Event Reconstruction Techniques for a (water-based) Liquid Scintillator Detector

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Outline:

- Motivation: next generation of (water-based) liquid scintillator detectors
- Cherenkov / scintillation light separation
- Optical tracking using fast timing
- Event reconstruction algorithms

TAUP2017, Sudbury, July 26, 2017
• Large scintillator detectors and large water-Cherenkov detectors have been very effective in measuring neutrino properties

• Combining the two technologies may allow expanded physics reach of the next generation large neutrino experiments

• Physics Program of THEIA:
  - Neutrinoless double beta decay
  - Solar neutrinos
  - Geo-neutrinos
  - Supernova burst neutrinos & DSNB
  - Nucleon decay
  - Long-baseline physics (mass hierarchy, CP-violation)
  - Unexpected surprises

Ability to extract the most information out of each event is crucial ➔ need dedicated reconstruction algorithms

For more on THEIA detector see talk by Leon Pickard tomorrow
Cherenkov vs Scintillation Light

Cherenkov

• Prompt emission
• Directional for each charged track segment
• Higher energy threshold
• Less abundant compared to scintillation light
• Conventionally used for particle ID, vertexing and “coarse” energy measurements

Scintillation

• Slow emission
• Isotropic for each charged track segment
• Very low energy threshold
• Abundant: usually completely overshadow Cherenkov light
• Conventionally used for vertexing and “precision” energy measurements

Combining the two should make for a very powerful detector

Very active field:
055801; arXiv:1610.02011

Current status: need fast timing and slow scintillators
A Note on Speed of Light

- Light travels one foot in 1 ns (in vacuum)
- 1 ns = 1000 ps
- In 1 picosecond light travels only 300 microns
- Light is slow in picosecond domain -> one can try “drift” photons, much like electrons in a TPC
- Speed of light in matter depends on the wavelength e.g. in a typical scintillator:
  \[ v(370 \text{ nm}) = 0.191 \text{ m/ns} \]
  \[ v(600 \text{ nm}) = 0.203 \text{ m/ns} \]

\[ \sim 2 \text{ ns difference over 6.5m distance} \]
\[ \text{(that's a lot of picoseconds)} \]

Large-Area Picosecond Photo Detectors (LAPPD) are being developed “Drifting” photons is one of the key applications of LAPPD
Optical Time Projection Chamber

- Like a TPC but drifts photons instead of electrons
- Exploits precise location and time for each detected photon
- Would allow track/vertex reconstruction in large liquid counters

![Diagram of an optical time projection chamber](image)

Need < 100 ps

Suggestion to use LAPPD’s for DUSEL and the name (OTPC) due to Howard Nicholson

- It doesn’t have to be water (use prompt Cherenkov light that arrives early)
- In fact, for long tracks optical tracking should also work using just scintillation
Eric Oberla’s Optical TPC

Water

Flat mirrors

H₂O

Direct Cherenkov light (yellow)

Photonis MCPs and Chicago striplines/PSEC4

1 foot/1000 psec muon

Reflected Cherenkov light (green)

780 psec later

Eric Oberla’s Ph.D thesis
Beam's Eye View of the OTPC

Water

Flat mirrors

24 cm

Stereo view mirror mount

5 cm

Normal view

5 cm

Normal view mirror mount

Reflected Cherenkov light arrives 780 psec later depending on position and angle

Photonis MCPs and Chicago striplines/PSEC4

Eric Oberla's Ph.D thesis
OTPC at Fermilab Test Beam

Eric Oberla’s Ph.D thesis

Five Photonis Planacons
• 60 mrad angular resolution over a lever arm of 40cm
• 1.5 cm spatial resolution (radiation length of H2O is 40cm)
• See 780 psec separation of direct and mirror-reflected light
Can We See Event Topology in a LS Detector?

Simulation of a $0\nu\beta\beta$ event
(selected event with large angle between electrons)

Fast (arrives early) and directional
• directionality reconstruction
• event topology reconstruction (e.g., 2-track vs 1-track)
Early Light Topology

Idealized event displays: no multiple scattering, all light after QE=30% cut

Spherical harmonics analysis

\[ f(\theta, \varphi) = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} f_{\ell m} Y_{\ell m}(\theta, \varphi). \]

Rotation invariant power spectrum

\[ S_{ff}(\ell) = \sum_{m=-\ell}^{\ell} |f_{\ell m}|^2 \]
Early Light Topology

Realistic event displays: early PEs only, KamLAND PMTs QE: \textbf{Che\textasciitilde12\%, Sci\textasciitilde23\%}

Key parameters determining separation of 0νββ-decay from 8B

- Scintillator properties
  (narrow spectrum, slow rise time)
- Photo-detector properties
  (fast, large-area, high QE, red-sensitive)
Spherical harmonics analysis is rather simple, but it doesn't use all available information.

Advanced machine learning techniques looking at 4-vectors of each photon hit should work better (probably makes more sense with a little more progress on the instrumentation front).

Topology reconstruction of MeV events could help against other backgrounds in searches for 0νββ-decay (e.g., 10C, 2.6MeV gammas).
3D Optical Tracking

Need:
• One reference point (space and time)
• Single photon hit times

\[ t = t_{\text{ref}} \pm \frac{|\mathbf{x} - \mathbf{r}_{\text{ref}}|}{c_0} + \frac{|\mathbf{r}_j - \mathbf{x}|}{v_g(\epsilon)} \]

Reconstruction algorithms work with Cherenkov or scintillation light
• B. Wonsak et al. Original motivation: LENA scintillator detector
• M. Wetstein et al. Original motivation: water-Cherenkov LBNE detector
For each photon hit:

- Time defines drop-like surface
- Gets smeared with time profile (scintillation & PMT-timing)
- Weighted due to spatial constraints (acceptance, optical properties, light concentrator, ...)

