Prospects of precision measurement of the neutrino oscillations by JUNO

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On behalf of the JUNO Collaboration
@ CMU, Pittsburg, MENU 2019
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Outline

• Physics and Prospects of precise measurement of the neutrino oscillation by JUNO
  – Neutrino mass hierarchy
  – Reactor neutrino detection and background
  – Expected measurement precision of the neutrino oscillation parameters

• JUNO project status
  – Central detector, Liquid Scintillator, PMT, Calibration, VETO......

• Summary
Weak Interaction

• One may expect a straightforward extension of the SM in which the phenomena of lepton flavor mixing and CP violation emerge for a similar reason. In this case the weak charged–current (CC) interactions of leptons and quarks can be written as:

\[-\mathcal{L}_{cc} = \frac{g}{\sqrt{2}} \left[ \begin{align*} (e \mu \tau)_L \gamma^\mu \ U & \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}_L W^-_\mu + \ (u \ c \ t)_L \gamma^\mu \ V \begin{pmatrix} d \ s \ b \end{pmatrix}_L W^+_\mu \right] + \text{h.c.} \]

where all the fermion fields are the mass eigenstates, \( U \) is the \( 3 \times 3 \) Maki–Nakagawa–Sakata–Pontecorvo (MNSP) matrix, and \( V \) denotes the \( 3 \times 3 \) Cabibbo–Kobayashi–Maskawa (CKM) matrix
The oscillations of neutrinos

$\theta_{12}$ solar neutrino oscillation

$\theta_{23}$ atmospheric neutrino oscillation

$\nu_1 \leftrightarrow \nu_2 \leftrightarrow \nu_3 \leftrightarrow \theta_{13}$

Flavor Eigenstates

$\begin{pmatrix}
V_{e1} \\
V_{\mu 1} \\
V_{\tau 1}
\end{pmatrix} =
\begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\
U_{\tau 1} & U_{\tau 2} & U_{\tau 3}
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}$

Mass Eigenstates

$\begin{pmatrix}
V_{e1} \\
V_{\mu 1} \\
V_{\tau 1}
\end{pmatrix} =
\begin{pmatrix}
\cos \theta_{13} & 0 & e^{-i\delta} \sin \theta_{13} \\
0 & 1 & 0 \\
-e^{-i\delta} \sin \theta_{13} & 0 & \cos \theta_{13}
\end{pmatrix}
\begin{pmatrix}
\cos \theta_{12} & \sin \theta_{12} & 0 \\
-sin \theta_{12} \cos \theta_{13} & \cos \theta_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}$

PMNS Mixing Matrix

Atmospheric, K2K, MINOS, T2K, etc. $\theta_{23} \sim 45^\circ$

Reactor $\theta_{12} \sim 8.7^\circ$

Accelerator $\theta_{13} \sim 8.7^\circ$

Solar $\theta_{12} \sim 30^\circ$

Unknown in the 6 parameters (there are some experimental results less than 3 $\sigma$):

- the neutrino mass hierarchy
- the leptonic CP-violating phase $\delta$
Basic and open questions for neutrino physics

- Neutrino mass hierarchy: normal or inverted?
- Is there CP violation in neutrino mixing?
- Are neutrinos their own antiparticle? (Dirac or Majorana)
- How many neutrinos are there? (Sterile neutrinos?)
- What is the absolute mass scale?
- How does neutrino get mass?

Neutrino as a telescope to study:

- The earth, the sun, the supernova, the cosmic ray ......
Mass Hierarchy

• Motivations
  – MH helps to define the goal of neutrino-less double beta decay (0νββ) search experiments, which aim to reveal whether neutrinos are Dirac or Majorana.
  – MH is a crucial factor for measuring the lepton CP-violating phase, like Hyper-K.
  – MH is a key parameter of the neutrino astronomy and neutrino cosmology.
  – MH is a critical parameter to understand the origin of neutrino masses and mixing.

