New Scintillation Water for Large Physics Experiments

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BNL Particle-physics Seminar

New Metallic Loading
Physics for WbLS
Other Applications

BNL Neutrino and Nuclear Chemistry

615-t $^{37}\text{Cl} + \nu_e \rightarrow ^{37}\text{Ar} + e^-$

30-t $^{71}\text{Ga} + \nu_e \rightarrow ^{71}\text{Ge} + e^-$

1-kt D2O CC/NC

200-kt $H_2O$ or 37-kt LAr

120-t 8% In-LS

200-t 0.1% Gd-LS

1-kt 0.1% Nd-LS

Nonproliferation & Reactor Monitoring by Li-, B- or Gd- LS

(metallic-loaded) multi-physics detection medium

Neutrino Chemistry

Radiochemical

Cerenkov

Scintillator

Hybrid

Water-based LS

Neutrino

Chemistry
What is water-based LS?

WbLS is not a mix of water and fluor or shifter. 

A net light gain of $4.4 \pm 0.5$


Previous WbLS trials are either gel-like or not stable over time.

A scintillation water serves as energy spectrometer that probes physics below Cerenkov threshold. 

bridged by non-ionic surfactant, i.e. LAB derivatives, sulfonate, sulfonic amine, etc.
Scintillation Matrix

M. Yeh, Review of Metal-loaded Liquid Scintillator for Neutrino Physics, IJMPB (in preparation).

- ability to catch ionization radiation
- photon-transferring mechanisms once excited (S/F/S)

\[ LS \rightarrow LS^* \rightarrow h\nu \]
Non-radiative fluorescence energy transfer (PPO/MSB)

Intensity (AU)

260 360 460 560

nm

diluted by x100
A Multi-Physics Water-based Scintillation Detector

- Proton decay
- Double-beta decay
- Supernovae neutrino
- Low-energy neutrino

See-Saw of organic% in the water-based medium
Typical Cerenkov & Scintillation Detectors

- Cerenkov (Super-K)
  - Proton decay, supernovae, beam physics FD, solar-ν

- Scintillator (Daya Bay)
  - ~<kt Detector
  - ~20% LS
  - ~100% LS

- Photon/MeV vs. Mean Attenuation Length (m)

- ~>50kt Detector
  - If large enough

- 0νββ, geo-ν, reactor-ν, solar-ν, beam physics ND

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Scintillation catches the $K^+$ and its decay daughters.

Cerenkov identifies the signatures of prompt and delay; and further suppress the atmospheric $\nu$ background.

Proton decay – physics below Cerenkov
**SUSY-favored PDK$^+$ Mode**

- $p \rightarrow k^+ \bar{\nu}$ ($T_{k^+} = 105 \text{ MeV}, \tau = 12.8 \text{ns}$)
  
  - $k^+ \xrightarrow[63.5\%]{\mu^+} \nu$ ($T_{\mu^+} = 152 \text{ MeV}$)
    - $\mu^+ \rightarrow e^+ \nu \nu$ ($\tau = 2.2 \mu\text{s}$)
  
  - $k^+ \xrightarrow[20.7\%]{\pi^+\pi^0} \pi^+(E=135 \text{ MeV}) \rightarrow 2\gamma$
    - $\pi^+ \rightarrow \mu^+ \nu$ ($T = 4 \text{MeV}$)
      - $\mu^+ \rightarrow e^+ \nu \nu$ ($\tau = 2.2 \mu\text{s}$)

  can be explored by Cerenkov or Scintillation via different decay channels
**Super-K proton decay**

The SUSY SU(5) model predicts the K-decay mode to be dominant with a partial lifetime varying from $10^{29}$ y to $10^{35}$ yrs!

