Developing the MCP-based 20-inch spherical Photomultipliers

Xing Wang

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On behalf of the collaboration group
Motivation

For the next generation neutrino experiments in China

To solve the mysteries of the universe by measuring neutrino particles. Relies on a large number of 20-inch diameter photomultipliers.

- Rich physics possibilities
  - Mass hierarchy
  - Precision measurement of mixing parameters
  - Atmospheric Neutrinos
  - Geo-Neutrinos
  - Solar Neutrinos

**JUNO, Jiangmen Underground Neutrino Observatory (Former Daya Bay II)**

- Muon detector
- Steel Tank
- Water seal
- 20kt water
- 6kt MO
- ~15000 20” PMTs coverage: ~80%
Challenges compared with KamLAND (Kamioka Liquid Scintillator Antineutrino Detector, Japan 2002)

<table>
<thead>
<tr>
<th></th>
<th>KamLAND</th>
<th>JUNO</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Detector</strong></td>
<td>~1 kt Liquid Scintillator</td>
<td>20 kt Liquid Scintillator</td>
</tr>
<tr>
<td><strong>Energy Resolution</strong></td>
<td>6%/(\sqrt{E})</td>
<td>3%/(\sqrt{E})</td>
</tr>
<tr>
<td><strong>Light yield</strong></td>
<td>250 p.e./MeV</td>
<td>1200 p.e./MeV</td>
</tr>
</tbody>
</table>

More photons, how and how many?

<table>
<thead>
<tr>
<th></th>
<th>KamLAND</th>
<th>JUNO</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>High transparent LS</strong></td>
<td>15m</td>
<td>25m</td>
</tr>
<tr>
<td><strong>High light yield LS</strong></td>
<td>1.5g/l PPO</td>
<td>5g/l PPO</td>
</tr>
<tr>
<td><strong>Photocathode coverage</strong></td>
<td>34%</td>
<td>80%</td>
</tr>
<tr>
<td><strong>High QE PMT</strong></td>
<td>20%</td>
<td>30%</td>
</tr>
</tbody>
</table>

Requirements for photodetectors

- Large area photocathode
- Temperature /Magnetic environment
- Low cost
- High QE

The QE of 20” PMT-R3600

Large area PMTs of Hamamatsu
MCP-PMT R&D collaboration

Started at 2009, the same time as LAPPD

Microchannel-Plate-Based Large Area Photomultiplier Collaboration (MLAPC)

2 Institutes, 1 University, 4 Companies
The R&D plan

The design of the IHEP-MCP-PMT

The project of Daya Bay II

- **2009-2010**
  - IHEP
  - Beginning
  - 5” MCP-PMT

- **2011 Prototype**
  - Collaboration 8” MCP-PMT
  - QE=20%
  - Trans—photocathode

- **2012 Prototype**
  - Collaboration 8” MCP-PMT
  - QE=20%
  - Trans—photocathode
  - Ref—Photocathode

- **2013 Prototype**
  - Collaboration 12” Dynode PMT
  - QE=SBA
  - Trans—photocathode
  - Ref—Photocathode

- **2014 Prototype**
  - Collaboration 20” MCP-PMT
  - QE=SBA
  - Trans—photocathode
  - Ref—Photocathode
Status

- Design
- Glass shell
- MCP
- Photocathode
- Prototype

![Diagram of Cherenkov light, Photocathode, MCPs, Anode]

5-inch 8-inch
The design of new MCP-PMT

- Using two sets of Microchannel plates (MCPs) to replace the dynode chain
- Using transmission photocathode (front hemisphere) and reflection photocathode (back hemisphere)

**LAPPD concept**

**Next generation**

**Conventional PMT**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quantum Efficiency (QE)</td>
<td>20%</td>
</tr>
<tr>
<td>Collection Efficiency (CE)</td>
<td>70%</td>
</tr>
<tr>
<td>Detection Efficiency (DE)</td>
<td>$Q_E_{Trans} \times CE = 14%$</td>
</tr>
</tbody>
</table>

**New PMT**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quantum Efficiency (QE)</td>
<td>$Q_E_{Trans} = 30%$, $Q_E_{Ref} = 30%$</td>
</tr>
<tr>
<td>Collection Efficiency (CE)</td>
<td>70%</td>
</tr>
<tr>
<td>Detection Efficiency (DE)</td>
<td>$Q_E_{Trans} \times CE + TR \times Q_E_{Ref} \times CE = 30%$</td>
</tr>
</tbody>
</table>
The Simulation work

- Simulate the possibility of the 20” spherical MCP-PMT
  - Electron Multiplier: small size MCP (φ=18mm);
  - Photocathode area: transmission + reflection, nearly $4\pi$ effective area ;
  - Could the small MCP collect all the photoelectrons from the photocathode?

