New Scintillator and Dopants

Minfang Yeh
Water-Cerenkov vs. Liquid Scintillation Detector

Cerenkov (Super-K) ~ >50kt Detector
proton decay, supernovae (Gd), beam physics FD

A cost-effective, large detector with
Cerenkov + Scintillation
Water-based liquid scintillator

~kt Detector
0νββ, geo-ν, reactor-ν, beam physics ND

~kt Detector

Scintillator (Daya Bay)

~20% LS
~100% LS

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**Liquid Scintillator continues to be a key detection medium**

<table>
<thead>
<tr>
<th>Few examples of Newly Proposed Experiments</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Accelerator-based</strong></td>
</tr>
<tr>
<td>LENA (low-energy neutrino astronomy, European LBNE)</td>
</tr>
<tr>
<td>OscSNS (precision short-baseline neutrino Oscillation at Spallation Neutron Source, ORNL)</td>
</tr>
<tr>
<td>IsoDAR (Isotope Decay-At-Rest; DAEδALUS; complementarity with LBNE)</td>
</tr>
<tr>
<td><strong>Reactor-based</strong></td>
</tr>
<tr>
<td>DayaBay-II (China), RENO-II (Korea)</td>
</tr>
<tr>
<td>NUCIFER at Osiris, SCRAAM at California, NBSR at NIST, and many others.</td>
</tr>
<tr>
<td><strong>Radioactive-source-based</strong></td>
</tr>
<tr>
<td>Ce-LAND ($^{144}$Ce at kCi)</td>
</tr>
<tr>
<td>LENS-Sterile ($^{51}$Cr at MCi)</td>
</tr>
</tbody>
</table>
## Comparisons of Liquid Scintillators for Neutrino Expt’s

**Table 1**
The chemical properties and physical performance of selected LS

<table>
<thead>
<tr>
<th>LS&lt;sup&gt;a&lt;/sup&gt;</th>
<th>PC</th>
<th>PCH</th>
<th>DIN</th>
<th>PXE</th>
<th>LAB</th>
<th>MO</th>
<th>DD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Molecular formula</td>
<td>C₆H₁₂</td>
<td>C₁₂H₁₆</td>
<td>C₁₆H₂₀</td>
<td>C₁₆H₁₈</td>
<td>C₁₈H₃₀&lt;sup&gt;b&lt;/sup&gt;</td>
<td>CₙH₂ₙ⁺²&lt;sup&gt;c&lt;/sup&gt;</td>
<td>C₁₂H₂₆</td>
</tr>
<tr>
<td>Can Gd be loaded into the LS?</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes&lt;sup&gt;d&lt;/sup&gt;</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Density (g/ml)</td>
<td>0.89</td>
<td>0.95</td>
<td>0.96</td>
<td>0.99</td>
<td>0.86</td>
<td>0.85</td>
<td>0.75</td>
</tr>
<tr>
<td>abs&lt;sub&gt;400&lt;/sub&gt; before purification</td>
<td>0.008</td>
<td>0.072</td>
<td>0.040</td>
<td>0.044</td>
<td>0.001</td>
<td>0.002</td>
<td>0.001</td>
</tr>
<tr>
<td>abs&lt;sub&gt;400&lt;/sub&gt; after purification</td>
<td>0.002</td>
<td>0.001</td>
<td>0.023</td>
<td>0.022</td>
<td>~0.000</td>
<td>0.001</td>
<td>~0.000</td>
</tr>
<tr>
<td>Purification method&lt;sup&gt;e&lt;/sup&gt;</td>
<td>v.d.</td>
<td>c.e.</td>
<td>c.e.</td>
<td>c.e.</td>
<td>c.e.</td>
<td>c.e.</td>
<td>c.e.</td>
</tr>
<tr>
<td>Index of refraction&lt;sup&gt;f&lt;/sup&gt;</td>
<td>1.504</td>
<td>1.526</td>
<td>1.565</td>
<td>1.565</td>
<td>1.482</td>
<td>1.461</td>
<td>1.422</td>
</tr>
<tr>
<td>S%&lt;sup&gt;g&lt;/sup&gt;</td>
<td>1</td>
<td>0.46</td>
<td>0.87</td>
<td>0.87</td>
<td>0.98</td>
<td>n.a.</td>
<td>n.a.</td>
</tr>
<tr>
<td>H-atoms per c.c. (× 10²²)</td>
<td>5.35</td>
<td>3.72</td>
<td>5.45</td>
<td>4.34</td>
<td>6.31</td>
<td>8.05</td>
<td>4.77</td>
</tr>
<tr>
<td>Flash point (°C)</td>
<td>48</td>
<td>99</td>
<td>&gt;140</td>
<td>145</td>
<td>130</td>
<td>215</td>
<td>71</td>
</tr>
</tbody>
</table>

