Optical Property Measurements in Neutrino Detection Media

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NSSC3 Kickoff Meeting and Advisory Board Review. April 19-20, 2022

Prepared by LLNL under Contract DE-AC52-07NA27344
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Focus: Radiation detection and nuclear instrumentation

Cross-cutting: Modeling and simulation

Project: Determination of optical properties of water-based liquid scintillator (WbLS) and other media in support of antineutrino detection for nonproliferation and safeguards applications
Background: Y detectors have been proposed for reactor monitoring.

Proposed applications from literature:
- Reactor power/fuel cycle monitoring
- Exclusion of undeclared reactors
Can a medium with a small scintillation component improve detector performance?

- Detection mechanism for (proposed) non-proliferation detectors is inverse beta decay
  \[ \bar{\nu}_e + p \rightarrow e^+ + n \]

- Correlated prompt and delayed signal
  - Positron Cherenkov cone
  - Delayed gamma cascade (8MeV in case of Gd) from radiative capture

- Scintillation light can aid in particle ID, improve event energy resolution can help separate signal from background,
  Create material with small scintillation component

Gd improves IBD performance—but can energy/position/ID performance be improved with a few tens of photons per MeV scintillation yield?

Image credit: Minfeng Yeh, Brookhaven National Lab
What problem does WbLS solve?

- **LS: High light yield, short attenuation length**
  - High energy resolution, but directional information from Cherenkov lost

- **Water: low light yield, long attenuation length**
  - Good directional information (long attenuation length), but no light yield below Cherenkov threshold (.8MeV)

- **WbLS: Best of both worlds?**
  - Can resolve events below water’s Cherenkov threshold while maintaining directional information—potentially revolutionary for rare event searches

Preservation of Cherenkov rings in a ~kT scale detector requires an attenuation length on the order of 20m.

WbLS may meet this threshold and allow significant physics exploration below the Cherenkov threshold.
WbLS optical property measurements are key to realizing nonproliferation monitoring goals.

Can neutrino detectors be used in the global nonproliferation and safeguards regime?

Can IBD detectors be used for km-range reactor monitoring?

Can new fill materials improve detection?

Is WbLS suitable for neutrino detectors useful for nuclear nonproliferation efforts?
- Light yield (LBNL)
- Stability (BNL)
- Optical attenuation
- Scattering
- Polarization-dependent effects
- Aging
Sealed, adjustable beamline concept avoids pitfalls of vertical column and integrating cavity systems

- Fluid under test is used as working fluid to move optical mount via pressure provided by peristaltic pump
- Dichroic beam combiner allows selection of wavelength without changes to optics

Design advantages
- Simultaneous attenuation/scatter measurement possible
- No fluid/gas interface in optical path
- Optical alignment is simple, durable
Scattering measurements can be performed simultaneously using a collimated compact PMT

\[
N_Y = N_{Y,0} \sum T_i Q(\lambda)_{PMT} e^{-\alpha x_w S \Omega d^{-2} \Delta t}
\]

In which:
- Sum over \( T_i \) represents the transmission properties of all optical elements downstream of the laser power meter,
- \( Q_{PMT} \) the quantum efficiency of the PMT
DI water attenuation measurements compare favorably with world-class metrology experiments.

Example data from measurement series:

- Many measurements per wavelength

Absorption measurements in DI water compare favorably with world-class metrology experiments.
DI water scattering measurements compare favorably with theory.

**Fig.1:** Direct measurements of the 90-degree scattering cross-section for vertically polarized show excellent agreement with theory. *Example dataset shown with multiple measurements conducted over ~2h.*
Gd-WbLS measurements
Gd-WbLS attenuates visible light significantly more than DI water

WbLS attenuates significantly more than shown in the RATPAC model.

Degradation of WbLS attenuation parameters was observed after seven days in the system under argon cover gas.
Gd-WbLS scatters more than water, but less than current RATPAC model.

WbLS is a much stronger scatterer than DI water, as expected. Scattering behavior was not measured with respect to aging. These tests are ongoing.

Deviation from the model is strongest at 450nm, which may be due to a systematic error.
Scattering components (Rayleigh, Mie) can be separated based on differential cross sections

- **Concept**: Rayleigh and Mie scattering components have dramatically different phase functions.
- Determination of phase function can be performed while measuring attenuation/scatter coefficient, assuring consistency for a given sample.
- Work in progress 😊

Measuring intensity-angle and intensity-polarization dependence can be used to characterize **deviations from Rayleigh scattering behavior**.
Gd-WbLS Initial Conclusions

- Gd-WbLS has a *longer* scattering length than modeled
- Gd-WbLS has a *shorter* attenuation length than modeled
- Degradation of attenuation length is evident in ~days

- Continuing investigation
  - More data points for aging likely useful
  - Adding more wavelength coverage
  - Angle and polarization dependent scatter measurements ongoing

(LY data from Orebi-Gann)
NON-LLNL Work

**MOBILE NUCLEAR POWER REACTORS WON’T SOLVE THE ARMY’S ENERGY PROBLEMS**

JAKE HECLA

DECEMBER 14, 2021

**War on the Rocks Commentary:** Analyzes unresolved technical questions about *Project Pele* related to fuel damage, intended deployment modalities and cost projections. Additionally quoted in *Military Times* article on 4/15/22 on mobile reactor technology.

**The Bulletin of the Atomic Scientists Papers:**

I) Suggests nuclear risk communication strategies based on “correlates of risk,” analyzes role of citizen-science groups in risk perception

II) Explores Russian INF violations, discusses technical roadblocks to developing INF-like agreements in the future

**Nuclear aircraft propulsion document preservation:**

Personal effort to find and digitize remaining documents from US Aircraft Nuclear Propulsion program. Left: The *original* hand-drawn sketch of the XNJ140 nuclear turbojet. Right: X211 nuclear turbojet internal history document. Both in the collection of David Carpenter, retired GE company historian.
NSSC Experience

Public Policy and Nuclear Threats (PPNT) 2018: Established links with CISAC and CSIS, began working with Sig Hecker’s international nuclear forum program.

• NSSC created connections with LLNL, opened doors to CISAC and supported my professional development through PPNT.

Meeting in Beijing with Stanford center affiliates to discuss verification technologies, November 2019.

CSIS Tech primer written with the Berkeley Nuclear Policy Working Group (NPWG) on a novel radiation detection technique.
Acknowledgements

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

This material is based upon work supported by the Department of Energy National Nuclear Security Administration under Award Number DE-NA0003996.

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