Status of Scintillator Development at Fermilab

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• Organic Scintillator
• FNAL Scintillator Extrusion and Injection Molding
• Applications
  • Archeology
  • Geology
  • Biology
  • Astroparticle
  • HEP
• R&D and future projects
Benzene, Sigma, Pi Orbitals, radiative, vibrational decays

All scintillators made at FNAL use benzene rings as the fundamental scintillator. PS, PC

Carbon 1s\(^2\);2s\(^2\);2p\(^2\)

Radiative deexcitation of polystyrene slow and low probability. Most are vibrational decays. Add primary dopant in high concentration (1%) to allow for direct energy transfer to primary. High probability. Photonic decay generates useful scintillation light
Primary scintillation light and dopants

Primary and secondary dopants absorb and re-emit the light at longer wavelengths until useable. Primary PT, PPO. Secondary bis-MSB, POPOP.
Fermilab Scintillator Extruder System

System ~50m long.
Can make ~75kg scintillator per hour, limited by cooling.
Hole(s) for fibers and white cladding coextruded. Each new shape usually needs new die.
Factory Floor. Largest part so far: 4x4cm
Injection Molding at Fermilab. Example Hexagon tile

3 injection molding machines, 20 ton, 100 ton, 165 ton presses
Can make parts from 1 gram to 200 grams
Fermilab Scintillator Extrusion and Injection Molding past/planned projects

- **FNAL experiments:**
  - MINOS (supervision & QC)
  - MINERvA
  - Mu2e CRV
  - TMS – DUNE
  - Mu2e II

- **Large projects:**
  - K2K (Supervision & QC)
  - T2K: P0D, ECal, INGRID
  - DoubleCHOOZ
  - Pierre Auger: CNEA, KIT
  - ICECUBE
  - IDEON – Canada
  - LDMX
  - MATHUSLA

- **DOE complex:**
  - ANL: STAR
  - JLAB: CLAS, CDet
  - LANL

- **Smaller Projects**
  - MURAVES – INFN Napoli
  - CANFRANC – Spain
  - SNOLAB -- Canada
  - INFN: Bologna, Brescia, Gran Sasso, Padova
  - Inst. Phys. Globe, France -- Volcano tomography Guadeloupe Soufrière
  - NYU – Abu Dhabi
  - Tel Aviv University – Erez City of David tomography
  - UIS – Colombia
  - Univ. Liverpool
  - LDMX Veto Prototype – Lund University
  - INO – mini ICAL Cosmic Veto
  - CMS
  - Naval Research Facility
  - MATHUSLA – U. Toronto
  - LHCB
  - INFN Catania

- **Injection Molding (New capability as of this year)**
  - CMS HGCAL
  - ePIC LFHCal – ORNL, BNL
  - Shashlik – HIKE calorimeter
Archeology
ScanPyramid Consortium uses 3 muon hodoscope technologies: scintillator (from FNAL), micromegas, emulsion.
City of David, Jerusalem
Archeology Muon Tomography

Group led by Erez Etzion in early phase of density mapping City of David (adjacent to Temple Mount) using muon detectors installed in water spring caverns under the site. Site dates from 4500 BC. Difficulties: access, high humidity
Astroparticle
Pierre Auger Observatory: 3000 km² detector in Malargue, Argentina. Goal to measure highest energy cosmic rays. Cosmics are detected through multiple methods to give rich information about the event. Scintillation, Cerenkov, radio, and fluorescence detection telescopes. FNAL produced XXX bars, YYY tons of extrusion for the SSD Surface Scintillator Detector. 1600 SSD used to provide muon aspect of cosmic shower. (figures from Nataliia Borodai, TIPP 2021 May 24-28, 2021)
IceCube

Ice Cube adding “IceTop” scintillator array on surface to study PeV cosmic rays and provide for partial veto of downward cosmics. Scintillator is cheap and can survive the harsh conditions.

Each panel has 16 extrusions, 2m x 1cm x 5cm, readout Y-11 fiber and SIPM

7 panels per hub. 37 hubs in array roughly 1km x 1km

https://pos.sissa.it/301/401/pdf
Geology
Array of triangles read out with WLS, designed to fit into Bore Hole. FNAL provided XXX extrusions.

Estimated sensitive solid angle. 1km diameter at surface

3 Detectors ~600m underground. Solid dark is ore deposit as understood by core samples. Colored is density slice from IDEON muon data, in agreement.
3 Stations of x-y planes of scintillator, Pb hardener, final station
Agriculture/Biology
Recent years have seen the development of radioisotope tracking or imaging systems based on detection of light from scintillators for agricultural studies [1,2]. The goal is to track the phosphorus movement between the roots of a plant and the beneficial fungi that are known to grow near the roots and have a beneficial role with the plant. Phosphorus is a macronutrient limiting plant productivity that is usually taken up as phosphate (PO₄³⁻). Several types of fungi found in soil near plant roots are capable of supplying plant hosts with phosphorus - the arbuscular fungi being well known for their contributions to plant health. While soil fungi communities can affect the plant nutrient content, they can be impacted and altered by agricultural management practices. A better understanding of the interactions between carbon, nitrogen, and phosphorus cycling below ground by plants and fungi should help improve plant productivity for biofuels and agriculture.
HEP
CMS – SIPM-on-tile for HL-LHC endcap calorimeter upgrade

HL-LHC upgrade. A 5-D calorimeter designed for particle-flow pattern recognition. Silicon for ECAL and high radiation prgions of HCAL. Scintillator for the rest. 240K channels of SIPM-on-tile.

