NEOS: reactor neutrino experiment at short baseline

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Abstract. Numbers of experiments are trying to measure an active-to-sterile neutrino oscillation using nuclear reactors. A precise measurement of the energy spectrum is also important to understand the reactor neutrinos and for their applications. The NEOS experiment is being conducted at 24 meter distance from a 2.8 gigawatt thermal power nuclear reactor core. It aims at finding a short baseline oscillation due to an eV scale sterile neutrino, and to provide a reactor neutrino energy spectrum with a high resolution and a high signal-to-background ratio.

1. Introduction
In the nuclear reactor, about 6 or 7 β-decays occur from a fission of a primary fissile isotope, which is one of $^{235}$U, $^{238}$U, $^{239}$Pu, $^{241}$Pu, etc. Therefore, the same number of electron antineutrinos ($\bar{\nu}_e$) as of the β-decays are emitted. It is known that about $2 \times 10^{20}$ $\bar{\nu}_e$ come out in a second from a gigawatt-thermal-power (GW$_{th}$) reactor [1, 2]. The $\bar{\nu}_e$'s of which the energies higher than 1.8 MeV can be detected via inverse beta decay (IBD, $\bar{\nu}_e + p \rightarrow e^+ + n$) process with an order of $10^{-42}$ cm$^2$ cross section [3]. For example, tens of thousands IBD events occur in a 1000 kg of organic scintillator with 10% mass of hydrogen atom, located at a 10 m distance from a multi-GW$_{th}$ reactor.

Numbers of experiments were conducted using the reactor sources during the past decades, and the average of the measured $\bar{\nu}_e$'s fluxes was found to be smaller than expected [1, 2] with a significance higher than 2-σ level [4]. The so-called reactor antineutrino anomaly (RAA), combined with other anomalies [5–8] suggested that there can be a neutrino mixing with an additional mass and a flavor state. The new flavor state is called sterile because it does not go through the standard electroweak interaction, and the new mass state is likely to be at around 1 eV [4, 9, 10].

More recently, Daya Bay [11], RENO [12], and Double Chooz [13] found out that there are disagreements between the measured IBD spectra and the predicted ones [1, 2]. And Daya Bay [14] and RENO [15] reported that the predicted $\bar{\nu}_e$ fluxes, especially for $^{235}$U, could be overestimated.

2. Reactor experiment for $\nu$-SBL oscillation
In order to solve the anomalies described above, various new reactor short baseline experiments have been designed and being conducted [16–19]. Each experiment has its unique detector design to reach the best sensitivity under high background level condition at very close distance to the reactor core. At very short baseline, i.e. less than a hundred meters from a reactor, the survival
Figure 1. An illustration of ratio of energy spectra between oscillation data and the no-oscillation reference. The NEOS condition ($L = 24$ m) and $\Delta m_{41}^2 = 1$ eV$^2$ are assumed. For a point-like neutrino source and with a perfect distance resolution, one would have an oscillation pattern as the pale blue curve. See the text for further description.

The probability of $\bar{\nu}_e$ can be approximated as following:

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \sim 1 - \sin^2 2\theta_{14} \sin^2 \left(1.27 \frac{\Delta m_{41}^2 L}{E_\nu} \left[\text{eV}^2 \cdot \text{m} \right]\right), \quad (1)$$

where $\Delta m_{41}^2$ is the mass squared difference between the fourth neutrino mass and the others, $\theta_{14}$ the mixing angle between the electron flavor and the fourth mass state, $L$ the distance from source (active reactor core) to the detector, and $E_\nu$ is the neutrino energy. At less than tens of meters from the reactor source, the IBD measurement is sensitive to $\Delta m_{41}^2$ value near 1 eV$^2$.

The oscillation pattern in the energy spectrum data divided by no-oscillation reference is illustrated in Fig. 1. The amplitude of the oscillation stands for the size of the mixing angle, and the frequency-like structure tell us about the mass-squared difference. Even without the absolute ratio between the data and the reference, one can tell the mixing size from its shape. However, the oscillation pattern is seriously smeared out by the distance resolution due to the finite sizes of the reactor core and the detector (dark blue curve). It is also washed out by the errors and resolution in the reconstructed prompt energy (green curve). The data quality is limited by the statistical precision and the signal-to-background (S/N) ratio (black points with error bars). And the sensitivity for detection of an oscillation is also limited by the uncertainties in the reference model spectrum (gray band).

3. NEOS phase-I and phase-II
The NEOS detector is located in the tendon gallery of the Hanbit-5 reactor in Yeonggwang, Korea. The center-to-center distance between the active reactor core and the detector is 23.7 m, while the closest neighboring reactor cores are 260 m away. The detector location is about 10 m underground and the overburden provided by the reactor building structure and the earth soil is at least 20 meter-water-equivalent. The muon rate is about 0.17 /cm$^2$ per minute, which is about one fifth of the surface muon rate. The detector uses 1000 L of homogeneous Gd-loaded liquid scintillator as the $\bar{\nu}_e$ target. The target is surrounded by layers of 10-cm thick borated polyethylene, 10-cm thick lead, and muon counter detector for passive and active shielding. The phase-I measurement was conducted from August 2015 to May 2016, and the DAQ livelays consist of 46 days of reactor-maintenance (OFF) and 180 days of reactor-operation (ON) periods. About 2000 IBD event candidates per day were measured with S/N higher than 20. As a result, a similar spectral distortion from the prediction [1, 2], especially the 5-MeV bump, was found as in the previous mid-baseline experiments [11–13]. No strong evidence of an active-to-sterile neutrino oscillation was found when the spectral shape was compared with the Daya Bay spectrum [20].

The phase-II measurement has started in September 2018 and will last until July 2020. The measurement period consists of two OFF periods of about 50 and 100 calendar days, and an ON
period of about 500 days in between. In addition to the slight improvement in eV sterile neutrino search sensitivity (Fig. 2) due to a higher statistical precision and with a rate+shape analysis, measuring a full reactor burnup cycle makes it possible to decompose the IBD spectrum for the primary fission elements, especially for $^{235}$U and $^{239}$Pu (Fig. 3). Measuring $\bar{\nu}_e$’s from a single, powerful and low-enriched-uranium fuel reactor makes it possible to have enough statistical precision to test each of the predicted $\bar{\nu}_e$ spectra of $^{235}$U and $^{239}$Pu.

**Figure 2.** NEOS experimental sensitivity for the active-to-sterile neutrino oscillation parameters. Shadow regions are 1-$\sigma$ range of 90% sensitivity. Red curve is the exclusion curve with 90% c.l. from the phase-I measurement result.

**Figure 3.** Decomposition of the pseudo-experimental spectrum for $^{233}$U and $^{239}$Pu. Dark blue and green histograms are the reference spectra [1], shadow areas are 1-$\sigma$ range of decomposed spectra. Black and pink points with error bars denote an example of decomposed spectra from a pseudo-data set.

4. Status and plan

As of August 2019, about a half of planned data has been taken, while the Hanbit-5 reactor is passing through its first half of the burnup cycle. A very preliminary analysis shows that there is no big difference between the phase-I and phase-II spectrum. The detector simulation is being revised for better understanding of the detector responses, such as the quenching effect and the neutron-Gd capture signals. Better understanding of such systematic effects will help the rate analysis for the sterile neutrion search as well as acquiring the absolute prompt energy spectrum and unfolding it to the neutrino energy spectrum.

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