Dichroic Winston Cones (‘Dichroicons’) for Cherenkov and Scintillation Light Separation in Large-Scale Neutrino Detectors

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Detecting Cherenkov Light in a Scintillation Detector

- Charged particle traveling through liquid scintillator creates both scintillation (\(~10,000\) photons/MeV) and Cherenkov light (\(~100\) photons/MeV)

- Challenge is to detect the Cherenkov light, which provides the direction of the traveling particle

- Cherenkov light is emitted promptly, scintillation light delayed and emitted with slower time-profile

Example timing in large neutrino detector
Why Cherenkov / Scintillation Separation?

➢ Recent trend in large monolithic neutrino detectors to move toward scintillator targets (Borexino, kamLAND-Zen, SNO+, JUNO, etc.)

➢ High light yield from scintillator provides excellent energy / position resolution, low energy thresholds

Neutrinoless double beta decay, low energy solar neutrinos, reactor & geo antineutrinos

➢ Cherenkov light allows one to reconstruct direction, improve particle ID

➢ Allow scintillator-based solar neutrino experiments to suppress backgrounds

➢ Largest expected backgrounds for SNO+ is solar neutrinos, which can be rejected by detecting the Cherenkov light

➢ Has not been demonstrated in an existing liquid scintillator detector

➢ R&D work will be focus of this talk
Ongoing R&D For Cherenkov / Scintillation Separation

Cheese setup at LBNL
J. Caravaca et al, 10.1103/PhysRevC.95.055801

Slow scintillator characterization for Jinping
Z. Guo et al, 10.1016/j.astropartphys.2019.02.001

FlatDot at MIT
J. Gruszko, et al, 10.1088/1748-0221/14/02/P02005

Only timing and isotropy used to identify the Cherenkov light.
Can we additionally use wavelength?

Ultimately we want to achieve Cherenkov and scintillation separation while losing as few total photons as possible.
Simulations of kamLAND-like detector show red-sensitive photocathodes improve Ch/Sc separation.

Absorption and scattering length increases with wavelength.

Cherenkov light that reaches the PMTs with its original direction is primarily long-wavelength.
Dichroic Winston Cones: The Dichroicon

Combining Two Technologies

Winston Cones

And Dichroic Filters
Dichroic Winston Cones: The Dichroicon

Sorting the scintillation and Cherenkov light towards different PMTs in order to achieve separation while maintaining a high detection efficiency for the scintillation light.

Example full-scale design

Visualizations from M. Luo

Complimentary to WbLS, slow scintillator, etc.
Familiar Technologies

SNO Winston Concentrator

Photon trap using dichroic filters proposed for Hyper-K

Borexino Winston Concentrator

ARAPUCA design for DUNE/protoDUNE


C. Rott et al. JINST 12 (2017)

E. Segreto et al., JINST 13 (2018)
Cherenkov and Scintillation Separation With Dichroic Filters

$^{90}\text{Sr}$ source

LAB+PPO inside UVT acrylic

“Photon Sorting”
LAB+PPO, 500 nm short-pass dichroic filter

LAB+PPO, 500 nm long-pass dichroic filter

LAB+PTP, 450 nm long-pass dichroic filter
Cherenkov/Scintillation Separation With a Large-Area PMT

Transit time spread ~ 640ps

First demonstration of Cherenkov and scintillation separation using a large-area PMT!
3D Printed Prototype

Custom cut short-pass filters from Knight Optical to fill out full 3D printed design

High performance short-pass dichroic filters from Edmund Optics

Custom cut long-pass filter from Knight Optical to fit the aperture

Measurements shown made with this prototype
Red sensitive photocathode
Dichroicon Data

Data with dichroicon coupled to PMT:
- # Ch. Photons ~ 4900
- P ~ 88%

Data with only dichroic long-pass coupled to PMT:
- # Ch. Photons ~ 1060
- P ~ 77%
Dichroicon Data

Introducing additional long-pass filter reduces scintillation light “background”

# Ch. Photons ~ 4600
P ~ 95%
Dichroicon Data

Particle ID using the Cherenkov light!