SIPM-on-tile: Green PCB  Red SIPM  Yellow ESR wrapper  Blue Scintillator

Tileboard with SIPMs, wrapped tiles

Tiles injection-molded at FNAL
MATHUSLA is a very large experiment being proposed to be built on the surface of LHC point 5 by the CMS experiment. It will search for long-lived particles produced by proton-proton collisions at the CMS interaction point. The experimental volume is quite large (100mX100mX30m), to allow for the LLPs to decay in the volume. Extruded scintillator layers are installed to allow for tracking of the decay products. 1000 tons of scintillator required.
HIKE, High Intensity Kaon Experiments at the CERN SPS

Main Electron Calorimeter based on Shashlik concept. 1M tiles Stack of Pb foils and scintillators

https://arxiv.org/abs/2211.16586

FNAL preparing to prototype molding the tiles
“VOXEL” – Volume pixels for scintillator trackers. Proposed 10M voxels for Dune Near Detector

6x6 array per layer, 7 layers high

3 orthogonal holes for WLS fibers

Voxel prototype with 1 layer of uncoated voxels and fibers

Voxels in frame

Stack 7 high
New Wavelength Shifting Fibers

We are working with Kuraray and Saint Gobain to study new WLS fibers.

Look at new WLS fibers from Saint Gobain and Kuraray: BCF9929A, YS-1, YS-2, YS-4, YS-6

Excite with laser. Count arrival time of single photoelectrons with SIPM

<table>
<thead>
<tr>
<th>Fiber</th>
<th>Diameter (mm)</th>
<th>Avg. Light Yield (sum of both ends)</th>
</tr>
</thead>
<tbody>
<tr>
<td>YS-1 MJ</td>
<td>1.0</td>
<td>32.2</td>
</tr>
<tr>
<td>YS-2 MJ</td>
<td>1.0</td>
<td>61.0</td>
</tr>
<tr>
<td>YS-4 MJ</td>
<td>1.0</td>
<td>50.6</td>
</tr>
<tr>
<td>YS-6 MJ</td>
<td>1.0</td>
<td>21.2</td>
</tr>
<tr>
<td>Y-11 MJ</td>
<td>1.0</td>
<td>64.9</td>
</tr>
</tbody>
</table>

Table 4. Measured light yields for WLS fibers.

Attenuation lengths of 5m long fibers, measured in region 1 to 2.5m
Improve timing for extrusion/WLS fiber system

Improving timing along length of extrusion gives better coordinate measurement in that direction. (Other direction coordinate determined by which bar is hit.) Measure time difference between ends to find hit location. Cosmic runs that create different light yields. **Timing resolution function of \( \sqrt{\frac{\tau}{N_{pe}}} \)**

System with most light and fastest WLS has best timing resolution.

Cosmics timing: Cut on single photoelectron

Position resolution \( \frac{(T4-T3)}{2} \)
Improve reflectivity of cladding around extrusion to improve light yield.

Geant sim to see what is effect of different reflectivity cladding on extrusion
Yucun Xie, UMD. Looking at new materials better than TiO2 for coating the scintillator.

Wrapper.
Measurement of LY for different wrappers around extrusion. Can make big improvement.

<table>
<thead>
<tr>
<th>Wrapper</th>
<th>Relative Light Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>TiO2 coextruded cladding</td>
<td>1.0</td>
</tr>
<tr>
<td>Tyvek</td>
<td>1.08</td>
</tr>
<tr>
<td>ESR</td>
<td>1.46</td>
</tr>
<tr>
<td>Black wrapper</td>
<td>0.24</td>
</tr>
</tbody>
</table>

Cladding. Light yield vs reflectivity. Clear that improved reflectivity of cladding can have big effect on LY

Extrusion Geant simulation

\( \lambda_{\text{scint}} = 100\text{cm} \)
Neutron scintillator: Use injection molding process to study making cheap neutron-sensitive scint. Study using polycarbonate base for improved radiation hardness.

- FNAL, LLNL, Erciyes University (Kayseri, Turkey), Beykent University (Istanbul)
- n-scint uses slow response to neutrons to separate gamma-neutron by pulse shape

Plot: $Q_{\text{tail}}/Q_{\text{total}}$ – fraction of pulse in tail of pulse

- High concentrations (>20%) of fluorescent dyes increases fraction of delayed light

New type of scintillator using long Stokes Shift quantum dots
Polystyrene/PT base. Use in Dual readout calorimetry. Use long stokes shift to move scint light to long wavelength. Use QD decay time to help with C/S separation. Collaboration with CapeSym, Inc.

**FNAL sample#2 PS/PT/QD**
Emission spectrum excited by 310nm

- Cerenkov region
- Scintillation region

N=2 diffraction grating artifact

**Figure 2** | Fluorescence decay behavior. Fluorescence decay behavior of typical organic fluorophores (mono-exponential, lifetimes of 1.5 ns (Cy5) and 3.6 ns (Nile Red)) in comparison to a typical QD (CdSe/ZnS, multi-exponential, mean lifetime ($\tau_{\text{ave}}$) of 10.3 ns).

https://pubs.acs.org/doi/10.1021/acsami.7b19144

Stokes-Shift-Engineered Indium Phosphide Quantum Dots for Efficient Luminescent Solar Concentrators
• Sadra Sadeghi

31
2x2 array of shipping containers with 4 planes of triangular scintillator extrusions in each container. Each plane ~3mx12m

Left: GEANT model of Great Pyramid. Right: simulated results of 3 year run. 4 container array moved to adjacent white region every 2 months. 36 regions $\rightarrow 18 \times 2 = 36$ month run. Anticipate 100X increased sensitivity to ScanPyramid
Summary

• Fermilab has lots of resources and experience making scintillator for wide diversity of applications.
• We have interesting R&D and future programs plans.
• We are ALWAYS looking for new collaborators to work with.