Neutrino Experiment for Oscillation at Short Baseline

Aug 04 @ ICHEP 2016, Chicago
Yoomin Oh for NEOS Collaboration
Center for Underground Physics, IBS
NEOS Collaboration

Hongjoo Kim, Jooyoung Lee, Kyungkwang Joo, Ba Ro Kim, Changhwan Jang, Siyeon Kim, Youngju Ko, Kyungmin Seo, Jinyu Kim, Hyunsoo Kim, Gwang-Min Sun, Boyoung Han, Hyunseo Park, Yeongduk Kim, Eun-ju Jeon, Jaison Lee, Moo-hyun Lee, Yoomin Oh, Hyangkyu Park, Kang-soon Park
3 v mixing and oscillation

\begin{align*}
\nu_1 & \quad \sim 9 \text{meV} \\
\nu_2 & \quad \sim 9 \text{meV} \\
\nu_3 & \quad \sim 45 \text{meV}
\end{align*}

\[\sin^2 \theta_{13} = 0.023\]
\[\Delta m_{21}^2 = 7.54 \times 10^{-5} \text{eV}^2, \quad \sin^2 \theta_{12} = 0.31,\]
\[\Delta m_{32}^2 = 2.43 \times 10^{-3} \text{eV}^2, \quad \sin^2 \theta_{23} = 0.44\]

but...
More than 3?

LSND, PRD 64 (2001) 112007

Ga Anomaly, PRC 73 (2006) 045805

MiniBooNE, PRL 102 (2009) 101802

Reactor Anomaly, arXiv:1204.5379
3+1 $\nu$ and Reactor SBL

$$P \simeq 1 - \sin^2 2\theta_{14}\sin^2 \left( 1.27\Delta m_{41}^2 \text{ [eV}^2] \frac{L \text{ [m]}}{E_\nu \text{ [MeV]}} \right)$$

- Challenges in reactor SBL experiment
  - small size detector, safety and security
  - poor S/N ratio, lack of overburden
  - shielding from reactor induced bkg.
NEOS Experiment

- 2.8 GWt commercial reactor
  - Hanbit NPP in Yeonggwang, Korea
  - core size: 3.1 m (φ), 3.8 m (H)
  - LEU fuel.

- Tendon Gallery
  - 24 m baseline
  - overburden > 20 mwe

- Homogeneous LS detector
  - 5% energy resolution @ 1 MeV
  - PSD capability

- Spectral shape analysis with a single detector/baseline measurement
  - dependence on reference spectrum
NEOS Detector

- Homogeneous LS target
  - 1008 L LAB+UG-F (9:1)
  - 0.5% Gd loaded
  - 38 PMT(8”) in mineral oil buffer

- Shieldings
  - 10 cm B-PE, 10 cm Pb
  - muon counter

- Data AcQuisition
  - 500 MS/s FADC (waveform)
  - 62.5 MHz SADC
Data successfully reproduced by MC

See Youngju Ko’s poster on Saturday
IBD candidates

1<Δt<30 μs

4<E_s<10 MeV

1<E_{s1}<8 MeV

4<E_{s2}<10 MeV

No event in 30 μs before

1<Δt<30 μs

No other event in 150 μs

and 150 μs muon veto.

99.9% γ-like events

accepting
Reactor OFF > ON

- IBD candidates: $81.2 \pm 1.2$ /day (off), $1972.2 \pm 3.3$ /day (on). S/N~23 ($1 < E_{s1} < 8$ MeV)
- Background not fluctuated by the reactor operation.
Prompt energy spectrum

- Prediction based on Huber’s and Mueller’s (H-M) flux calculation
- Uncertainty dominated by flux and energy scale
- Agreement but “bump”!
- Small deviations
5 MeV excess

- Simply assuming Gaussian
- Daya Bay absolute flux + H-M
- Large fitting error
- Almost same location, size differs

Daya Bay, PRL 116 (2016) 061801
Oscillation and bump

- Without 5 MeV excess
  - excluding 3σ of Gaussian
  - 3.4-6.3 MeV (29 bin)
  - loss of sensitivity

- With 5 MeV excess
  - possible bias from bump
  - assigning more error
$\chi^2$ Analysis for Oscillation

$$\chi^2(\sin^2 \theta_{14}, \Delta m^2_{41}) = \sum_i \left[ \frac{M_i - T'_i(\sin^2 2\theta, \Delta m^2_{41}) - B'_i}{M_i + (t_{on}/t_{off})B_i} \right]^2 + \chi^2_{\text{penalty}}$$

$M_i$: Measured IBD candidates in $i$'th energy bin during reactor on,
$T_i$: Expected number, including oscillation params and systematics*,
$B_i$: Background events, scaled with on-off time ratio ($t_{on}/t_{off}$).

