Overview of new detector technologies for neutrino experiments

Zhimin Wang (王志民)
IHEP, CAS, China

The 21st International Workshop on Neutrinos from Accelerators (NUFACT2019)
Daegu, Korea
Aug. 29, 2019
Contents

• Challenges from Neutrino Detection
• Detectors of Neutrino Experiments
• Developing for Future Directions
Face to the Challenges

Neutrino mass ordering
Neutrinoless-double-beta-decay (NLDBD)
Neutrino Mass
CP violation phase

Testing the three-favor paradigm
Precision measurements of mixing parameters
Neutrino-nucleus interactions over a wide range of energies
Face to the Challenges

Sterile Neutrinos
Non-Standard Neutrino Interactions
Non-Standard Neutrino Interactions with Dark Matter
Neutrino Tridents
Non-Unitarity
Lorentz Violation
Neutrino Decays
Heavy Neutral Leptons
Ultra-light dark matter
Large Extra-Dimensions
Neutrino Dipole Operators
BSM Physics with Tau Neutrinos
Face to the Challenges

Neutrino & Neutrino BSM

Accelerator neutrinos
Reactor neutrinos
Cosmogenic Neutrinos

Neutrino oscillation
Neutrino interaction
Neutrino properties
Neutrino astrophysics/cosmology

Energy Frontier
Intensity Frontier
Cosmic Frontier
Face to the Challenges

Neutrino & Neutrino BSM

Accelerator neutrinos
Reactor neutrinos
Cosmogenic Neutrinos

Neutrino oscillation
Neutrino interaction
Neutrino properties
Neutrino astrophysics/cosmology

Energy Frontier
Intensity Frontier
Cosmic Frontier

Pion decay-in-flight
Muon decay-in-flight
Pion decay-at-rest
Isotope decay-at-rest

Geo
Solar
Big Bang
Supernovae
Atmospheric
Solar Atmospheric
High-energy astrophysical

......
Face to the Challenges

Neutrino-nucleus interactions over a wide range of energies
Precision measurements of mixing parameters
Testing the three-favor paradigm
Neutrino mass ordering

Sterile Neutrinos
Neutrino Tridents
Non-Unitarity
Lorentz Violation
Neutrino Decays
Heavy Neutral Leptons
Ultra-light dark matter
Large Extra-Dimensions
Neutrino Dipole Operators
BSM Physics with Tau Neutrinos
Non-Standard Neutrino Interactions
Non-Standard Neutrino Interactions with Dark Matter

Neutrino oscillation
Neutrino interaction
Neutrino properties
Neutrino astrophysics/cosmology

Neutrinoless-double-beta-decay (NLDBD)
CP violation phase
Neutrino Mass
Coherent neutrino

Accelerator neutrinos
Reactors neutrinos
Cosmogenic Neutrinos

Pion decay-in-flight
Muon decay-in-flight
Pion decay-at-rest
Isotope decay-at-rest

Geo
Solar
Big Bang
Supernovae
Atmospheric
Solar Atmospheric
High-energy astrophysical
......
Face to the Challenges

Few MeV neutrinos from reactors
Few 100MeV to a few GeV in long-baseline experiments
UHE cosmogenic neutrinos...

Accelerator neutrinos
Reactor neutrinos
Cosmogenic Neutrinos
Face to the Challenges

Scintillator Detectors
Noble Liquid Detectors
Water Cherenkov Detectors
Ice Detectors
Photodetectors
Calorimetry
Gas Detectors
Silicon/Germanium Detectors
Superconducting Detectors
Quantum Sensors

Accelerator neutrinos
Reactor neutrinos
Cosmogenic Neutrinos
Face to the Challenges

