Scintillation Detector

- General introduction and physics of liquid scintillator
- Metal-loaded liquid scintillator
- Future liquid scintillator

Minfang Yeh (BNL)
Typical Cerenkov and Scintillation Detectors

- 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)

Mean Absorption Length (m)

Photon/MeV

~20% LS

~100% LS
Main Neutrino Interactions in Liquid Scintillator

- $\bar{\nu}_e + p \rightarrow n + e^+$; $n + p \rightarrow d + \gamma$
- $\bar{\nu}_e + ^{12}C \rightarrow e^+ + ^{12}B \rightarrow ^{12}C + e^- + \bar{\nu}_e$
- $\nu_e + ^{12}C \rightarrow e^- + ^{12}N \rightarrow ^{12}C + e^+ + \nu_e$
- $\nu_x + ^{12}C \rightarrow \nu_x + ^{12}C^* \rightarrow ^{12}C + \gamma$
- $\nu_x + e^- \rightarrow \nu_x + e^-$
- $\nu_x + p \rightarrow \nu_x + p$

Excellent detection medium for neutrino in MeV range; need NC background reduction in GeV range


Different LS combinations to meet the need of various physics
BNL Liquid Scintillator Development Facility

- Collaboration between Physics and Chemistry at BNL with expertise in low-background counting, organic scintillators, and in particular metal-loaded organic scintillator
  - Interest of neutrino and neutron detectors (Daya Bay, SNO+, LENS)
- Investigation of a large variety of liquid scintillators
  - PC, PCH, DIN, PXE, LAB
- Metal-loaded and water-based scintillators with high light-yield, long attenuation length and low flammability.
- Capability of purifying and synthesizing materials in-house and of controlling the chemical processes.

Scintillation mechanism

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

M. Yeh, Review of Metal-loaded Liquid Scintillator for Neutrino Physics, IJMPB (in prep.).
Comparisons of Liquid Scintillators for Neutrino Expt’s

Table 1
The chemical properties and physical performance of selected LS

<table>
<thead>
<tr>
<th>LS</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>(C_6H_{12})</td>
<td>(C_{12}H_{16})</td>
<td>(C_{16}H_{20})</td>
<td>(C_{18}H_{18})</td>
<td>(C_{18}H_{30})</td>
<td>(C_{n}H_{2n})</td>
<td>(C_{12}H_{26})</td>
</tr>
<tr>
<td>Can Gd be loaded into the LS?</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</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>0.98</td>
<td>0.86</td>
<td>0.85</td>
</tr>
<tr>
<td>abs (40^\circ), 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 (40^\circ), after purification</td>
<td>0.002</td>
<td>0.001</td>
<td>0.023</td>
<td>0.022</td>
<td>(\approx 0.000)</td>
<td>0.001</td>
<td>(\approx 0.000)</td>
</tr>
<tr>
<td>Purification method</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</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%</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.e. ((\times 10^{22}))</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>

(first identified by SNO+)

\(^a\)See the text in Section 3.4 for the chemical names of these organic compounds.
\(^b\)With alkyl side chain containing 12 carbon atoms.
\(^c\)n \(\approx 30\) [17].
\(^d\)Only stable for few months.
\(^e\)v.d. = vacuum distillation; c.e. = column extraction with solid \(Al_2O_3\).
\(^g\)Scintillation yield normalized to 100% PC; n.a. = non-aromatic compounds which do not scintillate.

## Past & Present Liquid Scintillator experiments

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Scintillator Mix</th>
</tr>
</thead>
<tbody>
<tr>
<td>Palo Verde</td>
<td>40% PC + 60% Mineral oil</td>
</tr>
<tr>
<td>CHOOZ</td>
<td>50% paraffinic liquid + IPB (isopropylbiphenyl)</td>
</tr>
<tr>
<td>Borexino</td>
<td>PC</td>
</tr>
<tr>
<td>LENS</td>
<td>LAB (PC)</td>
</tr>
<tr>
<td>MiniBOONE</td>
<td>MO</td>
</tr>
<tr>
<td>Daya Bay</td>
<td>LAB</td>
</tr>
<tr>
<td>SNO+</td>
<td>LAB</td>
</tr>
<tr>
<td>RENO</td>
<td>LAB</td>
</tr>
<tr>
<td>Double-CHOOZ</td>
<td>20%PXE + 80%dodecane</td>
</tr>
<tr>
<td>KamLAND$^2$</td>
<td>20% PC + 80%dodecane</td>
</tr>
<tr>
<td>NOvA</td>
<td>5% PC + 95% MO</td>
</tr>
</tbody>
</table>
## Possible Future Liquid Scintillator Experiments