0νββ mass relationship with MH

Hyper-K experiment, refer to arXiv: 1307.7335
A medium baseline detector would be able to determine Neutrino Mass Hierarchy through vacuum oscillation given non-zero $\sin^2 \theta_{13}$


2012: $\sin^2 \theta_{13}$ is large, opens a door to neutrino Mass Hierarchy

Take $\Delta M^2_{32}$ as reference

- NH: $\Delta M^2_{31} > \Delta M^2_{32}$, $\Delta M^2_{31}$ peak at the right of $\Delta M^2_{32}$
- IH: $\Delta M^2_{31} < \Delta M^2_{32}$, $\Delta M^2_{31}$ peak at the left of $\Delta M^2_{32}$

The big suppression is the “solar” oscillation $\rightarrow \Delta m^2_{21}, \sin^2 \theta_{12}$

The ripple is the “atmospheric” oscillation $\rightarrow \Delta m^2_{31}$ from frequency MH encoded in the phase
Fourier formalism

- A different Fourier formalism:
  \[
  FST(\omega) = \int F(t) \sin(\omega t) dt \\
  FCT(\omega) = \int F(t) \cos(\omega t) dt
  \]
  where $\omega = 2.54\Delta m^2_{23}$, $t = L/E$

- To quantify the symmetry breaking, we define:
  - RV/LV: amplitude of the right/left valley in FCT
  - P/V: amplitude of the peak/valley in FST
  - Define:
    \[
    RL = \frac{RV - LV}{RV + LV}, \quad PV = \frac{P - V}{P + V}
    \]
    - NH: RL>0 and PV>0
      IH: RL<0 and PV<0
  - No pre-condition of $\Delta m^2_{23}$

Clear distinctive features:
- FCT:
  - NH: peak before valley
  - IH: valley before peak
- FST:
  - NH: prominent peak
  - IH: prominent valley

Δχ² as the standard statistics

- With the observed spectrum of measurements, we can fit the (pseudo-data) with both hypotheses (normal and inverted hierarchies), and define Δχ² as our standard statistics.

\[ \Delta \chi^2_{\text{MH}} = |\chi^2_{\text{min}}(\text{NH}) - \chi^2_{\text{min}}(\text{IH})| \]

- For the MH significance
  - Energy resolution of 3%/\text{Sqrt}(E)
  - The baseline at 53 km

Fig. MH sensitivity as a function of the energy resolution (left) and as a function of the distance between the detector and the reactor cores (middle). Δχ² MH contour plot as a function of the energy resolution and the luminosity normalized to 10⁵ events (right).
# JUNO Site

**JUNO has been funded in Feb. 2013. ~ 300 M$ by China**

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

**Overburden ~ 700 m**

- **Kaiping, Jiang Men city, Guangdong Province**
- **Total: 36 GW**
# JUNO Collaboration

- **16 countries**
- **77 institutions**
- **618 members**

<table>
<thead>
<tr>
<th>Armenia</th>
<th>Yerevan Physics Institute</th>
<th>China</th>
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</table>
Rich Physics Program

- 20 kton LS detector
- 3% energy resolution
- 700 m underground
- Rich physics possibilities
  - Reactor neutrino for Mass hierarchy and precision measurement of oscillation parameters
  - Supernovae neutrino
  - Geoneutrino
  - Solar neutrino
  - Atmospheric neutrino
  - Exotic searches including proton decay, dark matter

Inverse Beta Decay (IBD)

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

**Neutrino energy:**

$$E_\nu \approx (T_{e^+} + T_n + (M_n - M_p) + m_{e^+})$$

**Antineutrino selection:**
- Coincidence in time, space and energy
- Cut on the edge of detector to reduce the background

**Antineutrino energy:**
- Determined by the measurement of the IBD prompt positron energy.
IBD signal

• IBD selection criteria in simulation

  • fiducial volume cut $r < 17$ m;
  • the prompt energy cut $0.7 \text{ MeV} < E_p < 12 \text{ MeV}$;
  • the delayed energy cut $1.9 \text{ MeV} < E_d < 2.5 \text{ MeV}$;
  • time interval between the prompt and delayed signal $\Delta T < 1.0 \text{ ms}$;
  • the prompt-delayed distance cut $R_{p-d} < 1.5$ m;
  • Muon veto criteria:
    – for muons tagged by Water Pool, veto the whole LS volume for 1.5 ms
    – for good tracked muons in central detector and water Cerenkov detector, veto the detector volume within $R_{d2\mu} < 3$ m and $T_{d2\mu} < 1.2$ s
    – for the tagged, non-trackable muons in central detector, veto the whole LS volume for 1.2 s
Background of IBD

- **The background estimation**
  - $^8\text{He}$ and $^9\text{Li}$: the $\beta$-n decays from cosmogenic $^8\text{He}$ and $^9\text{Li}$ can mimic IBD interactions, thus are the most serious correlated background to reactor antineutrinos.
  - **Fast neutron**: The energetic neutrons produced by cosmic muons can form a fast neutron background by scattering off a proton and then being captured in the LS detector.
  - $^{13}\text{C}(\alpha, n)^{16}\text{O}$: The alpha particles from the U, Th radio activities can react with the $^{13}\text{C}$ in LS. The $^{13}\text{C}(\alpha, n)^{16}\text{O}$ reaction could lead to a correlated background if the neutron is fast enough or there is a gamma from the de-excitation of the $^{16}\text{O}$ excited states.
  - **Geo-neutrino**: Antineutrinos produced from radioactive decays of Th and U inside the Earth constitute the geo-neutrino flux.

