New Materials and Techniques for Neutrino Detection

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Liquid Scintillator Detectors

- Serve neutrino community since Reines and Cowan in 1950s
  - Stokes shift, photon-yield, timing structure, and C/H density determine the detector responses
- Next generation LS detector development → directionality
  - **Slow Scintillator**: Timing separation of slow scintillation from fast Cherenkov
  - **LiquidO**: Stochastic light confinement; lossless scattering
  - **Water-based Liquid Scintillator**: Cherenkov and scintillation detection

Slow Scintillator

• The properties of slow fluors or wavelength shifters to provide a means to separate Cherenkov light in time from the scintillation signal which allows for directional and particle ID information while also maintaining good energy resolution.

• Readily applied to existing and planned large-scale liquid scintillator instruments without the need of additional hardware development and installation.
LiquidO → photon's “random walk” (self-confinement)

Transparency
\[ \lambda (\text{scattering}) \geq 10 \text{m} \]

Rayleigh & Mie Scattering
\[ \lambda (\text{scattering}) \leq 1 \text{cm} \]

inducing light (lossless) to a point...
Water-based Liquid Scintillator

- WbLS, initiated in 2010, is a novel detector liquid (flexible LS%), well characterized: (ORCiD: 0000-0003-2244-0499)
  - Scintillation provides the energy resolution necessary to get above most radioactive backgrounds and the ability to see slow-moving recoils
  - Cherenkov enables event direction reconstruction and background discrimination at low energies
- Principle proven and advancing R&Ds at several institutes; in prep for prototyping tests
  - 1-ton Testbed (BNL, FY22), 4-ton Eos (LBNL, FY23) and 30-ton Demonstrator (BNL, FY23)
  - ANNIE (SANDI), WATCHMAN, THEIA
  - (new)T2K/ND, LiquidO
Modern Metal-doped LS Neutrino Map

What has been achieved & What is new?
Loading isotopes into LS greatly enhances the physics implication; the challenge is the addition of the inorganic metallic compounds, typically in the form of salt, to the organic scintillator solvents.

- **Conventional isotope loading methods**
  - A mediator with high solubility for inorganic salt compounds as alcohols (Chooz)
  - Organometallic complex, which is soluble in the LS.
    - Carboxylates (Savannah River, LENS, Palo Verde, Daya Bay, RENO)
    - Diketone or phosphor-organic ligands (LENS, Double Chooz)

- **New isotope-loading techniques**
  - M-doped WbLS
  - New organocomplex
  - Quantum dot
Metal-doped Water-based Liquid Scintillator

- A simpler approach to add the metal in aqueous solutions directly into liquid scintillators using principle derived from Water-based Liquid Scintillator
- User cases: Li, Gd, Te, K, Fe, W in several frontiers for neutrinos, nonproliferation, $0\nu\beta\beta$, calibration, calorimetry
- A transformative technique for LSC cocktail (environmental and safeguard)

**PROSPECT Li-doped LS**

**Li-doped Plastics**

![Images of experiments and graphs]
New Organocomplexing Ligands

• A method developed from $0\nu\beta\beta$ (SNO+) for higher loading of tellurium into liquid scintillator.

• An organocomplex using butanediol in conjunction with N,N-dimethyldodecylamine (DDA), which acts as a stabilisation agent.

• Stability of the loading has been demonstrated to be at least on the timescale of years; a highly scalable and economical approach.

• Further advances in purification techniques could provide a practical path to realising sensitivity to the non-degenerate normal mass ordering.
Quantum Dots

• Introduced from semiconducting nanocrystals in which the optical and electrical properties of the quantum dots are directly proportional to their size through resonance process (tunable emission).

• The most commonly used quantum dot cores are binary alloys such as CdS, CdSe, CdTe, and ZnS.
  • neutron-enhanced isotopes (113Cd) and (106,116Cd) and Se, Te, and Zn, which are present in common quantum dot cores, 0νββ candidates.

• Colloidal suspension instead of homogeneous mixing, which could cause aggregation in the concentrated solutions over long time scales.
  • Mitigated by incorporating with chelating agents or WbLS surface active agents?

• limitations in use for particle physics detectors are probably cost and availability in large quantity (ton).
Summary

- Liquid scintillator instrumentation has been largely advanced over the past decades
  - New materials with competitive performance, less chemical hazard, and better material compatibility
  - Advanced detector development allowing Cherenkov directionality from scintillation emission
- Advanced metal loading techniques with
  - Improved stability
  - Reduced light-yield quenching introduced from high mass doping
- A 10s kiloton-scale (water-based and/or metal-doped) liquid scintillator detector, sensitive to directionality, enables a broad neutrino program complementary to other detector technologies.