<table>
<thead>
<tr>
<th>Scintillator Detectors</th>
<th>Low energy threshold</th>
</tr>
</thead>
<tbody>
<tr>
<td>Noble Liquid Detectors</td>
<td>Low background</td>
</tr>
<tr>
<td>Water Cherenkov Detectors</td>
<td>Large mass</td>
</tr>
<tr>
<td>Ice Detectors</td>
<td></td>
</tr>
<tr>
<td>Photodetectors</td>
<td></td>
</tr>
<tr>
<td>Calorimetry</td>
<td></td>
</tr>
<tr>
<td>Gas Detectors</td>
<td>High efficiency</td>
</tr>
<tr>
<td>Silicon/Germanium Detectors</td>
<td>Better Reconstruction</td>
</tr>
<tr>
<td>Superconducting Detectors</td>
<td>Fast timing</td>
</tr>
<tr>
<td>Quantum Sensors</td>
<td>PID</td>
</tr>
<tr>
<td></td>
<td>High voltage delivery</td>
</tr>
<tr>
<td></td>
<td>Cold electronics design</td>
</tr>
<tr>
<td></td>
<td>Beam-generated Fluxes</td>
</tr>
<tr>
<td></td>
<td>Directional detectors for low-energy neutrinos</td>
</tr>
<tr>
<td></td>
<td>Precise measurement of vertex substructure in neutrino scattering</td>
</tr>
</tbody>
</table>
Face to the Challenges

Scintillator Detectors
Noble Liquid Detectors
Water Cherenkov Detectors
Ice Detectors
Photodetectors
Calorimetry
Gas Detectors
Silicon/Germanium Detectors
Superconducting Detectors
Quantum Sensors

(Micro-)electronics
Calibration systems
Trigger and Data Acquisition
(Automated) event reconstruction
Computing and Machine Learning
# Face to the Challenges

<table>
<thead>
<tr>
<th>Detector Types</th>
<th>Challenges</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scintillator Detectors</td>
<td>Low energy threshold, Low background, Large mass</td>
</tr>
<tr>
<td>Noble Liquid Detectors</td>
<td>High efficiency, Better Reconstruction, Fast timing, PID</td>
</tr>
<tr>
<td>Water Cherenkov Detectors</td>
<td></td>
</tr>
<tr>
<td>Ice Detectors</td>
<td></td>
</tr>
<tr>
<td>Photodetectors</td>
<td></td>
</tr>
<tr>
<td>Calorimetry</td>
<td></td>
</tr>
<tr>
<td>Gas Detectors</td>
<td></td>
</tr>
<tr>
<td>Silicon/Germanium Detectors</td>
<td></td>
</tr>
<tr>
<td>Superconducting Detectors</td>
<td></td>
</tr>
<tr>
<td>Quantum Sensors</td>
<td></td>
</tr>
</tbody>
</table>

- **Accelerator neutrinos**: 
  - Reactor neutrinos
  - Cosmogenic Neutrinos

- **Beam-generated Fluxes**: 
  - Directional detectors for low-energy neutrinos
  - Precise measurement of vertex substructure in neutrino scattering

- **(Micro-)electronics**: 
  - Calibration systems
  - Trigger and Data Acquisition
  - (Automated) event reconstruction

- **High voltage delivery**: Cold electronics design

- **Few MeV neutrinos from reactors**: Few 100MeV to a few GeV in long-baseline experiments
  - UHE cosmogenic neutrinos...
Water detectors

A few MeV to over 100 GeV interactions

Kamiokande (1983-1996)
Super-Kamiokande (1996- now)
SK-Gd
Hyper-Kamiokande (plan to start 2026)

3kton
50kton
258 kton

A N T A R E S
KM3NeT-ORCA
KM3NeT-ARCA

Over GeVs interactions

Cherenkov light

Large mass
Direction
Ice detectors

Multi-component MeV to EeV neutrino detection

- seven strings, exact geometry still under optimization
- ~120 modules/string, 2–3m vertical spacing in deep ice
- precision calibration and GeV-scale neutrino physics
- funded, deployment in 2022–23
Optical module seems the baseline option for large neutrino telescopes.
finer granularity, good timing, directional sensitivity, lower dark noise, less sensitive to Earth magnetic field, etc.