- **The efficiencies of IBD selection cuts, signal and background rate**

<table>
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<tr>
<th>Selection</th>
<th>IBD efficiency</th>
<th>IBD</th>
<th>Geo-$\nu$s</th>
<th>Accidental</th>
<th>$^{9}\text{Li}/^{8}\text{He}$</th>
<th>Fast n</th>
<th>(\alpha, n)</th>
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<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>
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<tr>
<td>Fiducial volume</td>
<td>91.8%</td>
<td>76</td>
<td>1.4</td>
<td>410</td>
<td>77</td>
<td>0.1</td>
<td>0.05</td>
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<tr>
<td>Energy cut</td>
<td>97.8%</td>
<td>76</td>
<td>1.4</td>
<td></td>
<td>77</td>
<td></td>
<td></td>
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<tr>
<td>Time cut</td>
<td>99.1%</td>
<td>73</td>
<td>1.3</td>
<td></td>
<td>71</td>
<td>0.1</td>
<td>0.05</td>
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<tr>
<td>Vertex cut</td>
<td>98.7%</td>
<td>73</td>
<td>1.3</td>
<td></td>
<td>71</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>
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<tr>
<td>Combined</td>
<td>73%</td>
<td>60</td>
<td>1.1</td>
<td>0.9</td>
<td>1.6</td>
<td>3.8</td>
<td></td>
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</table>
• Spectra for the antineutrino signal and five kinds of main backgrounds
Systematics in the MH determination

- **Ideal distribution**: reactor cores with the equal baseline of 52.5 km gives the MH sensitivity of $\Delta \chi^2_{\text{MH}} \approx 16$.
- **The real baseline distribution** of reactor cores in Taishan and Yangjiang NPPs: induces a degradation of $\Delta \chi^2_{\text{MH}} \approx 3$.
- **Daya Bay and Huizhou nuclear power plants**: An additional reduction of $\Delta \chi^2_{\text{MH}} \approx 1.7$ is obtained due to them.
- **The reactor shape uncertainty**: will further degrade the $\Delta \chi^2_{\text{MH}}$ by 1.
- **The statistical and shape uncertainties of backgrounds**: with the estimation contribute $\Delta \chi^2_{\text{MH}} \approx -0.6$ and $-0.1$, respectively.

| Size   | Stat. | Core dist. | DYB & HZ | Shape | B/S (stat.) | B/S (shape) | $|\Delta m^2_{\mu\mu}|$ |
|--------|-------|------------|----------|-------|-------------|-------------|----------------|
| 52.5 km| 1-2   | 1-2        |          | 1%    | 6.3%        | 0.4%        | 1%             |
| $\Delta \chi^2_{\text{MH}}$ | +16   | -3         | -1.7     | -1    | -0.6        | -0.1        | +(4 − 12)      |

- Finally $\Delta \chi^2_{\text{MH}} > 9$, $\sigma > 3$ should be achievable.
- An increase of $\Delta \chi^2_{\text{MH}} \approx +8$, $\sigma \approx 4$ can be obtained by including a measurement of $|m^2_{\mu\mu}|$ at the 1% precision level.
Precision Measurements

- The energy spectrum of 100k antineutrinos of JUNO smeared by energy resolution for 3%/sqrt(E), which can be detected roughly within 6 year.

\[
P_{ee} \left( \frac{L}{E} \right) = 1 - P_{21} - P_{31} - P_{32}
\]

\[
P_{21} = \cos^4(\theta_{13}) \sin^2(2\theta_{12}) \sin^2(\Delta_{21})
\]

\[
P_{31} = \cos^2(\theta_{12}) \sin^2(2\theta_{13}) \sin^2(\Delta_{31})
\]

\[
P_{32} = \sin^2(\theta_{12}) \sin^2(2\theta_{13}) \sin^2(\Delta_{32})
\]

- The neutrino mixing parameters relevant to describe the JUNO energy spectrum are \( \theta_{13}, \theta_{12}, \Delta m^2_{12}, \Delta m^2_{31}, \Delta m^2_{32} \), while only two parameters of \( \Delta m^2 \) are independent.

