Status of JUNO experiment

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Reactor neutrinos

- Nuclear power plants are a pure and intense source of electron antineutrinos.
- Antineutrino detection through IBD (Inverse Beta Decay).
  - Relatively large cross section
  - Background rejection using coincidence between positron (prompt) and neutron (delayed) signals
  - $E_{\text{prompt}} = E_{\nu} - 0.8$ MeV
  - Disappearance probability independent from $\theta_{23}$ and CP violation.

History and perspectives of reactor neutrino physics:
- Neutrino discovery (Reines & Cowan, 1956)
- $\theta_{12}$ and $\Delta m^2_{21}$ measurement (KamLAND, 2003)
- Precision $\theta_{13}$ measurement (Daya Bay, RENO, Double Chooz)
- Neutrino mass hierarchy just around the corner (JUNO)
Open question: mass hierarchy

Two possible orderings. Important consequences on neutrinoless double $\beta$ decay.

Normal hierarchy slightly favored from present results (Nova, SK).

In the future, mass hierarchy determination with different methods:

- Matter effect in Long Baseline neutrino beams (DUNE)
- Matter effect in atmospheric neutrinos (PINGU, ORCA)
- Spectrum modification of reactor antineutrinos induced by oscillations with solar-atmospheric parameters interference (JUNO)
Reactor antineutrino disappearance

\[ P_{ee}(L/E) = 1 - P_{21} - P_{31} - P_{32} \]
\[ P_{21} = \cos^4(\theta_{13}) \sin^2(2\theta_{12}) \sin^2(\Delta_{21}) \]
\[ P_{31} = \cos^2(\theta_{12}) \sin^2(2\theta_{13}) \sin^2(\Delta_{31}) \]
\[ P_{32} = \sin^2(\theta_{12}) \sin^2(2\theta_{13}) \sin^2(\Delta_{32}) \]

\[ \Delta_{ij} = \Delta m_{ij}^2 \frac{L}{4E} \]

\[ \Delta m_{31}^2 = \Delta m_{32}^2 + \Delta m_{21}^2 \]

NH: \[ |\Delta m_{31}^2| = |\Delta m_{32}^2| + |\Delta m_{21}^2| \]
IH: \[ |\Delta m_{31}^2| = |\Delta m_{32}^2| - |\Delta m_{21}^2| \]

Antineutrino flux for L=53 km, maximum for solar parameters driven oscillations

Fast oscillations, dependent on mass hierarchy, induced by \( \Delta_{31} \)
JUNO (Jiangmen Underground Neutrino Observatory) is a multipurpose anti-$\nu_e$ detector near Kaiping (South China). Baseline (53 km) from Yangjian and Taishan reactors (10 cores) optimized in the region of maximum $\Delta m^2_{21}$-driven oscillations. Expected to start data taking in 2021.
JUNO experiment detector concept

10^5 events required in 6 years of data taking: 20 ktons of liquid scintillator in a sphere of about 35 m diameter.

Energy resolution 3%/√E(MeV):
- High liquid scintillator light yield and transparency.
- High photocathode coverage and photon detection efficiency.

Energy scale uncertainty < 1%:
- Calibration systems
- Stereo-calorimetry

JUNO will be the largest 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>
JUNO signal and background

Daily event rate after selection 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>Fiducial volume</td>
<td>91.8%</td>
<td>76</td>
<td>1.4</td>
<td>$\sim 5.7 \times 10^4$</td>
<td>84</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Energy cut</td>
<td>97.8%</td>
<td>73</td>
<td>1.3</td>
<td>410</td>
<td>77</td>
<td>0.1</td>
<td>0.05</td>
</tr>
<tr>
<td>Time cut</td>
<td>99.1%</td>
<td>60</td>
<td>1.1</td>
<td>1.1</td>
<td>0.9</td>
<td>1.6</td>
<td></td>
</tr>
<tr>
<td>Vertex cut</td>
<td>98.7%</td>
<td>60</td>
<td>1.1</td>
<td>1.1</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>3.8</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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

JUNO: R < 17.2 m

$\Delta T < 1$ ms

$\Delta R < 1.5$ m

Veto system

0.7 MeV < $E_{\text{prompt}}$ < 12 MeV

1.9 MeV < $E_{\text{delayed}}$ < 2.5 MeV

Careful treatment of cosmogenic $^9\text{Li}/^8\text{He}$ background.

After selection cuts:

60 IBD and 3.8 bkg events/day.
JUNO Physics reach

JUNO designed to reach 3-4 $\sigma$ precision on MH determination (with 100,000 events). But also other measurements possible:

- Oscillation parameters determination ($\theta_{12}$, $\Delta m^2_{21}$, $\Delta m^2_{31}$) at sub-% level.
- Neutrino observation from natural sources (solar, atmospheric, Supernova burst, diffuse Supernova neutrinos, geoneutrinos).
- Exotic searches (Lorentz-Invariance-Violation, Proton decay).

JUNO Collaboration

Collaboration established in 2014
77 institutions, ~600 collaborators
JUNO Experiment

700 m overburden.

Calibration box

Top Tracker:
3 layers of plastic scintillator strips (from OPERA)

Water Cerenkov veto:
35 kton of water and 2000 20” PMTs

Central detector:
20 kton of LS (LAB/PPO/bisMSB) contained inside an acrylic sphere.

