Triple PSD with Polysiloxane-Based Scintillators

Mackenzie Duce

2023 LANNS Symposium-2

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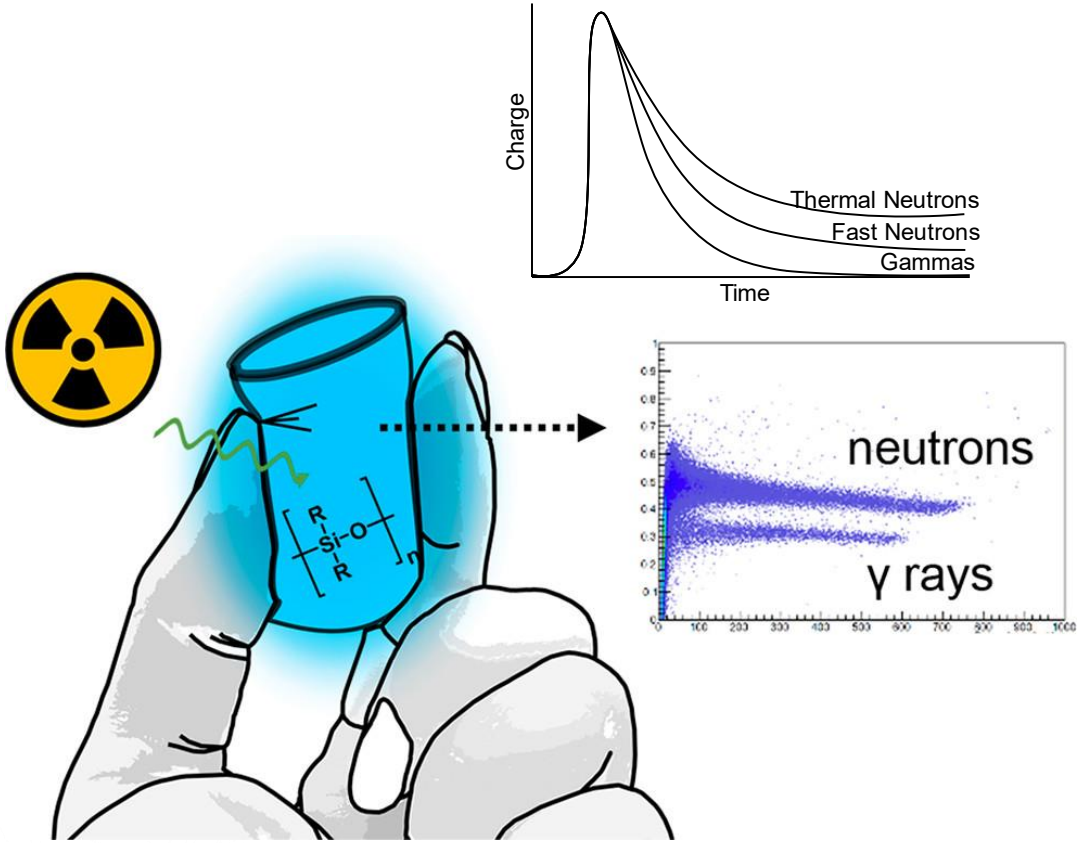
November 03, 2023

Georgia Tech

Organic scintillators for neutron detection

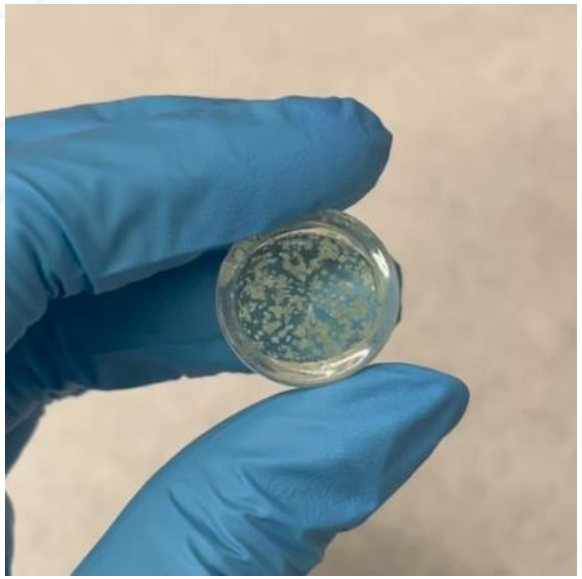
- Triple particle detection can support many detection applications



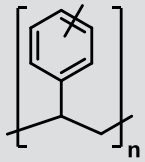
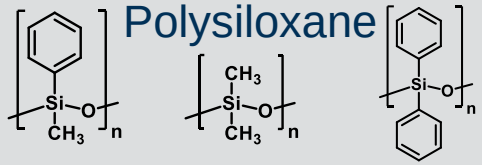
IAEA inspectors conducting fresh fuel verification

A. Lim, J. Arrue, P. Rose, A. Sellinger,, A. Erickson, ACS Appl. Polym. Mater., 2020, 2, 8, 3657-3662

Polysiloxanes as alternative to PVT matrices



Polysiloxane-based scintillator at Georgia Tech, fabricated November 2022 at Colorado School of Mines by Caleb Chandler. (KER6000/PHF/Phenyl)

	 PVT	 Polysiloxane
Transparency	Yes	Yes
Physical Properties	Hard, rigid	Variable
Radiation Hardness	No	Yes[2,6]
Thermal Stability	No[2]	Yes[3,7]
Fabrication	5 days, air sensitive	3 hrs, in air[1]
Cost	$0.08/g[5]	$0.75 - $16/g[5]
PSD	@ 20%wt dopant	@ 5%wt dopant[4,1]

[1]A. Lim, J. Arrue, P. Rose, A. Sellinger,, A. Erickson, ACS Appl. Polym. Mater., 2020, 2, 8, 3657-3662
[2]Bertrand, G. H. V.; Hamel, M.; Sguerra, F. *Chem. Eur. J.* 2014, 20 (48), 15660–15685.
[3]Arrue, J., et al., *NIM A*, 2023, 1056, 168650
[4]Marchi, T. et al. *Sci. Rep.* 2019, 9 (1), 9154.
[5]Prices from Sigma, Gelest, TCI America, and Nusil
[6]Quaranta, et al, *Mats. Chem. And Phys.* 2013, 137 (3) 951-958
[7]Deshpande, G, Rezac, M., *Polymer Deg. And Stability*. 2002, 76 (1) 17-24

Fabrication at Colorado School of Mines

Caleb Chandler
Sellinger Research Group

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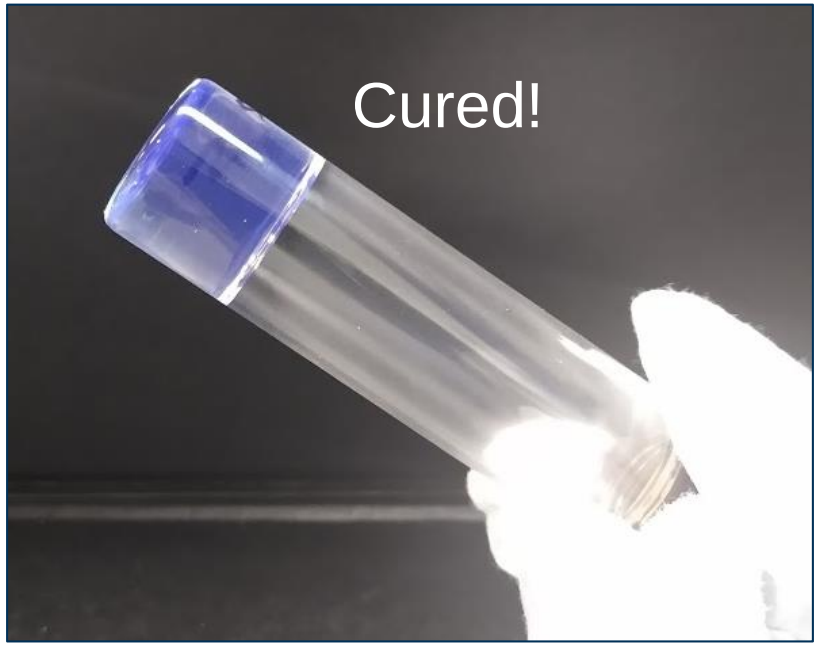
Prepare silanized vial (30-60 mins)

