Studies of Doped Scintillator at BNL
A Generic Method for Neutrino Experiment

BNL Neutrino/Nuclear Chemistry Group

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Students…

M. Yeh for LRT Workshop, Sudbury, December 2004
40 Years of BNL Chemistry and Neutrinos

- **HOMESTAKE** Radiochemical Detector
  615 tons of C$_2$Cl$_4$; $^{37}$Cl + $\nu_e$ $\rightarrow$ $^{37}$Ar + $e^-$ (~40 years)

- **GALLEX** Radiochemical Detector
  30 tons of Ga; $^{71}$Ga + $\nu_e$ $\rightarrow$ $^{71}$Ge + $e^-$ (1986 - 1998)

- **SNO** Water Čerenkov Detector (SNOLab)
  1000 metric tons of ultra-pure D$_2$O (1996 - ≥ 2006)

- **LENS** Real-time Detector (R&D)
  $^{115}$In in Liquid Scintillator (~2000 - ?)

- **BNL-AGS NEUTRINO FACTORY**
  Very Long-Baseline Experiment- Neutrino Beam from BNL (~2002 - ?)

- **THETA-13** Real-time Detector (R&D)
  Gd in Liquid Scintillator (~2003 - ?)
In-doped Scintillator for LENS-Sol

Stability: The UV-VIS absorbance (430 nm) with time over six months (BNL#115, In%=6.77)

Light yield with time over six months (BNL#115, 3g PBD/L, 15mg bis-MSB/L)

Bell Lab/Brookhaven National Lab developed a very consistent In-LS chemical synthesis method for LENS-Sol:

- high In content (~7%)
- good light yield (~40% of PC)
- long attenuation length (L(1/e) ~9 m without shifter)
- chemical stability for over 11 months since synthesis
Advantages of adding Gd into LS for neutrino detection:

- enhance neutron capture.
- at 0.1% Gd by weight, it reduces the capture time from 200 $\mu$s on H to 30 $\mu$s on Gd $\rightarrow$ accidental background reduced by $\sim 7$.
- energy release of a neutrino capture on Gd is about 8 MeV (a cascade of 3-4 $\gamma$-rays), compared to 2.2 MeV for H $\rightarrow$ target volume is better defined and low energy backgrounds from other sources can be excluded.
5t 0.1% Gd-loaded scintillators

- Not stable Gd-loaded scintillator ($L \sim 2 - 5$ m) \( \Rightarrow \) turned yellow after few months of deployment (0.4% degradation per day)
- Homogeneous detector \( \Rightarrow \) $n$ capture peak at 8 MeV
- Detector Efficiency \( \sim 70\% \)

12t 0.1% Gd-loaded scintillators

- Good Gd-loaded scintillator ($L \sim 11$ m) \( \Rightarrow \) slight deterioration with time (0.03% degradation per day)
- Segmentation detector \( \Rightarrow \) $n$ capture peak < 6MeV
- Detector Efficiency \( \sim 10\% \)
Loading Gd into LS is not trivial

- difficult to add *inorganic* salts of Gd into *organic* liquid scintillator → extracting agents required
- Gd-LS must be long attenuation, good light yield and stable for several years → chemical and material selections…
- purifications required to remove
  - Radioactive species that mimic the neutron-capture signal
  - Chemical species that affect the attenuation and stability
Gd-LS Chemistry and Preparation

- **Considerations of Gd-LS for \( \theta_{13} \) Measurement to 1% or better**
  - C/H of the liquid scintillator must be well determined
  - concentrations of Gd and mass of the organic LS need to be identical in Near and Far detectors → special care for batch-wide preparation

- **Scenarios of Gd-LS Preparation at BNL**
  - to develop a reproducible procedure for Gd-LS synthesis
  - to dope Gd into different scintillators (PC and mix of PC and mineral oil)
  - synthesize concentrated Gd-LS (1~2 %) first, then dilute to (0.1~0.2%)
  - to establish chemical assays to remove and measure chemical and radioactive impurities
Status of BNL Gd-LS for $\theta_{13}$ Experiments

Measurements of:

- Purification
- Attenuation Length
- Light Yield
- Long-term Stability
Purification of Radioactive Impurity

<table>
<thead>
<tr>
<th></th>
<th>$^{238}$U</th>
<th>$^{232}$Th</th>
<th>$^{40}$K</th>
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<tbody>
<tr>
<td>Gd$_2$O$_3$ [ppb] (IHEP)</td>
<td>&lt;13</td>
<td>440±32</td>
<td>&lt; 2.3</td>
</tr>
<tr>
<td>GdCl$_3$ [ppb] (BNL)</td>
<td>in preparation</td>
<td></td>
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- Require purity of Gd powder < 1 ppb $\rightarrow$ $10^{-12}$ g/g $\rightarrow$ 0.3 Hz for 10-ton, 0.1% Gd-LS + 45 cm $\gamma$-catcher.