Earth magnetic field compensating coils:
residual field < 10%

Stainless Steel Truss:
In water, holding
~18000 20” PMTs
~25000 3” PMTs (75% photo-coverage)
Civil engineering

- 564 m vertical shaft.
- 1266 m long tunnel (40% slope).
- 50 m diameter, 70 m high cavern.
JUNO liquid scintillator composition:
LAB + PPO (2.5 g/l) + bis-MSB (1-3 mg/l)
60 ton of PPO and 24-72 kg of bis_MSBA
needed in total.

Requirements from energy resolution:
High light yield \((10^4 \, \gamma/\text{MeV})\)
Attenuation length: > 20 m @ 430 nm
Good radiopurity: \(^{238}\text{U}/^{232}\text{Th} < 10^{-15} \, \text{g/g}, \)
\(^{40}\text{K} < 10^{-16} \, \text{g/g}.\)

Liquid scintillator purification pilot plant undet test @ Daya Bay:
• Distillation, \(\text{Al}_2\text{O}_3\) column purification, filtration, water extraction, gas stripping.
• Measured attenuation length of purified LAB > 25 m.
• Ongoing studies on radio-impurities.

OSIRIS detector design study for monitoring LS radio-purity at \(10^{-16} \, \text{g/g level}\)
(solar neutrinos specifications) during JUNO filling.
Central detector

The central detector will be built with acrylic panels of 12 cm thickness: about 260 panels for a total weight around 600 tons. The Stainless Steel main structure is connected to the acrylic sphere.

Acrylic requirements:
- 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 $10^{-12}$ g/g for $^{40}$K, $^{238}$U, $^{232}$Th

JUNO CD prototype 1:12 built @ IHEP, complete of FOC (Filling/Overflow/Circulation) systems for testing.
Large PMT system

JUNO will use 20” Photomultipliers as its main photodetection system.

Tight arrangement with a photocoverage of ~ 75%

Two complementary technologies:
- 15000 MCP-PMTs from NNVT
- 5000 dynode PMTs 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*CE)</td>
<td>%</td>
<td>27 (increased to 30)</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 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>After pulse rate</td>
<td>%</td>
<td>1, &lt;2</td>
<td>10, &lt;15</td>
</tr>
<tr>
<td>Glas radioactivity</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>
Large PMT testing

Large PMT production started in 2016. Dedicated facility for testing @PanAsia warehouse, Zhongshan: visual inspection followed by performance test using 2 containers (batch test) and 2 scanning stations (sampling test).

5000 dynode and 8000 MCP PMTS delivered. 11000 PMTs tested in the containers and 1500 in the scanning stations.

PMT potting facility assembled.
Large PMT electronics

The Large PMTs are read-out with full waveform digitization and operated (HV setting) independently. The signal is digitized near the voltage divider.
Small PMT system

JUNO will use also 3-inch PMTs as a complementary photo-detection system in order to improve the control of systematics and increase the dynamic range in photon-counting mode.

25600 PMTs from HZC company.
12000 already produced and in great part tested.

128 PMTs connected to one underwater box, to reduce the electronics channel number.
Calibration system

To keep energy scale uncertainty below 1%, four calibration systems under development, using e-, e+, γ and n sources.

- **Source change module**
- **Spool**
- **Chimney**
- **Source station**

**Cable loop system (CLS)**
2D plane inside vessel.

**Guide tube (GT)**
2D around outer surface vessel

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

**And in addition to this.....**

2 source positioning systems:
- USS (ultrasonic sensor system);
- CCD system.

266 nm laser system to monitor PMT gains.

Temperature monitoring of CD.
Veto system

To handle the cosmogenic background, the experiment is endowed with a VETO system, made by a water Cerenkov with 2000 LPMTs and a Top Tracker. Earth magnetic shielding coils are also part of the system.

Top Tracker made of scintillator strips refurbished from OPERA. Already on JUNO site. New electronics under development.

Water temperature:
\[ T = 21 \pm 1 \, ^{\circ}\text{C} \]

Radon concentration:
\[ < 0.2 \, \text{Bq/m}^3 \]
TAO
(Taishan Anti-neutrino Observatory)

Measure anti-neutrino spectrum at % level to provide:

- a model-independent reference spectrum for JUNO
- a benchmark for investigation of the nuclear database

Ton-scale detector at 30 m from reactor core with higher energy resolution.

Detector characteristics:
- 2.6 t Liquid scintillator detector (1 t FV=4000 interactions/day)
- Full coverage SiPM read-out (50% PDE)
- Operation of liquid scintillator and electronics at -50 °C.
- Expected resolution of ~1.5 %/√E.

Detector description from inner to outside:
- Liquid scintillator with Gd @-50 °C;
- SiPM and support;
- Cryogenic vessel;
- 1-1.5 m water or High Density PolyEthylene shielding;
- Muon detector.

Planned to be operative since 2020.

Welcome collaborators.....
Summary and Conclusions

JUNO is a next generation experiment in neutrino physics and astrophysics.

With its large mass (20 kton of liquid scintillator) and its unprecedented energy resolution (3% @ E=1 MeV), JUNO will address several physics items:

- Neutrino mass hierarchy measurement at 3-4 $\sigma$ level;
- Sub-% precision measurement of oscillation parameters ($\theta_{12}, \Delta m^2_{21}, \Delta m^2_{31}$);
- Solar, supernova, and geoneutrino measurements.

Precise understanding of detector performance with:

- Two independent photo-detection systems (Large and Small Photomultipliers)
- A calibration system with many ancillary sub-systems
- TAO reference detector looking for the fine structure of reactor energy spectrum.

Expected to start data taking in two years from now, during 2021.