# A New Optical Model for the 20-inch PMTs of JUNO

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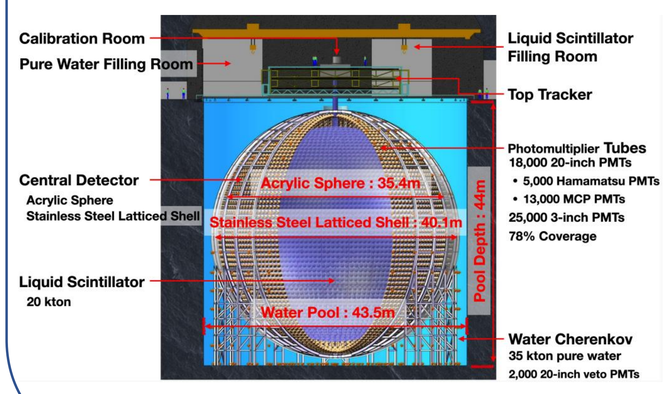
## Introduction

Photomultiplier tubes (PMTs) are widely used in scintillation and Cherenkov detectors for their great performances on photon detection. For example, the Jiangmen Underground Neutrino Observatory (JUNO) will use 17,612 20-inch PMTs in its central detector to achieve an unprecedented energy resolution of $3\%/\sqrt{E[\mathrm{MeV}]}$. It's critical to construct a reliable and accurate optical model to describe the angular and spectral responses of PMTs in their working media. Based on the optical theory of multilayer thin films and a GEANT4-based simulation toolkit, we establish a new optical model for the 20-inch PMTs used in JUNO, including the MCP-PMT manufactured by NNVT company and the dynode PMT manufactured by Hamamatsu company. In this model, both light interactions with the PMT window and optical processes inside PMTs are taken into consideration.

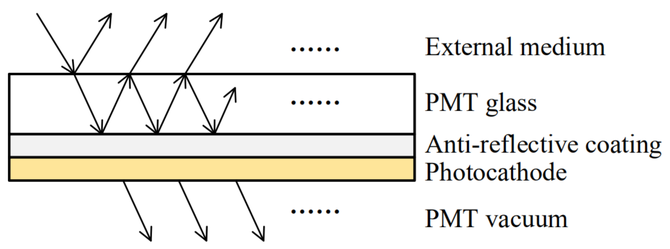


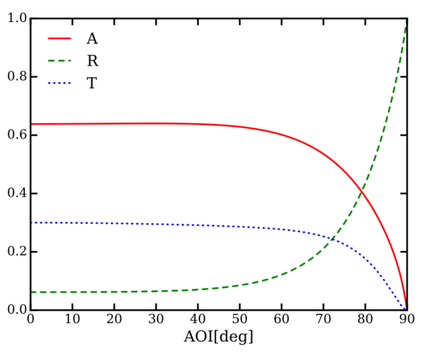

Hamamatsu R12860 NNVT MCP-PMT

## Optical Processes in PMT

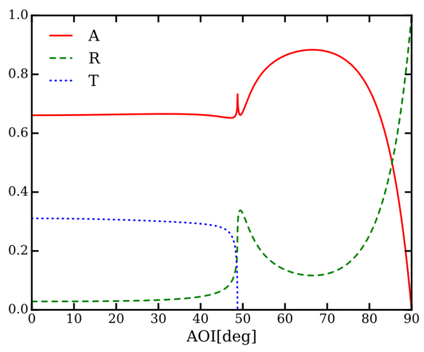
### PMT Window

- Layered structure
- **Anti-reflective coating** (ARC) and **photocathode** are thin films
- Multiple reflections




PMT in air

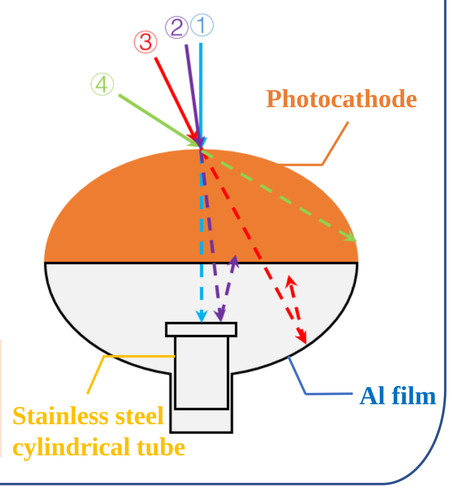



PMT in water

**Total internal reflection** happens between photocathode and PMT vacuum when working in water.

### Reflections inside PMT

① Directly hit on dynode or MCP, no reflection
② Reflected by metal tube
③ Reflected by bottom Al film
④ Directly hit on photocathode




◆ The reflection, transmission and absorption of PMT window can be calculated with multilayer thin film theory
◆ Using GEANT4 to track the photons inside PMT

