Scintillator Physics

- **0νββ** (e.g. SNO+, KamLAND-Zen)
- **Reactor ν** (e.g. Daya Bay, PROSPECT, JUNO)
- **Solar & Geo ν** (e.g. LENS, Borexino, KamLAND, SNO/SNO+)
- **Dark Matter & Accelerator Physics** (e.g. LZ, JSNS2)
- **Nonproliferation** (e.g. AIT-WATCHMAN)

**Liquid Scintillator** (Metal-loaded & Water-based)

Common features between detectors

unique requirement for individual detector
If you always do what you always did, you will always get what you always got. -Albert Einstein

Mean Absorption Length (m)

Cherenkov (e.g. Super-K, SNO)

Water-based Liquid Scintillator

Water-like WbLS
- Cerenkov/Scint. Detection
- Metal-doped flexibility

Oil-like WbLS
- Metal-loaded LS
- Directionality

BNL in-house facility and expertise for radiochemical, Cherenkov and scintillator detectors

Scintillator (e.g. SNO+, Daya Bay)
BNL Scintillator R&D’s

- Pure Liquid Scintillator (LS)
  - Stability, transparency, photon-yield, PSD
  - Scalability, Capability for purification/synthesis, Compatibility (and Directionality?)

- Metal-doped Liquid Scintillator (M-doped LS)
  - Extend physics reaches for scintillator detectors

- Water-based Liquid Scintillator (WbLS)
  - Cost-effective approach for large-scale detector
  - Directional scintillation water probing physics below Cherenkov threshold
Liquid scintillator today is safer and more environmental friendly with better compatibility.
Purification Development

- Impure LAB
- Distilled LAB
- Column-extracted LAB

Corrected F/F+P (%) vs pH

- Th
- Bi
- Ac
- Am
- Gd

Absorbance vs Wavelength (nm)

Self-scavenging Gd-purification

Pressurized Ion-exchange System
Ton-scale Liquid Production Facility

Currently dedicated to LZ; available for other experiments in 2020

10/11/2018
M. Yeh, AAP-2018
Metal-doped Liquid Scintillator

**Periodic Table of the Elements**

- **Reactor**
  - Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu

- **ββ**
  - Th, Pa, U, Np, Pu, Am, Cm, Bk, Cf, Es

- **Solar**
  - Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu

- **Others** (e.g. ~8.4% Pb-loaded LS, 2.8% Mo-doped LS)
Metal-loading Techniques

- Organometallic complexes (multi-step, water-exclude)
  - Require a complexing ligand
    - carboxylic acid
      - From C₂ to C₁₂ as early development by LENS (In-LS and Yb-LS)
      - C₆ for Gd-doped PC; C₉ for Gd-doped LAB
      - e.g. Palo Verde, Daya Bay, RENO
    - β-diketone (BDK)
      - Early development also in the context of LENS
      - 2,4-pentanedione (Hacac) and 2,2,6,6-Tetramethylheptane-3,5-dione (Hthd)
      - e.g. Double-Chooz, Nucifer

- Solvent Extraction vs. Solid Dissolution
- Not effective for hydrophilic elements

- Direct mixing (one-step, water-include)
  - Surfactant chemistry
  - Water-based mixing (e.g. PROSPECT)
Ex. $^6$Li-doped LS
(Criteria from PROSPECT prototype)

- In operation since March 2016, near continuous data-collection
- Measured light collection with $^6$LiLS: >550PE/Mev
  - 5% energy resolution at 1MeV
- Measured PSD Figure of Merit: 1.25 at (n,Li) capture
  - >99.9% background rejection
- Double-ended readout
  - Position reconstruction along cell length
Scalability (~5 tons in 6 months)

**Stability** from production to deployment with UV variation of 0.001 (< systematic uncertainty) over 6 months

**Consistency** over 60 batches of production

*preliminary*
2nd Generation Li-doped LS

Further Improvement of optical transparency by reducing Scattering
A Cherenkov-visible Scintillation Liquid is the key to future LS detectors:

- Oil-scintillator: reducing scintillation light or slowing scintillation decay-time to allow Cherenkov imaging
- Water-based Liquid Scintillator
- Fast photosensors/electronics (LAPPD)
- Liquid Scintillator Imaging?

LSND rejects neutrons by a factor of 100 at ¼ Cherenkov & ¾ Scintillation light (NIM A388, 149, 1997).
WbLS today: 1% WbLS Properties capable of detection below Cherenkov

See scintillation light below Cherenkov thres. for 0.4% and 1% WbLS

WbLS 2GeV protons

LAB in cyclohexane

WbLS 210MeV protons

WbLS 475MeV protons

L.J. Bignell et al 2015 JINST 10 P12009

Brookhaven Science Associates
10/11/2018
M. Yeh, AAP-2018
**WbLS AIT-detector**

- Cost-effective for Megaton detector
  - At LS~$3k per ton, 1% WbLS ~ $30M (+Water)
- Fundamentals known from previous DUNE design and other scintillator expt’s
- Yet R&D’s for *feasibility* and *scalability* need to be demonstrated
Sequential WbLS Deployment

In-situ WbLS deployment by direct injection of scintillator to water detector; followed by circulation mixing
### Summary

**WbLS Detector (liters)**

- 100,000,000
- 3,500,000
- 27,000
- 1,000
- 100
- 10
- 1
- 0.1

**2012**: survey, formulation, characterization

**2016**: optimization, purification, characterization

**2018**: circulation, S/C separation, scale-up product, material compatibility

**2019**: ANNIE

**2025+**: WATCHMAN

**20??**: THEIA

**THEIA**

**60m**

**AIT/WATCHMAN**

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