LA-UR-20-29469

Approved for public release; distribution is unlimited.

Title: Development of an ultra-fast BaF₂-based detector

Author(s): Jordan, Tyler Alexander

Intended for: Research update for PhD academic advisor

Issued: 2020-11-17

Disclaimer:

Los Alamos National Laboratory, an affirmative action/equal opportunity employer, is operated by Triad National Security, LLC for the National Nuclear Security Administration of U.S. Department of Energy under contract 89233218CNA000001. By approving this article, the publisher recognizes that the U.S. Government retains nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or to allow others to do so, for U.S. Government purposes. Los Alamos National Laboratory requests that the publisher identify this article as work performed under the auspices of the U.S. Department of Energy. Los Alamos National Laboratory strongly supports academic freedom and a researcher's right to publish; as an institution, however, the Laboratory does not endorse the viewpoint of a publication or guarantee its technical correctness.

Development of an ultra-fast BaF₂-based detector

Progress update

Tyler Jordan

November 20, 2020

Managed by Triad National Security, LLC for the U.S. Department of Energy's NNSA

Introduction

Motivation

- BaF_2 is one of the fastest known scintillators, emitting at 220 nm with sub-nanosecond decay constant [1]
 - Excellent for timing applications
- $4.88 \text{ g/cm}^3 \rightarrow$ High detection efficiency
 - At 15 cm thick, nearly 100% efficient for gammas up to 10 MeV [2]

Motivation

- BaF_2 is one of the best scintillators, emitting sub-nanosecond light
 - Excellent for timing
- $4.88 \text{ g/cm}^3 \rightarrow$ High density
 - At 15 cm thick, nearly transparent to gammas up to 10 MeV

Problem

- ~80% of the total light output consists of slower (600 ns decay constant) emission peaked at 310 nm [2]
 - Low count rate $\rightarrow$ slow component for energy resolution, fast component for timing
 - High count rate $\rightarrow$ pile up

Goal

- To develop a BaF_2 -based detector that leverages the fast emission component for optimal timing characteristics
 - Rare earth doping (e.g., La, Ce, Y) suppresses the slow component
 - Bandpass filters can selectively transmit the fast component to a photodetector

Goal

- To develop a BaF_2 -based detector that leverages the fast emission component for optimal timing characteristics
 - Rare earth doping (e.g., La, Ce, Y) suppresses the slow component
 - Bandpass filters can selectively transmit the fast component to a photodetector

Possible application: time-of-flight PET imaging

Development Plan

Proof of concept

1. “Off-the-shelf” prototype
 - Pure BaF_2
 - Commercially available bandpass filter
 - Commercially available photodetector
2. Create a suite of experimentally-validated simulations/ analytical calculations that captures various aspects of detector performance:
 - Example metrics:
 - Photoelectrons / MeV
 - Fast light output / Total light output
3. Optimize detector design in simulation space
 - Doped BaF_2
 - Custom bandpass filter
 - Hybrid photodiode

Proof of concept

1. “Off-the-shelf” prototype
 - Pure BaF_2
 - Commercially available bandpass filter
 - Commercially available photodetector
2. Create a suite of experimentally-validated simulations/ analytical calculations that captures various aspects of detector performance:
 - Example metrics:
 - Photoelectrons / MeV
 - Fast light output / Total light output
3. Optimize detector design in simulation space
 - Doped BaF_2
 - Custom bandpass filter
 - Hybrid photodiode

Experiments

1. Monolithic BaF₂

- Cylindrical BaF₂ crystal coupled to non-segmented photodetector
- Measurements with and without bandpass filter
- Quantities of interest:
 - Photoelectrons / MeV
 - Fast light output / Total light output
 - Time resolution

Bandpass
filter

1"x1" pure BaF₂ crystal

2. Segmented photodetector characterization

- Light pulser coupled to Photonis PLANACON photodetector via fiber-optic cable

PLANACON photodetectors:

- Left module with gain (microchannel plate), right without
- Footprint: 58mm x 58mm
- 32x32 grid of 1.1mm square anodes

2. Segmented photodetector characterization

- Readout circuit board
 - Each pin contacts 2x2 anode group (i.e., 256 channels per PLANACON)
 - Variation in signal trace length <1mm

2. Segmented photodetector characterization

- Anisotropic conducting foam (ACF) to couple PLANACON to readout board
 - Silicon rubber matrix with densely embedded metal wires

