phenomena are called the reactor antineutrino anomaly [14, 15]. On the basis of the 3 + 1 neutrino mixing model, many experiments want to find the existence of the sterile neutrino which mass range is about 1 eV scale, light sterile neutrino [16].

**STERILE NEUTRINO EXPERIMENT**

**NEOS Experiment overview**

The NEOS experiment is one kind of reactor experiments for searching light sterile neutrinos. The NEOS detector was installed in the tendon gallery of reactor at

![FIG. 1. The ratio of the measured and expected neutrino flux in reactor experiments at different distance L. The red band shows the average value and uncertainty.](image-url)
FIG. 2. Four experiments reject best-fit of reactor anti-neutrino anomaly. Except NEOS and DANNS, there are two additional results from similar reactor neutrino experiments, which are STEREO and Prospect. This experiment cannot find significant evidence of light sterile neutrinos.

Korea. The detector is located at 23.7 ± 0.3 m from the center of the reactor core. The NEOS detector consists of a neutrino target, mineral oil buffers, passive shieldings, muon counters, and supporting structures. The positron annihilation followed by a neutron capture from an electron antineutrino IBD process is detected in the target, which is a horizontal cylindrical stainless-steel tank filled with a 0.5% Gd-doped liquid scintillator. Each end of the target vessel is viewed photomultiplier tubes (PMTs) [17].

DANSS Experiment overview

The other sterile neutrino search experiment is DANSS experiment. The DANSS detector use solid scintillator without liquids scintillator. The detector is located very close to the core of a 3.1 GWth industrial power reactor. Since this detector can move, the baseline from the center of the reactor and detector can be varied from 10.7 to 12.7 m. DANSS is a highly segmented plastic scintillator detector with a total volume of 1 m$^3$, surrounded with a composite shielding system. The basic element of detector is a polystyrene-based extruded scintillator strip with a thin Gd-containing surface coating. The coating serves as a light reflector and a (n, γ)-converter simultaneously [18].

NEOS and DANSS global analysis

These two experiments excluded the best-fit of reactor anti-neutrino anomaly $(\Delta m^2_{41}, \sin^2 2\theta_{14}) =$ (2.3 eV$^2$, 0.14). Fig. 2 shows the excluded region of these experiments. However, NEOS and DANSS found small energy modulation. The best fit of NEOS is located at $(\Delta m^2_{41}, \sin^2 2\theta_{14}) = (1.3 \text{ eV}^2, 0.04)$ at a significance of 2.9σ. The best fit of DANSS is located at $(\Delta m^2_{41}, \sin^2 2\theta_{14}) = (1.4 \text{ eV}^2, 0.05)$ at significance of 2.8σ. These means the DANSS+NEONS combine results shows a about 3.3σ preference for sterile neutrino oscillation with $\Delta m^2_{41} = 1.3 \text{ eV}^2$.

Neutrino-4 Experiment results

Neutrino-4 reactor neutrino oscillation experiment measured the flux and spectrum 6 ~ 12 m from a reactor core. Sterile neutrino solution of reactor anomaly is excluded at 99.7% C.L. But an oscillation effect with $(\Delta m^2_{41}, \sin^2 2\theta_{14}) = (7.0 \text{ eV}^2, 0.35)$ is observed, also with 99.7% C.L. Fig. 3 shows the allowed region of parameter space $(\Delta m^2_{41}, \sin^2 2\theta_{14})$. This results must be discussed with future experiments [19].

CONCLUSION

Sterile neutrinos if discovered, the standard model of particle physics needs to be modified. The sterile neutrinos have significant implication to the evolution of the early universe, and they could also be a part of the dark matter component [20–22]. Furthermore, the smallness of neutrino mass can be determined by the seesaw mechanism, if super heavy sterile neutrinos exist [9].