Lorentz-3D EM simulation results shows that nearly all the photoelectrons could be collected by the small MCP.
The large area glass shell

- We have already got the 5 inch ~20-inch glass shell
  - with very good **water resistance** characteristics (to be submerged in liquid for long time)
  - With very low **radioactive background** (to reduce the background rates)

<table>
<thead>
<tr>
<th>Sample</th>
<th>U238</th>
<th>Th232</th>
<th>K</th>
<th>U238</th>
<th>Th232</th>
<th>K</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Bq/kg</td>
<td>Bq/kg</td>
<td>Bq/kg</td>
<td>ppb</td>
<td>ppb</td>
<td>ppm</td>
</tr>
<tr>
<td>Glass--YC</td>
<td>4.31</td>
<td>3.46</td>
<td>6.95</td>
<td>349.1</td>
<td>851.2</td>
<td>224.0</td>
</tr>
<tr>
<td>± 0.23</td>
<td>± 0.30</td>
<td>± 0.81</td>
<td></td>
<td>± 18.6</td>
<td>± 73.8</td>
<td>± 26.1</td>
</tr>
<tr>
<td>quartzite--YC</td>
<td>3.14</td>
<td>4.03</td>
<td>14.87</td>
<td>141.8</td>
<td>639.6</td>
<td>237.1</td>
</tr>
<tr>
<td>± 0.48</td>
<td>± 0.32</td>
<td>± 1.70</td>
<td></td>
<td>± 38.9</td>
<td>± 78.7</td>
<td>± 54.9</td>
</tr>
<tr>
<td>quartzite --7#</td>
<td>≤ 0.50</td>
<td>≤ 0.33</td>
<td>≤ 1.82</td>
<td>≤ 40.5</td>
<td>≤ 81.2</td>
<td>≤ 58.8</td>
</tr>
<tr>
<td>quartzite --8#</td>
<td>≤ 0.47</td>
<td>≤ 0.31</td>
<td>≤ 1.72</td>
<td>≤ 38.1</td>
<td>≤ 76.3</td>
<td>≤ 55.6</td>
</tr>
<tr>
<td>DayaBay</td>
<td>0.64</td>
<td>0.5</td>
<td>2.7</td>
<td>51.8</td>
<td>123.0</td>
<td>87.2</td>
</tr>
<tr>
<td>JUNO</td>
<td>0.149</td>
<td>0.106</td>
<td>0.403</td>
<td>12.1</td>
<td>26.1</td>
<td>13.0</td>
</tr>
</tbody>
</table>

Low background gamma spectrometer measurements
The low cost MCP

Based on our design, we can accept small MCP with some defects.

- Asymmetric surface
- Blind channels
- Non-uniform gains
- Flashing channels

<table>
<thead>
<tr>
<th>Diameter mm</th>
<th>Pore size μm</th>
<th>Volume resistance MΩ</th>
<th>Gain (800V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>18</td>
<td>6</td>
<td>70-250</td>
<td>&gt;7000</td>
</tr>
<tr>
<td>26</td>
<td>10</td>
<td>50-300</td>
<td>&gt;2500</td>
</tr>
<tr>
<td>33</td>
<td>12</td>
<td>80-300</td>
<td>&gt;3000</td>
</tr>
</tbody>
</table>

8 inches x 8 inches uniform MCP, Gain~10000, LAPPD

Low cost, 18mm and 33mm MCPs are supplied by North Night Vision Technology Limited Company (NNVT)
Main processes in PMT production

1. Cleaning of all materials
2. Selecting of MCPs
3. Assembling and wiring of the electrodes
4. Sealing of the glass shell and stem
5. Leak detection
6. Photocathode activation
7. Sealing in vacuum
The photocathode deposition

Oven
400 °C, 10^{-7} Pa

Measurement

Monitor

Control panel

Non-transfer system

Burle system at ANL

Photocurrent

Time
Different deposition processes

Bialkali (Sb-K-Cs):
matches the wavelength of Cherenkov light (350-410 nm)

\[ \text{Sb} + \text{K} \rightarrow \text{K}_3\text{Sb} \]
\[ \text{K}_3\text{Sb} + \text{Cs} \rightarrow \text{K}_2\text{CsSb} \]
Uniformity

- Scanning photocathode platform
  - 3D rotation
  - 8-inch PMT
  - Moveable in x, y, z
  - QE, uniformity

2D display of the PC

3D display of the PC in Matlab software
Quantum efficiency

QE test system and result

\[ QE_{pc} = \frac{I_{PD,\text{trans}}}{I_{PMT,\text{trans}}} \cdot \frac{I_{PC}}{I_{PD}} \cdot QE_{PMT} \]
Prototype with horizontal MCPs

QE ~ 29%@410nm

I-V curve

P/V~ 1.6 @ 2100V
Gain=1.5*10E7

Single Photoelectron Spectrum
Prototype with vertical MCPs

I-V curve

P/V~ 2.1 @ 2100V
Gain=5*10E7

Single Photoelectron Spectrum
Near future work

• Vacuum transfer system
  ➢ 8, 12, 20 inch PMT prototype
  ➢ Chamber 1: alkali source, anode, and other glow discharge part
  ➢ Chamber 2: photocathode deposition, hot seal
  ➢ Chamber 3: MCP scrubber