Add SFS, PPO

Add xylenes

Solubilize and add Part A, mix, add Part B



Vortex, then cure at 150 C for 3 hrs in air

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Common Fabrication Challenges

Caleb Chandler
Sellinger Research Group

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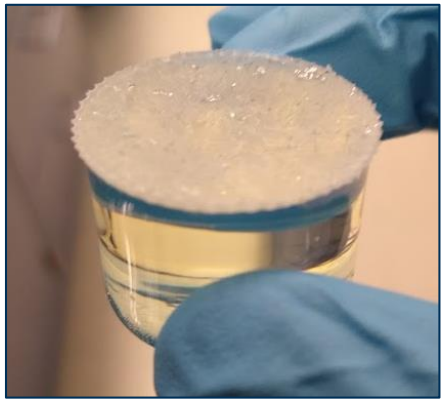
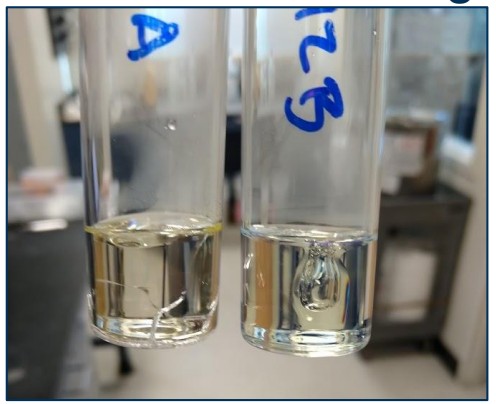
Dopant Precipitation on Surface



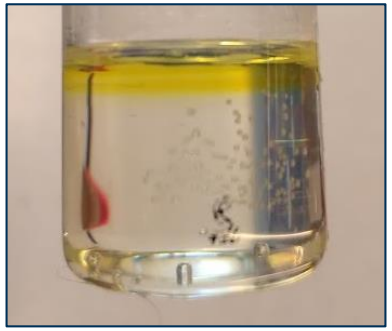
Internal Precipitation

Glass Cracked

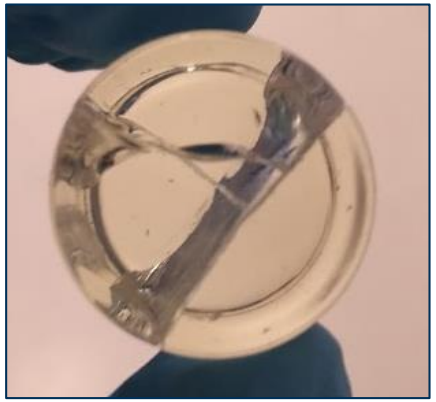
Internal Bubbling



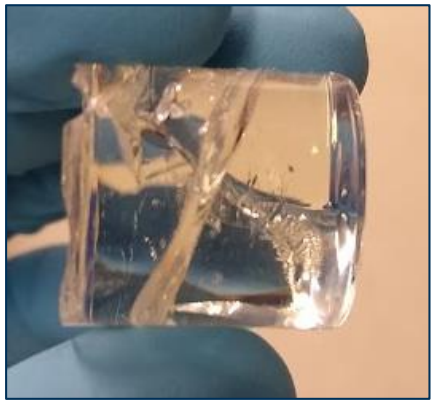
Surface Coloration



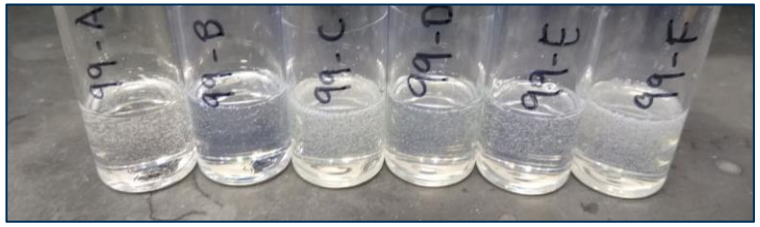
Cracked



Cracked



Air Bubbles Trapped



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Toward 3 Particle Imaging

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- Add thermal-neutron sensitive material to polysiloxane scintillators
- Iterate recipe for:
  - Stability
  - High light output
  - Pulse shape discrimination-capable
  - Minimal quenching
- Fabricate array
- Characterize
- Add image reconstruction

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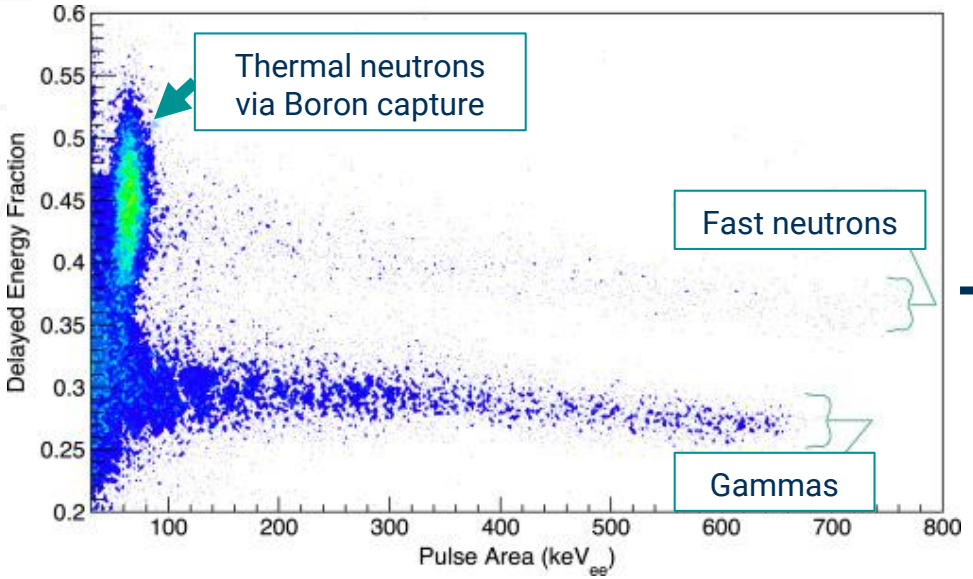
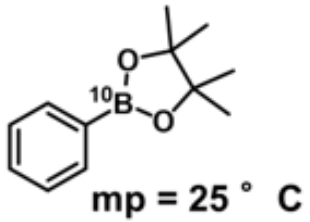
(Enriched) Boron-10 Doped PVT Scintillators

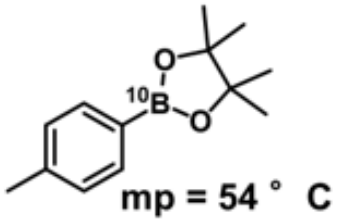


Previous work synthesizing and incorporating MBB in PVT scintillators

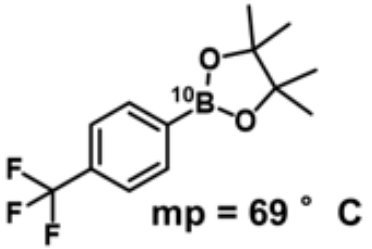
- Derivatives of MBB used in this study
  - Synthesized from enriched boric acid (>96% ^{10}B)