\( \sin^2 \theta_{13} \) will be precise to 3% in 2020.
**Precision Measurements**

The oscillation parameters’ precision will be better than 1%, which can help to probe the unitarity of PMNS matrix.

### Important systematic errors
- The bin-to-bin (B2B)
- Energy linear scale (EL) uncertainty
- Energy non-linear (NL) uncertainty
- Background (BG)

### Table:

<table>
<thead>
<tr>
<th></th>
<th>Nominal</th>
<th>+ B2B (1%)</th>
<th>+ BG</th>
<th>+ EL (1%)</th>
<th>+ NL (1%)</th>
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<tr>
<td>$\sin^2 \theta_{12}$</td>
<td>0.54%</td>
<td>0.60%</td>
<td>0.62%</td>
<td>0.64%</td>
<td>0.67%</td>
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<tr>
<td>$\Delta m^2_{21}$</td>
<td>0.24%</td>
<td>0.27%</td>
<td>0.29%</td>
<td>0.44%</td>
<td>0.59%</td>
</tr>
<tr>
<td>$\Delta m^2_{31}$ or $\Delta m^2_{32}$</td>
<td>0.27%</td>
<td>0.31%</td>
<td>0.31%</td>
<td>0.35%</td>
<td>0.44%</td>
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</table>
JUNO Event Rates after selection

Supernova $\nu$
5-7k in 10s for 10kpc

Atmospheric $\nu$
several/day

Solar $\nu$
(10s-1000s)/day

Cosmic muons
$\sim$ 250k/day

0.003 Hz/m$^2$
215 GeV
10% muon bundles

36 GW, 53 km

reactor $\nu$, 60/day
Bkg: 3.8/day

20k ton
LS

Geo-neutrinos
1.1/day

215 GeV
10% muon bundles

20
Three phases of supernova, Fischer et al. (Basel group), A&A 517:A80, 2010 [arxiv:0908.1871]

The neutrino event spectra with respect to the visible energy $E_d$ in the JUNO detector for a SN at 10 kpc

<table>
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<tr>
<th>Channel</th>
<th>Type</th>
<th>Events for different $\langle E_\nu \rangle$ values</th>
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<tbody>
<tr>
<td>$\bar{\nu}_e + p \rightarrow e^+ + n$</td>
<td>CC</td>
<td>$4.3 \times 10^3$</td>
</tr>
<tr>
<td>$\nu + p \rightarrow \nu + p$</td>
<td>NC</td>
<td>$6.0 \times 10^2$</td>
</tr>
<tr>
<td>$\nu + e \rightarrow \nu + e$</td>
<td>ES</td>
<td>$3.6 \times 10^2$</td>
</tr>
<tr>
<td>$\nu + ^{12}\text{C} \rightarrow \nu + ^{12}\text{C}^*$</td>
<td>NC</td>
<td>$1.7 \times 10^2$</td>
</tr>
<tr>
<td>$\nu_e + ^{12}\text{C} \rightarrow e^- + ^{12}\text{N}$</td>
<td>CC</td>
<td>$4.7 \times 10^1$</td>
</tr>
<tr>
<td>$\bar{\nu}_e + ^{12}\text{C} \rightarrow e^+ + ^{12}\text{B}$</td>
<td>CC</td>
<td>$6.0 \times 10^1$</td>
</tr>
</tbody>
</table>

Table. JUNO can detect the quantity of neutrino from a galactic SN @10 kpc
Special trigger and buffer memory are designed.

- Distinguish between different $\nu$ flavors
- Reconstruct $\nu$ energies and luminosities
- Almost background free due to time information
Geoneutrino detection

- Geoneutrino: antineutrino from the decay of $^{238}\text{U}$, $^{232}\text{Th}$, $^{40}\text{K}$ in the Earth, occupying 99% radiogenic heat in the earth. Nature. 310 (5974): 191–198

- **Results from Kamland:**
  - PRD 88 (2013) 033001
  - 2002-2012 data: geoneu.

- **Results from Borexino:**
  - PLB 722 (2013) 295
  - 2007-2012 data: geoneu.

