Reactor Neutrino Experiments Daya Bay and JUNO

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NTUHEP25+ status report
Feb. 28, 2020
R104
A Powerful Neutrino Source at an Ideal Location

Mountains shield detectors from cosmic ray background

Daya Bay NPP 2 $2.9 \text{ GW}_{th}$

Ling Ao I NPP $2 \times 2.9 \text{ GW}_{th}$

Ling Ao II NPP $2 \times 2.9 \text{ GW}_{th}$

Among the top 5 most powerful reactor complexes in the world, 6 cores produce $17.4 \text{ GW}_{th}$ power, $35 \times 10^{20}$ neutrinos per second

Entrance to Daya Bay experiment tunnels
Interior of Antineutrino Detector
Daya Bay

- 8 identical detectors positioned around the Daya Bay Power Plant in China

Main Principle:

(i) sample the reactor antineutrino flux in the near and far locations, and

(ii) look for evidence of disappearance

Note:

6-AD Data Taking
2011/12 - 2012/07

8-AD Data Taking
2012/10 - now

(Dec. 24, 2011)
Antineutrino detection

- Antineutrinos are detected via the Inverse Beta Decay (IBD) reaction:

\[ \bar{\nu}_e + p \rightarrow e^+ + n \quad \text{(prompt signal)} \]

\[ \sim 200\mu s \rightarrow + p \rightarrow D + \gamma \ (2.2 \ MeV) \quad \text{(delayed signal)} \]

\[ \sim 30\mu s \quad \text{for } 0.1\% \ Gd \rightarrow + \ Gd \rightarrow Gd^* \rightarrow Gd + \gamma's \ (8 \ MeV) \quad \text{(delayed signal)} \]
Spectral Measurement

- A spectral measurement allows to measure both $\theta_{13}$ and the mass splitting:

  ![Graph showing energy distribution for far and near sites with comparison of each energy.]

  - Far site: large oscillation
  - Near site: small oscillation (normalization)

  ![Graph showing the ratio $\Delta N_{\text{far}} / \Delta N_{\text{near}}$ with $\theta_{13}$ as a variable.]

  - But require good understanding of the detectors’ energy response!

- Which mass splitting do we measure? Define an effective mass splitting $\Delta m_{ee}^2$:

  $$ P_{\nu_e \rightarrow \nu_e} = 1 - \sin^2 2\theta_{13} \sin^2 \left( \frac{\Delta m_{ee}^2 L}{4E} \right) - \sin^2 2\theta_{12} \cos^4 \theta_{13} \sin^2 \left( \frac{\Delta m_{21}^2 L}{4E} \right) $$

  $$ \sin^2 \left( \frac{\Delta m_{ee}^2 L}{4E} \right) \equiv \cos^2 \theta_{12} \sin^2 \left( \frac{\Delta m_{31}^2 L}{4E} \right) + \sin^2 \theta_{12} \sin^2 \left( \frac{\Delta m_{32}^2 L}{4E} \right) $$

  so that:

  $$ |\Delta m_{ee}^2| \sim |\Delta m_{32}^2| \pm 5.21 \times 10^{-5} \text{eV}^2 $$

  -+: Normal Hierarchy
  - -: Inverted Hierarchy
Energy Calibration

- One key is achieving a consistent and stable energy response between the detectors

After calibration, achieve energy response that is stable to ~0.1% in all detectors, with a total relative uncertainty of 0.35% between detectors.

ACU: $^{60}\text{Co}$, $^{68}\text{Ge}$, AmC
Spallation: nGd, nH
Gamma: $^{40}\text{K}$, $^{208}\text{Ti}$
Alpha: $^{212}\text{Po}$, $^{214}\text{Po}$, $^{215}\text{Po}$

After initial reconstruction, position non-uniformity is also corrected for
Energy Nonlinearity Calibration

- Combined fit with mono-energetic gamma peaks and $^{12}$B beta-decay spectrum
- Cross-validated with $^{214}$Bi, $^{208}$Tl beta-decay spectrum, Michel electron spectrum and standalone bench-top Compton scattering measurement.

