Snowmass2021 - Letter of Interest

Additvely Manufactured Architected Multimaterial Scintillators

Topical Groups:
(IF06) Calorimetry
(IF03) Solid State Detectors and Tracking
(F01) Applications and Industry
(NF10) Neutrino Detectors

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Abstract:

Architected multimaterial scintillator systems (AMSS) are structured combinations of heterogeneous scintillators with emergent detection capabilities. Additive manufacturing allows for the fabrication of AMSSs with structure as fine as tens of microns, allowing for sensitivity to recoil track length and direction in the nuclear energy scale, allowing for discrimination based on recoil length scales, directional detection of neutrons, and extremely fine position resolution. We have also achieved a $(1\,\mathrm{cm})^3$ prototype AMSS using a polysiloxane-based direct ink write approach. The work described was conducted with nuclear nonproliferation applications in mind but can be extended to a variety of HEP applications as well, including the scintillator fabrication of the 3D-projection Scintillator Tracker subsystem of DUNE.

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The Capabilities of Architected Multimaterial Scintillator Systems

AMSSs are structured combinations of heterogeneous scintillators that encode additional properties of radiation interactions by measuring that radiation's interaction with the structure. When fabricated using additive manufacturing (AM) the scintillation properties, such as emission color or pulse shape, can be controlled as a function of location in the scintillator on scales as small as a few tens of microns. A detector based on these structures can observe these scintillation properties and infer the behavior of radiation deposits in the scintillator.

Over the past two years, the authors have designed and simulated several detectors based on this broad principle. Figure 1 illustrates one of these detectors which employs a structure of alternating anisotropic zones of blue-emitting and green-emitting scintillators. Each zone has a size of $50\,\mu\mathrm{m} \times 50\,\mu\mathrm{m} \times 500\,\mu\mathrm{m}$, such that a MeV-scale proton recoil (e.g. from a neutron-emitting radioactive source) will remain within a single zone when the recoil angle aligns with the long axis of the zone but will pass between zones at other recoil angles. As a result, this scintillator will produce either a single color (either blue or green) or both colors of light depending on the recoil angle and energy. This measurement of the proton recoil angle is not exceptionally precise, but has the advantage of requiring only a simple instrumentation package: a liter-sized AMSS requires only two simple light sensors, one with a filter to differentiate green from blue light. A single scintillator can measure the proton recoil angle relative to its "grain" direction.

We have shown an array of eight such modules, each 1 L in size and instrumented with two photosensors, can make precise measurements of the absolute neutron source direction in 4π. Our simulations show that such an array can detect the direction of a Cf-252 source to 14 degree precision with 50 neutrons, at a detection efficiency for incident neutrons of 12.6%. For a 10^5 neutron/s source at 10 m, an 8 kg detector will achieve this measurement in just 31 seconds. Similar microstructures sensitive to track length can complement PSD and improve electron/proton recoil discrimination.

In another example, an AMSS can be additively manufactured such that the emitted light is a mixture of blue and green determined by a gradient of dyes. Sensing the mixture of emitted colors indicates the location of interactions in the scintillator, with a precision proportional to the rate of change of the gradient. When

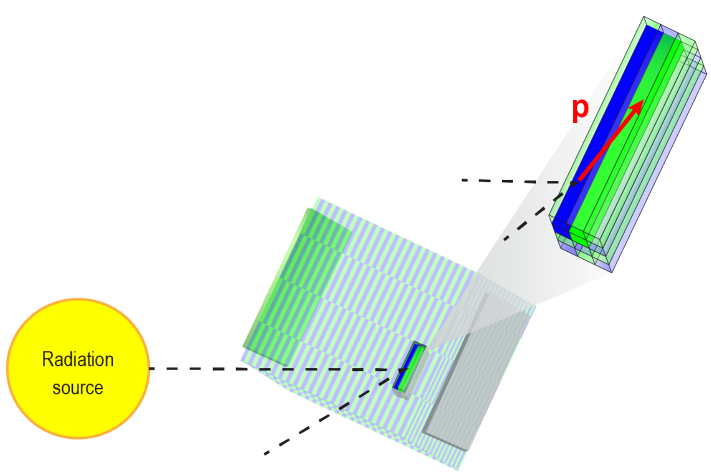

FIG. 1. An anisotropic structure of blue- and green- emitting scintillators produces either one or two colors of light depending on the angle between a recoil proton and the $50\,\mu\mathrm{m} \times 50\,\mu\mathrm{m} \times 500\,\mu\mathrm{m}$ structure. For purposes of illustration, the size of the blue and green zones are exaggerated relative to the $(10\,\mathrm{cm})^3$ overall scintillator volume.

