NEOS Experiment

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Abstract. The NEOS detector take data from August 2015 to May 2016. The energy resolution of the detector is about 5\% at 1 MeV and the ratio of signal to background is about 23. PSD is used to reduce backgrounds and it reduces more than 70\% of backgrounds. The prompt energy spectrum was compared to the two models and the 5 MeV excess is first confirmed at short baseline. There is no strong evidence of light sterile neutrino with 3+1 hypothesis and region of low mass squared difference $\Delta m^2_{41}$ in allowed region of Reactor Anti-neutrino Anomaly\cite{1} is disfavored.

1. Introduction

There are some anomalies about neutrino such as LSND\cite{2}, MiniBooNE\cite{3}, Gallium (GALLEX and SAGE)\cite{4,5,6,7}, and Reactor Anti-neutrino Anomaly (RAA)\cite{1}. LSND and MiniBooNE are the neutrino-appearance experiments with accelerator and they report the excess of neutrino apperance. GALLEX and SAGE are Gallium radioactive source experiments and their results show the deficit of survived neutrinos (same to the excess of neutrino disappearance). There are updates of electron anti-neutrino flux from reactor, so predicted number of neutrinos increases. The ratio of measured to predicted number is 0.943 ± 0.022 with past short baseline reactor experiments\cite{1}.

These anomalies can be explained with 3+1 framework. There are three active neutrinos and a sterile neutrino in 3+1 framework and the excess or deficit can be explained with oscillating to sterile neutrino. There are some allowed and excluded regions with 3+1 framework such as LSND\cite{2}, Ice Cube\cite{8}, and Daya Bay/Bugey-3 + MINOS\cite{9}. NEOS is an experiment to search for sterile neutrino with electrons anti-neutrino from reactor at short baseline of about 25 m.

2. NEOS-Neutrino Experiment for Oscillation at Short baseline

The experimental site of NEOS is Hanbit Nuclear Power Plant (NPP) in Younggwang, Korea. The Reactor Unit 5 in Hanbit NPP is commercial reactor which has 2.8 GW\textsubscript{th} thermal power.
The reactor core is cylindrical shape of 3.1 m diameter and 3.8 m height. The fuel is Low Enriched Uranium (LEU) (4.6% $^{235}\text{U}$). NEOS detector is located in Tendon Gallery of Reactor Unit 5 at Hanbit NPP and this location has about 24 m baseline and about 20 meter water equivalent (m.w.e) overburden.

2.1. NEOS Detector

NEOS detector consists of active target, buffer tank including PhotoMultiplier Tubes (PMTs), shields, muon detectors, and Data Acquisition (DAQ) systems as shown in Figure. 1. The active target is Liquid Scintillator (LS) and contained in a cylindrical stainless steel tank with PTFE reflector. It is homogeneous of 1000 L volume and mixed LS which consists Linear Alkyl Benzene- (LAB) and Di-IsopropylNaphthalene- (DIN) based LS with 9:1. This mixture improves Pulse Shape Discrimination (PSD) compared to LAB only. The active target contains 0.5% Gd and neutron capture on Gd makes it possible to separate the signals of positron and neutron from Inverse Beta Decay (IBD).

![Figure 1. NEOS detector. There are active target, buffer tanks with PMTs, shields, and muon detector.](image)

There are two buffer tanks filled with mineral oil at both sides of the target and two acrylic windows between target and buffers. Nineteen R5912 (8-inch) PMTs are installed in each buffer tank. There are also two shields, one is 10 cm thick borated polyethylene against neutrons and the other is 10 cm thick lead against external gammas. Muon detectors for muon veto consists fifteen plastic scintillators with PMTs except the bottom side. There are 500 Mega Sampling/s (MS/s) Flash ADC for active target and it records waveform for PSD. The 62.5 MS/s ADC is used for muon detectors.

Data was taken from August 2015 until May 2016 and the reactor-on and -off period are about 180 and 46 days, respectively. IBD candidates of each period are 2000 (on) and 80 (off) per day, so the on-off ratio is about 24. The energy resolution is about 5% at 1 MeV and most sensitive range of NEOS is about eV-scale sterile neutrinos.

2.2. Detector Response and MC Simulation

Some gamma sources such as $^{137}\text{Cs}$, $^{60}\text{Co}$, Po-Be, and $^{252}\text{Cf}$ are used for calibration and simulation tuning the energy (charge) and the energy resolution. These sources are centered at detector. Position dependency tuning is also done via 3D calibration with $^{137}\text{Cs}$ and $^{60}\text{Co}$. The sources are located at various positions and the escaped gammas from active target are tuned with this process.