## Modeling of Detection Efficiency

- Photon detection efficiency (PDE) measured in experiment is contributed by several points on photocathode, due to inner reflections

$$\mathrm{PDE} = \sum_i a_i \cdot \boxed{\rho_i \cdot CE_i} = \sum_i a_i \cdot \boxed{F_i}$$

$a_i$: absorption ratio to the incident light
$\rho_i$: probability of photoelectron escaping from photocathode

- By choosing $n$ reference points on photocathode, the PDE of each point can be denoted as the weighted average of their F-factors

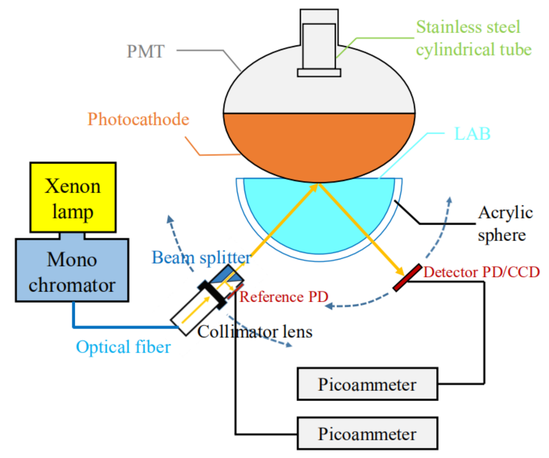
$$\mathrm{PDE_i} = \sum_{k=0}^{n} A_{ik} F_k \quad \xrightarrow{\text{Matrix Form}} \quad \begin{pmatrix} \mathrm{PDE}_1 \\ \mathrm{PDE}_2 \\ \vdots \\ \mathrm{PDE}_n \end{pmatrix} = \begin{pmatrix} A_{11} & \cdots & A_{1n} \\ \vdots & \ddots & \vdots \\ A_{n1} & \cdots & A_{nn} \end{pmatrix} \begin{pmatrix} F_1 \\ F_2 \\ \vdots \\ F_n \end{pmatrix}$$

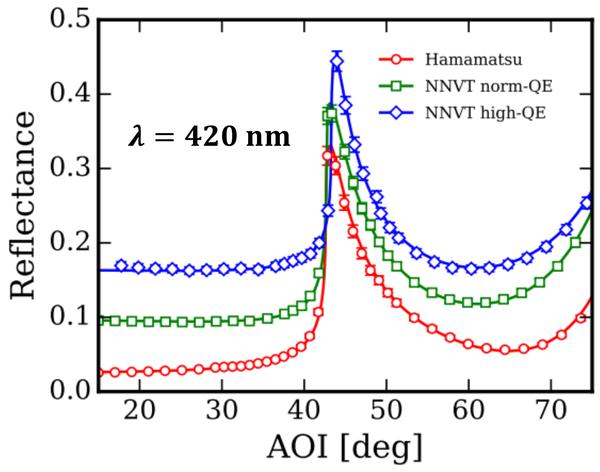
- The left-hand side can be determined by performing PDE measurements
- The A-matrix can be obtained using Monte Carlo simulation with the new optical model
- The F-factors are crucial input of the simulation to predict the PDE at any incident point and any direction

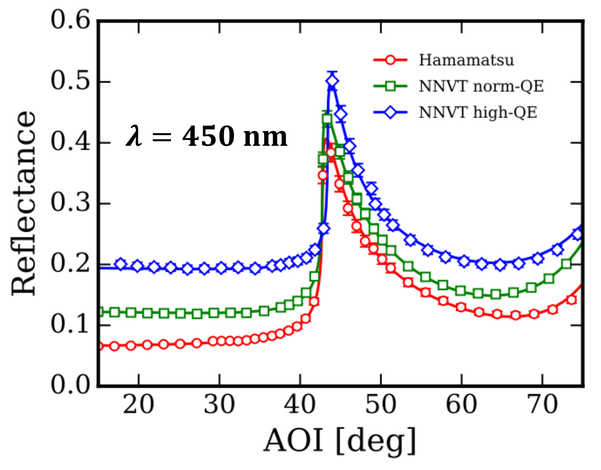
## Experimental Test

### Reflectance vs angle of incidence (AOI)

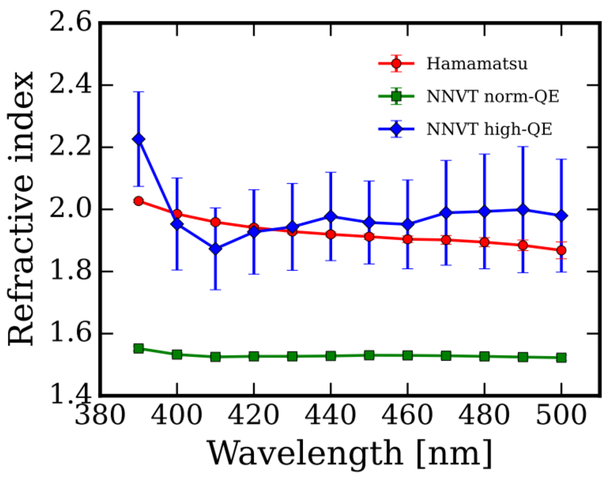
- Measure the reflectance of PMT window **in liquid** (LAB)
- **Three types of PMTs measured**
  - Hamamatsu R12860
  - NNVT High-QE PMT
  - NNVT normal-QE PMT
- **Wavelength:** 390~500 nm
- Extract optical parameters of ARC and photocathode by **fitting** reflectance data

