Chemistry in Neutrino Search

Sunej Hans, Minfang Yeh And Neutrino Group
What are Neutrinos?

- Neutrinos are generated as a result of radioactive decay or nuclear reactions such as in the Sun, nuclear reactors, and when cosmic rays hit atoms.
- Neutrinos are passing through the Earth which are generated in the Sun.
  - 65 billion solar neutrinos per second pass through every square centimeter

[Image: Illustration of neutrinos generated by the Sun]

**FACT:** About 65 million neutrinos pass through your thumbnail every second.

http://lsned.com/facts/neutrino/
Properties of Neutrinos

- There are three types neutrinos flavors
  - Electron neutrinos
  - Muon neutrinos
  - Tau neutrinos

- Neutrino have its antiparticle called antineutrino

- Neutrino (ν) is an electrically neutral, subatomic particle and has mass that has never yet been measured precisely.
Why We need to Study Neutrinos?

• Neutrinos are important to understand the Sun

• As Physicist Hooper said “neutrinos are like blueprint of nature

• The tiny mass of neutrinos might explain why universe is made of matter not antimatter.

• Early in the process of the Big Bang, there were equal amounts of matter and antimatter, according to Conway. "But as the universe expanded and cooled, matter favored over antimatter.

• Neutrinos may have something to do with that process
How To Detect Neutrino

charged-current interactions,

- inverse beta decay
- antineutrino + p → n + e⁺
What is Needed for Detection of Neutrino

- Large Detector
- Shielding from cosmic background
- Filled with tons of scale of liquid
Role of Chemistry in the Neutrino Experiments

• Development of various metal loaded Liquid Scintillator (M-LS) and unloaded detectors, the central piece of detection medium, that is specialized for neutrino experiment.

• Ability to load many different metals although different conditions and materials are required for various metals.

• Production of Low cost WBLS (water based liquid scintillators) detectors.

• Synthesis, Characterization, Purification and QC/QA.
Challenges in Developing LS

- Selection of the Scintillator
- Selection of the metal
- Long term Stability
- Loading of the metal
- Purification
- QC/QA for database
Liquid Scintillator Development Facility

- A unique facility (since 2002) for Radiochemical, Cerenkov, and Scintillator (water-based and metal-doped) detectors for particle physics experiments.

- facility including XRF, LC-MS, GC-MS, FTIR, UV, Fluorescence emission, light-yield coinc. PMT, 2-m system, low bkg. counting, etc. (access to ICP-MS at SBU) for detector R&Ds and prototype tests.
Metal-loaded LS for Neutrino Physics
Requirements for Liquid Scintillator for $\nu$ Experiments

- Long-term Stability
- Long attenuation length: $> 10 \text{ m}$
- High photon yield
- Low radioactive background
- ESSH
Components of LS

- **Aromatic solvent** that contains a high density of π-electrons for energy transfer
- Scintillation the property of luminescence when excited by ionizing radiation
- Luminance materials absorb the energy of the incoming particle and emit the energy in the form of light
- **Fluor** that transfers the energy (<400 nm) to light (>400 nm) within the optimal detection range of PMT
Selection of Liquid Scintillator

- High density, flash point, low toxicity, and low cost
- Chemical compatibility with acrylic
- High light yield and long attenuation
- Able to load organometallic compound
Ligand for the Metal Loading into the Liquid Scintillator

- Alcohol – light yield quencher

-Phosphate – Stability issues over longer time

-Carboxylic Acid – Higher metal extracting, longer attenuation length and stable
  - Different Carbon Chain Carboxylic acids are used for different metal extraction
    - Loading concentration
    - Loading efficiency
    - Light yield
Selection of the Flours and Shifters

Optimal fluor/shifter: shifting the light to clean region that still have good PMT QE (~450nm)
Purification of all the Precursors
LAB Purification using Column Chromatography

Packed with Al₂O₃
Distillation of the Carboxylic Acid (TMHA)
Metal Salt Purification by using Scavenging method
Purification of PPO by Recrystallization
Synthesis of M-LS

M-LS, the central piece of detection medium

\[ \text{GdCl}_3 + \text{3,5,5 trimethyl hexanoic acid (TMHA) excess amount} \]

2,5-diphenyl oxazole

p-Bis-(o-methylstyryl)-Benzene
Absorbance by UV-VIS and Attenuation Length

\[ \mathcal{L} = \frac{\log(e)L}{A(L)} \]

- \( \mathcal{L} \) is attenuation length
- \( L \) is path length = 10 cm for UV-Vis and >> 1m for laser
- \( A(L) \) is absolute absorption at 430 nm
- \( \mathcal{L} = (0.434 \times 10 \text{ cm})/(0.008) = 542 \text{ cm} = 5.4 \text{ m} \)