< 1% uncertainty (correlated among all detectors)
## Signal and Background Summary

<table>
<thead>
<tr>
<th></th>
<th>Near Halls</th>
<th></th>
<th>Far Hall</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AD 1</td>
<td>AD 2</td>
<td>AD 3</td>
<td>AD 4</td>
</tr>
<tr>
<td>IBD candidates</td>
<td>101290</td>
<td>102519</td>
<td>92912</td>
<td>13964</td>
</tr>
<tr>
<td>DAQ live time (days)</td>
<td></td>
<td>191.001</td>
<td>189.645</td>
<td>189.779</td>
</tr>
<tr>
<td>Efficiency $\epsilon_\mu \cdot \epsilon_m$</td>
<td>0.7957</td>
<td>0.7927</td>
<td>0.8282</td>
<td>0.9577</td>
</tr>
<tr>
<td>Accidentals (per day)</td>
<td>$9.54 \pm 0.03$</td>
<td>$9.36 \pm 0.03$</td>
<td>$7.44 \pm 0.02$</td>
<td>$2.96 \pm 0.01$</td>
</tr>
<tr>
<td>Fast-neutron (per day)</td>
<td>$0.92 \pm 0.46$</td>
<td></td>
<td>$0.62 \pm 0.31$</td>
<td></td>
</tr>
<tr>
<td>$^9\text{Li}/^8\text{He}$ (per day)</td>
<td>$2.40 \pm 0.86$</td>
<td></td>
<td>$1.2 \pm 0.63$</td>
<td></td>
</tr>
<tr>
<td>Am-C corr. (per day)</td>
<td>$0.08 \pm 0.04$</td>
<td>$0.07 \pm 0.04$</td>
<td></td>
<td>$0.26 \pm 0.12$</td>
</tr>
<tr>
<td>$^{13}\text{C}^{16}\text{O}$ backgr. (per day)</td>
<td>$0.08 \pm 0.04$</td>
<td>$0.07 \pm 0.04$</td>
<td>$0.05 \pm 0.03$</td>
<td>$0.04 \pm 0.02$</td>
</tr>
<tr>
<td>IBD rate (per day)</td>
<td>$653.30 \pm 2.31$</td>
<td>$664.15 \pm 2.33$</td>
<td>$581.97 \pm 2.07$</td>
<td>$73.31 \pm 0.66$</td>
</tr>
</tbody>
</table>

*Background and IBD rates were corrected for the efficiency of the muon veto and multiplicity cuts $\epsilon_\mu \cdot \epsilon_m$*

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**Collected more than 300k antineutrino interactions**

- Consistent rates for side-by-side detectors
- Uncertainties still dominated by statistics
Daya Bay Results

- Precision Oscillation results from 1958 days data (PRL 121, 241805, (2018))
  - New $\sin^2(2\theta_{13}) = 0.0856 \pm 0.0029$ and
    - New $\Delta_{m_{32}}^2 = (2.471 \pm 0.007) \times 10^{-3}$ eV$^2$ (Normal)
    - $\Delta_{m_{32}}^2 = -(2.575 \pm 0.007) \times 10^{-3}$ eV$^2$ (Inverted)
- Other results – Reactor Antineutrino flux and spectra, Sterile Neutrino Search, Reactor Fuel Evolution, Cosmogenic Background, etc.
- Analysis contributions: rolling gain calibration of PMTs, simulation on GPU, muon background studies, nH analysis, unified analysis (nH+nGd), Cosmogenic Li9/He8 background, etc.
Plan to run to 2020 before JUNO starts!

Sensitivity still dominated by statistics

- Statistics contribute 73% (65%) to total uncertainty in $\sin^2 2\theta_{13}$ ($|\Delta m^2_{ee}|$)
- Major systematics:
  - $\theta_{13}$: Reactor model, relative + absolute energy, and relative efficiencies
  - $|\Delta m^2_{ee}|$: Relative energy model, relative efficiencies, and backgrounds
  - Precision of mass splitting measurement closing in on results from $\mu$ flavor sector
Comparison with Other Exps
(2017 PRD 95, 072006 Results)

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daya Bay</td>
<td>0.0841±0.0033</td>
</tr>
<tr>
<td>RENO</td>
<td>0.082±0.010</td>
</tr>
<tr>
<td>D-CHOOZ</td>
<td>0.111±0.018</td>
</tr>
<tr>
<td>T2K</td>
<td>0.100±0.017</td>
</tr>
<tr>
<td>MINOS</td>
<td></td>
</tr>
<tr>
<td>NH</td>
<td>0.051±0.038</td>
</tr>
<tr>
<td>IH</td>
<td>0.093±0.054</td>
</tr>
</tbody>
</table>
Spectral Shape

