ArgonCube
novel approach to large mass tracking detectors for neutrino physics

International Session-Conference of the Section of Nuclear Physics of the Physical Sciences Department of the Russian Academy of Sciences "Physics of fundamental interactions" dedicated to 50th anniversary of Baksan Neutrino Observatory Nalchik, June 2017

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AEC/LHEP University of Bern
Towards multi-kt high granularity detectors

High-precision measurements era for neutrino physics

<table>
<thead>
<tr>
<th>Normal Ordering ($\Delta m^2 = 0.97$)</th>
<th>Inverted Ordering (best fit)</th>
<th>Any Ordering</th>
</tr>
</thead>
<tbody>
<tr>
<td>bfp $\pm 1\sigma$</td>
<td>3$\sigma$ range</td>
<td>bfp $\pm 1\sigma$</td>
</tr>
<tr>
<td>$\sin^2 \theta_{12}$</td>
<td>0.304$^{+0.013}_{-0.012}$</td>
<td>0.270 $\rightarrow$ 0.344</td>
</tr>
<tr>
<td>$\theta_{12}$</td>
<td>33.48$^{+0.75}_{-0.75}$</td>
<td>31.29 $\rightarrow$ 35.91</td>
</tr>
<tr>
<td>$\sin^2 \theta_{23}$</td>
<td>0.452$^{+0.022}_{-0.023}$</td>
<td>0.382 $\rightarrow$ 0.643</td>
</tr>
<tr>
<td>$\theta_{23}$</td>
<td>42.3$^{+3.0}_{-1.6}$</td>
<td>38.2 $\rightarrow$ 53.3</td>
</tr>
<tr>
<td>$\sin^2 \theta_{13}$</td>
<td>0.0218$^{+0.0010}_{-0.0010}$</td>
<td>0.0186 $\rightarrow$ 0.0250</td>
</tr>
<tr>
<td>$\theta_{13}$</td>
<td>8.50$^{+0.20}_{-0.21}$</td>
<td>7.85 $\rightarrow$ 9.10</td>
</tr>
<tr>
<td>$\delta_{CP}$</td>
<td>366.3$^{+69}_{-22}$</td>
<td>0 $\rightarrow$ 360</td>
</tr>
<tr>
<td>$\frac{\Delta m^2}{10^{-3} eV^2}$</td>
<td>7.50$^{+0.19}_{-0.17}$</td>
<td>7.02 $\rightarrow$ 8.09</td>
</tr>
<tr>
<td>$\frac{\Delta m^2}{10^{-3} eV^2}$</td>
<td>$+2.457^{+0.087}_{-0.087}$</td>
<td>$+2.317$ $\rightarrow$ $+2.607$</td>
</tr>
</tbody>
</table>

Table 2. Three-flavor oscillation parameters from our fit to global data after the NOW 2014 conference [1]. The results are presented

M.C.Gonzalez-Garcia et al., Nuc.Phys. B00(2015)1-16

CP-violation in lepton sector ($\delta$ phase)
Neutrino mass hierarchy
Ultra-low cross-section physics
(e.g. Proton decay)

Present state-of-art:
Water Cerenkov ( Super-K )
Bulk scintillators ( Daya Bay, (D)-Choos )
Liquid Argon TPC ( ICARUS, uBooNE, SBND)

Need:
Larger detectors
Higher resolution
Higher granularity

Example: DUNE far detector

- Active mass 12 kton
- Drift distance 12 meters
- Drift times of the order of 10 ms
- Ultra-high argon purity required (<0.1ppb oxygen equivalent impurities)
- High voltage of the order of MV!
Liquid Argon Time Projection Chamber

![Diagram of Liquid Argon Time Projection Chamber]

- Charge yield (MIP): \( \sim 9000 \text{ e/mm (1.5 fC/mm)} \)
- \( T_0 \) by scintillation

Charge readout:
- X: Induction (non-destructive)
- Y: Collection
ARGONCUBE concept

**Challenges:**

- Keeping high purity in enormous volume
- Ultra-high voltage (\(\sim\) MV) -> large size & stored energy
- Wire readout -> pileup -> Reconstruction ambiguity

**ArgonCube:**

- Volume split to modules in common cryostat
- Low voltage -> low risk associated with breakdown
- Pixel readout -> simple reconstruction

LAr anomalous dielectric strength studied in detail by our group:

JINST 11 (2016) no.03, P03017.

