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Neutrino Physics and Nuclear Security Motivations for the Continued Development of Organic Scintillators with Pulse Shape Discrimination Capability and ^{6}Li-doping

Neutrino Frontier Topical Groups:	(NF2) Sterile neutrinos
	(NF3) Beyond the Standard Model
	(NF7) Applications
	(NF9) Artificial neutrino sources
	(NF10) Neutrino Detectors
Instrumentation Frontier Topical Group:	(IF6) Calorimetry

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Abstract:

Organic scintillator materials have been the central technology in studies of reactor antineutrinos for almost seven decades. Continued advances in the performance of organic scintillator materials remain critical to enable the full physics potential of experiments using reactors and other neutrino sources. Nuclear physics and nuclear security applications also depend upon the continued development of these materials. Key performance requirements common to these diverse applications are Particle Identification, especially for fast neutrons and neutron capture, high scintillation light yield, and good optical transmission. Organic scintillators with Pulse Shape Discrimination properties and ^{6}Li-doping excel in these respects. Support for continuing development of these materials, leveraging decades of accumulated expertise, has the potential to increase performance significantly, enabling new or improved detector designs and yielding significant advances in neutrino physics and beyond.

Introduction

Organic scintillator materials have been the central technology in studies of reactor antineutrinos for almost seven decades. They enabled discovery of the neutrino [1], helped to elucidate the 3-flavour paradigm [2], and have been used to established the era of precision oscillation parameter measurements [3–5]. Continued advances in the performance of organic scintillator materials remain critical to enable the full physics potential of experiments using reactors and other neutrino sources. Nuclear physics and nuclear security applications also depend upon the continued development of these materials. Key performance requirements common to these diverse applications are Particle Identification (PID), especially for fast neutrons and neutron capture, high scintillation light yield, and good optical transmission. Organic scintillators with Pulse Shape Discrimination (PSD) properties and ^{6}Li-doping excel in these respects. Liquid PSD-capable scintillators with ^{6}Li-doping (LiLS) have been produced and used in experiments at the ton-scale [6]. Plastic scintillators with these properties (LiPS) have recently been invented and are in use at the prototype scale [7–9]. Support for continuing development of these materials, leveraging decades of accumulated expertise, has the potential to increase performance significantly, enabling new or improved detector designs and yielding significant advances in neutrino physics and beyond.

Capabilities provided by Organic Scintillators with PSD and ^{6}Li-doping

Organic scintillators remain a dominant tool for the study of nuclear-energy scale interactions at large scale. Materials that also support PSD and ^{6}Li-doping while maintaining excellent performance have many attractive features for further improvements in neutrino and neutron detection; providing important capabilities for a wide variety of experiments. This is particularly true when time and spatial correlations between several particles and/or interactions are of interest. Advantages of organic scintillators that are capable of PSD and include ^{6}Li-doping are outlined below:

- For detectors using Inverse Beta Decay, organic scintillators provide the free proton target integral to the detection medium
- The PID features inherent to these materials provide positive selection of IBD signals, and identify and reject the predominant neutron-based classes of background
- The ability to scale to large volumes, especially LiLS.
- They readily support detector segmentation, which provides additional information for background rejection, neutrino baseline measurement, directionality information, and detector fiducialization. LiPS is especially amenable to 3D segmentation schemes.
- With proper handling, these materials provide long-term stable operation at standard temperature and pressure, reducing system complexity and operating costs, for example relative to cryogenic technologies.
- In many cases the chemistry used for solubilization of ^{6}Li can be adapted to other species of interest, e.g. radioactive isotopes like ^{227}Ac for full volume calibration.

When combined, these capabilities have recently enabled the first high sensitivity detection of reactor antineutrinos on the earth's surface [10].

Scientific Opportunities

There are a number of compelling scientific opportunities that are exclusively or primarily supported by detectors based upon organic scintillator materials. These are significantly enhanced by the incorporation of PSD and ^{6}Li-doping

- Short Baseline Neutrino Oscillation studies at nuclear reactors. These probe the physics associated with neutrino mass and the existence of ev^2-scale sterile neutrinos.
- Efforts to understand the reactor antineutrino flux and develop precision prediction methods that rely on Inverse Beta Decay measurements using these materials. Developing precision flux models enables many other physics opportunities [11].
- Unique phase space in Beyond Standard Model searches, based on boosted dark matter scenarios, can be accessed using LiLS or LiPS detectors near the Earth's surface.

Nuclear Science and Technology Application Opportunities

- As noted above, LiLS has been used for the first demonstration of aboveground reactor antineutrino detection. This greatly broadens the range of locations at which such technology could be used for reactor monitoring and safeguards applications.
- Organic scintillators have been extensively used to measure neutron-related nuclear data. These new classes of ^{6}Li-doped material are attractive for measurements involving multiple neutrons, e.g. $\overline{\nu}(E)$, the average number of neutrons emitted per fission.
- Highly selective neutron detectors are of interest in nuclear security and safeguards applications for the detection and characterization of Special Nuclear Materials. LiLS or LiPS would be ideal for fast neutron spectroscopy using segmented detectors and the capture-gating technique.

Technology Development Priorities

Improvements in following aspects of LiLS and LiPS materials will enable experiments to reduce cost, further extend sensitivity and physics reach, while also benefiting the many applications mentioned above:

- Increased light output, reduced scattering, and reducing optical attenuation would all improve detector performance and enable a wider range of geometries and size-scales.
- A better understanding of energy loss and transfer mechanisms in scintillator-fluor systems could support inherently better PSD performance.
- Improvements in loading schemes, processing and production could improve the long-term stability of these materials, allowing optimal detector performance for greater time periods and ultimately reducing cost.
- Effort to identify and minimize the cost drivers for these materials would be beneficial. This is especially true for LiPS which in current formulations use relatively expensive fluors at high concentrations.
- Continued development of LiPS formulations and production techniques to produce $\sim$ meter length elements would enable robust, readily transportable antineutrino detectors of the scale needed for reactor neutrino physics and applications studies.

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