Radiation Hardness Characterization of LKH-5 Scintillating Glass

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Mairead Montague
University of Tennessee, Knoxville
Introduction

- **Academic Advisor:** Jason Hayward
  - Department of Nuclear Engineering

- **Lab Mentor:** Paul Hausladen
  - Radiation Detection and Imaging

**Radiation Detection and Instrumentation**

- Glass Scintillator Characterization for High Energy Cargo Scanning
- Fast Neutron Tomography for Spent Nuclear Fuel Verification
Cargo Scanning for Non-Proliferation

- **High Energy X-Ray Radiography**
  - Linear accelerator to image cargo containers
  - Search for SNM through detection of signatures of photonuclear reactions
  - Use both scintillator detectors and neutron detectors

- **Radiation Hardness**
  - Radiation damage: decrease light transmission by ionizing electrons within the scintillator and creating myriad defects within the crystal
  - Scanning system lifetime is dependent on scintillator lifetime
    - Scintillator lifetime dependent on radiation resistance
    - Important in order to make associated systems field-ready

Quantifying a scintillator’s reductions in light transmission after irradiation results in information on its expected lifetime and therefore the expected lifetime of the scanning system.

[1]
Scintillator Detectors for Cargo Scanning

**Cadmium Tungstate**
- High density,
- High spatial resolution,
- No afterglow
- Difficult to manufacture, Performance variability, Expensive

**Cesium Iodide**
- High optical yield
- Hygroscopic, Visible afterglow

**LKH-5 Glass**
- Low manufacturing cost; Well coupled with conventional a-Si TFT array sensitivity
- Radiation hardness must be investigated

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2. M. Kobayashi et. al “Cadmium Tungstate Scintillators with Excellent Radiation Hardness and Low Background,” NIMA 1994
Transmission Measurements

- **36 Samples: 10 mm x 10 mm x 20 mm**
  - All 6 sides polished
  - All close in starting color
  - Minimal aberrations from glass pouring

- **Transmission Measurements**
  - Spectrophotometer with wavelengths from 800 nm to 200 nm
  - Baseline 100% transmission with an unobstructed beam
  - Relative transmission with the sample in the beam path
  - Baseline 0% transmission with completely obstructed beam
Experimental Procedure

- **Irradiation**
  - 9MV Linear Accelerator
  - Doses from 11 kRad–5 MRad
  - Dose Rate at 150 mm: 133.3 kRad/min
  - Placed 150 mm from target with the 10 mm x 10 mm face centered in the beam path

- **Activation**
  - Some activation seen after irradiation
  - Geant4 simulation to determine source of activation
  - Most likely: Neutron capture with 161Gd (t1/2 = 3.66 min)

<table>
<thead>
<tr>
<th>Sample #</th>
<th>Actual time (s)</th>
<th>Dose (krads)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1, 2, 3</td>
<td>5</td>
<td>11.1</td>
</tr>
<tr>
<td>4, 5, 6</td>
<td>23</td>
<td>51.1</td>
</tr>
<tr>
<td>7, 8, 9</td>
<td>45</td>
<td>100.0</td>
</tr>
<tr>
<td>10, 11, 12</td>
<td>123</td>
<td>273.3</td>
</tr>
<tr>
<td>13, 14, 15</td>
<td>225</td>
<td>500.0</td>
</tr>
<tr>
<td>16, 17, 18</td>
<td>338</td>
<td>751.1</td>
</tr>
<tr>
<td>19, 20, 21</td>
<td>450</td>
<td>1000.0</td>
</tr>
<tr>
<td>22, 23, 24</td>
<td>900</td>
<td>2000.0</td>
</tr>
<tr>
<td>25, 26, 27</td>
<td>1350</td>
<td>3000.0</td>
</tr>
<tr>
<td>28, 29, 30</td>
<td>1800</td>
<td>4000.0</td>
</tr>
<tr>
<td>31, 32, 33</td>
<td>2250</td>
<td>5000.0</td>
</tr>
<tr>
<td>34, 35, 36</td>
<td>0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Sample glowing brightly within the beam path
Annealing Process