Simple solutions for severe challenges
Modular TPC — performance

- ArgonCube modular structure
  - Total argon volume split by ~1-10 ton modules
  - High active mass-ratio (95%)
  - Transportable modules
  - Unified modules → high redundancy
  - Step-by-step commissioning
  - Extract module → repair → re-insert
  - Scalable and extendable (same tech. for ND and FD)
  - Iterative upgrade with new technologies

Allows efficient detector start-up
Drastically reduced cost of failures
ARGONCUBE module (collaboration with CERN)

Module: an independent TPC

- Individual thermal/purity management

- Cathode bias (-100 kV) supplied via HV feed-through

- Relatively low voltage => breakdown-free setup

- Electrically transparent container => low dead volume

- Drift time ~ 0.5 ms => reduced purity requirements

- Mechanically robust production technology

- Low failure cost

- Charge readout: pad arrays, e.g. 4x4 mm$^2$ pads

- Light readout via WLS light guides & SiPMs

Reliable/repairable self-contained unit
Pixelized TPC readout (collaboration with BNL, LBNL, USA)

Pixels (pads) charge readout
- PCB-technology for R/O plane manufacturing
- 8x8 pads ROIs served by cold ASICs
- Unambiguous event reconstruction
- High track reconstruction efficiency
- High accuracy of kinematics reconstruction
- High overall detection efficiency
- Challenge for data compression (~ 1M ch/module)

Improves reconstructed physics accuracy
Scintillating light detection (collaboration with JINR, Russia)

- Tetraphenil-butadiene (TPB) as primary WLS
- Kuraray green fibers as secondary WLS
- SiPMs as photon detectors
- SiPM dark current at 87K is $O(\text{Hz})$ at 1 p.e.
- Estimated efficiency — 1%

Efficient light collection from large area

TPB: 128 nm → 420 nm
WLS fiber or bar 420 nm → 500 nm
Scintillating light detection (collaboration with JINR, Russia)

- Tetraphenil-butadiene (TPB) as primary WLS
- Bar light guide as secondary WLS
- Dichroic mirror to keep 500 nm photons inside
- SiPMs as photon detectors
- SiPM dark current at 87K is $O(\text{Hz})$ at 1 p.e.
- Measured efficiency — 1%

Mechanically very robust

LAr scintillation light 128 nm

TPB: 128 nm $\rightarrow$ 420 nm

WLS bar light guide 420 nm $\rightarrow$ 500 nm

Dichroic mirror
At LHEP, Bern - 4 tons prototype

Vacuum insulated cryostat
4 modules in G10/FR4 containers
67x67 cm$^2$, 1.8m high
Argon volume $\sim 0.6$ m$^3$ per module
Argon mass $\sim 820$ kg per module
Active mass $\sim 750$ kg per module
Drift length 33 cm
Cathode bias 33 kV

Test all involved novel solutions at a reduced scale, verify mechanical and thermal simulations.
Obtain reconstructed tracks of cosmic ray events.
DUNE Near Detector

Foam insulated cryostat

Cryostat dimensions 5 x 7 x 4 m$^3$

15 modules

1 x 1 m$^2$, 2 m high

Argon volume ~ 2 m$^3$

Argon mass ~ 2.8 t per module

Active mass ~ 2.6 t per module

Total Active mass — 39 t

Drift length 0.5m, cathode bias 50 kV

High performance, low operational risks

Potentially scalable to FD scale (future upgrades)
Summary

ARGONCUBE concept — an optimal solution for large, scalable tracking detector.

