JUNO Experiment: Design and Status

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On behalf of the JUNO collaboration
The JUNO Project – Introduction

**Jiangmen Underground Neutrino Observatory**

Multi-purpose experiment but with a main focus:
Measurement of the Neutrino Mass Ordering using reactor electron anti-neutrinos

Neutrinos from two Nuclear Power Plants
26.6 GW$_{th}$ power by 2020 (35.8 GW$_{th}$ final)

JUNO Central Detector
20 kton Liquid Scintillator Target
Underground Laboratory civil construction:

- Slope tunnel completed (1265 m)
- Vertical shaft completed (563 m)
- Excavating the experimental hall
77 institution members from 17 countries! 632 collaborators
Neutrino rates

Proton Decay Search
\[ p \rightarrow K^+ + \nu \]

SN v 5000/10s (10kpc)

Solar v 10-1k/day

52.5km, 36GW

700m underground

20kt LS

Atmospheric v several/day

Muon \sim 250k/day
215GeV
10\% multi-muon

Reactor $\bar{\nu}_e \sim 60$/day

Geo-$\bar{\nu}_e$ 1~2/day
MH and Survival probability

\[ P_{ee} = \left| \sum_{i=1}^{3} U_{ei} \exp \left( -i \frac{m_i^2}{2E_i} \right) U_{ei}^* \right|^2 \]

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

Or to make the effect of the mass hierarchy explicit, exploiting the approximation \( \Delta m^2_{32} \approx \Delta m^2_{31} \):

\[ P_{ee} = 1 - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 (\Delta_{21}) - \sin^2 2\theta_{13} \sin^2 (|\Delta_{31}|) - \sin^2 \theta_{12} \sin^2 2\theta_{13} \sin^2 (\Delta_{21}) \cos (2|\Delta_{31}|) + \frac{\sin^2 \theta_{12}}{2} \sin^2 2\theta_{13} \sin (2\Delta_{21}) \sin (2|\Delta_{31}|) \]

+ NH
- IH

The big suppression is due to the “solar” oscillation \( \Delta m^2_{21} \), \( \sin^2 \theta_{13} \)

The ripple is the “atmospheric” oscillation \( \Delta m^2_{31} \) from frequency MH encoded in the phase “high” value of \( \theta_{13} \) crucial
Methodology to infer the Mass Hierarchy

The determination of the mass hierarchy relies on the identification on the positron spectrum of the “imprinting” of the anti-$\nu_e$ survival probability.

Detection through the classical inverse beta decay reaction

$$\bar{\nu} + p \rightarrow n + e^+ \quad E_\nu > 1.8 \text{ MeV}$$

The time coincidence between the positron and the $\gamma$ from the capture rejects the uncorrelated background.

The “observable” for the mass hierarchy determination is the positron spectrum. It results that $E_{\text{vis}}(e^+) = E(\nu) - 0.8$ MeV.
Requirements for the JUNO Detector

Reactor baseline variation: < 0.5 km
JUNO site in Jiangmen meets this requirements!

Energy resolution: $\sim \frac{3\%}{\sqrt{E(\text{MeV})}}$
This is a crucial parameter!

Energy scale uncertainty:
Large uncertainties and unknown non-linearity could lead to the wrong mass ordering result!
$\Rightarrow$ Meticulous Calibration!
$\Rightarrow$ Double calorimetry via small PMT system

Statistics: 98.5k Events within 6 years!
26.6 GW$_{th}$ reactor power
20 kt detector target ($\sim$ 45 Evts. / Day)
Minimization of the vetoed volume by precise muon track reconstruction

JUNO MH sensitivity with 6 years' data (nominal power):

<table>
<thead>
<tr>
<th>PRD 88, 013008 (2013)</th>
<th>Relative Meas.</th>
<th>Use absolute $\Delta m^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistics only</td>
<td>4$\sigma$</td>
<td>5$\sigma$</td>
</tr>
<tr>
<td>Realistic case</td>
<td>3$\sigma$</td>
<td>4$\sigma$</td>
</tr>
</tbody>
</table>

Energy spectrum of the JUNO $\bar{\nu}_e$ events
(Effect of the energy resolution on the expected signal)
Overall Detector Design