The partial lifetime is given by

$$\tau(p \rightarrow k^+\bar{\nu}) > 2.3 \times 10^{33} \text{ yrs}$$

- 22.5-kT (7.5 x $10^{33}$ protons & 6.0 x $10^{33}$ neutrons) at 40% coverage
- $T_{K^+} \sim 105$ MeV: below Cerenkov threshold
- $^{16}\text{O} (p_{3/2}) \rightarrow ^{15}\text{N}^* + \gamma_{6.3} \text{ MeV}$
For proton decay, a pulse that is
- <12ns
- long attenuation length
- with Cerenkov or Scintillation capabilities
- deep UG

- Timing structure (10-MeV electron-beam by LEAF; time-resolved fluorescence)
- Mean attenuation length (UV normalized to Super-K absorption curve; followed by simulation) and Emission Spectra (fluorescence)
- Light-yield (Cs-137) and (1-GeV p-beam)

**WbLS Characterizations**
$\tau_{WbLS(PPO)}$ *between 2 – 4 ns*

**10-MeV e⁻ beam at LEAF**

**Time-resolved fluorescence system**

Decay of sample 3, deoxygenated

- $\tau_1 = 3.80$ ns (58%)
- $\tau_2 = 10.02$ ns (42%)

ex=250nm
em=329nm

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Absorption Length Calculation

Water has long attenuation lengths (136 – 200m) observed by Super-K, SNO, etc.; dominated by scattering <350nm

UV + \lambda_{1/e} LBNE simulation match with the 2-m measurement very well!

\begin{tabular}{|c|c|c|c|}
\hline
 & Gd-LS & LS & LAB \\
\hline
\lambda (m) & 20.9 & 20.4 & 22.8 \\
\hline
\end{tabular}
Mean-Free Attenuation Length close to pure water after 400nm

- improvement of optical transmission over the past 6 months

- UVs of 18-MΩ water and WbLS normalized to Super-K abs. curve.
- Mean-free absorption length calculated by LBNE water attenuation simulation (developed for Compatibility test).
- Need large-scale verification
**Emission at the PMT sensible region is almost clean**

The fluor/shifter transmission needs to be optimized.
Little LS gives away lots of light

 photon-yield function of liquid scintillator % in the cocktail is not linear!
Cerenkov increases by ~4x using Carbostyril-124 (SNO)
- A ratio of 5:1 for scintillation vs. Cerenkov
WbLS at NSRL high-energy particle-beam in 2011

• 1-GeV proton beam
• Daya Bay sees ~32:1 of Scintillation vs. Cerenkov in pure LS.
• WbLS obtains ~1/3 of LS light (10:1 compared to water-filled)
• Reinvestigate with 100 – 300 MeV p-beam this fall (LDRD funded, Hide et. al.).

Figure 2: The instantaneous intensity in Hz as a function of time in spill in ms.
How much Scintillation can be added to keep the Cerenkov valid?

WbLS has a fast, long attenuation-length pulse with Cerenkov + Scintillation
## Simulation Parameters *(tunable)*

<table>
<thead>
<tr>
<th>X% -WbLS (d = 0.9945 g/cm³) + PPO</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Element Composition (%)</strong></td>
</tr>
<tr>
<td>H</td>
</tr>
<tr>
<td>65.9</td>
</tr>
<tr>
<td><strong>Timing (τ)</strong></td>
</tr>
<tr>
<td>1.23 ns (26%) + 9.26ns (74%)</td>
</tr>
<tr>
<td><strong>Refractive Index</strong></td>
</tr>
<tr>
<td>1.3492 (580-nm) <em>(need wavelength-dependent measurement)</em></td>
</tr>
<tr>
<td><strong>Rayleigh scattering</strong></td>
</tr>
<tr>
<td>same as water <em>(need measurement)</em></td>
</tr>
</tbody>
</table>

- Based on the WCSim software *(used for LBNE detector simulation)*
- changed the material to match WbLS
- Added the Scintillation process for WbLS
- Temporary code repository: [https://github.com/czczc/WbLS](https://github.com/czczc/WbLS)
- Xin Qian (Caltech)
  - LBNE baseline
- Chao Zhang (BNL)
  - Super-K geometry
• 200-kt
• 10% coverage
• 12-inch HQE PMT (~30%)