• But can also make an absolute shape comparison between the data and the prediction:

  - Prediction uses best knowledge of the detector response

  - Local significance of deviations in 4-6 MeV region is ~4σ

Also seen in RENO, D-Chooz

PROPECT will check it too!
Daya Bay was proposed in 2003. The 1st international workshop in Nov. 2003 in University of Hong Kong. The 2nd international workshop in Jan. 2004 at IHEP.

Feb. 2006, the Daya Bay Collaboration established.

Project approved in China in 2006 by CAS and MoST

Oct. 2007, ground breaking

Aug. 15, 2011, EH1 data taking.

Dec. 24, 2011, 3-hall data taking with 6 ADs (217 days)

Mar. 8, 2012, announced the discovery of the non-zero $\theta_{13}$


Jan. 26, 2017, started data taking with 7 ADs (1416 days)

Mar. 14, 2018, RPCs pulled out

Dec. 12, 2020, complete the Daya Bay operation

Complete all analyses in 2022.
Daya Bay Collaboration Meeting in Shenzhen (power plant or Shenzhen campus of HKUST) on Dec. 9-12, 2020

3 days for scientific meeting, 1 day for ceremony.

Completion Ceremony tentatively on Dec. 12, 2020. All collaborators, former collaborators, and funding agency representatives are welcomed!

Please inform our Project Office (Ms. Lei Liu, liulei@ihep.ac.cn) if your funding agency representatives would come, and whether Dec. 12 is good. We may fine tune the date with collected information. The final date could be determined at the next half of 2020.

Another collaboration meeting on May 7-9, 2020 in Prague, to prepare for Neutrino2020.
JUNO

- Neutrino Mass hierarchy (ordering) measurement
- Precision measurements on $\sin^2(\theta_{12})$ and $\Delta m^2$ (sub-percent)
- Probing the unitarity of $U_{PMNS}$ to ~1% level

Taiwan’s contribution:
- R&D on central detector design and supporting nodes, mechanical simulation
- HZC 3” PMTs testing and final acceptance tests
- Simulation of photon propagation with GPU, etc.
**Location of JUNO**

<table>
<thead>
<tr>
<th>NPP</th>
<th>Daya Bay</th>
<th>Huizhou</th>
<th>Lufeng</th>
<th>Yangjiang</th>
<th>Taishan</th>
</tr>
</thead>
<tbody>
<tr>
<td>Status</td>
<td>Operational</td>
<td>Planned</td>
<td>Planned</td>
<td>Under construction</td>
<td>Under construction</td>
</tr>
<tr>
<td>Power</td>
<td>17.4 GW</td>
<td>17.4 GW</td>
<td>17.4 GW</td>
<td>17.4 GW</td>
<td>18.4 GW</td>
</tr>
</tbody>
</table>

**Overburden ~ 700 m**

Kaiping, Jiangmen city, Guangdong Province

By 2020: 26.6 GW

Location map showing the distances and locations of JUNO sites:
- **Daya Bay NPP**
- **Huizhou NPP**
- **Lufeng NPP**
- **Yangjiang NPP**
- **Taishan NPP**

Distances:
- 2.5 h drive from Guangzhou
- 53 km from Hong Kong
- 53 km from Macau

Previous site candidate

Overburden ~ 700 m

Guangzhou, Dongguan, CNS

CNS

Shen Zhen

Zhu Hai

Hong Kong

Macau

Kaiping, Jiangmen city, Guangdong Province

Distance to Reactor (m)
Neutrino mass hierarchy

\[ \Delta m_{ij}^2 = m_i^2 - m_j^2 \]
\[ \Delta m_{21}^2 = 7.5 \times 10^{-5} \text{eV}^2 \]
\[ |\Delta m_{31}^2| = 2.4 \times 10^{-3} \text{eV}^2 \]

Sign and absolute value of \( \Delta m_{31}^2 \) depend on mass hierarchy

\[ m_1 < m_2 < m_3 \]
\[ m_3 < m_2 < m_1 \]

Measuring the neutrino mass hierarchy enables the study of further unknown parameters in neutrino physics:

- Resolving \( \delta_{CP} \)
- Octant of \( \theta_{23} \)
- Parameter space for 0\( \nu \beta \beta \) decay
Reactor electron antineutrinos oscillations

Electron antineutrino survival probability:

\[ P_{\bar{\nu}_e \rightarrow \bar{\nu}_e} = 1 - \sin^2 2\theta_{13} \cos^2 \theta_{12} \sin^2 \frac{\Delta m^2_{31} L}{4E} - \sin^2 2\theta_{13} \sin^2 \theta_{12} \sin^2 \frac{\Delta m^2_{32} L}{4E} - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \frac{\Delta m^2_{21} L}{4E} \]

- Nuclear reactors (\( \sim 10^{21} \) ν/s/GW_e)
- Neutrino detector

- Mass hierarchy is measurable only because \( \theta_{13} \) is ‘large’
- Way to determine NH/IH using reactor neutrinos by measuring the interference between \( \Delta m^2_{31} \) and \( \Delta m^2_{32} \)
- Best L/E ratio for maximum interference is \( \sim 10 \) km/MeV, i.e. \( \sim 50-60 \) km distance for reactor antineutrinos energy
To distinguish between NO/IO at 3σ, one needs:

- at least 100,000 events (nominal luminosity)
- an energy resolution of 3%/√E(MeV)
- baseline ∼53 km with core dispersion <0.5 km
- an energy scale uncertainty below 1%

→ impose the size and the performances of the JUNO experiment
Neutrino oscillation parameters with JUNO

- Advantage of JUNO for mass hierarchy determination: no matter effect and not sensitive to CP phase
- JUNO will be the first experiment ever built able to measure simultaneously the fast ($\Delta m_{31}^2$) and slow ($\Delta m_{21}^2$) oscillations along multiple oscillation periods
- Measurement of 3 parameters at a subpercent precision level, especially the solar oscillation parameters ($\Delta m_{21}^2$ and $\sin^2(2\theta_{12})$) in order to solve the tension between solar $\nu_e$ and KamLAND results

### Oscillation parameters

<table>
<thead>
<tr>
<th></th>
<th>Current precision at 1σ level *</th>
<th>JUNO only**</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>\Delta m_{31}^2</td>
<td>$</td>
</tr>
<tr>
<td>$\Delta m_{21}^2$</td>
<td>$\sim 2.3%$</td>
<td>$\sim 0.6%$</td>
</tr>
<tr>
<td>$\sin^2(2\theta_{12})$</td>
<td>$\sim 5.8%$</td>
<td>$\sim 0.7%$</td>
</tr>
<tr>
<td>Mass hierarchy</td>
<td>N/A</td>
<td>3-4 σ</td>
</tr>
<tr>
<td>$\sin^2(\theta_{13})$</td>
<td>$\sim 3.9%$</td>
<td>$\sim 15%$</td>
</tr>
</tbody>
</table>


→ will help to probe the unitarity of the PMNS matrix at $\sim 1\%$ level
JUNO detector: size and concept

- 100,000 events required in 6 years of data taking at 53 km distance
  - 20 ktons of target detector needed (liquid scintillator) in a sphere of ~35 m diameter

- Energy resolution of $3\%/\sqrt{E(\text{MeV})}$
  - high LS transparency + very high photodetection coverage (~78%)
  - 1200 p.e. with 18,000 20-inch PMTs

JUNO will be the largest liquid scintillator detector ever built!

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Daya Bay</th>
<th>Borexino</th>
<th>KamLAND</th>
<th>JUNO</th>
</tr>
</thead>
<tbody>
<tr>
<td>LS mass (tons)</td>
<td>20 /detector</td>
<td>~300</td>
<td>~1,000</td>
<td>20,000</td>
</tr>
<tr>
<td>Nb of collected p.e. per MeV</td>
<td>~160</td>
<td>~500</td>
<td>~250</td>
<td>~1200</td>
</tr>
<tr>
<td>Energy resolution @ 1 MeV</td>
<td>~7.5%</td>
<td>~5%</td>
<td>~6%</td>
<td>~3%</td>
</tr>
</tbody>
</table>
Electron antineutrino detection

- Electron antineutrinos detected by Inverse Beta Decay (IBD):