Hamamatsu R12199-02

Hyper-K multi-PMT module R&D

ET Enterprises
**JUNO-TAO**

- 8-in R5912 (192 per AD)
- 8-in R1408 ** (~9,300)
- 20-in PMTs (~18,000)
- 20-in (~40,000 per tank)
- 20-in R3600 (11,146)
- 17-in R7250 (554)

* 1,800 were equipped with light concentrators
** each PMT was equipped with a 27 cm diameter concentrator
**LS detectors**

(1 ~20k ton; <MeV ~ 10s MeV)

<table>
<thead>
<tr>
<th>Detector</th>
<th>PMTs</th>
<th>PE/MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bx</td>
<td>2212 PMTs</td>
<td>~500 PE/MeV</td>
</tr>
<tr>
<td>DC</td>
<td>390 PMTs</td>
<td>~180 PE/MeV</td>
</tr>
<tr>
<td>DB</td>
<td>190 PMTs</td>
<td>~180 PE/MeV</td>
</tr>
<tr>
<td>KamLAND</td>
<td>1880 PMTs</td>
<td>~250 PE/MeV</td>
</tr>
<tr>
<td>JUNO</td>
<td>17000 PMTs</td>
<td>~1200 PE/MeV</td>
</tr>
</tbody>
</table>

**SNO+**

- 780 t, 6 m
- ~9300 PMTs

\[ \lambda^\circ = \text{mean illumination per channel @ center} \]

\[ \lambda \leq 0.5 \Rightarrow \sim \text{photon-counting regime} \]
Search for new scintillation medium with Scalability, Stability, Compatibility and Photon-yield

Cleaner and Brighter (Purification)

Metallic-ion loadable (M-doped LS)

Pulse-shape discrimination

Directionality
  - PID and background rejection
  - Water-based Liquid Scintillator (WbLS) and Slow liquid scintillator

Achieve both a high light yield and direction reconstruction

From Mingfang
Directional Liquid Scintillator

A Cherenkov-visible Scintillation Liquid is the key to future LS detectors:

- Oil-based scintillator: reducing scintillation light or slowing scintillation decay-time to allow Cherenkov imaging
- Water-based Liquid Scintillator (WbLS)
- Fast photosensors/electronics (LAPPD)
- Liquid Scintillator Imaging

LSND rejects neutrons by a factor of 100 at ¼ Cherenkov & ¾ Scintillation light (NIM A388, 149, 1997).
Directional detector

**Interference filters**

Cerenkov/scintillation separation by wavelength sorting

- **Cut off**

- **506 nm Long-Pass: LAB+PPO Transmitted Light beta source, LAB+PPO target, transmitted light shows clearly separated Cherenkov peak!**
Liquid Argon Scintillation Light

- LAr is a scintillator that emits about 40,000 ph/MeV (E = 0) when excited by MIP -at nominal DUNE SPE = 500 V/cm the yield is approximately 24,000 ph/MeV (reduced due to recombination)

- Ionization radiation in LAr results in formation of excited dimer \( \text{Ar}_2^* \)
  - photon emission follows through de-excitation of singlet \( ^1\Sigma \) and triplet \( ^3\Sigma \) states
  - photons emitted in a narrow band around 128 nm (VUV region)
  - de-excitation from \( ^1\Sigma \) is fast with \( \tau_{\text{fast}} \approx 6 \text{ ns} \)
  - de-excitation from \( ^3\Sigma \) is slow with \( \tau_{\text{slow}} \approx 1.3 \mu\text{s} \)
  - ratio of fast and slow components dependent on the ionizing particle through ionization density of LAr (0.3 for e\(^-\); 1.3 for \( \alpha \); 3 for n)
  => basis for PID capability

Higher light yield
Photon and charge
PID
Cleaner

Light collection (VUV region)
Charge collection
Noble Element Detectors

Sub-KeV to few GeV, kg to few 10 kt

The Short-Baseline Neutrino Program at Fermilab

- Noble Element Detectors for Accelerator Neutrino Physics
  - Optimally Granular Charge Collection and Electronics
  - Efficient and High-Quality VUV Light Detection
  - Delivery of Very High Voltage
  - Calibration of a large detector system.