3.75wt% phenylpinacolborane



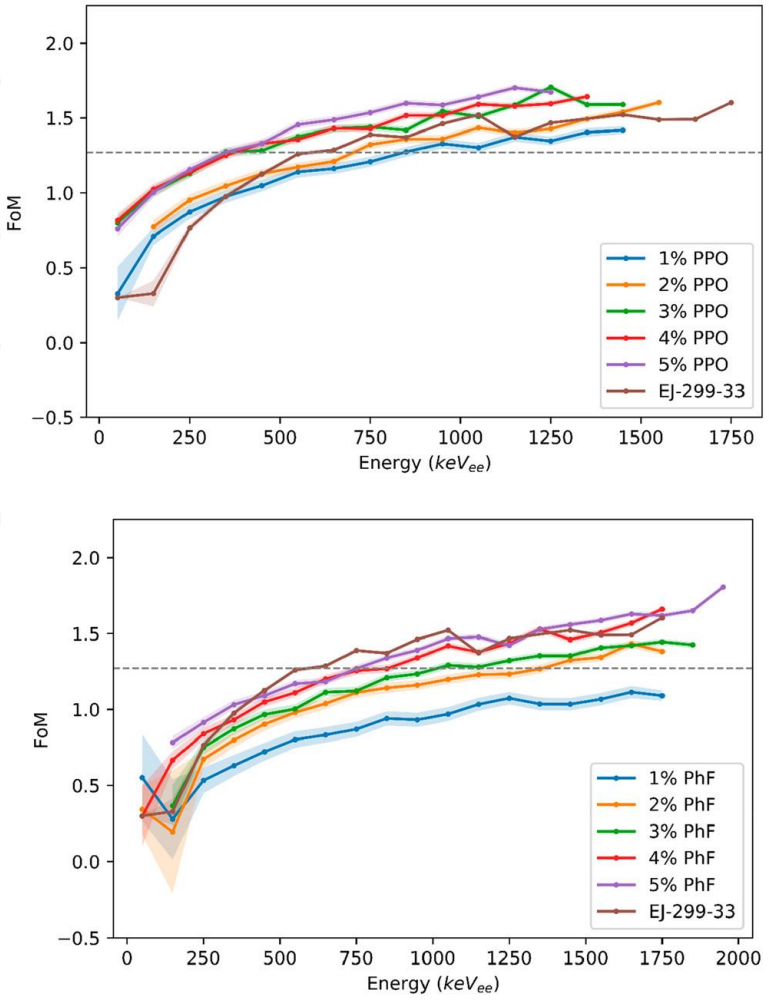
4wt% tolyl-



5wt% trifluoro-

A. Mahl, H.A. Yemam, R. Fernando, J.T. Koubek, A. Sellinger, U. Greife, *NIM A*, 2018, 880, 1-5

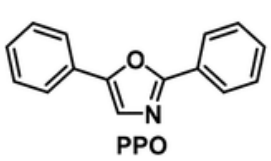
Polysiloxane Matrices & Fluorophores Tested

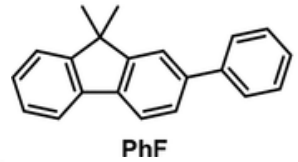


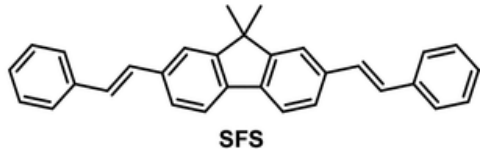
PSD FOM results for Wacker LUMISIL-based polysiloxane scintillators of varying dopant concentrations

A. Lim, J. Arrue, P. Rose, A. Sellinger,, A. Erickson, ACS Appl. Polym. Mater., 2020, 2, 8, 3657-3662

- Primary dopants:
  - PHF: 9,9-dimethyl-2-phenyl-9H-fluorene
  - PPO: 2,5-diphenyloxazole
- Secondary dopant (wavelength shifter):
  - SFS: 9,9-dimethyl-2,7-distyryl-9H-fluorene
- Polymer resins modified:
  - Shin-Etsu KER-6000
    - LED encapsulant
  - Wacker SILRES H62C
    - electronics encapsulant







	R.I.	Hardness	Mix	Cure
Wacker 579	1.53	25 Shore A	2-component	150 °C / 1 hr
KER-6000	1.51	22 Shore A	2-component	100 °C / 1 hr, 150 °C / 2 hr
SilRes H62C	1.50	65 Shore D	1-component	150 °C / 10 hr

Testing Scintillator Compositions

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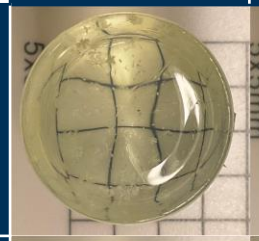
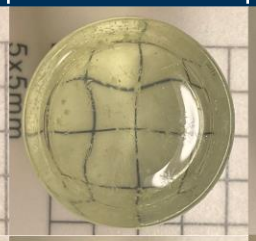
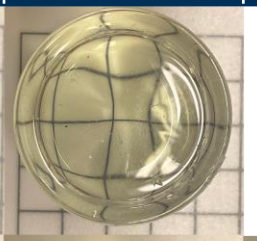
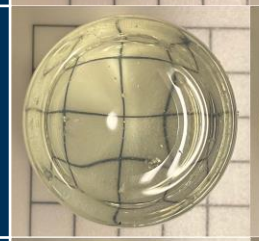
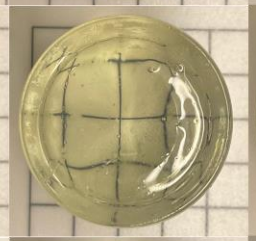
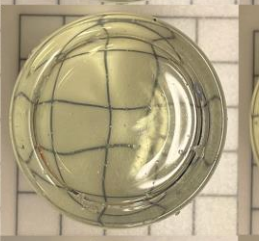
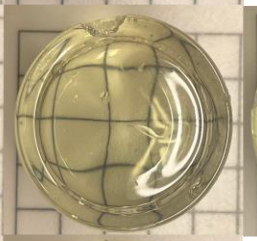
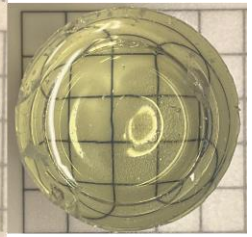
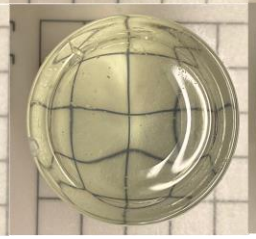
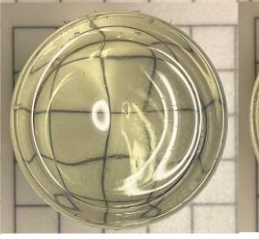
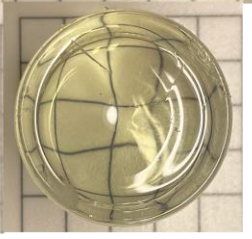
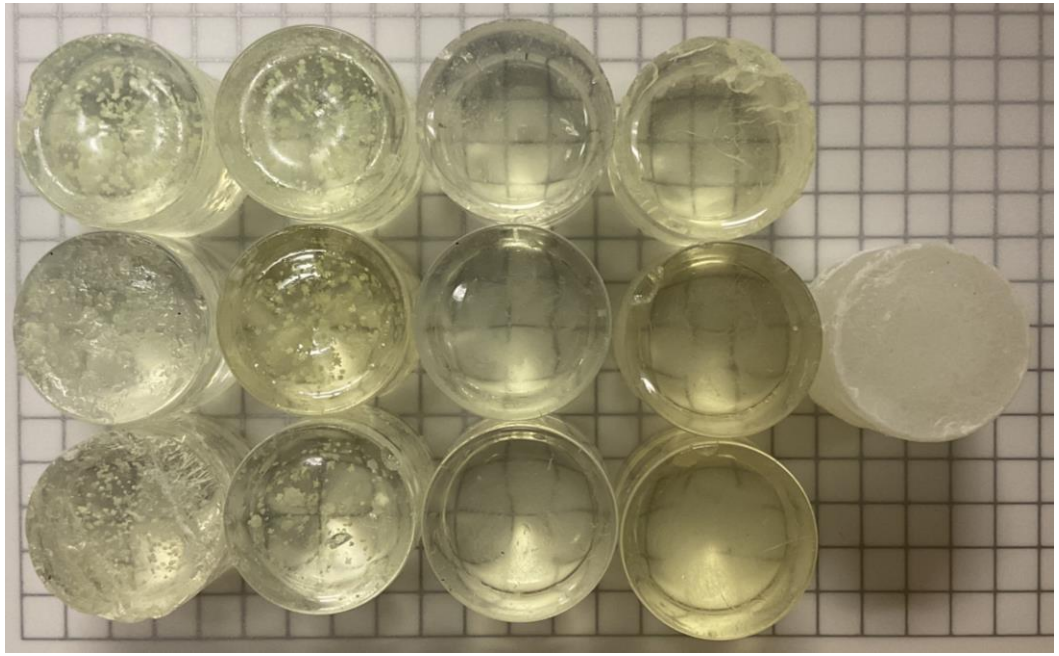
	KER6000		SILRES		SILRES
	PHF	PPO	PHF	PPO	20% PHF
3.75% Phenyl-					
4% Tolyl-					
5% Trifluoro-					



One year later!

