Usage of PEN as self-vetoing structural material in low background experiments

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On behalf of the PEN working group

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PEN working group

- **Oak Ridge National Laboratory** - Synthesis
  - M. Febbraro, D. Radford, B. Dial, M. Kidder
- **Max-Planck Institute for Physics** – Characterization & Simulations
  - B. Majorovits, O. Schultz, I. Abt, F. Fischer, M. Guitart, L. Manzanillas
- **TUM** - WLS & test in LAr
  - S. Schoenert, M. Schwarz, P. Krause, K. Gusev, N. Rumyantseva
- **Lancaster University** – Surface Treatment & Simulations
  - D. Muenstermann, C. Hayward
- **Technical University Dortmund** – Machining & Characterization
  - M. Stommel, M. Pohl, R. Rouhana, J. Weingarten, I. Schilling
- **Czech Technical University** – Radio-purity measurements & characterization
  - I. Stekl, R. Hodak, L. Fajt, E. Rukhadze
- **University of Tennessee** – Synthesis & Radio-purity measurements
  - Y. Efremenko, B. Hackett
- **Nuvia A.S.** Czech Republic - Synthesis
  - R. Pjatkan
- **AstroCeNT**: Particle Astrophysics Science & Technology Centre - WLS
  - Marcin Kuźniak
Motivation: Low background experiments

- Rare event **physics experiments demand ultra low backgrounds**
  - Ultrapure materials required
  - **Inactive materials need to be minimized**
    - Important source of backgrounds
    - Absorb light that can be used to veto external backgrounds
  - Can we do better? → **replace inactive** materials with self-vetoed **active materials** ⇒ PEN
PEN: Poly(ethylene 2,6-naphthalate)

- PEN is a **commercially available polyester**
- PEN has **yield strength higher than copper** at cryogenic temperatures
  - Ideal for experiments using cryogenic liquids
- **Fluorescence** reported in 2011
- **WLS** capabilities ([1806.04020](https://arxiv.org/abs/1806.04020))
  - Deployed in Proto-DUNE DP
- Good candidate to use as a **structural self-vetoing material**
PEN mechanical properties

- 3-point bending test of material at room and LN$_2$ temperatures at MPI
  - High structural stability at room and cryogenic temperatures
- Very chemically resistant to most acids and organic solvents
  - Can be aggressively cleaned

<table>
<thead>
<tr>
<th></th>
<th>PTFE$^1$</th>
<th>Cu$^2$</th>
<th>Electroformed Cu$^5$</th>
<th>PEN</th>
<th>PEN at 77 K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile Strength $\sigma_{el}$ [MPa]</td>
<td>&lt; 45.0</td>
<td>100</td>
<td>85.8 ± 7.8</td>
<td>108.6 ± 2.6</td>
<td>209 ± 2.8</td>
</tr>
<tr>
<td>Young’s Modulus E [Gpa]</td>
<td>&lt; 2.25</td>
<td>128</td>
<td>77.8 ± 15.6</td>
<td>1.86 ± 0.01</td>
<td>3.71 ± 0.08</td>
</tr>
</tbody>
</table>

1. [https://www.treborintl.com/content/properties-molded-ptfe](https://www.treborintl.com/content/properties-molded-ptfe)
2. [http://www.memsnet.org/material/coppercubulk/](http://www.memsnet.org/material/coppercubulk/)
PEN scintillation properties

- **PEN scintillates** in the **blue regime**
  - Peaks around 445 nm
    - **Ideal for most of photosensors**
  - Scintillation yield around \( \frac{1}{3} \) of standard plastic scintillators
    - > 3500 photons / MeV

- **Shifts light from VUV to visible light**
  - Can be used to shift light of LAr (128 nm) or LXe (175 nm)
  - Efficiency **about 40% of TPB**

- **Pulse Shape Discrimination (PSD)** possible with PEN
  - Alpha decay identification