• 20-inch PMT mass production
<table>
<thead>
<tr>
<th>Effective area</th>
<th>20 inches x 20 inches</th>
<th>8 inches x 8 inches</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quantum efficiency</td>
<td>30%</td>
<td>24%</td>
</tr>
<tr>
<td>Readout electronics</td>
<td>Simple</td>
<td>Complicated</td>
</tr>
<tr>
<td>Time resolution</td>
<td>2-3 nanoseconds</td>
<td>&lt; 100 picoseconds</td>
</tr>
<tr>
<td>Volume</td>
<td>Large</td>
<td>Small</td>
</tr>
<tr>
<td>Cost</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Applications</td>
<td>Neutrino experiments</td>
<td>Neutrino experiments, medical applications, etc</td>
</tr>
<tr>
<td></td>
<td>Success in 8 inches MCP-PMT, 20 inches PMT will come on June</td>
<td>The first 6 cm photodetector will come to world on May</td>
</tr>
</tbody>
</table>
Other Research Areas in XIOPM

• Streak camera

The streak camera is an ultra high-speed detector which captures light emission phenomena occurring in extremely short periods.

Features

• Simultaneous measurement of light intensity on both temporal and spatial axis
• Superb temporal resolution (<0.2 ps)
• Measurement ranges from X-rays to the near infrared rays
• Ultrahigh sensitivity (single photoelectron can be detected)

Guide to streak cameras, Hamamatsu
Other Research Areas in XIOPM

• **Streak camera** *National funding: 160M CNY for 42 months*

Applications
- Dynamics: semiconductor physics, photochemistry
- Diagnostics: electron and photon beam profile in advanced light source and accelerator *(APS/AWA)*
- Plasma physics: high energy laser nuclear fusion
- Ultrafast electron diffraction

Streak tubes made in XIOPM  Compact streak camera
Other Research Areas in XIOPM

• Ultrafast electron diffraction

Ultrafast electron diffraction (UED) has the potential for real-time imaging of structural changes on atomic length scales, thus promising to make a profound impact on a large area of science including biology, chemistry, nano and material sciences™

High resolution
  • 100 fs
  • sub-Angstrom

Experimental setup

UED facility in XIOPM

Diffraction pattern of polycrystalline Al film (20 nm)

Summary

• 8-inch MCP-PMT prototype using non-transfer system (finished)
  – Fabrication and evaluation
  – High QE, single photoelectron spectrum, good uniformity

• 20-inch MCP-PMT prototype production using transfer vacuum system (coming soon)

• Streak cameras and ultrafast electron diffraction (possible collaboration?)
Thanks
What I learned

• Advanced design of MCP-PMT
• Sealing of a nonfunctional MCP-PMT
• Photocathode growth by MBE
• MCPs and their measurements using phosphor screen and cross delay lines

• The cooperation with a large team
• The American style of writing a proposal
• The management of a big project in America

• Very appreciate the two business trips to Berkeley and Cornell
• Communications and potential cooperation with ANL, BNL, LBNL and UIUC

Thanks all of you! Hope I have chance to come here again! Welcome to Xi’an!
Quantum Efficiency with 6 types of Photocathodes

QE curves of 6 types

Wavelength (nm)

QE (%)
Super-K and Hamamatsu
### Hyper-Kamiokande Overview

- **Water Cherenkov**, proved technology & scalability:
  - Excellent PID at sub-GeV region >99%
  - Large mass → statistics always critical for any measurements.

<table>
<thead>
<tr>
<th>Volume Type</th>
<th>Volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Volume</td>
<td>0.99 Mton</td>
</tr>
<tr>
<td>Inner Volume</td>
<td>0.74 Mton</td>
</tr>
<tr>
<td>Fiducial Volume</td>
<td>0.56 Mton (0.056 Mton × 10 compartments)</td>
</tr>
<tr>
<td>Outer Volume</td>
<td>0.2 Mton</td>
</tr>
</tbody>
</table>
| Photo-sensors             | • 99,000 20”Φ PMTs for Inner Detector (ID) (20% photo-coverage)  
• 25,000 8”Φ PMTs for Outer Detector (OD) |
| Tanks                     | • 2 tanks, with egg-shape cross section 48m (w) × 50m (t) × 250 m (l)  
• 5 optically separated compartments per tank |

25 x Super-Kamiokande
Overall Schedule

- **2013**: Complete conceptual design, complete civil design, & bidding
- **2014**: Start civil construction, complete prototyping (PMT & detector)
- **2015**: PMT production line manufacturing
- **2016**: Start PMT production, start detector production or bidding
- **2017**: Complete civil construction, start detector construction & assembly
- **2018**: Start LS production
- **2019**: Complete detector assembly & installation, & LS filling