### Newly Proposed Experiments (selected)

<table>
<thead>
<tr>
<th>Accelerator-based</th>
<th>Reactor-based</th>
<th>V-sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>LENA</td>
<td>Daya Bay-II, RENO-II</td>
<td>Ce-LAND</td>
</tr>
<tr>
<td>OscSNS</td>
<td>SCRAAM, Stereo, NIST</td>
<td>LENS-Sterile</td>
</tr>
<tr>
<td>IsoDAR</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- LS not decided; but LAB is the favor
- Gd-loaded for most reactor expt’s
Metal-loaded LS for Physics

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

PX workshop M.Yeh
Inverse Beta Decay Detection with Gd

- $E_{\text{threshold}} = 1.8 \ MeV$
- ‘Large’ cross section $\sigma \sim 10^{-42} \ cm^2$
- 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 using Nd

<table>
<thead>
<tr>
<th>Isotope</th>
<th>$G^{\nu\nu} \text{ (x} 10^{-15} \text{ y}^{-1})$</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>$^{76}\text{Zr}$</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>

- 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.**
- **Installation and production in FY13**

Searching for $0\nu\beta\beta$-decay to answer:

- whether neutrinos are Dirac or Majorana particles
- probe neutrino masses at the level of tens of meV; $A_{m_{\beta\beta}}$ limit of $\sim 20$ meV would exclude Majorana neutrinos in an inverted hierarchy.
Low Energy Neutrino Spectroscopy (LENS)  
detection of pp, $^7$Be, CNO and pep solar $\nu$ in In-LS, Luminosity of Sun

Tagged $\nu$ capture reaction in Indium  
→ LENS is the only developed CC real time detector for solar neutrinos

$$\nu_e + ^{115}In \rightarrow e^- + ^{115}Sn \rightarrow 2\gamma + ^{115}Sn$$

Unique:
- Specifies $\nu$ Energy
  $$E_\nu = E_{e} + Q$$
→ Complete LE $\nu$ spectrum
- Lowest $Q$ known → 114 keV
→ access to 95.5% pp $\nu$'s
- Target isotopic abundance ~96%
- Powerful delayed coinc. Tag
  Can suppress bgd $= 10^{11} \times$ signal

Downside:
- Bgd from $^{115}$In radioactivity to
  (pp $\nu$'s only) → rate $= 10^{11} \times$ signal

Tools:
1. Time & Space coinc. → Granularity
   (10$^6$ suppression)
2. Energy Resolution
   In betas <500 keV; $\Sigma$Tag = 613 keV
3. Other analysis cuts

- 8% Indium loaded LS meets the experiment needs
- micro-LENS is ongoing in Kimberton mine with mini-LENS in preparation
How to make a clean and stable metal-loaded LS?

• Synthesis procedure
• Purification (radioactive & optical)
• QA/QC
Ex. of Gd-LS production at Daya Bay:

- Gd-LS production done in 3 months
- >3-yrs R&D and >1-yr 1-t prototype monitoring on Gd-LS stability
- Optical improvement and U/Th removal
- QA/QC during and after production

Self-scavenge, PH-controlled Gd salt purification

Low flash point, compatible light-yield, know-how production, high compatibility
Self-scavenge Gd purification

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

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 $^{226}$Ra to correct for those losses, see text. The dashed curve is based on

M.Yeh et al. NIM A 618 (2010) 124–130

Fig. 8. Optical spectra of a 2.4% aqueous GdCl$_2$ 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.
Complexing acid and PPO purifications

- Purification is a must for optical and stability improvements.
- LAB produced specially by the vendor.
- PPO purified by re-crystallization after washes (can also purified by mixing in PC or LAB by direct distillation)
- Gd-complexing ligand purified by thin-film vacuum distillation.

heavy potion removed from the ligand solvent by 3x in 300-500nm
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!

<table>
<thead>
<tr>
<th></th>
<th>Gd-LS</th>
<th>LS</th>
<th>LAB</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda$ (m)</td>
<td>20.9</td>
<td>20.4</td>
<td>22.8</td>
</tr>
</tbody>
</table>

PX workshop M. Yeh
QA/QC and AD Identification

- **Stability**

**All 6 ADs:**

- [Gd] agrees within 0.16%
- [H] agrees within 0.17% (Combustion analysis)
- [Gd-LS] $\lambda_{\text{ave.}} > 20m$
- Light-yield emission agrees within 1% (Fluorescence Spectroscopy)
• Binary liquid scintillator
• Singular liquid scintillator
• Water-based liquid scintillator