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

Energy threshold: \(E(\nu) > 1.8 \text{ MeV}\)

\(E_{\text{visible}} = E(\nu) - 0.8 \text{ MeV}\)

Neutrino signature:
- Prompt signal from \(e^+\): ionization+annihilation in 2\(\gamma\) (1-10 MeV) \(\rightarrow\) visible energy
- Delayed signal from neutron: capture on \(^1\text{H}\) (2.2 MeV)
- Time correlation < 1 ms
Signal and backgrounds

- Visible energy of oscillated spectrum from reactor antineutrinos in JUNO

- Energy spectrum contribution from the main 5 backgrounds (correlated and uncorrelated backgrounds)

→ backgrounds need to be under control by design and by active/passive cuts

<table>
<thead>
<tr>
<th>Selection</th>
<th>IBD efficiency</th>
<th>IBD</th>
<th>Geo-νs</th>
<th>Accidental</th>
<th>$^9\text{Li}/^8\text{He}$</th>
<th>Fast n</th>
<th>$(\alpha, n)$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-</td>
<td>83</td>
<td>1.5</td>
<td>$\sim 5.7 \times 10^4$</td>
<td>84</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Fiducial volume</td>
<td>91.8%</td>
<td>76</td>
<td>1.4</td>
<td></td>
<td>77</td>
<td>0.1</td>
<td>0.05</td>
</tr>
<tr>
<td>Energy cut</td>
<td>97.8%</td>
<td>73</td>
<td>1.3</td>
<td>410</td>
<td>71</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time cut</td>
<td>99.1%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vertex cut</td>
<td>98.7%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Muon veto</td>
<td>83%</td>
<td>60</td>
<td>1.1</td>
<td>0.9</td>
<td>1.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Combined</td>
<td>73%</td>
<td>60*</td>
<td>1.1</td>
<td></td>
<td>3.8</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* At a nominal power of 36 GWth (26.6 GWh in 2020)

→ after selection cuts: 60 neutrino events/day and 3.8 background events/day
JUNO non-reactor neutrino physics

43 (2016) no.3, 030401

- Supernova $\nu$: $\sim 5000 / 10 \text{ s}$ @ 10 kpc
- Solar $\nu$: 10-1000/day
- Atmospheric $\nu$: several/day
- Cosmic muons: 0.003 Hz/m², 216 GeV
- Geo $\nu$: 1.1/day
- JUNO + proton decay search

Helmholtz Alliance for Astroparticle Physics
The JUNO collaboration

Collaboration established in 2014
77 institutions, ~600 collaborators
Civil construction

Surface buildings

Overburden: 700 m

Vertical shaft

Access tunnel to experimental hall
Underground Construction Status

Dark Gray/Blue/Green Finished Transportation tunnel: 389/506 m
EXP. Hall: one month more to finish above hall
Issues

- Still a large amount of rock to dig: ~100k meter$^3$
- Bottleneck: tunnel size and equipment capacity to lift rock from underground to the surface
- Installation of the rebar support system was a challenge due to the high pressure of water and complicated geological condition
- ~50% more rebars for the roof than the original design
- Water pressure above the dome is decreased to almost zero but the amount of water pumping out is still ~500 m$^3$/hr

<table>
<thead>
<tr>
<th>Rock to dig(m$^3$)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental hall</td>
<td>15174</td>
</tr>
<tr>
<td>Water pool</td>
<td>72611</td>
</tr>
<tr>
<td>Transportation tunnel</td>
<td>3089</td>
</tr>
<tr>
<td>LS storage room</td>
<td>6342</td>
</tr>
<tr>
<td>LS filling room</td>
<td>2610</td>
</tr>
<tr>
<td>Installation hall</td>
<td>4397</td>
</tr>
<tr>
<td>Other</td>
<td>1000</td>
</tr>
</tbody>
</table>
Central detector
Acrylic sphere+
20kt Liquid Scint+
~17000 20” PMT+
~25000 3” small PMT
Double Calorimetry

Water Cherenkov
~2000 20” PMT
35kton ultrapure water

AS: Acrylic sphere; SSLS: stainless steel lattice shell
JUNO liquid scintillator

JUNO LS requirements for $3\%/\sqrt{E(\text{MeV})}$ $E_{\text{res}}$
- High light yield: $10^4$ photons/MeV
- High transparency: attenuation length >20m@430nm
- Good radiopurity for $\bar{\nu}_e$ physics: $^{238}\text{U} < 10^{-15}$ g/g, $^{232}\text{Th} < 10^{-15}$ g/g, $^{40}\text{K} < 10^{-16}$ g/g