**WbLS at LBNE Geometry**
$105\text{-}MeV\ k^+ \rightarrow \mu^+ \nu_\mu \ (br.\ 63\%) \ at\ 1800\ \gamma s/MeV$

Scintillation lights swamp Cerenkov rings
Adjust the scintillation light to 180 $\gamma$/MeV

one event and No Cut

next to select the $\mu^+$ by 20-40ns timing-cut
select the $\mu^+$ window (20→40 ns)

can ID the rings by either eye- or software-view!
reduce the light further to $90 \, \gamma s/\text{MeV}$

- one event No Cut
- select different timing windows for $k^+$ and $\mu^+$ events
select the $k^+$ Window (0 $\rightarrow$ 13ns)

- scintillation light only
- no Cerenkov ring
select the $\mu^+$ window (13→22ns)

clean $\mu$-rings can be identified among scintillation
A quick look of $k^+ \rightarrow \pi^+ \pi^0$

- Very clear Cerenkov ring even without cut
WbLS at Super-K Geometry

- 50 kton
- 40% coverage
- 20-inch PMT (~20%)
Sanity Check I

- Set Photon Yield to zero (only Cerenkov light)
Sanity Check II

- Set Photon Yield to 9000 photons/MeV (Like pure LS)
Sanity Check III

- Set photon yield to 90 photons/MeV (to keep a reasonable Scintillation/Cherenkov ratio)

105 MeV K⁺  500 MeV Muon
Atmospheric Neutrino Background

- Atmospheric neutrino interaction is a complicated process.
- $\bar{\nu}_\mu + \nu_e + \nu_\mu + \bar{\nu}_e$ generated from $\mu^\pm$ and $\pi^\pm$ interaction.
- IMB, Super-K, Soudan-2, and other experiments study the bests of it.
- >100 publications/talks address this studies.
- A proposal submitted to study this background.
- Most atmospheric background events associated with multi Michel electrons, while either $\pi^+$ or $\mu^+$ from PDK$^+$ mode only gives one electron.
Sensitivity with Scintillation + Cerenkov

- how much can we improve on a Super-K type detector?

- **WbLS signal-like:**
  
  **Prompt**
  - K$^+$ scintillation
  
  **Delay**
  - $\pi^+$ and $\mu^+$ scintillation
  - $\pi^0$ scintillation
  - Cerenkov rings from $\mu^+$, $\pi^+$, $\pi^0$, Michel electron, etc.

**Event Selection Rules**

- 12.8 ns between prompt and delay.
- No ring in Prompt.
- Energy Cut on prompt event.
- Rings in delay
- Energy cuts in delay with rings
- etc...

Will extra Cerenkov help?

- Compare to SK
  
  (170 event/1489 days), the 3-fold coincidence cuts down to $\sim$5/y; PSD can further suppress the bkg. event to 0.25/y.

  10-yr run could reach a sensitivity of $10^{34}$ for the PDK$^+$ mode.)
Other Physics

- **SRN**
- **DSNB**
- Important for low-energy electron neutrino and proton decay
- SN at 10kpc
- Solar-neutrino
- Geo-neutrino
- Reactor-neutrino
- etc.

\[ Why \text{ not Gd-scintillating water?} \]
### Cerenkov & Scintillation for WbLS

<table>
<thead>
<tr>
<th></th>
<th>50-kt</th>
<th>LENA</th>
<th>WbLS</th>
<th>Super-K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protons (free)</td>
<td>3.70×10^{33}</td>
<td>3.32×10^{33}</td>
<td>3.35×10^{33}</td>
<td></td>
</tr>
<tr>
<td>Protons (bound)</td>
<td>1.29×10^{33}</td>
<td>1.34×10^{34}</td>
<td>1.34×10^{34}</td>
<td></td>
</tr>
<tr>
<td>Scintillation</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>p → K+ capture</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Cerenkov ring ID</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Cerenkov yield</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

Fermi motion and secondary particle collisions are important for $p \rightarrow \pi^0 e^+$. 39% with 180° for ¹⁶O (Gabriel, T.A. and Goodman, M.S. Physical Review D, 25, 9 (1982) 2463-2465.)
Proton-decay in US