- Noble Detectors for Neutrinoless Double Beta Decay Searches
  - Energy Resolution
  - Material Screening and Radio purity
  - Topology
  - Daughter Tagging
  - High Voltages and Long Drift Lengths
  - Calibration
  - Isotope Enrichment
DUNE Challenges

- So far largest LAr TPC operated ICARUS 2 x 235t (active) \(\rightarrow\) 1 DUNE FD module will be ~10kt
- Several new challenges to scale to DUNE. Need prototypes to develop solutions scalable for DUNE
- Engineering aspects
  - Test full scale detector elements used in DUNE, for SP
  - Installation sequence and test procedures
  - Long term operation stability
- Physics aspects
  - Benchmark reconstruction performance
  - dQ/dx recombination
  - calibration techniques
  - Characterize hadron – argon interactions

The biggest small prototype (1/20 of one DUNE module)
2 11x11x11 m³ cryostats
2 LAr TPC technologies, SP and DP
750t of LAr \(\rightarrow\) 420t active TPC
ArgonCube Modules

Opaque dielectric G10 structure (200 kV/cm @ 1 cm)
Transparent to tracks:

<table>
<thead>
<tr>
<th></th>
<th>LAr</th>
<th>G10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rad. Lengt (cm)</td>
<td>14.0</td>
<td>19.4</td>
</tr>
<tr>
<td>Had. Int. Length (cm)</td>
<td>83.7</td>
<td>53.1</td>
</tr>
</tbody>
</table>

Maximise active volume. Minimise dead material.

Charge readout:
Compact, mechanically robust, and unambiguous

Light readout:
Compact, dielectric, and large area coverage

ARAPUCA concept

- ARAPUCA is the light trap
  - Dichroic (short-pass) filter to trap wavelength-shifted light inside ARAPUCA reflective cell
  - p-Terphenyl on outer surface TPB on inner surface (trapped)
  - Provides segmentation along beam direction

ND280:
SuperFGD
Photodetectors

- **PMT**: low noise, detection of single photons with nanosecond timing
- **LAPPD** (Large Area Picosecond Photodetector): timing to <100 ps and more immune to magnetic fields
- **Silicon Photomultipliers (SiPMs):** solid
  - Small but economical, and when cooled, have dark noise levels competitive to PMTs.
  - Sensitive in VUV, release the limiting needs for secondary wavelength shifters.
  - Lower high voltage, Low power consumption
  - Not affected by magnetic fields, Robust, Negligible aging effects, Mass production
  - Cross-talk, After-pulsing.
- **Superconducting transition edge sensors (TES)**
  - Fast and high efficiency
  - Challenges: to build larger arrays and readout technology

20-inch PMTs

Photons detection is fundamental to particles’ detection at ranging from liquid nitrogen up to room temperature.
In 2015, the MCP-PMT work group did the best to improve the CE of the MCP modules, and finally, the CE of the MCP-PMTs was improved from 70% to 100%.
**LAPPD features**

- Glass/ceramic body
- Large Active Area: 195 x 195 mm\(^2\)
- Picosecond timing resolution
- mm spatial resolution
- QE >20% w/bi-alkali photocathode
- Fused Silica/Borosilicate window
- Flat square geometry, high filling factor
- Lower Cost per Unit Area

Active area 92%

Peak Gain >> 10^6 @ low voltages

Transit Time Spread 64 psec electronics limited (with 40pS FWHM laser pulses)

Dark count rate 30-60 Hz/cm\(^2\)
• **Electronics**

• **Trigger and Data Acquisition**
  - Extract the data at high bandwidth from the tracking detectors without adding a prohibitive burden of material due to the large number of drivers and the power and cooling
  - Data volume to be produced will be at PB scale, which will require significant DAQ infrastructure and computation resource.