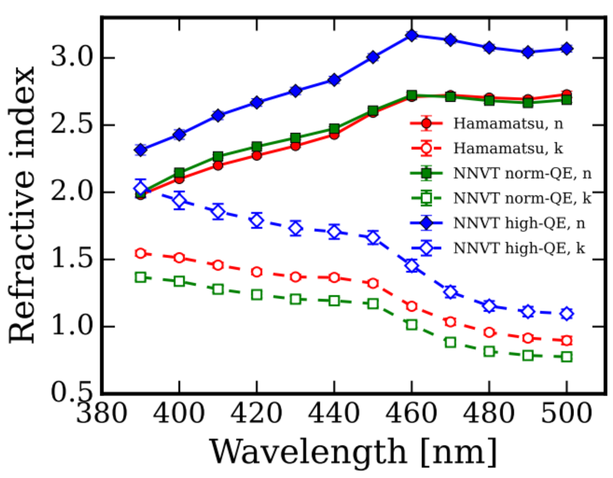



### Optical parameters of ARC and photocathode

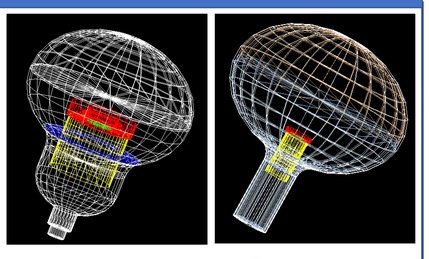


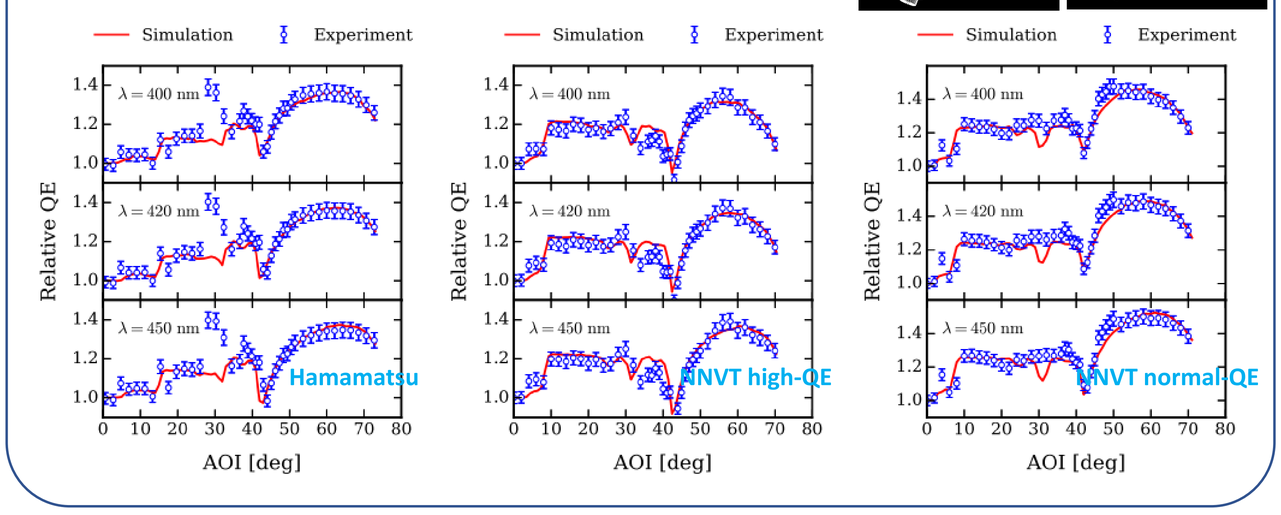




| Thickness [nm] | Hamamatsu | NNVT High-QE | NNVT Normal-QE |
|---|---|---|---|
| **ARC** | $32.6 \pm 0.5$ | $6.3 \pm 1.3$ | $26.5 \pm 8.4$ |
| **Photocathode** | $20.8 \pm 0.2$ | $19.0 \pm 0.4$ | $20.3 \pm 0.2$ |

## Simulation of QE Angular Response

- Detailed PMT Geometry model implemented
- ARC and photocathode are defined as an optical surface between PMT glass and vacuum
- User-defined optical process on thin films






## Conclusion

- A new PMT optical model based on multilayer thin film theory, experimental tests and GEANT4 simulation has been established and validated
- Key optical parameters of ARC and photocathode obtained by fitting reflectance data
- A new method is proposed to model the experimental data of PDE

◆ *For more details please refer to* ***arXiv:2204.02703***

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