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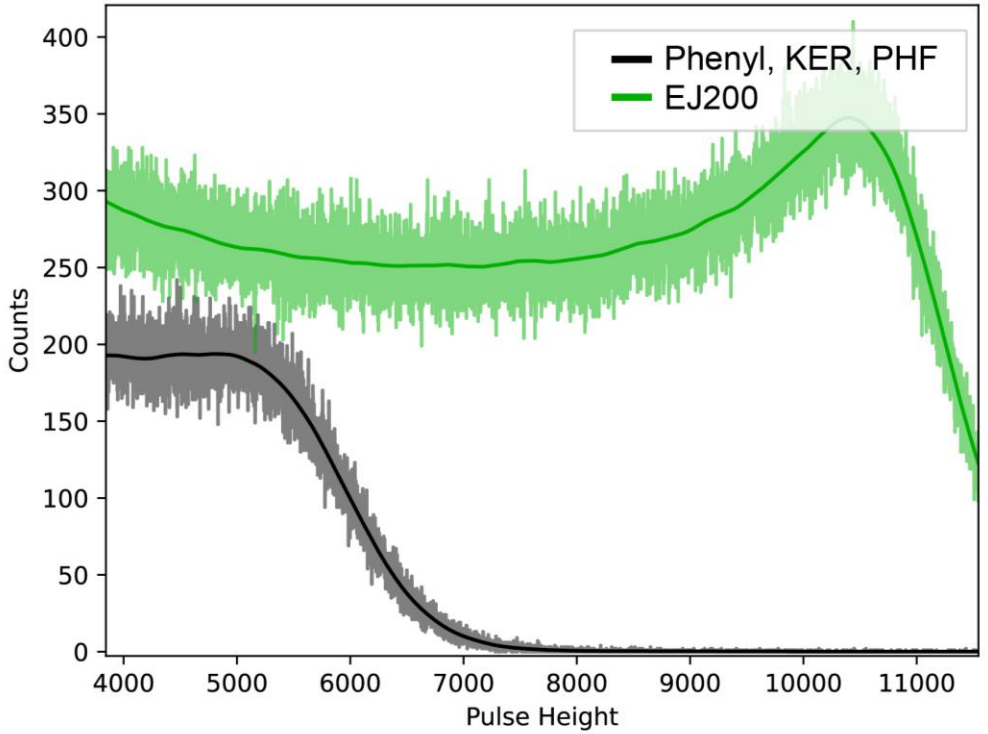
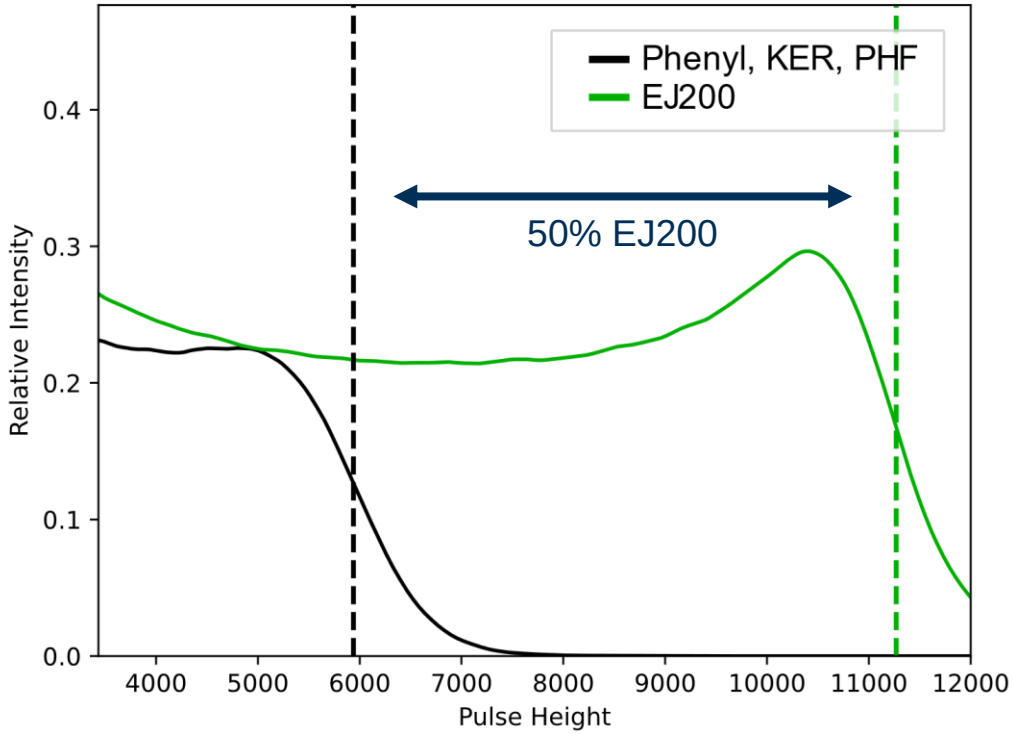
Measuring Light Yield (electron equivalent)

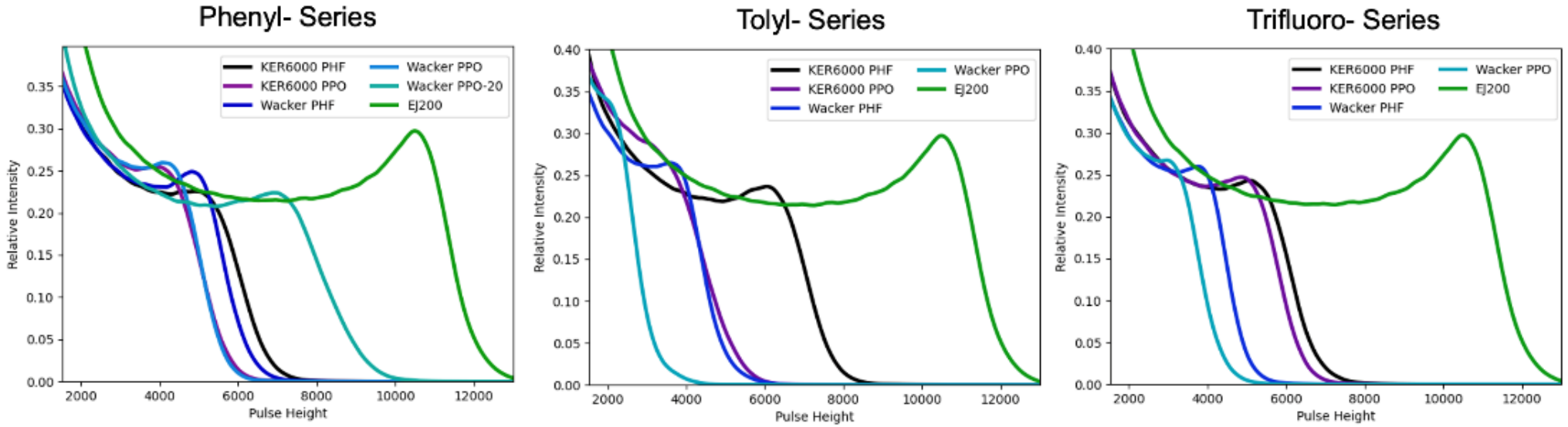




- 477 keV Cs-137 Compton edge
- Differentiation method
- Compare to EJ200: 10,000 ph/MeVe