2. Segmented photodetector characterization

- 3D printed enclosure for photodetector, with bulkheads for fiber-optic cable

Square annulus to center ACF
beneath PLANACON

2. Segmented photodetector characterization

- Assembly

2. Segmented photodetector characterization

- Assembly

2. Segmented photodetector characterization

- Assembly

2. Segmented photodetector characterization

- Assembly

2. Segmented photodetector characterization

2. Segmented photodetector characterization

3. LYSO array

- Saint-Gobain array coupled to PLANACON
- Basic radiation measurements

- 32x32 LYSO pixel array
- Pixel dimensions: 1mm x 1mm x 30mm
- Teflon reflector

3. LYSO array

- Assembly

3. LYSO array

- Assembly

3. LYSO array

- Assembly

3. LYSO array

- Assembly

3. LYSO array

- Assembly

3. LYSO array

4. BaF₂ Array

- Custom BaF₂ array coupled to PLANACON
- Design goals:
 - 1 BaF₂ pixel per 3x3 anode group (i.e., 144 channels per PLANACON)
 - Consistent pixel-anode alignment across multiple photodetectors
 - Airgap around each pixel for total internal reflection

- To-scale schematic of pixel anode alignment (generated with root)
- Pixel width: 4.5mm
- Unit cell width: 4.83mm

4. BaF₂ Array

- Filletted corners to maintain air gap around each pixel

$$r = x\sqrt{2} \Rightarrow x = \frac{r}{\sqrt{2}}$$

$$a + x = r \Rightarrow a + \frac{r}{\sqrt{2}} = r$$
$$\Rightarrow a = r\left(1 - \frac{1}{\sqrt{2}}\right)$$

- A slightly more complicated equation accounts for machining tolerance
- Air gap: 0.1mm
- Corner radius: 0.11mm
- Hole width: 4.7mm
- Wall thickness: 0.13mm

4. BaF₂ Array

Pixel frame design

Photo-etched titanium foil

4. BaF₂ Array

Pixel frame design

Aluminum foil “loom” base

4. BaF₂ Array

Pixel frame design

Aluminum foil “loom”
top plate

4. BaF₂ Array

- Pixel frame assembly
- 237 foils, 30 mm tall

4. BaF₂ Array

4.5mm x 4.5mm x 30mm
pure BaF₂ pixel

Single-pixel bandpass filter

4. BaF₂ Array

4. BaF₂ Array

- Side note: command-configurable GEANT4 application in development

4. BaF₂ Array

- Side note: command-configurable GEANT4 application in development

Commands:

```
/baf2/detcon/arrayn 12  
/baf2/detcon/unitxy 4.83  
/baf2/detcon/unitz 30  
/baf2/detcon/wallt 0.13  
/baf2/detcon/cornerr 0.11  
/baf2/detcon/scintxy 4.6
```

4. BaF₂ Array

- Assembly
 - Cap not shown

4. BaF₂ Array

- Assembly
 - Cap not shown

4. BaF₂ Array

- Assembly
 - Cap not shown

4. BaF₂ Array

- Assembly
 - Cap not shown

4. BaF₂ Array

- New readout circuit board
 - Corner pins each contact single anode
 - Side pins each contact 1x3 anode group
 - Interior pins each contact 3x3 anode group
 - 144 channels
 - Variation in signal trace length <1mm

5. PET-like source localization

- One BaF_2 array on either side of a ^{22}Na source
 - Alternatively, one BaF_2 array and the LYSO array
- Can potentially build larger arrays with more PLANACONS

- Goal: to measure the difference in times-of-arrival for coincident annihilation photons
 - Entirely determined by geometry, i.e., distance from source to each detector
 - Source localization in 3D space

Conclusion

Current and Future Work

- Currently running light pulser setup with gainless PLANACON
- Recently began radiation measurements with LYSO array
- BaF₂ array assembly nearly complete
- Familiarizing myself with the team's custom DAQ software
- Need to set up monolithic BaF₂ experiments
- Need to expand GEANT4 application with command-configurable sources and materials

References

- [1] M. Laval et al., “Barium fluoride—Inorganic scintillator for subnanosecond timing,” *Nucl. Instrum. Methods Phys. Res.*, **206**, 169 (1983)
- [2] K. Wisshak, F. Käppeler, “Large barium fluoride detectors,” *Nucl. Instrum. Methods Phys. Res.*, **227**, 91 (1984)
- [3] A. I. Nepomnyashchikh et al., “Luminescence of $\text{BaF}_2\text{-LaF}_3$,” *Radiat. Meas.*, **33**, 759 (2001)
- [4] C. Hu et al., “Development of yttrium-doped BaF_2 crystals for future HEP experiments,” *IEEE Trans. Nucl. Sci.*, **66**, 1854 (2019)

Questions?