**Result of a single toy Monte Carlo for 1-year measurement of JUNO**
- FV 18.35 kton (17.2 m radial cut)
- 80% detection efficiency;
- 3% @ 1 MeV energy resolution

JUNO’s unprecedented size and sensitivity allows for the recording of 300 to 500 geoneutrinos interactions per year. In approximate six months JUNO would match the present world sample of recorded geoneutrino interactions, which is less than 150 events.
Outline

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• Summary
Option selection route

March, 2014: SS truss + Acrylic sphere + Balloon + SS tank

July, 2015: Final decision: Acrylic sphere + SS structure

Balloon + Acrylic support + SS tank

Option selection route

Acrylic sphere + SS truss

Balloon + SS tank

Acrylic module + SS tank

Acrylic sphere + SS tank
Central detector
- Acrylic sphere contains: 20kt Liquid Scintillator
- Steel structure holding:
  ~18000 20” PMT
  ~25000 3” PMT

AS: ID35.4m

SSS: ID40.1m

Top Tracker
Earth Magnetic Field shielding coils

Liquid scintillator and Water Filling system

Water depth and diameter: 43.5m
- Shielding the background
- Making a water Cherenkov with ~2400 20” PMT

AS: Acrylic Sphere; SSS: Stainless Steel Structure
Structure Design & Optimization

- **Optimization:**
  - Reduce the max stress on the acrylic node
  - Simplify the structure, reduce the weight
  - Evaluate the influence from earthquake and fluid solid coupling

- In the LS-Water filled configuration, total net buoyancy: ~3000 tons, counteracted by the connecting bars
- Forces in the connecting bars: Pulling < 9 tons (< 3.5 Mpa) / Pushing < 15 tons (< 3.0 Mpa)
R&D about acrylic

• How about the life time of acrylic?
  – Strength reduce to ~70% for 20 years @ 5.5 Mpa
  – Creep: over 100 years
• Can the spherical panel be made?
  – 3 companies made samples
  – 2017.2 Donchamp won the bid.
• How about the max stress control on acrylic?
  – ≤ 3.5 Mpa, less than 5 Mpa in Daya Bay
• How strong the acrylic node need to be?
  – Max pulling load: ~ 8 tons
  – Break at load: ~100 tons
• How to control the radiation background and the quality of acrylic?
• How to make the bulk-polymerization on site?
Acrylic panels and production line

Be composed of 265 spherical panels, Net Weight: ~600 tons

- A new production lines special for JUNO are finished
- A constant temperature workshop is being made for acrylic panels machining and pre-assembly
1:12 scaling CD prototype

Manufacturing and assembly and test

Tests to be done
- Verify the FEM calculation
- Check the spring effects
- Check the temperature load
- Test the monitor system
- Test the filling/overflow system

Small prototype of acrylic sphere manufacturing

Pre-assembly

Lifting test

Adjusting steel structure

Small prototype and steel cylinder for testing
Low radiation BG for acrylic and steel

- **Low radiation background requirements:**

<table>
<thead>
<tr>
<th>Parts</th>
<th>Mass (t)</th>
<th>$^{238}$U</th>
<th>$^{232}$Th</th>
<th>$^{40}$K</th>
<th>$^{60}$Co</th>
<th>Singles (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acrylic</td>
<td>600</td>
<td>1 ppt</td>
<td>1 ppt</td>
<td>1 ppt</td>
<td></td>
<td>0.39</td>
</tr>
<tr>
<td>Node stainless steel</td>
<td>23.6</td>
<td>0.1 ppb</td>
<td>2 ppb</td>
<td>0.05 ppb</td>
<td>2 mBq/kg</td>
<td>1.9</td>
</tr>
<tr>
<td>Shell stainless steel</td>
<td>583.79</td>
<td>1 ppb</td>
<td>5 ppb</td>
<td>0.2 ppb</td>
<td>20mBq/kg</td>
<td>0.02</td>
</tr>
<tr>
<td>Connection bar</td>
<td>67.18</td>
<td>0.1 ppb</td>
<td>2 ppb</td>
<td>0.05 ppb</td>
<td>2 mBq/kg</td>
<td>0.28</td>
</tr>
</tbody>
</table>

- **Process control for low radiation background**
  - Filter in MMA material
  - Special reaction kettle/pipe
  - Moulding: pure water/clean room
  - Thermoforming: film or placket to shield the dust and radon
  - Bonding: filled with clean air or N$_2$
  - Shield Rn: plastic film on the surface of the acrylic
  - Clean the inner surfaces of the acrylic sphere: air cushion to support
  - Filling: first to fill pure water then replace with LS / LS tank covered with pure N$_2$