- **Attenuation length of few cm**
Production of moulded arbitrary shapes

- PEN is a semi-crystalline polymer
- Crystallization leads to polymer appearing opaque
- PEN must be cooled from ~300°C to 220°C in <10 seconds to remain amorphous
  - Parts can be made by injection moulding
- Progress on producing arbitrary shapes
  - Holding plates
  - Containers
  - Capsules
  - Fibers
- Current efforts to synthesize PEN ongoing at ORNL (publication coming soon)
Radio-Clean production method of PEN parts

- In 2019: **radio-clean PEN plates** were **produced** by injection compression moulding using commercially available PEN pellets
  - PEN pellets were washed to remove surface impurities
  - Inner components of injection moulding machine were replaced and cleaned
  - Entire process from granulate to finished plates was completed in < 4 min in a Class-1000 clean room
- **Radio-clean production protocol defined** *(publication coming soon)*

Cleaning raw material

Clean injection moulding technology developed

Production of PEN tiles
**PEN radiopurity of moulded parts**

- **About 20 kg of PEN samples measured** at LNGS and LSM
  - 112 tiles at OBELIX
  - 130 at GeMPI4
- **For a 5 g detector mount base plate**
  - ~ 0.5 μBq/plate $^{228}$Ra ✅
  - ~ 0.3 μBq/plate $^{226}$Ra ✅
  - ~ 0.2 μBq/plate $^{228}$Th ✅

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Radiopurity GeMPI4 at LNGS</th>
<th>Radiopurity OBELIX at LSM</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{228}$Ra</td>
<td>92 ± 25 μBq/kg</td>
<td>107 ± 38 μBq/kg</td>
</tr>
<tr>
<td>$^{228}$Th</td>
<td>32 ± 16 μBq/kg</td>
<td>67 ± 18 μBq/kg</td>
</tr>
<tr>
<td>$^{226}$Ra</td>
<td>60 ± 15 μBq/kg</td>
<td>76 ± 22 μBq/kg</td>
</tr>
<tr>
<td>$^{234}$Th</td>
<td>&lt; 1.9 mBq/kg 90 %C.L.</td>
<td>-</td>
</tr>
<tr>
<td>$^{234}$Pa</td>
<td>&lt; 1.7 mBq/kg 90 %C.L.</td>
<td>-</td>
</tr>
<tr>
<td>$^{235}$U</td>
<td>&lt; 56 μBq/kg 90 %C.L.</td>
<td>-</td>
</tr>
<tr>
<td>$^{40}$K</td>
<td>&lt; 0.24 mBq/kg 90 %C.L.</td>
<td>0.567 ± 0.014 mBq/kg 90 %C.L.</td>
</tr>
<tr>
<td>$^{137}$Cs</td>
<td>&lt; 0.15 μBq/kg 90 %C.L.</td>
<td>-</td>
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_M. Laubenstein (LNGS)  E. Rukhadze (CTU)_

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9 Legend plates machined from 180 grams PEN plate.
Machining procedure for PEN plates

- PEN plates were **CNC machined** at UT Physics machine shop
  - **Machine** was cleaned with ethanol and machine cleaner
  - **Nitrogen gas boil-off blowing during machining**
- **Jig designed to minimize PEN plate exposure** in machine shop by creating a “sandwich”
  - Jig was assembled and disassembled inside a laminar flow hood inside a clean room
- **Cleaning procedure for tools** (except end mills):
  - 2% sol. Micro-90, 18 MOhm water (24 hrs)
  - Rinse with 18 MOhm water
  - Rinse water conductivity measured
Deployment of PEN during post-GERDA test at LNGS

- **Design of PEN holders** optimized to reduce mass
  - Deployed at TUM cryogenic facility
- **PEN plates cleaned and mounted at LNGS**
  - 3% nitric acid solution used
  - Successful integration
- **PEN plates used in about 40% of detectors**
  - Allows for direct comparisons with Si plates
  - Data with PEN holders from PGT being analyzed
    - Preliminary results showed that detector response is not affected by PEN
- Production and characterization of LEGEND-200 plates ongoing
- **R&D for further application in LEGEND-1000** ongoing