<sup>a</sup>See the text in Section 3.4 for the chemical names of these organic compounds.
<sup>b</sup>With alkyl side chain containing 12 carbon atoms.
<sup>c</sup>n ≈ 30 [17].
<sup>d</sup>Only stable for few months.
<sup>e</sup>v.d. = vacuum distillation; c.e. = column extraction with solid Al₂O₃.
<sup>g</sup>Scintillation yield normalized to 100% PC; n.a. = non-aromatic compounds which do not scintillate.

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Options of pure liquid scintillator

Binary-system with partial LS%

Singular-system with controlled fluor%

Searching for new LS with longer attenuation length and compatible light-yield is the future.
Self-scavenge Gd purification

M. Yeh et al. NIM A 618 (2010) 124–130

- U/Th removed to < 0.1 ppb
- Optical improvement by 2x from 300-450 nm

Fig. 7. Fraction of the activity of tracers for five elements remaining in the filtrate as a function of pH. Values are in percent of the total recovered activity, corrected for losses to the precipitate. The horizontal line at 100% for Ra is a consequence of the use of $^{228}$Ra to correct for those losses, see text. The dashed curve is based on

Fig. 8. Optical spectra of a 2.4% aqueous GdCl$_3$ solution before (dashed) and after (solid) adjustment to pH 6.0 and filtration. Removal of the broad band at ~340 nm due to iron is apparent. Peaks due to Gd remain essentially unchanged.
Daya Bay Liquid Scintillator

\[ \text{Abs}_{430} = 0.002 \sim 20 \text{m} \]

\begin{tabular}{|c|c|c|}
  \hline
  \( \bar{\lambda} \) (m) & Gd-LS & LS & MO \\
  \hline
  20.9 & 20.4 & 22.8 \\
  \hline
\end{tabular}

- PMT QE and emission corrected.
- Verified by 1-m auto-guided attenuation system.

\(~10,000\) photons/MeV
**Goals of Water-based Liquid Scintillator (WbLS)**

- To develop a new liquid medium; which is mass-producible and cost-effective with the capability of Cerenkov and Scintillation detection:
  - the physics below Cerenkov that is inaccessible to the water detector (next slides).
  - a large economic veto system (LUX, LBNE, etc.).
  - minimum ES&H concerns; to be deployed at any locations
  - also load metallic ions of interest for different applications (low-energy detection)
Adding oil to the water: Physics below Cerenkov - PDK+

\[ K^+ \rightarrow \mu^+ + \nu_\mu \]

\[ e^+ + \nu_e + \bar{\nu}_\mu \]

12 ns

2.2 ns

152 MeV

105 MeV

Invisible to water Cerenkov

WbLS

Missing channel of water Cerenkov

\[ K^+ \rightarrow \mu^+ + \nu_\mu \ (63.47\%) \]

(simulated at 90 ph/MeV ~ 1% LAB)
Cerenkov cone can be seen among scintillation

\[ K^+ \rightarrow \mu^+ + \nu_\mu \ (63.47\%) \]

A clear ring!

\[ K^+ \rightarrow \mu^+ + \nu_\mu \ (63.47\%) \]
$p \rightarrow \nu + K^+$

PDK+ sensitivity at Super-K

Scintillation + Cerenkov = Super-K + LENA?

Energy cut in prompt

Ring in delay

PSD, reconstruction, …, etc.
WbLS has scintillation in addition to Cerenkov light and is fast.

137-Cs gamma Compton

Time-resolving fluorescence

LEAF 10-MeV $e^-$ beam

NSRL -proton beam at 1GeV
$\lambda_{1/e}$ of emission at 365nm is $\sim 60$m and longer toward PMT sensible region

$\lambda_{1/e}$ of emission at 365nm is $\sim 60$m and longer toward PMT sensible region

\[ WbLS-2012 \]
\[ Daya Bay LS \]
\[ Super-K scattering + absorption \]
\[ WbLS-2012 emission at 365nm \]
\[ PPO emission at 365nm \]
\[ MSB emission at 425nm \]
\[ R7081 PMT QE \]

$1/e$ of emission at 365nm is $\sim 60$m and longer toward PMT sensible region

$\lambda_{1/e} = 20$m

Working on shifting emission by optimizing the fluor/shifter

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Biodegradation?