Liquid scintillator Options for future experiments
Option-1: Binary scintillating liquid system

Linear Alkylbenene + dodecane or mineral oil
Density Matching and Solvent Purity are the keys to the stability of binary system

- For the bottle with 2 phases, the top layer is light mineral oil at 80% with 0.00529%Gd and the bottom layer is PC at 20% with 0.01149%Gd.
- Others of Gd in PC and DD with and without shifters have been stable since 2005.
Option-2 singular liquid scintillator

\( \text{LAB + PPO (3g/L) + bis-MSB (15 mg/L)} \approx 10,000 \text{ } \gamma \text{s / MeV} \)
Option-3: Water-based Liquid Scintillator

- Cost-saving for larger detector (see talk in cost-effective detector session)
- Clean Cerenkov cone with scintillation at few hundreds of photons per MeV (tunable)
- Fast pulse and long attenuation length with minimum ES&H concerns
- A new technology ready to use:
  - Excellent detection medium for proton decay; and other physics
  - Easy to be handled for large detector
  - Gd-soluable
  - A economic large veto solvent
$\tau_{\text{WsLS(PPO)}}$ between 2 – 4 ns

Time-resolved fluorescence system

10-MeV $e^-$ beam at LEAF

Brookhaven Science Associates

PX workshop M.Yeh
WbLS Attenuation Length close to pure water after 400nm

- 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 very clean

The fluor/shifter transmission needs to be optimized.
WbLS Scintillation vs. Cerenkov (Cs-137)

- Cerenkov increases by ~4x using Carbostyril-124 (SNO)
- A ratio of 5:1 for scintillation vs. Cerenkov

PX workshop M.Yeh
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.
Scintillation light at 90 $\gamma$s/MeV

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

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

clean $\mu$-rings can be identified among scintillation

Brookhaven Science Associates

PX workshop M.Yeh


**Sensitivity of WbLS for PDK+**

- **Event 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…

- Compare to SK (170 events in 1489 days), the 3-fold coincidence cuts down to \(\sim 5/\text{y}\); PSD/Michel position cut can further suppress the bkg. event to \(0.25/\text{y}\).

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

---

Brookhaven Science Associates
PX workshop 2012 M. Yeh
A new way of loading hydrophilic metallic ions (Li, Ca, Te, etc) in scintillator

- Double-beta decay
- Reactor neutrino
- Geo neutrino
- Supernovae neutrino
First DBD isotope in WbLS

- Efforts to load certain metallic-ions in pure LS (ε=80%)
- Quick and straight in preparation of X-WbLS (ε=100%)
Typical Cerenkov and Scintillation Detectors

Mean Absorption Length (m)

Cerenkov (Super-K)

proton decay, supernovae
(\text{Gd}), beam physics FD

~\gg 50\text{kt Detector}

~\text{kt Detector}

0\nu\beta\beta, geo-\nu,
reactor-\nu, beam physics ND

~\text{100\% LS}

Organometallic-ion WbLS

Scintillator (Daya Bay)

~\text{20\% LS}

~\text{10000}

Photon/MeV

Brookhaven National Laboratory

34

PX workshop 2012 M. Yeh
LS reactivity (compatibility) favors LAB

Material Compatibility and Cleaning Program

- Current study
  - the liquid-effect on material
  - the material-effect to liquid
  - Kinetics of leaching
  - ~400 samples being tested in H2O, LS and Gd-LS

- Future study:
  - develop pre-cleaning procedures to reduce the cost and time for purification
  - identify the leaching-materials by GC-MS, ICP-MS, XRF
  - compile a database for science community

Material and chemical QC/QA Assessment

BNL leading the role of

- developing QA/QC assessments for material selection and liquid qualification
- conducting radioactivity screening
- setting up a well-equipped QA/QC lab for neutrino experiments
Liquid Scintillation Veto film

- current experience with LS veto-film (a project in collaboration with LNGS) to produce μm-thin, Teflon-based films targeting surface α/β 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.
Summary

- Liquid scintillator continues to play a key role for neutrino detection in (non)accelerator, reactor, double-beta decay experiments.
- There are several liquid options for the future detector; depending on the physics requirements and costs.
- The technology of meal-loaded LS is well developed; and its M%, attenuation length, and photon-production are tunable as needed.
- The synthesis technology, material compatibility, and cost of production & purification of scintillator have been worked out and demonstrated to be stable.
- WbLS with scintillation & Cerenkov detections is an excellent medium for proton decay (and other physics) and can be used for neutron tagging (enhanced by Gd loaded).
- A cost-effective large detector as well as veto system for future experiment