• **Computing and Machine Learning**
  - Overtaken more traditional approaches based on expert hand-tuning and found natural applications in a variety of areas in particle physics
    - Deep Learning for Detector Reconstruction, Data Reconstruction using Deep Neural Networks for LArTPCs, End-to-end Deep Learning for Particle and Event Identification, Identification of Double-beta Decay Events, Computational and Real-time Inference Challenges
    - Deep Learning on FPGAs for CMS Level-1 Trigger and DAQ, Track Reconstruction in High-pileup Collider Environment, Integrated Research Software Training in HEP
Summary

• Facing to the challenges on neutrino detection
  • Large mass
  • Low background
  • Low energy threshold
  • Directional detectors

• Interesting technologies developing and needed for better detectors
• Interesting Precise detectors for short baseline
• Neutrino BSM & Neutrino Detector
Thank you for your attention!
Backup
DUNE

- Precise measurement of neutrino oscillations parameters, particularly $\delta_{CP}$ violation phase and determination of mass hierarchy
- Detection of galactic-core supernovae neutrinos
- Nucleon decay
- Search for NSI (Non Standard Interactions)

Far Detector

- Located 4850 ft (1500 m) underground at SURF, enables low-energy and atmospheric neutrino physics
- Four 10 kton (fiducial) LArTPC modules, with single and dual phase detector designs
- Integrated photon detection systems

Single Phase
- Active height: 12 m
- Active length: 58 m
- Maximum drift: 3.5 m
- Wire spacing: 5 mm
- Wire channels: 384,000
- Phot. det. ch.: 6000

Dual Phase
- Active width: 12 m
- Active length: 60 m
- Maximum drift: 12 m
- CRP pixel size: 3 mm
- CRP channels: 153,600
- PMT channels: 720

Design drift field: 500 V/cm
Electron drift speed at 500 V/cm: 1.6 mm/µs
ICARUS T600 Detector

- Two identical LArTPC modules
  - 476 tonnes total fiducial mass
  - Two drift modules per module sharing central cathode
  - 1.5 m drift length
  - ~500 V/cm drift field (~1.6 mm/μs drift velocity)
- Three wire planes with 3 mm pitch (0°, ±60° wrt horizontal)
  - Two induction and one collection (last plane)
  - ~54,000 total wires
  - 400 ns sampling time
- VUV scintillation light read out by PMTs coated in wavelength shifter
MicroBooNE TPC

- 170 tonnes of liquid argon (90 tonnes active).
- Cathode at -70 kV. $E_{\text{drift}} \approx 273$ V/cm.
- **Maximum drift length: 2.5 m.** Drift time: 2.3 ms.
- Three wire planes to reconstruct 3D interaction. 3 mm wire pitch. **8256 channels.**
- Two induction planes with 2400 wires each at $\pm 60^\circ$ from vertical. One collection plane with 3456 vertical wires.
- Cold front-end electronics.
- 2 MHz digitization with warm electronics.
JUNO 20-inch PMTs selection

- Multiple vendors: \{A, B, C, \ldots\}
- Award fractions of certain combination: \{\eta_A, \eta_B, \eta_C, \ldots\}, \Sigma \eta_i = 1
- The best combination of different products was determined by selecting the maximum total score

\[
S = \sum_{i \in \{A,B,C,\ldots\}} (P_{i,\text{spec}} + P_{i,\text{price}} + P_{i,\text{committee}}) \cdot S_i \cdot \eta_i
\]

Final Choice in Dec 2015
15k MCP-PMT from NNVVT
5k dynode-PMT (R12860-50) from Hamamatsu
**Incom MCPs**

Glass capillary arrays functionalized in-house with ALD

Gain Uniformity in 203mm X 203mm MCP

Gain >$10^7$

**MCPs are a separate product line.**
Standard dimensions DIA33mm, SQ53mm, SQ60mm, SQ127mm, SQ200mm. Curved MCPs.

**Gain Uniformity**

**Figure 8:** Average gain image “map” (<15% overall variation). 8” MCP pair 20μm pore, 60:1 L/D ALD-MCP pair. ~7 x $10^5$ gain, 0.7mm inter-MCP gap at 200V.