- Proton-decay is one of Intensity-Frontier research topics.
- LBNE is asked to revise the scope to reduce the cost; and even so-be-approved after revision, it’s >10-yr from now.
- A megaton water Cerenkov detector is unlikely to be happening in 10-yrs.
- It might not be so crazy to propose a mid-range, 50-kt WbLS detector for proton-decay and other physics (at DUSEL? SNOLAB?).
- need MC simulations to guide the design and understand the performances.
A new way of loading **Hydrophilic Isotopes in 80+% LS**

- Double-beta decay
- Reactor neutrino
- Geo neutrino
- Supernovae alarm
BNL Metal-loaded LS for Physics

### Periodic Table of the Elements

- **hydrogen**
- **alkali metals**
- **alkali earth metals**
- **transition metals**
- **poor metals**
- **nonmetals**
- **noble gases**
- **rare earth metals**

### Reactor, ββ, Solar, Others

- **Reactor**
- **ββ**
- **Solar**
- **Others**

M. Yeh, Review of Metal-loaded Liquid Scintillator for Neutrino Physics, IJMPB (in preparation).
**Inverse Beta Decay Detection**

- $E_{\text{threshold}} = 1.8 \text{ MeV}$
- ‘Large’ cross section $\sigma \sim 10^{-42} \text{ cm}^2$
- Distinctive coincidence signature in a large liquid scintillator detector

\[
\bar{\nu}_e + p \rightarrow e^+ + n
\]

\[
n + {}^A\text{Gd} \rightarrow {}^{A+1}\text{Gd} + \gamma's
\]

*Cowan & Reines, Savannah River 1956*
Double-beta Decay

<table>
<thead>
<tr>
<th>Isotope</th>
<th>$G^\text{ov}$ ($\times 10^{-15}$ y$^{-1}$)</th>
<th>Q-value (MeV)</th>
<th>Abundance %</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{48}\text{Ca}$</td>
<td>75.8</td>
<td>4.27</td>
<td>0.2</td>
</tr>
<tr>
<td>$^{76}\text{Ge}$</td>
<td>7.6</td>
<td>2.04</td>
<td>7.8</td>
</tr>
<tr>
<td>$^{82}\text{Se}$</td>
<td>33.5</td>
<td>3.00</td>
<td>9.2</td>
</tr>
<tr>
<td>$^{85}\text{Zr}$</td>
<td>69.7</td>
<td>3.35</td>
<td>2.8</td>
</tr>
<tr>
<td>$^{100}\text{Mo}$</td>
<td>54.5</td>
<td>3.03</td>
<td>9.6</td>
</tr>
<tr>
<td>$^{116}\text{Cd}$</td>
<td>58.9</td>
<td>2.80</td>
<td>7.5</td>
</tr>
<tr>
<td>$^{130}\text{Te}$</td>
<td>52.8</td>
<td>2.53</td>
<td>34.5</td>
</tr>
<tr>
<td>$^{136}\text{Xe}$</td>
<td>56.3</td>
<td>2.48</td>
<td>8.9</td>
</tr>
<tr>
<td>$^{150}\text{Nd}$</td>
<td>249.0</td>
<td>3.37</td>
<td>5.6</td>
</tr>
</tbody>
</table>

Searching for $0\nu\beta\beta$-decay could answer:
- whether neutrinos are Dirac or Majorana particles
- probe neutrino masses at the level of tens of meV; $A_{\text{mbb}}$ limit of ~20 meV would exclude Majorana neutrinos in an inverted hierarchy.

- SNO+ is the only metal-loaded liquid scintillation detector.
- Flexible and easy scale-up
- Any hydrophilic DDB isotopes that cannot be done in pure LS; **NOW is possible.**
First DBD isotope in WbLS

- Efforts to load certain metallic-ions in pure LS ($\varepsilon=80\%$)
- Quick and straight in preparation of X-WbLS ($\varepsilon=100\%$)
A balance of light-yield vs. attenuation-length

- Cerenkov (Super-K)
- proton decay, supernovae (Gd), beam physics FD
- ~>50kt Detector
- ~kt Detector
- 0νββ, geo-ν, reactor-ν, beam physics ND
- Scintillator (Daya Bay)
- ~20% LS
- ~100% LS
Two WbLS-formulas for proton-decay and for DBD expts.