Safari, M.J., et al, *arxiv Physics*, 2016
https://eljentechnology.com/products/plastic-scintillators/ej-200-ej-204-ej-208-ej-212

Measuring Light Yield (electron equivalent)

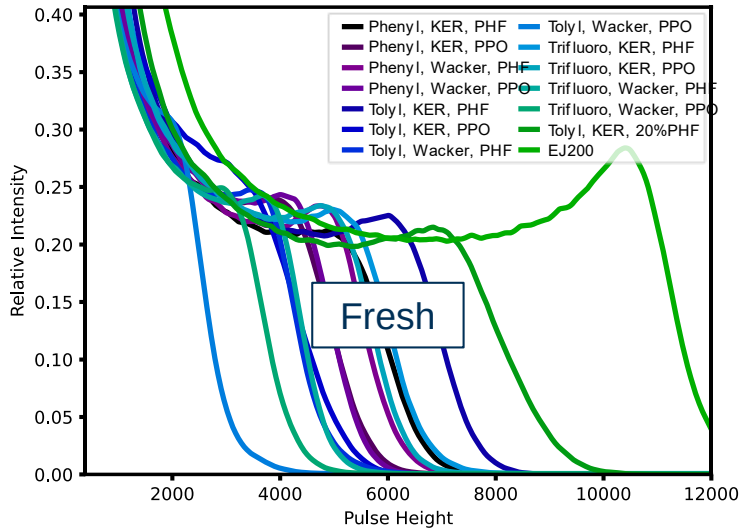


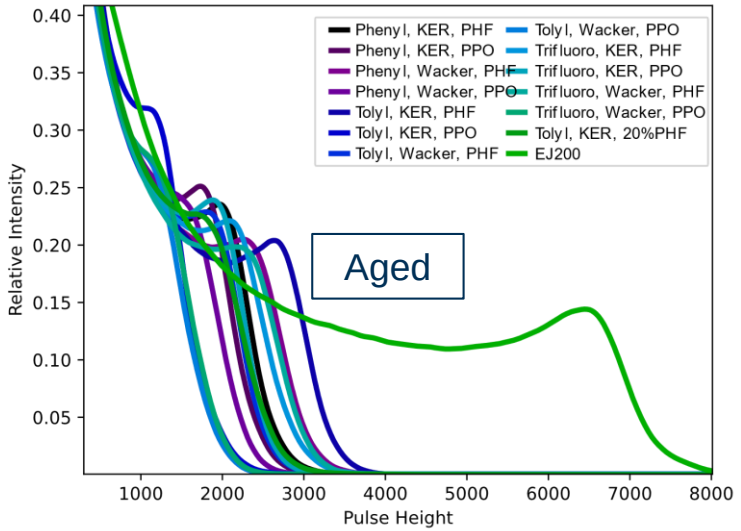
		5% PHF	5% PPO	20% PHF
B10	Matrix	*Fresh*	*Fresh*	*Fresh*
Phenyl	KER6000	**0.53**	0.45	
	SILRES	0.49	0.45	
Tolyl	KER6000	**0.62**	0.39	
	SILRES	0.39	0.23	**0.71**
Trifluoro	KER6000	**0.55**	0.51	
	SILRES	0.39	0.33	

Values reported as fraction of similar size EJ200 under same experiment conditions.

Tolyl, KER6000, 5%PHF
~6,200 photons/MeV
Tolyl, SILRES, 20%PHF
~7,100 photons/MeV

Aging Effects on Light Yield



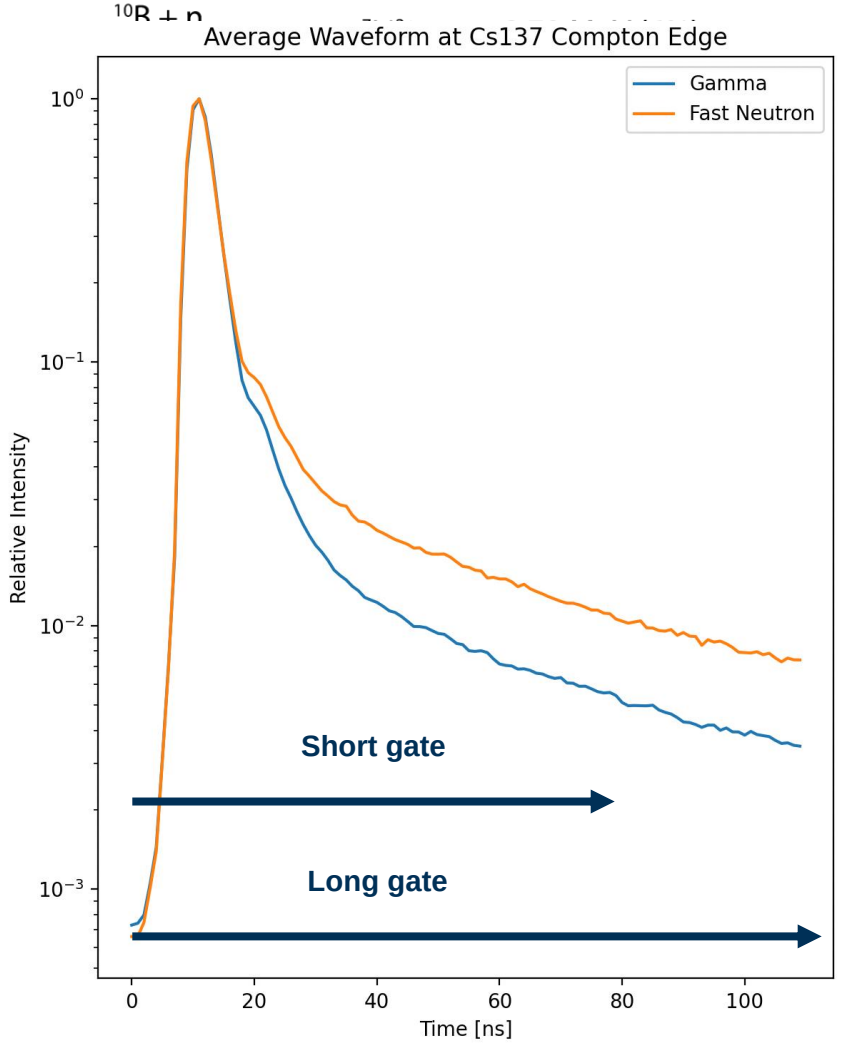


		5% PHF			5% PPO			20% PHF		
B10	Matrix	*Fresh*	*Aged*	*Change*	*Fresh*	*Aged*	*Change*	*Fresh*	*Aged*	*Change*
Phenyl	KER6000	0.53	0.36	-32%	0.45	0.33	-27%			
	SILRES	0.49	0.42	-14%	0.45	0.31	-69%			
Tolyl	KER6000	0.62	0.46	-26%	0.39	0.35	-10%			
	SILRES	0.39	0.35	-10%	0.23	0.24	4%	0.71	0.35	-51%
Trifluoro	KER6000	0.55	0.38	-31%	0.51	0.35	-31%			
	SILRES	0.39	0.41	5%	0.33	0.26	-21%			

Values reported as fraction of similar size EJ200 under same experiment conditions.