Fully modular structure

- High active mass ratio (95%)
- Unified modules → high redundancy
- Step-by-step commissioning: «democratic» construction and incremental installation
- Repairing single module without stopping data taking
- Scalable and extendable (same tech. for ND and FD)
- Iterative upgrade with new technologies
- Low cost of module failure

Short-drift length modules

- Relatively low electric potentials — reduced risk for breakdowns
- Reduced purity requirements

Pixel charge readout

- Up to 50% increase in reconstruction efficiency w.r.t. wire readout
- Improved accuracy of kinematical event reconstruction

ARGONCUBE is accepted as the technology for DUNE Near Detector.
Thank you!
Backup slides
Charge readout baseline (final goal) option

Pad array divided into Regions Of Interest (ROI)
- ROI is a 8x8 pad area
- Pad size to be optimized, baseline is 4x4 mm$^2$
- One ROI – one readout ASIC
- Charge amplifier, ADC, zero suppression logic, data MUX
- Wake-up channel sensing early induction signal
- Low power in wait-state (2 to 5 W/ton)
- Low pad capacitance (~5 pF)
- ENC ~ 500 e-
- Detection threshold 165 keV for LET (1 MIP), S/N=10

Top tracking performance for a kton-scale TPC
Module insertion
Breakdown in liquid Argon: detailed study (combined LHEP+FNAL)
ARGONTUBE

Cosmic ray events

Free electron life time >2ms

S/N ratio MIP near R/O ~30

Drift time ~4 ms
@ ~400 V/cm

Voltage reached: >400 kV

Experience gained, problems learned, conclusion made:

More than 100 kV in LAr is not easy!
Liquid argon properties
http://atlas.web.cern.ch/Atlas

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atomic number</td>
<td>18</td>
</tr>
<tr>
<td>Atomic weight (u)</td>
<td>39.94</td>
</tr>
<tr>
<td>Radiation length (cm)</td>
<td>14.2</td>
</tr>
<tr>
<td>Absorption length (cm)</td>
<td>83.6</td>
</tr>
<tr>
<td>Molière radius (cm)</td>
<td>10.1</td>
</tr>
<tr>
<td>Critical energy (MeV)</td>
<td>30.5</td>
</tr>
<tr>
<td>( &lt; \text{DEmip} \ (1 \text{ cm}) &gt; \ (\text{MeV}) )</td>
<td>2.1</td>
</tr>
<tr>
<td>( W )-value (1 MeV electrons) (eV/ion-pair)</td>
<td>23.3</td>
</tr>
<tr>
<td>Fano factor</td>
<td>0.107</td>
</tr>
<tr>
<td>Electron mobility at bp (m² V⁻¹ s⁻¹)</td>
<td>0.048</td>
</tr>
<tr>
<td>Ion mobility at bp (x10⁵) (m² V⁻¹ s⁻¹)</td>
<td>0.016</td>
</tr>
<tr>
<td>Dielectric constant</td>
<td>1.6</td>
</tr>
<tr>
<td>Heat capacity (Cp) (cal mol⁻¹ K⁻¹)</td>
<td>10.05</td>
</tr>
<tr>
<td>Thermal conductivity (x10³) (cal s⁻¹ cm⁻¹ K⁻¹)</td>
<td>30</td>
</tr>
<tr>
<td>Critical point temperature (K)</td>
<td>150.85</td>
</tr>
<tr>
<td>Normal boiling point (bp) (K)</td>
<td>87.27</td>
</tr>
<tr>
<td>Liquid density at bp (g cm⁻³)</td>
<td>1.40</td>
</tr>
<tr>
<td>Heat of vaporization at bp (cal mol⁻¹)</td>
<td>1557.5</td>
</tr>
<tr>
<td>Gas/liquid ratio</td>
<td>784.0</td>
</tr>
<tr>
<td>Temperature (K) : Pressure (bars)</td>
<td>87.15 : 1.0</td>
</tr>
<tr>
<td></td>
<td>89.3 : 1.25</td>
</tr>
<tr>
<td></td>
<td>91.8 : 1.6</td>
</tr>
</tbody>
</table>
Electron Drift Velocity in LAr

- \( T = 87.3 \text{ K} \)
- \( T = 89.3 \text{ K} \)
- \( T = 91.3 \text{ K} \)
- Icanis [24]

Drift Velocity (mm/\( \mu \text{s} \))

Electric Field (kV/cm)

Recombination Factor in LAr

- \( R_c, R_L \)
- 1 mips
- 3 mips
- 10 mips
- 30 mips

\( \varepsilon \) (kV/cm)