- LAS degradation only occurs at <50mg/L.
- LAS stability and compatibility (acrylic) stable for 2+ years since formulation
- LAS at 100mg/L completely inhibits bacteria growth (extensive studies by environmental-research groups in academia and industry).

Figure 5 Time-course analysis of consortium growth at different linear alkylbenzene sulfonate concentrations (in mg l⁻¹): (●) 10; (▲) 20; (■) 50; and (○) 100. Values are means ± standard deviations for three replicates.
Micro-organism growth is known to degrade attenuation length in water detectors and requires constant circulation (leaching needs to be addressed).

LAS/PC inhibits bio-activity; is circulation needed? If so, apply filtration and/or distillation.

All raw materials will be purified before mixed together.

Inorganic metallic ions can be removed either by vacuum distillation (SNO+) or multi-filtration (GADZOOKS).

WbLS can be vacuum distilled and 10% LS-loaded water can pass 0.1μ Teflon filter without loss.

R&D of

- Testing with ultra-/nano- filters
- Testing with ion exchange and reverse osmosis

In process of consulting industrial for an on-line purification system
Metal-loaded LS for Physics

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

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[Image of the periodic table with annotations for Reactor, \(\beta\beta\), Solar, and Others]
A new way of loading metallic ions in scintillator

→ adding water to the oil

• Double-beta decay
• Reactor neutrino
• Geo neutrino
• Supernovae neutrino
Arts of Organometallic-loaded LS

\[ M = \text{Li, B, Ca, Gd, In, Te, etc.} \]

- Conventional method (CX, P=O, -OH, etc.) that is metal-dependent; need R&D for each element.
- Limitations of
  - hydrophilic metallic ions
  - complexing ligands could impact the optical and light-yield properties

R&Ds of new LS & ligands

- New metallic-loading technology that is “almost” no limit of elements.
- Need understandings of raw materials, quenching and fluor/shifters.

R&Ds of optimization and purification
Advancing metal-loaded performance using WbLS tech.

Double-beta decay

Solar-ν

Reactor ν
- DayaBay-II, RENO-II, etc.
- Sterile
- Anomaly
- Nuclear fuel monitoring and safeguard.
First metal-loaded WbLS’s for DBD and for Solar V

- WbLS-X loading is faster and higher efficiency ($\varepsilon=100\%$)
- The M-WbLS has 20% higher light-yield than the Nd-LS (and optically better).
- The light-yield improves as a factor of 2 for ~7% Indium-loaded LS
- A new loading technology for metallic ions that cannot be loaded before; extends the physics applications.
- Short half-life calibration sources possible.
- Better cocktails for environmental samples

AAP-2012 M.Yeh
Low-energy $\bar{\nu}_e$ detection

- New liquid, Gd-LAB, has been developed and demonstrated.
- Water-detector (Gd) has been a very successful operation.
- Larger-scale at few Km’s is a challenge
  - Wavelength-shifter to re-cap the Cherenkov
    - Amino-G, ~2x; Carbostyril-124, ~4x (SNO)
- What about adding (little) scintillator to enhance Gd-capture signal?
  - How much light do we need?
    - What is the impact of ring-imaging ability?
    - Improve $e^+$ resolution.
- Can we use WbLS as a veto system?
A 2-L test stand for **All** (metal-loaded) scintillation liquids

- **NSRL** p-beam below and above Cerenkov (200-MeV to 2-GeV)
- Cosmic-induced muons (ongoing)
- Neutron tagging efficiency
- Calibration sources; R&Ds energy non-linearity

**NASA Space Radiation Research Laboratory**

A run in 2010 saturated the light

- Schedule to run with precise energy and intensity in Oct. 2012
- Apply beam-time for 2013 (~$5k/hr).
1-ton Demonstrator

- An enable technology (with metal-loaded) ready to do the real-prototyping study of (1) neutrino interaction; (2) veto efficiency:
  - Neutrino beam: WbLS (neutrinos at few GeV)
  - Reactor: Gd-WbLS (antineutrino at few MeV)
  - NSRL: proton beam at 200 MeV – 2 GeV
  - Cosmic-induced Muons:
    - How well can we measure the muon
    - How well can we tag the neutron

- Design and location are under discussion