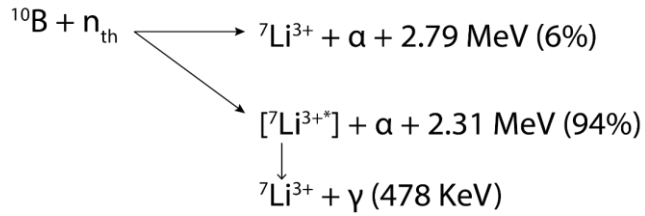
KER6000 reduced **~-30%**
SILRES reduced **~-15%**

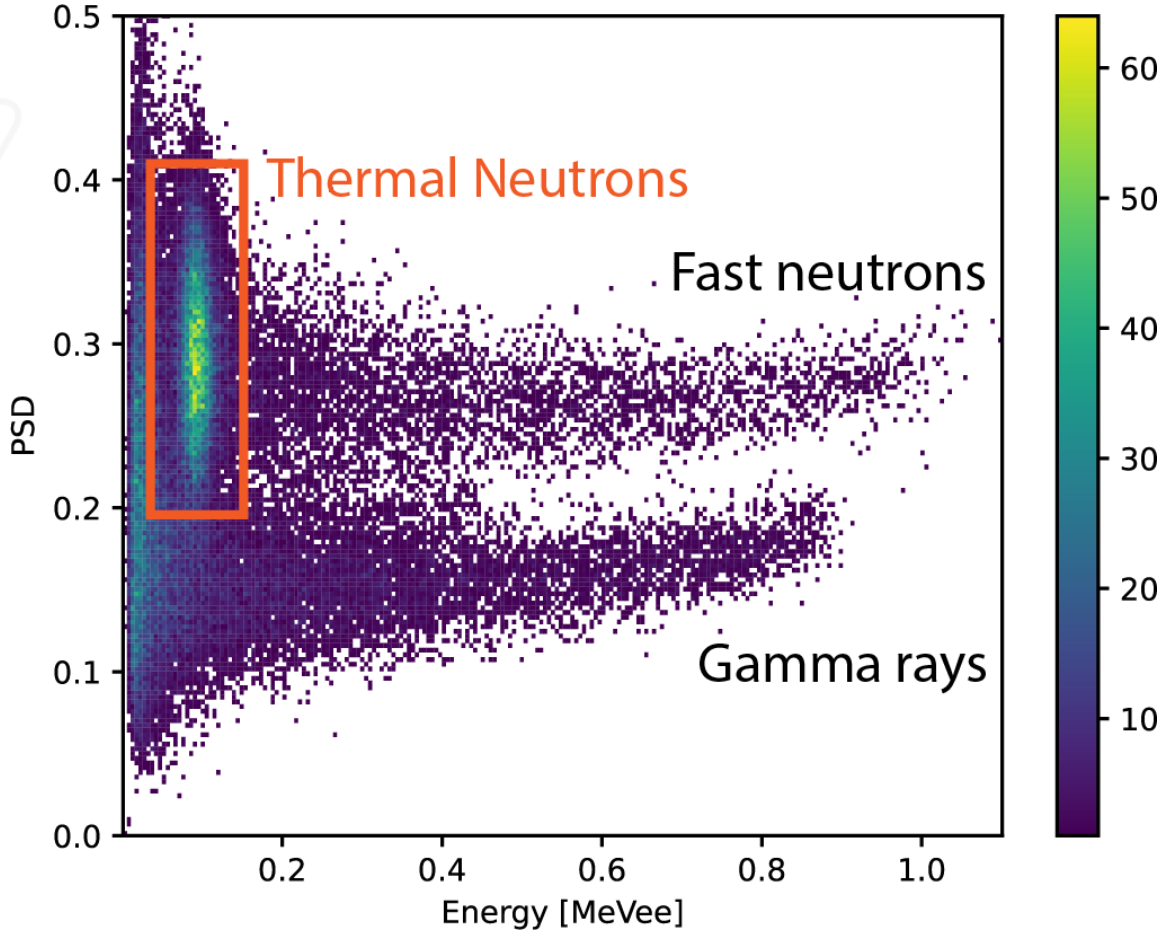
Pulse Shape Discrimination Measurements



AmBe setup: Poly, concrete, water, 3" lead to knock down gammas

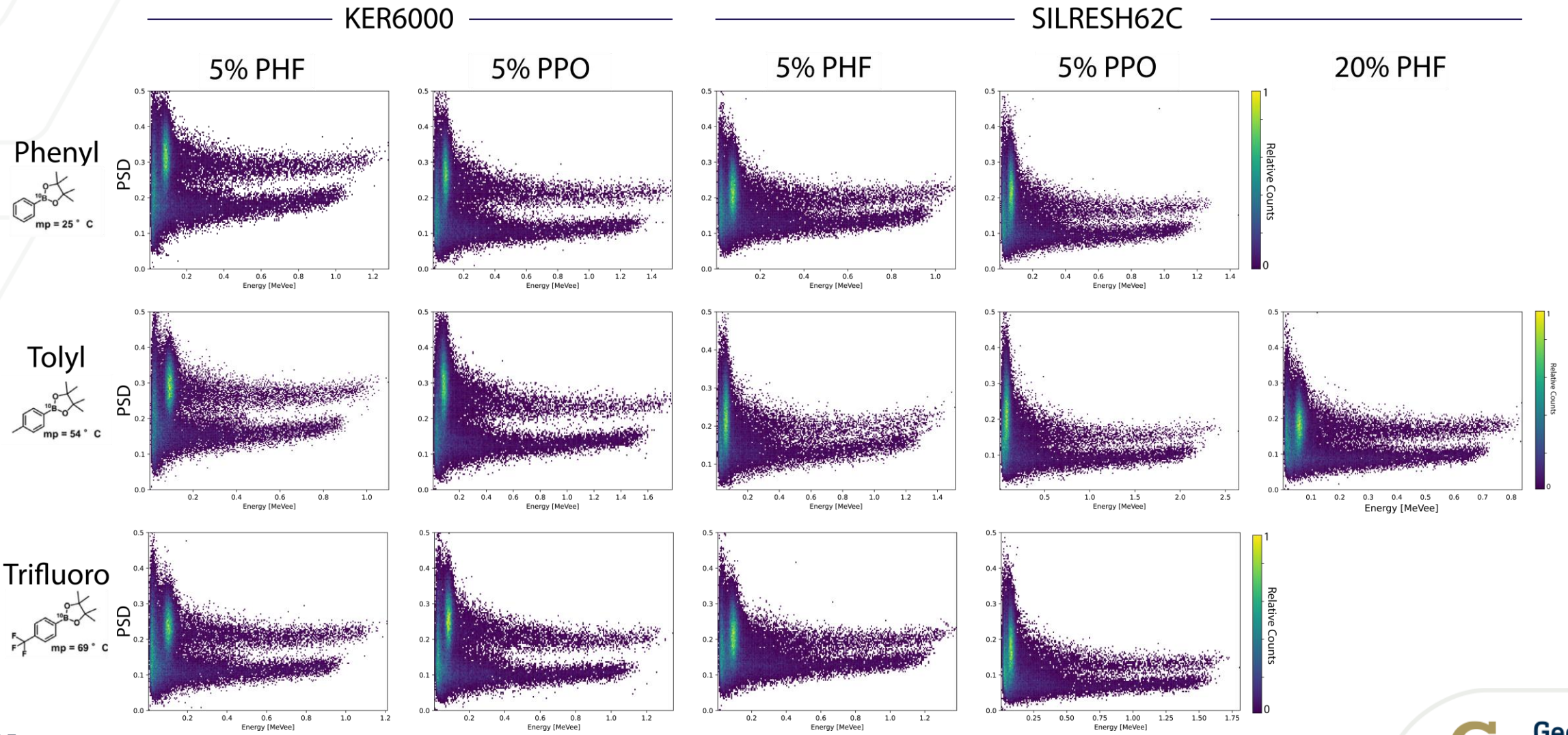
Pulse Shape Discrimination Measurements





AmBe setup: Poly, concrete, water, 3" lead to knock down gammas

Pulse Shape Discrimination for all Samples



Pulse Shape Discrimination for all Samples (Aged)