Central detector:
- Acrylic sphere + 20 kton liquid scintillator
- 17571 large PMTs (20-inch)
- 25600 small PMTs (3-inch)
- 78% PMT coverage
- PMTs installed in water buffer

Water Cherenkov muon veto:
- 2400 20” PMTs
- 35 kton ultra-pure water
- Efficiency > 95%
- Radon control → less than 0.2 Bq/m³

Compensation coils:
- Earth magnetic field <10%
- Necessary for 20” PMTs

Top tracker:
- Precision muon tracking
- 3 plastic scintillator layers
- Covering half of the top area

<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 Target Mass [t]</td>
<td>8 x 20</td>
<td>~ 300</td>
<td>~ 1000</td>
<td>20000</td>
</tr>
<tr>
<td>Collected p.e./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>
Central Detector Acrylic Sphere R&D

- SS structure to hold a acrylic sphere and to mount PMTs
  - Supporting bar to hold the Acrylic tank
  - Stress of acrylic <3.5 MPa everywhere
- Main issues:
  - Mechanical precision for 3 mm PMT clearance
  - Thermal expansion matching: 21°C ± 1°C
  - Earth quake and liquid-solid coupling
  - Transparency 96.5%, U/Th/K < 1 ppt
- Started panel production

Panel size: 3m x 8m x 0.12m

Acrylic divided into 200+ panels
### Large PMT array

- 15000 MCP-PMTs from NNVT (Northern Night Vision Technology)
- 5000 dynode PMTs from Hamamatsu (R12860 HQE)
- 17571 PMTs will read out the scintillation light of the Central Detector
- In production since 2016
- PMT testing:
  - Finished for dynode PMTs
  - \(~10000\) of \(15000\) MCP-PMTs already tested

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Unit</th>
<th>MCP-PMT (NNVT)</th>
<th>R12860 Hamamatsu HQE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Det. Efficiency (QE*CE)</td>
<td>%</td>
<td>26.9% (new Type: 30.1%)</td>
<td>28.1%</td>
</tr>
<tr>
<td>Peak to Valley 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>RT<del>2, FT</del>12</td>
<td>RT<del>5, FT</del>9</td>
</tr>
<tr>
<td>Anode Dark Count</td>
<td>kHz</td>
<td>20, (&lt;30)</td>
<td>10, (&lt;50)</td>
</tr>
<tr>
<td>After Pulse Rate</td>
<td>%</td>
<td>1, (&lt;2)</td>
<td>10, (&lt;15)</td>
</tr>
<tr>
<td>Radioactivity (glass)</td>
<td>ppb</td>
<td>(^{238}\text{U}: 50)</td>
<td>(^{238}\text{U}: 400)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(^{232}\text{Th}: 50)</td>
<td>(^{232}\text{Th}: 400)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(^{40}\text{K}: 20)</td>
<td>(^{40}\text{K}: 40)</td>
</tr>
</tbody>
</table>

Protection acrylic cover for protecting implosion chain reaction
Large PMT testing facility

PMT Testing Containers (all PMTs):
• Capacity: 36 (-5) PMTs per Container
• Relative PDE Measurement
  • 1 fixed & 4 rotating reference PMTs
• Four containers
  • 1 & 2 operational
  • 3 & 4 in commissioning
• Magnetic shielding: 10% EMF
• Climate control systems
• Two light sources:
  • stabilized LED
  • Picosecond-Laser

Scanning Station (5-10% of PMTs):
• Provide non-uniformity measurement of PMT parameters
• Study dependence of PMT performance on magnetic field
• Provide a tool for precise PMT studies and cross calibration
JUNO CD Electronics Readout Scheme

- Signal is digitized very close to the PMT voltage divider
- 20000 ch for LPMT & 100 m cable needed
- Dynamic range: 1-4000 PE
- Noise: < 10% @ 1 PE
- Resolution: 10%@1PE, 1%@100 PE
- Failure rate: < 0.5%/6 years
- Final solution: 1 GHz sampling FADC in a small box (×3 ch) in water; all cables in corrugated pipes
Small PMT array

Double calorimetry

Always in photon counting mode

Less non-linearity: calibration of large PMT array

Better dynamic range for high energy signals

Higher granularity of the CD

25600 PMTs in the Central Detector

- 2.5% coverage
- Provided by HZC Photonics (Hainan, PR China)

