Status of Scintillator Development at Fermilab

Jim Freeman
Fermilab
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Outline

- 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. Polystyrene, polycarbonate

Carbon 1s2;2s2;2p2

Radiative deexcitation of polystyrene slow and low probability. 95% are vibrational decays. Add primary dopant in high concentration (1%) to allow for direct energy transfer from benzene to primary. ~100% probability. Photonic decay
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.
100 tons/year. One of largest scintillator producers in the world.
Hole(s) for fibers and white (TiO$_2$) cladding coextruded. Each new shape usually needs new die.
Factory Floor. Largest part so far: 4x4cmxL
Injection Molding at Fermilab. Example Hexagon tile

3 injection molding machines, 20 ton, 100 ton, 165 ton presses
Can make parts from 0.1 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

Jim Freeman FNAL  IPRD23
Archeology
ScanPyramid Consortium uses 3 muon hodoscope technologies: scintillator (from FNAL), micromegas, emulsion. 2 layers, 1.2x1.2m

Extrusion Profile 1cmx1cmx120cm co-extruded hole and cladding
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.

Muon detector for underground tomography 2205.03722 [physics.ins-det]
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 ~80,000 bars, 100 tons of extrusion for the SSD Surface Scintillator Detector. SSD used to provide muon aspect of cosmic shower. (figures from Nataliia Borodai, TIPP 2021 May 24-28, 2021)
IceCube

Ice Cube adding 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 30,000 extrusions.

3 Detectors ~600m underground. Solid dark is ore deposit as understood by core samples. Colored is density slice from IDEON muon data, in agreement.
Figure 2: Top: The 32 scintillator bars and WLS fibers assembled in a half of a planar array. Bottom: triangular section of the scintillator bars.

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.

Top and bottom hemispheres glued to orthogonal fibers. 4mm diameter sphere. Glue seals optical interface from dirt, water.
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.

Tileboard with SIPMs, wrapped tiles

Tiles injection-molded at FNAL

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

9/28/2023
MATHUSLA

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.

100 9mx9mx30m modules. 10 planes of scintillator

10x10 array of 9x9x30m modules
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

5.5x5.5x0.3cm

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

3 orthogonal holes for WLS fibers

Small scale prototype: 6x6 array per layer, 7 layers high

Voxels in frame

Voxel prototype with 1 layer of un-coated voxels and fibers
R&D
New Wavelength Shifting 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. Measure fiber decay time

<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.

BCF9929A light yield somewhat less than YS-4

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 $\sqrt{t/N_{pe}}$

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

Cosmics timing: Cut on single photoelectron

Position resolution $(T_4-T_3)/2$
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.

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

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>
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: Qtail/Qtotal – 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

<table>
<thead>
<tr>
<th>Cerenkov region</th>
<th>Scintillation region</th>
</tr>
</thead>
<tbody>
<tr>
<td>N=2 diffraction grating artifact</td>
<td></td>
</tr>
</tbody>
</table>

**Figure 2** | Fluorescence decay behavior. Fluorescence decay behavior of typical organic fluorophores (mono-exponential, lifetimes of 1.5 ns (Cy5) and 3.8 ns (Nile Red)) in comparison to a typical QD (CdSe/ZnS, multi-exponential, mean lifetime ($\tau_{1/e}$) 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
2x2 array of shipping containers with 4 planes of triangular scintillator extrusions in each container. Each plane ~3mx12m ~10 tons for total experiment.

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 → 18 * 2 = 36 month run. Anticipate 100X increased sensitivity to ScanPyramid
Summary

• Organic plastic scintillator very versatile and robust.
• It can be used in many applications.
• 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.