There is non-linearity between charge and true energy due to Birks’ Law and Cherenkov’s Effect and this non-linearity should be reflected in the energy calibration. The non-linearity is shown in Figure. 2 and Figure. 3 shows a comparison of the data with the tuned simulation considering this non-linearity. Data and MC are compared for three beta decay cases ($^{214}\text{Bi}$, $^{212}\text{Bi}$, and $^{12}\text{B}$) and they are in good agreement.
3. Data Analysis

Through the above process, the energy of events is reconstructed. Events with energies above 0.6 MeV are selected as single events and IBD reconstructions are performed using these single events. Figure 4 shows the energy distribution of single events.

3.1. IBD Reconstruction

IBD consists of a signal by a positron and a signal by a neutron (captured on Gd). The signals by the positron and neutron are called the prompt signal (S1) and the delayed signal (S2), respectively. The energy range of the S1 is determined by the energy range of the neutrino and the range is 1-10 MeV. Total gamma energy due to n-Gd capture is about 8 MeV, but the energy range of S2 is 4-10 MeV considering escaped gamma due to the target size. The time difference between two separated signals is 1-30 $\mu$s considering the neutron capture time.

In addition, there are criteria for reducing the backgrounds. PSD is used for fast neutrons, multiplicity cut is used for multiple neutrons, and muon veto is also applied. The PSD cut is set to accept 99.9% of gamma-like events. (See Figure 5) The multiplicity cut should have no single event between S1 and S2, and there should be no single event for 30 $\mu$s before and 150 $\mu$s after S1. Time window is 150 $\mu$s for muon veto.

3.2. IBD Prompt Energy Spectrum and Shape Only Analysis

The data in the reactor-on period has both signals and backgrounds. On the other hand, the data of the reactor-off period has only the backgrounds. Thus, the ratio of signal to background is about 23, and the energy spectrum of prompt signal can be seen in the top plot of Figure 6. Data are analyzed using Huber and Mueller (HM) model[10][11] with Vogel’s calculation of IBD cross section [12] and Daya Bay spectrum[13], and 5 MeV excess is clear with HM model. Therefore, the oscillation analysis was carried out through Daya Bay spectrum.

For the comparison with the Daya Bay spectrum, the fission fraction is corrected using HM model. As a result of comparison, the model seems to describe the data as a whole, and the size of 5 MeV excess is much smaller than the HM model. The oscillation analysis is performed...
Figure 4. Energy spectrum of selected single events. The gray-filled area is before muon veto and the orange- and cyan-filled regions are after muon veto. The blue and red lines mean the reactor-on and -off period, respectively.

Figure 5. PSD distribution. The orange-filled area is data in reactor-off period and the cyan-filled area is data in reactor-on period. The cut is set for accepting 99.9% gamma-like events.

Figure 6. (top) Prompt energy spectrum of NEOS. Black dots are data signals (on-off) and red-filled area is data background (off). The blue line is MC prediction with Daya Bay absolute spectrum and last bin is a sum of 7 to 10 MeV. (bottom) The ratio of measured to predicted. The red line is the case of the best fit of RAA and the blue line is the case of the best fit of NEOS with 3+1 hypothesis.

using chi-square and shape-only analysis and chi-square used is as follow,

\[ \chi^2 = \sum_{i,j} (N^\text{on}_i - (t_{\text{on}}/t_{\text{off}})N^\text{off}_i)M^{-1}_{ij}(N^\text{on}_j - (t_{\text{on}}/t_{\text{off}})N^\text{off}_j - N^\text{exp}_j) \]  

(1)

where \( N^\text{on} \) and \( N^\text{off} \) are measured number in reactor-on and -off period, respectively, \( N^\text{exp} \) is predicted number, and \( M_{ij} \) is covariance matrix including statistical and systematic uncertainties. There is no significance at whole searching area including the best fit with 3+1 hypothesis and disagreement of the best fit of RAA. The bottom plot of Figure. 6 shows the
Figure 7. Excluded region of NEOS (blue line). Black thin line is the combined result of Daya Bay and Bugey-3cite:dbm. The allowed area is green-filled region with 90% (dark green) and 95% (light green) CL.

best fit of NEOS and RAA. The raster scan is used for exclusion limit and $\Delta m^2_{41} \leq 3$ eV$^2$ in allowed region of RAA including its best fit is excluded as shown in Figure. 7.

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