LS Purification pilot plant
- Under operation at Daya Bay
- Distillation, $\text{Al}_2\text{O}_3$ column purification, filtration, water extraction, gas stripping
- Attenuation length >25 m after filling (measured)
- Optimizing LS recipes (LAB+2.5 g PPO+1-3 mg/L bis-MSB) and studying radio-impurities
- Same plant to be scaled for JUNO

OSIRIS detector design study for monitoring the LS radiopurity at a level of $10^{-16}$ g/g in $^{238}\text{U}$ during JUNO filling
JUNO acrylic and CD prototype

- Central Detector will be built from acrylic panels with 12 cm thickness: about 260 panels with a total weight of \(~600\) tons

- Several requirements have been defined:
  - Max stress control on acrylic \(< 3.5\) Mpa
  - Max pulling load for acrylic node \(~8\) tons
  - Break at load for acrylic node \(~100\) tons
  - Radiopurity of the acrylic & quality test control

- A JUNO 1:12 prototype has been successfully built at IHEP!
JUNO will use large 20-inch PMTs as its main photodetection system.

- Tight arrangement with a photocoverage of ~75%
- 15,000 MCP-PMTs from NNVT
- 5,000 dynode PMTs from Hamamatsu
- In production since 2016
- ~10,000 produced and >5,000 tested
- Recent 10% improvement of PDE efficiency for MCP-PMT (27→30%)
- JUNO PMTs equipped with implosion protection cover

### Comparison Table

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Unit</th>
<th>MCP-PMT (NNVT)</th>
<th>R12860 (Hamamatsu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detection Efficiency (QE*CE)</td>
<td>%</td>
<td>27%</td>
<td>27%</td>
</tr>
<tr>
<td>P/V of SPE</td>
<td></td>
<td>3.5, &gt; 2.8</td>
<td>3, &gt; 2.5</td>
</tr>
<tr>
<td>TTS on the top point</td>
<td>ns</td>
<td>~12, &lt; 15</td>
<td>2.7, &lt; 3.5</td>
</tr>
<tr>
<td>Rise time/ Fall time</td>
<td>ns</td>
<td>R<del>2, F</del>12</td>
<td>R<del>5, F</del>9</td>
</tr>
<tr>
<td>Anode Dark Count</td>
<td>Hz</td>
<td>20K, &lt; 30K</td>
<td>10K, &lt; 50K</td>
</tr>
<tr>
<td>After Pulse Rate</td>
<td>%</td>
<td>1, &lt;2</td>
<td>10, &lt; 15</td>
</tr>
<tr>
<td>Radioactivity of glass</td>
<td>ppb</td>
<td>238U: 50</td>
<td>238U: 400</td>
</tr>
<tr>
<td></td>
<td></td>
<td>232Th: 50</td>
<td>232Th: 400</td>
</tr>
<tr>
<td></td>
<td></td>
<td>40K: 20</td>
<td>40K: 40</td>
</tr>
</tbody>
</table>
Small PMT system

- JUNO will also have to control the non-stochastic term of the energy resolution at an unprecedented level below (<1%)

→ JUNO will use 3-inch PMTs as a complementary photodetection system in photon-counting mode with:
  - a better control of systematics (stereo-calorimetry)
  - an increased dynamic range (for muons, …)
  - a nice complementary physics potential (precise measurements of $\Delta m^2_{21}$ and $\sin^2(2\theta_{12})$, Supernova neutrinos with unbiased energy and rate meas.)

- 25,000 PMTs from HZC company
- Production started in Jan. 2018
- Already 9,000 accepted in Oct. 18!
- 128 PMTs connected to one underwater electronics box in order to reduce the number of channels
sPMT Production at HZC

- More than 6,000 sPMTs produced and qualified at HZC
  - Yield steadily increased and stabilized at >80% since start of production in January 2018
  - Very good performance so far!