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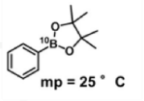
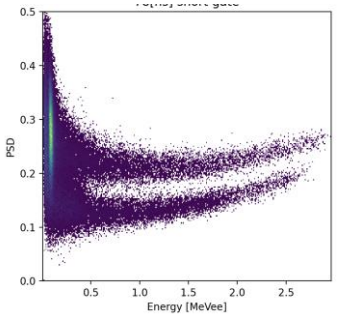
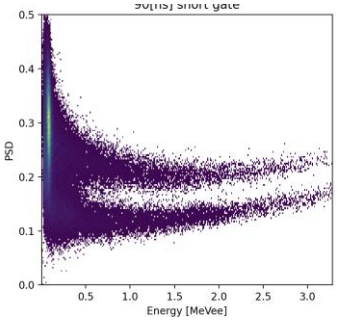
KER6000 | SILRESH62C

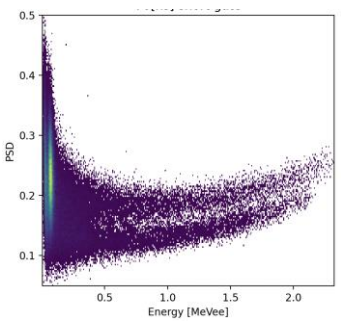
5% PHF | 5% PPO | 5% PHF | 5% PPO | 20% PHF