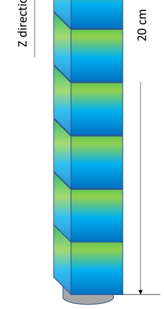

FIG. 2. A periodic gradient enables enhancement of ordinary double-ended position resolution to sub-mm precision.

ordinary event position reconstruction is available, e.g. by double-ended readout of segments, a periodic gradient can be used to complement the ordinary position reconstruction. This approach is illustrated in Figure 2. The ordinary double-ended reconstruction (with somewhat reduced performance due to the use of color filters) provides a rough position which is then refined using the color readout. Our simulations show this approach in a 20 cm scintillator bar can achieve a position resolution below 1 mm for proton recoils above 0.5 MeV.

Status of Additvely Manufactured Scintillators

The authors have developed a polysiloxane-based feedstock for direct ink write additive manufacturing. The direct ink write process is advantageous for AM scintillators because it requires neither heat, which can damage scintillator dyes, nor UV light curing, which requires UV absorbers that can interfere with scintillation. Using this feedstock, we have produced a $(1\,\mathrm{cm})^3$ prototype scintillator and demonstrated a light output of 3,000 photons/MeV. This technique can also produce fine structure as small as $50\,\mathrm{\mu m}$ and can mix scintillator with continuously varying dye concentrations. The index of refraction can be tuned to avoid light scattering at structure interfaces, and the green dye used does not absorb and remit light from the blue dye, avoiding cross-talk.

In the next year, we anticipate extensive progress in this technique in both scale and light output due to refinements in the formulation and printing process. We also anticipate the demonstration of other AM techniques for scintillator production which will expand the range of applications that can benefit from AM scintillators.

Impact on HEP Research

The work described so far was performed with the sponsorship of the U.S. DOE National Nuclear Security Administration Office of Defense Nuclear Nonproliferation Research and Development. Our work has focused on applications of AMSSs in the field of nuclear nonproliferation, such as searching for or characterizing neutron-emitting material. However, the AM scintillator capabilities and the AMSS concept offer significant benefits to the HEP field as well, potentially making this an unusual case of technology transfer from nonproliferation applications to science.

AM scintillators have been identified as an important technology for fabricating the 3D-projection Scintillator Tracker subsystem of DUNE. In a SNOWMASS LOI on this topic [1], the authors say: “If we were to able to produce 3DST ‘super-cubes’ by 3D-printing, it would avoid a rather complicated and labor intensive production and assembly process.” The requirements listed for 3DST, including “using two separate resins to print optically separated scintillator cubes” align with the requirements to produce AMSSs. The techniques already developed can be extended to produce optical separating layers, including both reflective layers and refractive-index mismatches to contain light in its cube of origin.

Another application of AMSSs is in stochastic trapping, as described in the LiquidO SNOWMASS LOI [2]. AM scintillators offer the potential to print a structured pattern of opacity in the scintillator offering tunability to the stochastic trapping behavior.

The general principle of encoding additional radiation properties using AMSSs may have wide applications in other experiments not yet identified. AMSSs may require some compromise in light output compared to scintillators optimized purely for light production, moreso for structures that produce multiple colors of light. In exchange, AMSSs can create emergent capabilities in particle detection. Even where structure-enabled capabilities are not needed, AM scintillators may be a cost-effective form of fabrication for many specialized scintillators.

In conclusion, we propose collaboration between researchers in HEP, in additive manufacturing, in scintillator chemistry, and in the AMSS concept to identify and advance scientific applications of additively manufactured scintillators and AMSSs.

[1] S. Gokhale et al. “3D-Projection Scintillator Tracker (3DST) in SAND, a DUNE Near Detector Subsystem” (). URL: https://www.snowmass21.org/docs/files/summaries/NF/SNOWMASS21-NF10_NF1-IF6_IF0_C.K._Jung-118.pdf.

[2] “LiquidO: A Novel Approach to Detecting Neutrinos”. In: URL: https://www.snowmass21.org/docs/files/summaries/NF/SNOWMASS21-NF10_NF0_Pedro_Ochoa-030.pdf (visited on 09/18/2020).