In the clean room class 10000 with the radon < 100 Bq/m$^3$, totally exposed time: less than 10 days

The samples for acrylic has met the 1 ppt requirements for U/Th/K.
Liquid Scintillator

- Use one of Daya Bay detectors through replacing the target LS of 20 tons by the produced LS from the pilot plant to test and check:
  - Optimize the recipe
  - Reduce radioactive background
  - Increase the transparency
Liquid Scintillator

- Using a recipe inspired from Daya Bay’s experience
- Tested and changed to be more suitable for JUNO
  - High light-yield VS transparency:
    - 2.5g/L PPO: 1st luminescent material
    - 1-4mg/L bis-MSB: 2nd luminescent material
- Requirements and methods:
  - Attenuation length: > 20 m @ 430 nm with Al$_2$O$_3$ purification
  - Good radio purity:
    - < 10$^{-15}$ g/g in U/Th
    - < 10$^{-16}$ g/g in K

3 methods to reduce the radio BG
- Distillation
- Water extraction
- Steam stripping: Rn/Kr

Linear alkylbenzene (LAB) as solvent

- 3 g/L PPO
- 15 mg/L bis-MSB

The old recipe in Daya Bay

A.L. = Attenuation Length

> 20 m @ 430 nm
20000 20" PMT

- Contracts were signed in 2015
- 15000 MCP-PMT (75%) from NNVT in China
- 5000 Dynode (25%) from Hamamatsu

<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<em>CE</em>area)</td>
<td>%</td>
<td>27%, &gt; 24%</td>
<td>27%, &gt; 24%</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>
</tbody>
</table>
• Work together with the 20-in PMT to provide a double calorimeter system
  – Energy measurement via “photon counting”, better control of systematics
  – Muon tracking, supernova detection …
  – Increase the dynamic range.
  – Increase photon statistics by ~2.5%
• 25000 3-inch PMTs, contracted to HZC (China), which has produced ~10000 3-inch PMTs
Calibration system

• The goal:
  – Overall energy resolution: ≤ 3%/√E
  – Energy scale uncertainty: <1%

• Radioactive sources:
  – $\gamma$: $^{40}$K, $^{54}$Mn, $^{60}$Co, $^{137}$Cs
  – e+: $^{22}$Na, $^{68}$Ge
  – n: $^{241}$Am-Be, $^{241}$Am- $^{13}$C or $^{241}$Pu- $^{13}$C, $^{252}$Cf

• Four complementary calibration systems
  – 1-D: Automatic Calibration Unit (ACU) → for central axis scan,
  – 2-D:
    • Cable Loop System (CLS) → scan vertical planes,
    • Guide Tube Calibration System (GTCS) → CD outer surface scan,
  – 3-D: Remotely Operated under-LS Vehicle (ROV) → full detector scan
Readout Electronics

1F3 scheme

- PMT: photomultiplier tubes
- HV: High Voltage units
- ADU: Analog to Digital Unit
- GCU: Global Control Unit
- CAT cable: Category 5e cable
- High reliability needed
- Severe constraints by power consumption

20-in PMT signals’ waveform are read out by FADC, which is near PMT and guarantee the quality of the analog signals.
Veto Detectors

- **Cosmic muon flux**
  - Overburden: ~700 m
  - Muon rate: 0.003 Hz/m²
  - Average energy: 214 GeV

- **Water Cherenkov Detector**
  - ~4 m water shielding, Radon: <0.2 Bq/m³
  - ~2000 20” PMTs
  - 40 kton pure water, HDPE lining on pool
  - Similar technology as Daya Bay (99.8% efficiency)

- **Compensation Coil for EMF shield**

- **Top muon tracker**
  - Decommissioned OPERA plastic scintillator
JUNO-TAO

- Taishan Antineutrino Observatory (TAO), a ton-level, high energy resolution LS detector at 30 m from the core, a satellite exp. of JUNO.
  - Taishan Nuclear Power Plant, 30-35 m from a 4.6 GW_th core
  - 2000 IBD/day
- Measure reactor neutrino spectrum w/ sub-percent E resolution.
  - model-independent reference spectrum for JUNO (Spectral distortions in the original antineutrino reactor energy spectrum have been pointed out)
  - a benchmark for investigation of the nuclear database
- The design parameters of detector of TAO
  - Ton-level Liquid Scintillator (Gd-LS)
  - Full coverage of SiPM w/ PDE > 50%
  - Operate at -50 °C (SiPM dark noise)
  - 4500 p.e./MeV