- **Annealing**
  - 12 samples annealed
    - 1 sample from each of the dose levels
  - Manufacturer recommended annealing method
    - Heat furnace to 585°C at a rate of 10°C per minute ~1hr
    - Hold at 585°C ~30 minutes.
    - Lower temperature to 550°C at a rate of 1°C per minute ~35 min
    - Lower temperature to 450°C at a rate of 2°C per minute ~50 min
    - Lowers to room temperature at a maximum rate of 11°C per minute ~40 min

Before Irradiation | After Irradiation | After Annealing
Irradiation and Annealing Results

400 nm Data
27% change in transmission at 5Mrad
Demonstrates annealing process

550 nm Data
Less than 3% change in transmission
Demonstrates radiation hardness
LKH-5 Comparison to Conventional Scintillators

LKH-5 Pros

- Low Cost
- Potential use in conventional a-Si TFT arrays
- Comparable signal-to-noise to CWO through many inches of steel with increasing glass thickness

LKH-5 Drawbacks

- Modest light yield
- Moderate density

Radiation Hardness

- LKH-5 comparable to CWO at their respective emission peaks and 5 MRad of dose
- LKH-5 better than CsI(Tl) at 4.2 MRad of dose at 550 nm

<table>
<thead>
<tr>
<th>Scintillator Property</th>
<th>CdWO</th>
<th>CsI(Tl)</th>
<th>LKH-5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (g/cm$^3$)</td>
<td>7.9</td>
<td>4.5</td>
<td>3.8</td>
</tr>
<tr>
<td>Optical Yield (photons/MeV)</td>
<td>15,000</td>
<td>54,000</td>
<td>4,000</td>
</tr>
<tr>
<td>Cost ($/cm$^3$)</td>
<td>$35</td>
<td>$9</td>
<td>~$1</td>
</tr>
<tr>
<td>Emission Peak (nm)</td>
<td>470</td>
<td>550</td>
<td>550</td>
</tr>
<tr>
<td>Rad Hardness Discrepancy</td>
<td>2%</td>
<td>19%</td>
<td>3%</td>
</tr>
</tbody>
</table>

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Conclusion

- Light transmission at the emission peak decreases by 3% at 5 MRad of dose
  - Indicates that radiation will have little effect on scintillator performance
  - Indicates long scintillator lifetime, which could lead to long cargo scanning system lifetime and low replacement detector costs
  - Glass annealing improves transmission and this process can prolong scintillator lifetimes

- Appealing alternative if a detector design based upon LKH-5 glass can be consistently engineered to yield similar performance
  - Comparable radiation hardness to CWO and low cost
  - Same emission peak as CsI(Tl) and lower cost

- A journal paper on this work is currently under review, and plans for transition to commercial production by Varex Imaging are in progress
Fast Neutron Tomography for Spent Fuel Verification

- Modified parallel slit collimator for 3D imaging
- Used to verify spent fuel quantities and composition

Collimator annulus
(a) inner stainless steel
(b) outer borated polyethylene ring
(c) 96 slits - define lines of response across the field of view.
Neutron detection
(d) 12 detector modules - 24 rows of 8 boron straws each
(e) 5-cm-thick ring of borated polyethylene shielding
NSSC Experience

- **2017:** NSSC Undergrad Affiliate
- **5/2018:** B.S. Nuclear Eng, UC Berkeley
- **6/2018:** ORAU Summer Fellowship
- **5/2019:** ORNL Research
- **12/2019:** M.S. Nuclear Eng, UTK
- **5/2019:** NSSC Fellow
- **6/2018:** Nuclear and Particle Physics • 2017-2018
- **Radiation Detection and Instrumentation • 2019-2020**
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