**Figure 9:** 20 cm ALD MCP pair background, 500 sec, 0.03 events/cm² sec. Overall background ~8× better than standard glass MCPs (less K+).

**Dark count rate**

- 0.3 Hz/cm²

**Dark count rates per 13.5cm² strip**

- At optimal operation conditions @ 50V extraction voltage, 875V-900V MCP voltage with Dark count rate 30-60 Hz/cm²

**Peak Gain >> $10^6$ @ low voltages**

**Typical Single PE Pulses**

- FWHM: 1.1 nsec
- Rise time: 850 psec

**Transit Time Spread**

- 64 psec
- Electronics limited (with 40pS FWHM laser pulses)
SiPM

- SiPM are matrices of avalanche photo diodes with a common cathode that are operated in Geiger mode.
  - Operates under a substantially lower high voltage than the PMT
  - Low power consumption
  - Not affected by magnetic fields
  - Robust, since it is not affected by light as much as PMTs
  - Negligible aging effects, on the contrary to what happens to PMTs
  - Mass producible and their price is fastly decreasing.
  - Cross-talk between neighboring photo-cells
  - After-pulsing.
Superconducting transition edge sensors (TES)

- A transition-edge sensor is a thermometer made from a superconducting film operated near its transition temperature.
- It allows to push measurement to the point that quantum effects become the dominant effect limiting the sensitivity of the technique.
  - One design allows the device to obtain low timing jitter, 18.4 ps, and high absorption efficiency 99.9% at 775 nm.
  - **Challenges**: to build larger arrays (tens of thousands of pixels) while striving for an energy resolution allowing for the detection of individual photons.
  - Superconducting detector readout technology.
Organic sensors

• These ultra-thin organic sensors – with carbon instead of silicon as material converting light into electrical signals – can be applied to CMOS chips over large and small surfaces, as well as to glass or flexible plastic films.

• more sensitive to light than the conventional silicon versions, with the advantage of simple and cheap to produce.
• Calorimetry
  • Imaging Calorimeters
  • Crystal and Homogenous Calorimetry
  • Precision Timing for Calorimeters
    • Picosecond time resolution.
    • Modern image processing technology,
    • Low-cost, high-light-yield, fast and radiation-tolerant organic and inorganic scintillators.
    • Further advances in Silicon Photomultiplier (SiPM) technology
    • Low-cost radiation-tolerant electro-optical transceivers,
    • Continued development of GEANT to match the new information being used in calorimeters
• Micro-Pattern Gas Detectors
  • MPGD Applications
    • Gas Electron Multiplier (GEM), Micro-Mesh Gaseous Structure (MicroMegas, MM), THick GEMs (THGEM), also referred to in the literature as Large Electron Multipliers (LEM), GEM-derived architecture (-REWELL), Micro-Pixel Gas Chamber (-PIC), and integrated pixel readout (InGrid) are being optimized for a broad range of applications.

• Silicon Detectors
  • Silicon-based Detectors in Cosmology
    • Astronomical CCD cameras
  • Silicon-based Detectors for Dark Matter Detection
    • CCD arrays to directly search for dark matter
    • Germanium CCDs
    • Si(Li) detectors to indirectly search for dark matter
  • Ionization pixel detectors with integrated-circuit readout
  • Silicon Detectors for Collider Experiments
    • Development of fast timing sensors based on LGADs
    • Monolithic Silicon Pixel detectors (MAPS)
  • 3D Si sensors
  • Substrate engineering
  • 3D integrated IC and small pixel sensors
  • Direct access to industrial vendors and foundry processes