The largest discrepancy is 6.3 σ in 4–6 MeV between data & Huber-Mueller model prediction of the spectra.
Summary

• **JUNO: Rich neutrino physics prospects**
  - MH with 3-4 $\sigma$ can be achieved with 6 years data
  - The measurement precision of $\theta_{12}$, $\Delta m^2_{12}$, $|\Delta m^2_{31}|$ will be less than 1%
  - Studies about neutrinos from cosmic background, supernova, earth and sun will be able with quantity and quality

• The detector: a massive LS detector with the precise energy resolution, breaking new ground in LS detection technology
  - The largest acrylic sphere ever constructed
  - 20 ktons of highly transparent LS
  - 18000 20” PMT and 25000 3” PMT
  - 4 calibration subsystems
  - Reference measurement for neutrino energy spectrum by Near detector
Backup
HK experiment

HK is optimized for both appearance and disappearance searches

**ν_μ Disappearance:** determine θ_{23} and Δm_{32}^2

\[ P(ν_μ \rightarrow ν_μ) \approx 1 - \sin^2 2\theta_{32} \sin^2 \left( \frac{Δm_{23}^2 L}{4E_ν} \right) \]

**ν_e Appearance:** determine θ_{13}, constrain δ_{CP}

\[ P(ν_μ \rightarrow ν_e) \approx \sin^2 θ_{23} \sin^2 2θ_{13} \sin^2 \left( \frac{Δm_{31}^2 L}{4E_ν} \right) - \sin 2θ_{12} \sin 2θ_{23} \sin 2θ_{13} \cos θ_{13} \sin^2 \left( \frac{Δm_{23}^2 L}{4E_ν} \right) \]

\[ \sin^2 \left( \frac{Δm_{31}^2 L}{4E_ν} \right) \sin^2 \left( \frac{Δm_{21}^2 L}{4E_ν} \right) \sin δ_{CP} + CPC \]

+ matter + solar terms

For maximum power fit both data samples **jointly**
Hyper-K Sensitivity to $\delta_{CP}$

Errors (%) on the expected number of events

<table>
<thead>
<tr>
<th></th>
<th>$\nu$ mode</th>
<th>$\bar{\nu}$ mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_e$</td>
<td>3.0</td>
<td>2.8</td>
</tr>
<tr>
<td>$\nu_\mu$</td>
<td>5.6</td>
<td>4.2</td>
</tr>
<tr>
<td>Flux &amp; ND</td>
<td>1.2</td>
<td>1.5</td>
</tr>
<tr>
<td>ND-independ. xsect</td>
<td>1.2</td>
<td>1.5</td>
</tr>
<tr>
<td>Far Detector</td>
<td>0.7</td>
<td>1.0</td>
</tr>
<tr>
<td>Total</td>
<td>3.3</td>
<td>3.3</td>
</tr>
</tbody>
</table>

$58\%$ of $\delta$ for $5\sigma$

$76\%$ of $\delta$ for $3\sigma$

CPV discovery sensitivity to $\delta_{CP}=0, \pi$ w/ MH known

Fractional region of $\delta(\%)$ for CPV ($\sin \delta \neq 0$) > 3, 5 $\sigma$

1$\sigma$ uncertainty of $\delta$ as a function of the beam power: < $19^\circ$($6^\circ$) for $\delta = 90^\circ$($0^\circ$)
Hyper-K Sensitivity to MH

Significance for MH determination as a function of Hyper-K lifetime

- Use **atmospherics** for $3\sigma$ mass hierarchy determination.
- $3\sigma$ mass hierarchy determination for $\sin^2\theta_{23} > 0.42$ (0.43) for normal (inverted) hierarchy for 10y data taking.
- Also combine with beam data to enhance physics capability.
HK experiment

Hyper-K Sensitivity to MH

Significance for MH determination as a function of Hyper-K lifetime

- Use atmospherics for 3\sigma mass hierarchy determination.
- 3\sigma mass hierarchy determination for \( \sin^2 \theta_{23} > 0.42 \) (0.43) for normal (inverted) hierarchy for 10y data taking.
- Also combine with beam data to enhance physics capability.
- Taking antineutrino data since 2017, switch back to neutrinos in 2019, run 50% neutrino, 50% anti-neutrino
- Extended running through 2024, test beam program and potential accelerator improvement to enhance ultimate reach