Special thanks: Konstantin G. et al (detector mounting) + Michael W. et al (electronics) + LNGS + TUM + MPIK+ MPP + many others
Optical characterization

- Several setups mounted to fully characterize first production run
  - Light yield: $\frac{1}{3}$ of standard plastic scintillators
  - Emission spectrum: peaks at $\sim$445 nm
  - Attenuation: of the order of cm and wl dependent
  - Surfaces: Being studied

- Geant4 developed to extract absolute optical parameters
  - Light yield: $> 3500$ photons/MeV
  - Absorption as function of wavelength: Ongoing
  - Surface effects: Ongoing

- Results will be used as input for detailed studies/optimization of PEN effect/improvements in LEGEND
Summary and outlook

- **PEN is an attractive scintillator to be used as active structural material**
  - Successful production of low background PEN holders
  - Design optimized with reduced mass for LEGEND-200
  - Protocol for production under clean conditions defined

- **PEN holders deployed in detector mount prototypes in LEGEND-200 prototyping tests at LNGS**

- **Optical characterization ongoing**
  - Preliminary **light yield**: > 3500 photons / MeV
  - Preliminary **attenuation length**: Of the order of cm and wl dependent
  - Detailed Geant4 simulations of setups ongoing

- **Papers on production run and synthesis in preparation**
  - *Stay tuned*

- **Next steps:**
  - Production of holders for LEGEND-200
  - Extract absolute values for optical parameters: light yield, attenuation(wl), surface effects, etc
  - Complete characterization of WLS capabilities
  - Continue R&D for LEGEND-1000
Thanks for your attention!
Backup
Mass optimization for PEN detector holder

- **Design of PEN holders optimized** to reduce mass
  - 3 different **models**
  - Geometry can be adjusted if needed

- Mechanical simulations using PEN rods instead of copper also performed

- **Some areas thinned** to fit thickness of Si plates
  - No problem for mounting front-end electronics board

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Acceleration: 0.05 m/s²

019375-PEN: 7.3 g → 5.3 g

018695-PEN: 8.25 g → 6.25 g
Light output

- PEN samples (L200 production) placed in PMT setup
  - Excite PEN with $^{207}$Bi source
  - Select electrons (~1 MeV and ~400 keV)
- Compare with PS samples of same dimensions

<table>
<thead>
<tr>
<th>PEN (? ph/MeV):</th>
<th>PS (~10000 ph/MeV):</th>
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<tbody>
<tr>
<td>282 pe/MeV</td>
<td>853 pe/MeV</td>
</tr>
<tr>
<td>σ ~11% at 1 MeV</td>
<td>σ ~7% at 1 MeV</td>
</tr>
</tbody>
</table>

- Light yield of PEN larger than 3500 ph/MeV
  - Attenuation length much more important for PEN
Light attenuation

- **PEN samples** *(LEGEND-200 production)* coupled to two PMTs
- **Active + passive collimation**
- **Steps of 5 mm**
  - 15 positions in total
- **Use** \( f(x) = \frac{Q_1}{Q_1 + Q_2} \)
  - \( Q_i \) = detected charge in PMT\(_i\)
  - \( A \) = Emitted light at position of interaction
  - \( Q_1 = A \eta_1 e^{-x/\lambda} \quad Q_2 = A \eta_2 e^{-(74-x)/\lambda} \)
  - \( f(x) = 1/(1+\varepsilon e^{-(74/\lambda)} e^{(2x/\lambda)}) \)
  - \( \varepsilon = \frac{\eta_2}{\eta_1} \)
- **Two data sets**
  - \( \lambda \sim \) order of cm and wl dependent
- **More data expected soon**