$^{90}\text{Sr} \beta$ source

$^{210}\text{Po} \alpha$ source
Scintillation light drowns the Cherenkov, but we’ve identified it by sorting the photons!
Future Measurements

➢ Transmission and reflections in water/oil
➢ Measurements with more PMTs
➢ Simulation studies using RAT-PAC
➢ Engineering of “monolithic” design
➢ Scintillation readout design
➢ Measurements with different fluors and filters
Conclusions

- Cherenkov / scintillation separation at the center of a lot of interesting R&D work
- Applications for many future experiments: THEIA, ANNIE, WATCHMAN, Jinping, JUNO
- Bench-top measurements of single dichroic filter demonstrated the potential for “photon-sorting”
- Cherenkov / scintillation separation demonstrated with first prototype dichroicon
- Lots of interesting measurements and simulations forthcoming with dichroicons

Work supported by Department of Energy Office of High Energy Physics Advanced Detector R&D
Backup
Interest in this topic has developed from our experience working on SNO+

SNO+ in a unique position of having phases as a water Cherenkov detector and liquid scintillator detector.

Expertise in running a water Cherenkov detector, but also lots of experience with scintillator (bench-top measurements, modeling in simulation, etc.)

Neck fill with LAB+PPO ongoing!
 Several proposed WbLS detectors hoping to achieve Cherenkov and scintillation separation

 THEIA is a proposed 50kT WbLS (or equivalent technology) detector, potentially complimentary to DUNE

 ANNIE is 26-ton water-based detector measuring neutrino-nucleus interactions. Future phases will likely include LAPPDs and WbLS

 WATCHMAN hot-bed for future technologies – WbLS, LAPPDs, fast PMTs, *dichroicons*

*Schematic from J. Klein*
Calculate $\Delta t$ between the two waveforms.

Data with no bandpass filter shows typical scintillation spectrum.

Characterized by intrinsic rise $\tau_r \sim 1\text{ns}$ followed by exponential decay with $\tau_{1,2,3} \sim 5\text{ns, } 20\text{ns, } 400\text{ns}$. 

LAB+PPO inside UVT acrylic

$^{90}\text{Sr}$ source
Cherenkov / Scintillation Separation With Bandpass Filters

Using a set of bandpass filters to span emission spectrum of LAB+PPO

<table>
<thead>
<tr>
<th>Center (nm)</th>
<th>FWHM (nm)</th>
<th>Peak Transmission (%)</th>
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<tr>
<td>355</td>
<td>10</td>
<td>95</td>
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<td>60</td>
</tr>
<tr>
<td>530</td>
<td>10</td>
<td>54</td>
</tr>
</tbody>
</table>
Clear Cherenkov peak emerges at long wavelengths.
Simultaneously fit both the Cherenkov and scintillation components of the timing profile

Purity, \( P \), of the Cherenkov light in a prompt window

\[ F = C \times f_{PMT}(t - t') + (1 - C) \times \sum_{i=1}^{2} \frac{A_i \times (e^{-t/\tau_i} - e^{-t/\tau_R})}{(\tau_i - \tau_R)} \times f_{PMT}(t - t') \]

\[ P = \int_{8.0}^{9.5} \frac{F_C}{F} dt \]

> 90% of prompt light is Cherenkov light!
Measuring $T(\lambda, \theta)$ and $R(\lambda, \theta)$

Characterize the transmission and reflection of the dichroic filters as a function of wavelength and incident angle.
Very little light lost to the dichroic filter over range of wavelengths and incident angles

Measurements for a 500 nm long-pass dichroic filter

Used for input into our simulation model
Prototype 1

3D printed holder for dichroic filters
Dichroicon Data

- Acrylic Cherenkov source
- With dichroic Winston cone!
- No Winston cone

Graph showing the difference in counts with and without a Winston cone.
Dichroicon Data