- Cerenkov (Super-K)
- Cerenkov & Scintillation WbLS
- Proton decay, supernovae
- ~kt Detector
- ~50kt Detector
- ~100% LS
- ~20% LS
- Super WbLS
- Organometallic-ion WbLS
- 0νββ, geo-ν, reactor-ν
- Beam physics ND
- Scintillator (Daya Bay)

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Other Applications

- Biodegradable liquid scintillator cocktail
- Veto system
- Short half-life calibration source
**Biodegradable Water-based Scintillation Cocktail**

- Take more % aqueous sample than commercial product
- No permeation of scintillation vials (long-stable counting)
- Environmentally friendly (easy disposed)

![Graph showing AU vs. Channel for different cocktails](image)

- **WbLS-1 Cocktail + 10% water**
- **WbLS-2 Cocktail + 8% water**
- **B-S + 8% water**

20 minutes

>24-hrs

Temperature-sensitive
Veto film for cryogenic or solid-state detector

- current experience with LS veto-film (a project in collaboration with LNGS) to produce $\mu$m-thin, Teflon-based films targeting surface $\alpha/\beta$ for background reduction.

- Related applications to LAr light collection.
  - Current PVT (polyvinyl toluene) – based polymer deteriorates under UV-light; questionable to be used under cryogenic condition.
  - Current toluene-TPB (tetraphenyl butadiene) combination is not the best match for LAr emission at 128nm.
LAr light collection

• Toluene QY is only 0.17 or ~½ of liquid scintillators (PC, LAB, PXE, etc.).

• TPB absorption at 350\text{nm} doesn’t match with toluene emission at 300\text{nm} well and emission at 460\text{nm} is not the most sensible zone of PMT.

• A (LAB or PC)-PPO/MSB-mixed, Teflon-based film could improve the light collection efficiency significantly (cost-saving).

Handbook of Fluorescence Spectra of Aromatic Molecules, 1967
**WbLS veto system**

- Scintillation water could serve as a large and economic Cerenkov/Scintillator veto system.
- LBNE (LAr) proposing large 20%PC+80%DD LS; if not at 4850.
- LUX and other dark matter researches are looking for veto system (Gd-water, LS, Gd-LS, etc.).
- Long-range reactor monitoring.
- etc.

*WbLS can be molded as a surrounding shielding or multiple NoVA-type segmentations*

- Cost-saving than pure LS
- Nonflammable & ESSH (95%+ water)
- Scintillator & Cerenkov & can be Gd-loaded....
Short Half-live Calibration Sources

- Conventional method of loading metallic-ion into pure LS takes ~1-day.
- WbLS opens a quick and easy way to add metallic isotopes into liquids (~a hour) that can be blended into either organic or aqueous solvents (detectors).
  - Positron isotopes mostly have short half-life (<1 day); A calibration source for IBD event, such as reactor-ν experiments.
  - Short half-life naturally-occurring isotopes: Pb-212 (10.6-h), Bi-212 (60.6m), or Tl-208 (3.1-m) calibration sources for low-energy neutrino experiments.
  - etc…
1-ton WbLS demonstrator at neutrino-beam or reactor-site

what if build the demonstrator with few generic detector R&D pieces together?
Summary

- A multi-physics, new detection medium with long attenuation length and Scintillation & Cerenkov features to explore the physics below Cerenkov (nucleon decay).
- A tunable detector that can adjust photon production vs. attenuation length for different physics.
- A new metallic loading technology that opens the doors for some double-beta decay, reactor and other physics that cannot be done before.
- A long-term stable and ease-mixed scintillation cocktail for aqueous (environmental) samples.
- A new matrix detector that is environmentally friendly, low-cost and easy to dispose; compare to pure scintillation solvent.

Futures:

- (1) long-pathlength measurements, (2) confirmation of light-propagation (scintillation/Cerenkov), (3) fluor/shifter optimization, (4) simulations, (5) ton-scale demonstrator, (6) super-WbLS R&D
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