[Graph showing absorbance and attenuation length]
Metal Concentration Analysis in M-LS

Spectrum Acquired: 12/12/12 10:40:01

Counts 718340
Counts Limit 0
Live Time (s) 60
Live Time Limit 60
Dead Time 52%
Scale = 84K
Examples of International Neutrino Projects:

Daya Bay Antineutrino Experiment (200 tons)
China

SNO+ Double Beta Decay (1000 tons)
Canada
High-Precision $\theta_{13}$ Experiment (Daya Bay) measure reactor antineutrino for $\theta_{13}$ in Gd-LS

IBD (inverse $\beta$-decay) events in Gd-doped liquid scintillator:

Among the top 5 most powerful reactor complexes in the world, 6 cores produce $17.4 \text{ GW}_\text{th}$ power, $35 \times 10^{20}$ neutrinos per second
The Daya Bay Experiment

Far Hall
1615 m from Ling Ao I
1985 m from Daya Bay
350 m overburden

Ling Ao Near Hall
481 m from Ling Ao I
526 m from Ling Ao II
112 m overburden

Daya Bay Near Hall
363 m from Daya Bay
98 m overburden

- 17.4 GW_{th} power
- 8 operating detectors
- 160 t total target mass
Daya Bay Nuclear Power Complex

12th most powerful in the world (11.6GW)

One of top five most powerful by 2011 (17.4 GW)

Next to mountain, feasible for tunnel construction to underground lab with sufficient overburden to suppress cosmic background
Construction Phase

US scope ~$36M incl. contingency

CD-2 in 2007, CD-3a in 02/2008, CD-3b in 06/2008

Civil construction began in 10/2007
Antineutrino Detectors

- Target 20 ton (0.1% Gd LAB based LS)
- Gamma Catcher 20 ton (LAB based LS)
- Buffer 40 ton (mineral Oil)

8 functionally identical detectors reduce systematic uncertainties

3 zone cylindrical vessels

<table>
<thead>
<tr>
<th>Liquid</th>
<th>Mass</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner acrylic</td>
<td>20 t</td>
<td>Antineutrino target</td>
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<tr>
<td>Gd-doped liquid scint.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Outer acrylic</td>
<td>20 t</td>
<td>Gamma catcher</td>
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<tr>
<td>Liquid scintillator</td>
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<tr>
<td>Stainless steel</td>
<td>40 t</td>
<td>Radiation shielding</td>
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<tr>
<td>Mineral oil</td>
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192 8 inch PMTs in each detector
Top and bottom reflectors increase light yield and flatten detector response
Liquid Scintillator Hall
Daya Bay Liquid Scintillator
- 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
Oscillation Results

FIG. 1. Layout of the Daya Bay experiment. The dots represent reactors, labeled as D1, D2, L1, L2, L3 and L4. Six ADs, AD1–AD6, are installed in three EHs.

\[ \sin^2 2\theta_{13} = 0.089 \pm 0.009 \]
QA/QC and AD Identification

- **Stability**
  - All 6 ADs:
  - $\text{[Gd]}$ agrees within 0.16%
  - $\text{[H]}$ agrees within 0.17% (Combustion analysis)
  - $\text{[Gd-LS]}$ $\lambda_{\text{ave.}} > 20$ m
  - Light-yield emission agrees within 1% (Fluorescence Spectroscopy)
Transition from SNO to SNOLAB
• Neutrinoless $\beta\beta$-decay

• Solar neutrinos:
  • precise measurement of pep survival probability
  • CNO neutrinos

• Reactor neutrinos:
  • several reactors contribute to oscillations

• Geo neutrinos:
  • Th and U distributions in earth’s crust

• Supernova neutrinos:
  • hundreds of events
Double Beta Decay Isotopes in LS (SNO+) search for $0\nu\beta\beta$ in Te-LS

- 1kton Tellurium loaded LS
- Finding suitable ligand for Te was difficult
- Alternative way to load Te was established which could also be very useful for the future experiments.
- Search for the secondary shifter is on going
What else chemistry can do for Development of detector for neutrinos? 
Material Testing for all the detector Parts
Material Testing Lab

8 1L bottles
24 0.5L bottles

6/26/2015
MATERIAL COMPATIBILITY PROGRAM

- Our goal is to study for various detectors
  - Impacts of material to liquid: UV
    - Effect the optical transparency caused by inorganic/organic components
  - Impacts of liquid to material: XRF, ICP-MS, Microscope
Summary

• Neutrino research is marching into high precision era.

• Scintillator continues as one of main-stream detection mediums for neutrino detection.

• BNL has the expertise and facility for all-aspect development of neutrino detector: (1) development of detection medium; (2) monitoring the performance; (3) resolve any chemical issues during the operation.
Acknowledgement

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