→ spatial p.d.f. for photon emission points
3D Optical Tracking using Scintillation

B. Wonsak et al.

- Add up all signals
- Divide result by local detection efficiency → Number density of emitted photons
- Use knowledge that all signals belong to same topology to 'connect' their information → Use prior results to re-evaluate p.d.f. of each signal

Access to $dE/dx$

Decreased cell size

3 GeV muon simulated in LENA

Decreased cell size
3D Optical Tracking using Scintillation

Current Status (slide by S. Lorenz)

- Early version tested with real Borexino data
- Developed C++ reconstruction framework
  - LENA implemented
  - JUNO implementation ongoing (more complicated optical model)
  - Borexino implementation ongoing (real data!)
- First performance evaluation with fully-contained MC muon events in LENA
• Light is slow if measured in picoseconds

• Lots of information can be recovered by ‘drifting’ photons to a highly segmented photo-detectors

• Using Cherenkov and scintillation light in the same detector is a very attractive option

• New algorithms are being developed for detailed event reconstruction covering MeV to GeV energy range
A Note on Mirrors and the Optical TPC

E. Oberla

E. Angelico

- Photo-cathode coverage is expensive
- Mirrors may help to reduce cost of very large detectors

Simulation of reflection points of 20 photons inside a silvered sphere, color-coded by time

“Adding psec-resolution changes the space in which considerations of Liouville’s Theorem operates from 3-dimensional to 4-dimensional. In analogy with accelerator physics, we can exchange transverse emittance to longitudinal emittance.

There may be interesting and clever ways to exploit this in large water/scint Cherenkov counters”

-H. Frisch

Homage to T. Ypsilantis
Electron TPC and the Optical TPC

- Drift electrons at constant velocity (E field)
- Limit diffusion with B field
- Charged particles create ionization along track
- Collect position and time at end of drift
- Single path for electrons

- Drift photons at constant velocity
- Limit dispersion by various stratagems (inc. near light)
- Charged particles create Cherenkov light along track
- Collect position and time at end of drift
- Photons can be reflected to increase sensitive area using path length to identify bounce

OTPC:
- Current LAPPD microstrip readout gives 700 micron by 700 micron resolution for a 90cm x 20cm anode with cheap CMOS readout- gives $2 \times 10^6$ pixels/m$^2$
- Resolution in 3rd dimension set by timing: 50 psec = $\frac{3}{4}$"; 1 psec = 300 microns
- Longitudinal information allows unambiguous use of mirrors
\[ \frac{1}{2} Q ({}^{116}\text{Cd}) = 1.4 \text{ MeV} \]

\[ \frac{1}{2} Q ({}^{48}\text{Ca}) = 2.1 \text{ MeV} \]
**0νββ vs 8B**

For details see NIM A849 (2017) 102

Vertex res 5cm, events within R<3m
Scintillation rise time 1 ns

![Graph](image1.png)

Background rejection factor = 2
@ 70% signal efficiency

Vertex res 5cm, events within R<3m
Scintillation rise time 5 ns

![Graph](image2.png)

Background rejection factor = 3
@ 70% signal efficiency

Other backgrounds (gammas, alphas, $^{10}$C, etc) also have distinct topologies
Event reconstruction in liquid scintillator would enable new opportunities
\(0\nu\beta\beta\)-decay vs \(^{10}\text{C}\)

two-track vs a “complicated” topology

\(^{10}\text{C}\) decay chain:

- \(0^+\) final state consist of a positron and gamma (\(e^+\) also gives 2x0.511MeV gammas after losing energy to scintillation)
- Positron has lower kinetic energy than \(0\nu\beta\beta\) electrons
- Positron scintillates over shorter distance from primary vertex
- Gammas can travel far from the primary vertex

\(^{10}\text{C}\) vs \(0\nu\beta\beta\)-decay: photons arrival time profile

\(^{10}\text{C}\) background can be large at a shallow detector depth

Diagram by Jon Ouellet
OTPC Optics — direct light

The time projection of the direct Cherenkov photons on the OTPC z-axis is a measure of the Cherenkov angle ($\beta$) and the particle angle with respect to the OTPC longitudinal axis.

\[
\Delta t_{\gamma_1} = t_0 \left( 1 - \frac{\beta c}{\langle v_{\text{group}} \rangle} \tan \theta_i \right)
\]

\[
\Delta z_{\gamma_1} = \beta c t_0 \cos \theta_i
\]

\[
\frac{dt}{dz} \approx \frac{1}{\beta c} \frac{\tan \theta_i}{\langle v_{\text{group}} \rangle}
\]
OTPC Optics – direct + reflected light

Time-resolving the direct and reflected photons provides the lateral particle displacement from the OTPC center-line as a function of z- and φ-position.

\[ r = (\Delta t \ < v_{group} > - D) \frac{1}{2} \left( \frac{1}{\sin \theta_c} - \frac{< v_{group} >}{\beta c \tan(\theta_c)} \right)^{-1} \]
OTPC Photodetector Module (PM)

- 1024 anode pad mapped to thirty-two 50Ω micro-strips with custom anode card
- MCP-PMT mounted to anode card with low-temperature Ag epoxy
- Terminate one end of micro-strip, other end open (high-impedance):

Expressions for the position and time-of-arrival of the detected photon:

\[ x = \frac{v_{prop} t_2 - t_1}{2} - \frac{D + 2 C_1}{2} \]

\[ t_0 = \frac{t_2 + t_1}{2} - \frac{1}{v_{prop}} \left( D + C_2 + C_1 \right) \]
OTPC spatial reconstruction (3)

Example event

Typical event (thru-going μ)

Projecting the direct photons onto the reconstructed r-coordinate at each PM