Can effectively help in:

- Muon tracking (+ shower muon calorimetry)
- Supernova readout
- Solar oscillation parameter measurement

Under water box provides supply for 128 PMTs
(Prototype already built and successfully tested!)
Liquid scintillator: 20 kton of Linear Alkyl-Benzene

Purification of LAB in 4 Steps:

- **Al₂O₃ filtration column**: improvement of **optical properties**
- **Distillation**: removal of **heavy metals**, improvement of transparency
- **Water Extraction**: removal of **radio isotopes** from uranium and thorium chain and furthermore of **⁴⁰K (underground)**
- **Steam / Nitrogen Stripping**: removal of **gaseous impurities** like \(^{39}\)Ar, \(^{85}\)Kr, and \(^{222}\)Rn (underground)

Optical Requirements:
- Light output: \(~10,000\) Photons / MeV \(\rightarrow\) \(~1200\) p.e. / MeV
- Attenuation length: > 20 m @ 430 nm

Required Radio-purity:
- Reactor anti-neutrinos: \(^{238}\)U / \(^{232}\)Th < \(10^{-15}\) g/g, \(^{40}\)K < \(10^{-16}\) g/g
- Solar neutrinos: \(^{238}\)U / \(^{232}\)Th < \(10^{-17}\) g/g, \(^{40}\)K < \(10^{-18}\) g/g, \(^{14}\)C < \(10^{-18}\) g/g

Solvent:
- Linear alkylbenzene (LAB) as solvent
- Fluor:
  - 2.5 g/l PPO
- Wavelength Shifter:
  - 3 mg/l Bis-MSB
Liquid scintillator purification pilot plants (in one Daya Bay detector)

Distillation system
Steam / N₂ Stripping plant
Water Extraction
Ultra pure Nitrogen

LS storage Tank
\( \text{Al}_2\text{O}_3 \text{ column} \)

Paper Stripping & Distillation pilot plants:
OSIRIS - Online Scintillator Internal Radioactivity Investigation System

Liquid Scintillator purity monitor:

Detect radioactive contaminated scintillator after purification but before filling it into the acrylic vessel!

Exploit fast coincidences in the $^{238}$U and $^{232}$Th chains

18t LS volume ($\varnothing=3$ m, $H=3$ m)

Instrumentation:
68x 20” PMTs for the scintillator
12x 20” PMTs for the muon veto

Expected Sensitivity (Simulation): JUNO IBD limit within a few hours
JUNO solar limit possible
Calibration Systems

Overview of JUNO’s Calibration Systems (including laser calibration system)

ACU (Automatic Calibration Unit)

ROV (Remotely Operated Vehicle)

Guide Tube System

Cable Loop System
JUNO TAO - Taishan Antineutrino Observatory

Measure reactor anti-neutrino spectrum with high resolution

- Provide model-independent reference for JUNO
- Possible improvement of nuclear databases
- Shed light on reactor spectrum anomaly (5 MeV bump)
- 30 × JUNO statistics

TAO Design Features: at the Taishan NPP

- Detector placed at 30 m distance from one reactor core
- 2.6 ton Gd-LS as target material (1 ton fiducial target)
- 10 m² SiPM, with 50% PDE, Coverage: > 94%
- SiPMs and LS cooled down to -50 °C

Expected Performance:

- ∼ 4500 p.e. / MeV collected charge
- Energy Resolution: ∼ 1.7% @ 1 MeV, < 1.0% above 3 MeV

Planned to be online in 2021!
Schedule & Milestones

2014
- Int. Collaboration established!

2015
- PMT production line setup
- Start civil construction
- CD parts R&D

2016
- Start PMT production
- Start CD parts production

2017
- Start PMT testing
- Top Tracker arrived!
- Daya Bay LS tests

2018
- PMT potting start
- Delivery of surface buildings
- Start production of acrylic sphere
- OSIRIS was funded
- TAO working group formed

2019-20
- Electronics production starts
- Civil work and lab preparation completed
- Detector construction

2021
- Detector filled & commissioned
- TAO ready
- Detector ready

Data Taking

INFN
Istituto Nazionale di Fisica Nucleare
Thanks you for your attention!