- Purification of Water (positive/negative ion exchange).

- Purification of Gd (ion exchange vs solvent extraction).
Purification of Chemical Impurity

- Purify Aqueous GdCl$_3$ separately.
- Purification of Aqueous Phase (NH$_4$ – carboxylate) by mixtures of organic solvents.
- Purification of Organic Phase (carboxylic acid, liquid scintillators) by dry column and temperature-dependent, vacuum distillation.
- Measure by attenuation.
Purification of carboxylic acid
Purification of Phenyl Cyclohexane, PCH
Attenuation by Shimadzu UV-1601

- 1-cm/10-cm cell
- scanning wavelengths from 190 nm to 1100 nm
- silicon photodiode
- 50W halogen lamp and deuterium lamp
- Spectrum/Quantitation/Photo metric/Kinetics modes
Attenuation by Long-path Optic System

- 48 mW HeCd blue laser
- single $\lambda$ at 442 nm
- 2.5 mm blue beam
- $\geq$ 1-m horizontal cell
- silicon photodiode

$$A(\lambda) = -\log\left(\frac{I}{I_o}\right) = \varepsilon \times b \times c$$

$$L = \frac{\log(e) \times b}{A(\lambda)}$$
Reproducibility of Gd-LS Synthesis

Samples are prepared from different batches under different conditions.

The quality of PC is the main concern.

The synthesis is very reproducible in terms of Gd extraction and physical properties.

Need long-path laser measurement for attenuation length.

Mixtures of Gd16 to Gd20 $\rightarrow$ L~16 m by 1-m Laser measurement.
Long-term Stability Test: ~1.2% Gd-LS as a Function of Time
Light Yield: a Function of PC

- Light yield is a function of PC%.
- 1.2% Gd-LS is ~81% of PC.
- 0.2% Gd-LS is > 95% of PC.
Comparisons of Different Scintillation Systems

- Pure PC
- 0.2%Gd + 40%PC + 60% MO
- 40%PC + 60% MO
- 20%PC + 80% MO
- Pure MO
UV-vis of PC/MO/Mix

<table>
<thead>
<tr>
<th>Scintillator</th>
<th>Abs (430 nm)</th>
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<tbody>
<tr>
<td>Pure PC</td>
<td>0.004</td>
</tr>
<tr>
<td>40%PC60%MO</td>
<td>0.002</td>
</tr>
<tr>
<td>0.2%Gd40PC60%MO</td>
<td>0.003</td>
</tr>
<tr>
<td>20%PC80%MO</td>
<td>0.002</td>
</tr>
<tr>
<td>Pure MO</td>
<td>0.001</td>
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Light Yield of PC/MO/Mix

<table>
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<tr>
<th>Scintillator</th>
<th>S%</th>
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<tbody>
<tr>
<td>Pure PC</td>
<td>100</td>
</tr>
<tr>
<td>40%PC60%MO</td>
<td>88.9</td>
</tr>
<tr>
<td>0.2%Gd40%PC60%MO</td>
<td>87.7</td>
</tr>
<tr>
<td>20%PC80%MO</td>
<td>82.7</td>
</tr>
<tr>
<td>Pure MO</td>
<td>23.8</td>
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Counts vs. Channel
# BNL Gd-LS vs BC-521 (Palo Verde)

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<tr>
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<th>BNL Gd-LS</th>
<th>BC-521</th>
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<tr>
<td>Measured by</td>
<td>BNL</td>
<td>BNL</td>
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<tr>
<td>Gd %</td>
<td>~1.2%</td>
<td>~1%</td>
</tr>
<tr>
<td>Attenuation Length (m)</td>
<td>13.5 (1-m laser)</td>
<td>2.55 (10-cm UV)</td>
</tr>
<tr>
<td></td>
<td>6.23 (10-cm UV)</td>
<td></td>
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<tr>
<td>Light Yield (s%)</td>
<td>81.9% PC</td>
<td>85% PC</td>
</tr>
<tr>
<td>Stability</td>
<td>2 months and continuing</td>
<td>N/A</td>
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The synthesis of Gd-doped scintillator is very reproducible in terms of Gd extraction (~85%), attenuation (~15 m for 0.2%Gd), and light yield (>95% of pure PC).

Chemical purification is essential for attenuation and long-term stability.

Mineral oil has better attenuation than PC.

High concentrated Gd-doped scintillator has been stable for over 2 months in terms of attenuation and light yield.

Long-Path Optical Measurement is necessary.
Future R&D at BNL

- Assays to remove radioactive impurities.
- Compatibility test of scintillator with acrylic.
- Aging test, temperature-dependent kinetics approximately doubles per $\Delta 10^\circ C$.
- C/H ratio determination.
- Scale-up, closed-loop production.