(QE = 25.0%  σ_{SPE} = 32.5%  Dark rate ~ 530Hz  TTS = 1.5ns@3:2 HV ratio)

(Prepulse = 0.35%  Afterpulse = 4.9%  HV ~ 1110V  QE non-uniformity = 5%)

(red dashed lines and arrows indicate acceptance criteria)
SPMT Production

All 26,000 PMTs have been produced and tested!

100% test by HZC

Quality control:
10% sampling test by JUNO at HZC. Measured >2,600, rejected 15.

~3% sampling test by JUNO

Progress of the SPMT system

<table>
<thead>
<tr>
<th>Year</th>
<th>Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>2017</td>
<td>30.7%</td>
</tr>
<tr>
<td>2018</td>
<td>77.5%</td>
</tr>
<tr>
<td>2019</td>
<td>87.8%</td>
</tr>
<tr>
<td>Average</td>
<td>80.5%</td>
</tr>
</tbody>
</table>
Control of the energy scale uncertainty

- The JUNO challenge is to keep energy scale uncertainty below 1%

**New results from ESCAPE workshop (June 2018)**

- Other experiments already achieved 1% accuracy (Daya Bay ~0.5%, Double Chooz 0.74%, Borexino <1% (at low energies), KamLAND 1.4%)

→ JUNO with an unprecedent size needs a accurate energy calibration strategy
JUNO calibration strategy

- The JUNO challenge is to keep energy scale uncertainty below 1%

5 complementary calibration systems under development using $e^-$, $e^+$, $\gamma$ and $n$ sources

- Cable Loop System (CLS)
  - 2D plane inside the vessel

- Guide Tube (GT)
  - 2D around outer surface vessel

- Automatic calibration unit (ACU)
  - 1D along detector z-axis

- Guide Tube

- + Laser fiber system
  - 1D like, fixed position on PMT

- Remotely Operated Vehicle (ROV)
  - 3D anywhere in the vessel
Taishan Antineutrino Observatory (TAO) has several physics motivation:

- Precisely measure the 4-6 MeV bump and the fine structure of reactor antineutrino spectrum with unprecedented energy resolution.
- Provide a benchmark for investigation of nuclear database
- Measure antineutrino spectra from $^{235}$U and $^{239}$Pu after combined with other reactor neutrino experiment.
- Search for sterile neutrino with good vertex reconstruction capability

**JUNO-TAO detector design**

- 1 ton fiducial volume Gd-LS detector at 30 m from core
  → 30 times JUNO event rate
- Full coverage 10 m$^2$ SiPM with 50% PDE operated at -50°C
  → energy resolution of $1.7\%/\sqrt{E}$ (MeV)
- R&D in progress
  → welcome new collaborators!
Milestones and Schedule

2014:
- International collaboration established
- Start civil construction

2015:
- PMT production line setup
- Start CD parts production

2016:
- Start PMT testing
- TT arrived

2017:
- PMT potting starts
- Delivery of surface buildings
- Start production of acrylic sphere

2018:
- Electronics production starts
- Civil work and lab preparation completed
- Detector constructing

2019-2020:
- Detector ready for Data taking!

2021:
- Detector ready for Data taking!
Competitions

✧ RENO-50 – no news since 2016
✧ PINGU – delayed due to funding constraint
✧ T2K – 2018.6-2018.10 SK detector refurbish work done, pure water filling done, starts physics observation in 2019.1, will add 0.01% Gd in a year or two for T2K.
RENO-50

18 kton LS Detector
~47 km from YG reactors
Mt. Guemseong (450 m)
~900 m.w.e. overburden
Summary

🔹 Daya Bay continue data taking by 7 ADs for physics till 2020 --- the world best measurements for \( \theta_{13} \) and \( \Delta m^2_{ee} \), as well as the reactor antineutrino spectrum.

🔹 JUNO has a rich physics program besides mass hierarchy.


🔹 Stereo Calorimetry (LPMT+SPMT), Energy Calibration, and TAO reference detector for fine structure in reactor energy spectrum.

🔹 then go for long physics run for mass hierarchy measurement and other physics in 2022-2027.
Thank you for your attention
Reactor shape uncertainties

✓ “Standard” reactor shape uncertainties have minor impact on the MH sensitivity
✓ But reactor spectrum might show micro-structures

✓ These micro-structures degrade the MH sensitivity by mimicking periodic oscillation pattern

→ reference detector needed for JUNO