- If $\delta CP = 3\pi/2$, 3 $\sigma$ sensitivity to MH by 2020, $\sim 5$ $\sigma$ by 2024
- 3 $\sigma$ to MH for 30-50% (depending on octant) of $\delta CP$ range by 2024
- 2+ $\sigma$ to CP at $\delta CP = 3\pi/2$ or $\delta CP = \pi/2$ by 2024

**NOvA expectation**
First batch of stainless steel with low background

- the first batch of raw materials for the CD steel structure: ~330 ton, smelting and low radioactive background testing were completed, and the test results met the technical requirements;

<table>
<thead>
<tr>
<th></th>
<th>Radioactive background requirements for steel structure</th>
<th>Sample1 A2802246</th>
<th>Sample2 A2802245</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{238}$U</td>
<td>1 ppb (12.4mBq) /kg</td>
<td>$6.14 \pm 1.69$ mBq/kg</td>
<td>$&lt; 8.3$ mBq/kg</td>
</tr>
<tr>
<td>$^{232}$Th</td>
<td>5 ppb (20mBq) /kg</td>
<td>$&lt; 2.68$ mBq/kg</td>
<td>$&lt; 8$ mBq/kg</td>
</tr>
<tr>
<td>$^{40}$K</td>
<td>0.2 ppb (51.36mBq) /kg</td>
<td>$&lt; 16.10$ mBq/kg</td>
<td>$&lt; 20$ mBq/kg</td>
</tr>
<tr>
<td>$^{60}$Co</td>
<td>20 mBq/kg</td>
<td>$&lt; 0.83$ mBq/kg</td>
<td>$&lt; 1.1$ mBq/kg</td>
</tr>
</tbody>
</table>
Solar Neutrino

- **Sun:** as the benchmark for evolving stars
- **Main challenges:**
  - Radio---purity similar to previous LS experiments (requirements for reactor $\nu$ physics are looser than for solar $\nu$)
  - Cosmogenic background, e.g. long lived $^{11}\text{C}$ under $^8\text{B}$
- **Advantages of JUNO**
  - Large mass/lower E threshold $\rightarrow$ $^7\text{Be}$ and low tail of $^8\text{B}$
  - Precise energy resolution

![Table showing internal radiopurity requirements and cosmogenic background rates](image)

<table>
<thead>
<tr>
<th>Decay Channel</th>
<th>Radioactivity Requirement</th>
<th>Cosmogenic Background Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{210}\text{Pb}$</td>
<td>$5 \times 10^{-24}$ [g/g]</td>
<td>1860 [counts/day/kton]</td>
</tr>
<tr>
<td>$^{85}\text{Kr}$</td>
<td>$500$ [counts/day/kton]</td>
<td>100 [counts/day/kton]</td>
</tr>
<tr>
<td>$^{238}\text{U}$</td>
<td>$1 \times 10^{-16}$ [g/g]</td>
<td>$1 \times 10^{-17}$ [g/g]</td>
</tr>
<tr>
<td>$^{232}\text{Th}$</td>
<td>$1 \times 10^{-16}$ [g/g]</td>
<td>$1 \times 10^{-17}$ [g/g]</td>
</tr>
<tr>
<td>$^{40}\text{K}$</td>
<td>$1 \times 10^{-17}$ [g/g]</td>
<td>$1 \times 10^{-18}$ [g/g]</td>
</tr>
<tr>
<td>$^{14}\text{C}$</td>
<td>$1 \times 10^{-17}$ [g/g]</td>
<td>$1 \times 10^{-18}$ [g/g]</td>
</tr>
</tbody>
</table>

![Graph showing neutrino signal rates and energy distribution](image)

- Assumed radio purity gives $S:B \approx 1:3$
Motivation of TAO

1. Provide reference spectrum for JUNO, to remove model dependence by measuring fine structures
   - Required equal or better energy resolution than JUNO

2. Provide a benchmark to examine nuclear database, measuring fine structures
   - Design TAO w/ as high E resolution as possible (1%)

Energy smearing w/ statistics

Credit: J.R. Hu
Fine Structures

- Large “bump” will not destroy MH sensitivity at JUNO
- Small peaks will bring model dependence → arbitrary sampling tests show no major effect on MH.

Represent the worst case: small peaks are unlikely to follow many oscillation circles in the spectrum

D. Dwyer et al. PRL114, 012502