<table>
<thead>
<tr>
<th>NEOS Preliminary</th>
<th>H-M w/o bump</th>
<th>H-M w bump fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\chi^2$ minimum</td>
<td>25.5</td>
<td>47.9</td>
</tr>
<tr>
<td>anomaly best fit</td>
<td>52.3</td>
<td>111</td>
</tr>
<tr>
<td>$\chi^2$ null</td>
<td>33.1</td>
<td>59.1</td>
</tr>
<tr>
<td>$N_{\text{DoF}}$</td>
<td>38</td>
<td>67</td>
</tr>
<tr>
<td>$\chi^2$ minimum at significance</td>
<td>(0.055, 1.35 eV$^2$)</td>
<td>(0.039, 1.73 eV$^2$)</td>
</tr>
<tr>
<td></td>
<td>2.00σ</td>
<td>2.68σ</td>
</tr>
</tbody>
</table>
Limits

- Reactor Anomaly 90% CL
- Reactor Anomaly 95% CL
- Daya Bay/Bugey-3 90% CL excluded
- NEOS Preliminary
- 95% CL excluded

- H-M without excess
- H-M + excess fit

\[ \Delta m^2_{41} [\text{eV}^2] \]

\[ \sin^2 2\theta_{14} \]
Summary

- Reactor $\bar{\nu}_e$ IBD spectrum is measured at 24 m baseline.
- 49 days’ reactor off, 180 days’ reactor on data accumulated.
  ~2000 IBD candidates/day with S/N~23 observed.
- 5 MeV excess seen at this short baseline, too.
- Part of allowed oscillation parameter space including reactor anomaly
  best fit is ruled out at 95% CL.
- On the bases of $\nu$ flux by Huber and Mueller with / without 5 MeV excess
  — 2.0$\sigma$ / 2.7$\sigma$ significances at (0.055, 1.35 eV$^2$) / (0.039, 1.73 eV$^2$).
  — Results may depend on $\nu$-spectrum models.
- Analyses with other reference $\nu$-spectra are on going.

Result will be in arXiv soon.
Backup
Detector responses

NEOS Preliminary

- $^{60}\text{Co}$ at center
- $^{60}\text{Co}$ at Z-48cm
- $^{60}\text{Co}$ at radial border

- $^{212}\text{Bi}$
- $^{214}\text{Bi}$
- $^{12}\text{B}$

- Reconstructed Energy [MeV]
- Decays time [ns]
- Decay time [ms]

$^{60}\text{Co}$ at center
- Data
- Simulation

$^{60}\text{Co}$ at Z-48cm
- Data
- Simulation

$^{60}\text{Co}$ at radial border
- Data
- Simulation

$^{212}\text{Bi}$
- Data
- Simulation

$^{214}\text{Bi}$
- Data
- Simulation

$^{12}\text{B}$
- Data
- Simulation

Entries /3 pC

Entries /50 keV

Entries /0.5 MeV

$^{12}\text{B}$ half-life $\tau = 0.4 \text{ ms} \pm 0.2 \text{ ms}$
\( \chi^2 \) and systematic uncertainties

\[
\chi^2(\sin^2\theta_{14}, \Delta m^2_{41}) = \sum_i \frac{[M_i - T'_i(\sin^22\theta, \Delta m^2_{41}) - B'_i]^2}{M_i + (t_{on}/t_{off})B_i} + \chi^2_{\text{penalty}}
\]

\[
T'_i = (1 + \alpha_n + \alpha_f a_i + \alpha_{f,i})(T_i + \alpha_o T^o_i) + \alpha_\varepsilon \frac{\partial(T_i + \alpha_o T^o_i)}{\partial \alpha_\varepsilon}
\]

\[
B'_i = (1 + \alpha_b)B_i
\]

\[
\chi^2_{\text{penalty}} = \left(\frac{\alpha_n}{\sigma_n}\right)^2 + \left(\frac{\alpha_f}{\sigma_f}\right)^2 + \left(\frac{\alpha_o}{\sigma_o}\right)^2 + \sum_i \left(\frac{\alpha_{f,i}}{\sigma_{f,i}}\right)^2 + \left(\frac{\alpha_f}{\sigma_f}\right)^2 + \left(\frac{\alpha_b}{\sigma_b}\right)^2 + \left(\frac{\alpha_\varepsilon}{\sigma_\varepsilon}\right)^2
\]

- \( \alpha \): nuisance parameter corresponding to systematic uncertainty \( \sigma \)
  - \( \sigma_n = 1 \): overall normalization of reference spectrum,
  - \( \sigma_f a_i / \sigma_{f,i} \): correlated / uncorrelated flux uncertainties,
  - \( \sigma_\varepsilon = 0.005 \): energy scale uncertainty
  - \( \sigma_b = 0.1 \): for unknown background instability

\[
\sum_{i} \chi'^2_{i} = \chi^2 + \chi^2_{\text{penalty}}
\]
\[(\sin^2 2\theta, \Delta m^2_{41}) = (0.039, 1.73 \text{ eV}^2)\]