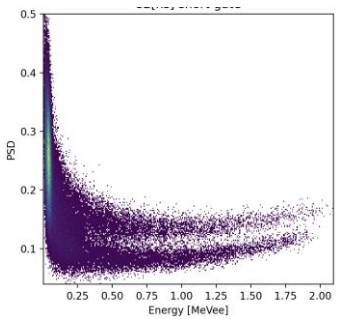
Phenyl



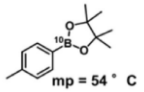


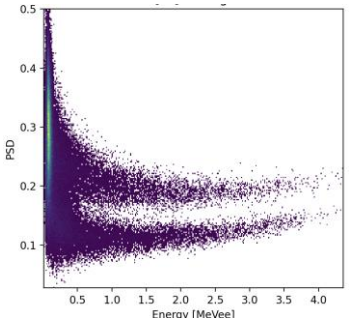


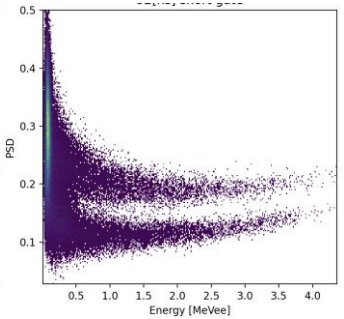


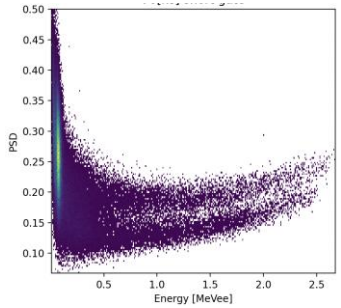


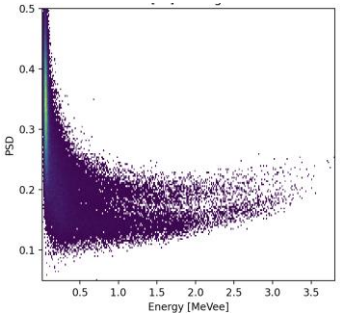
Tolyl

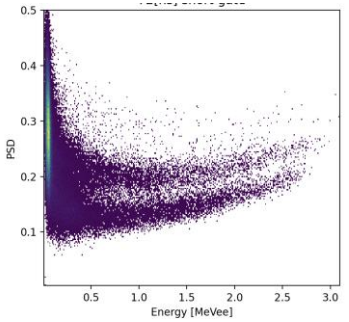




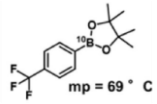


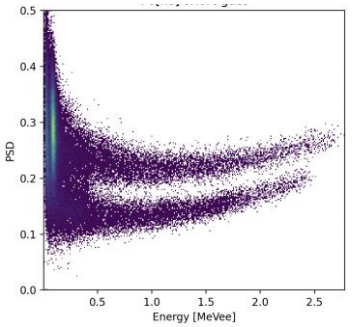


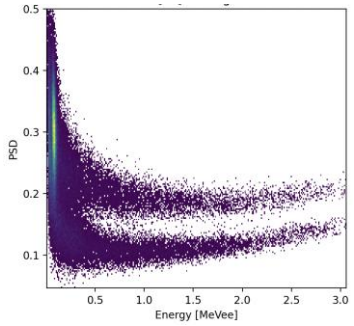


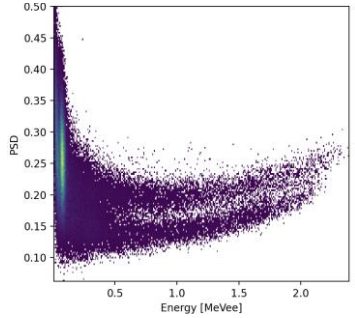


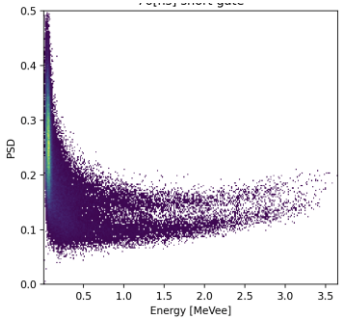
Trifluoro











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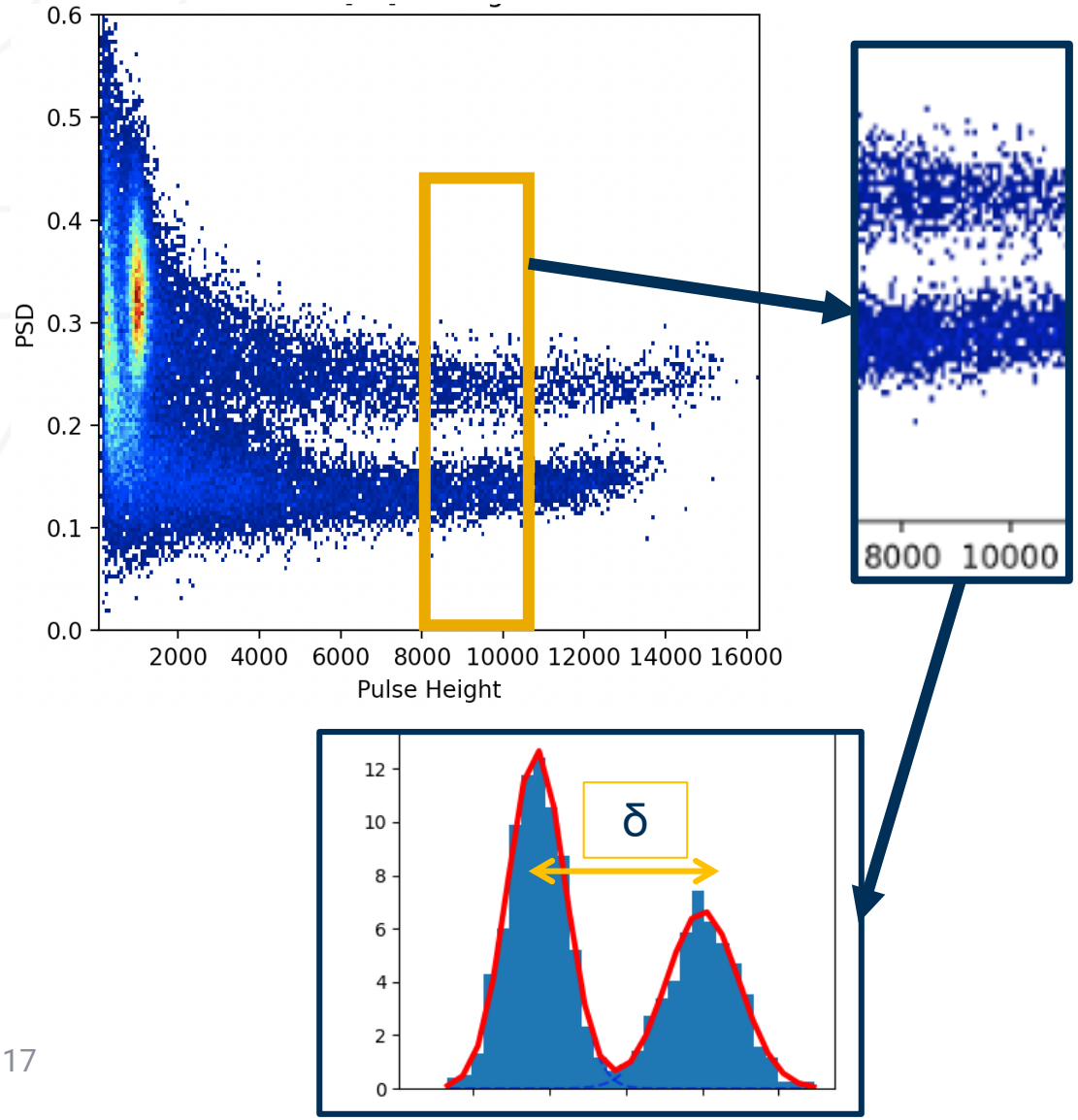
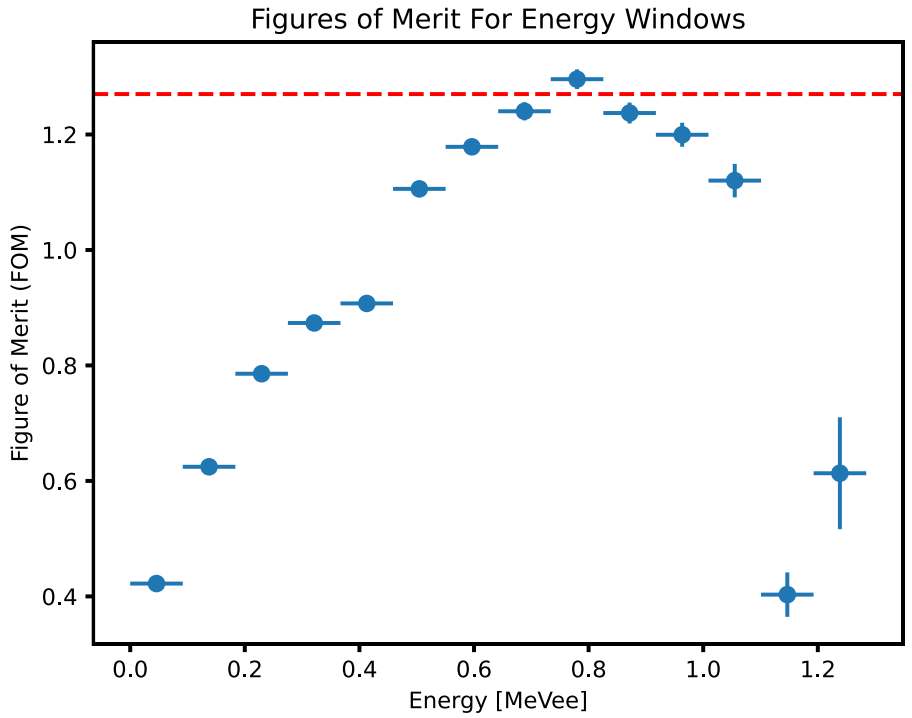
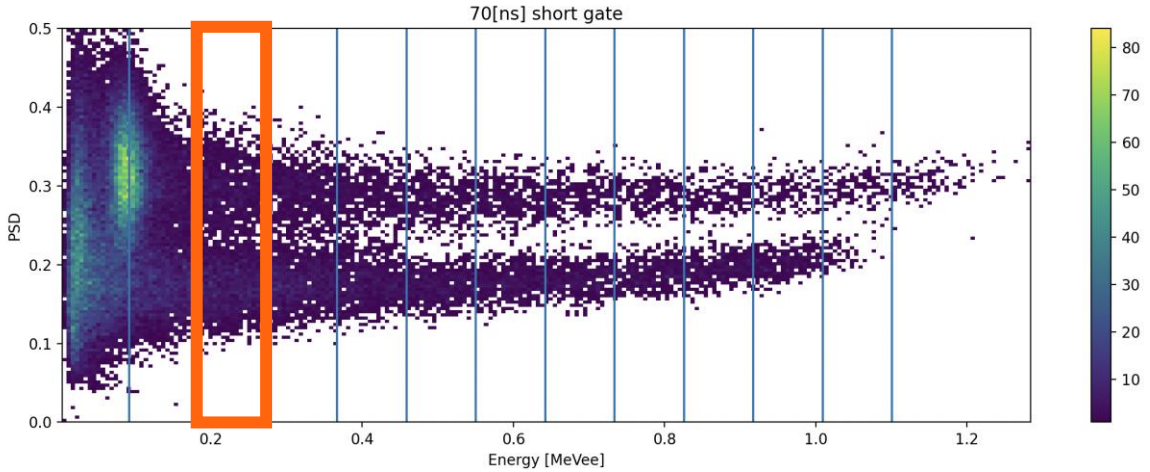
PSD Effectiveness: Figure of Merit

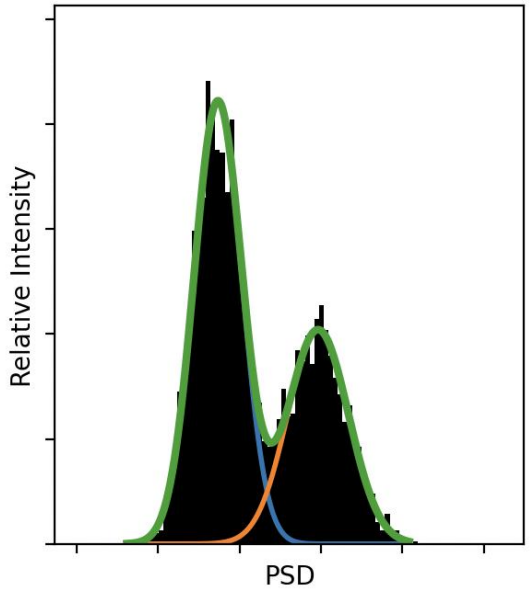


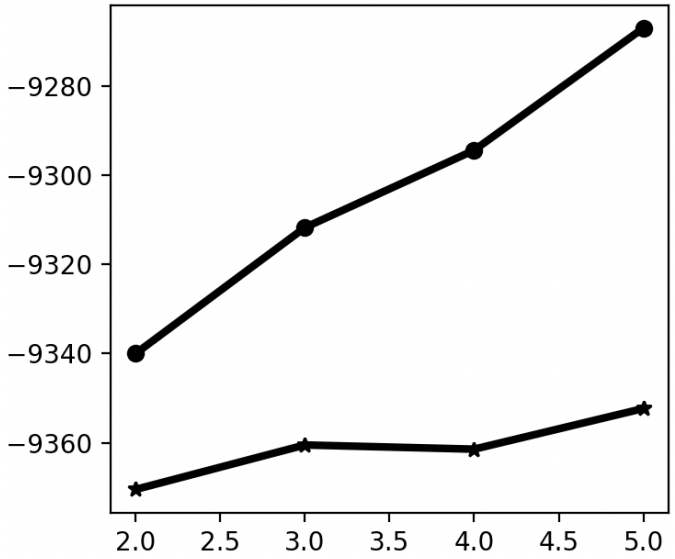
- FOM = $(\delta)/(FWHM_{\gamma}+FWHM_{n})$
  - Efficiency separation at FOM = 1.27 (δ >3std)



Unsupervised Gaussian Mixture Model for FOM



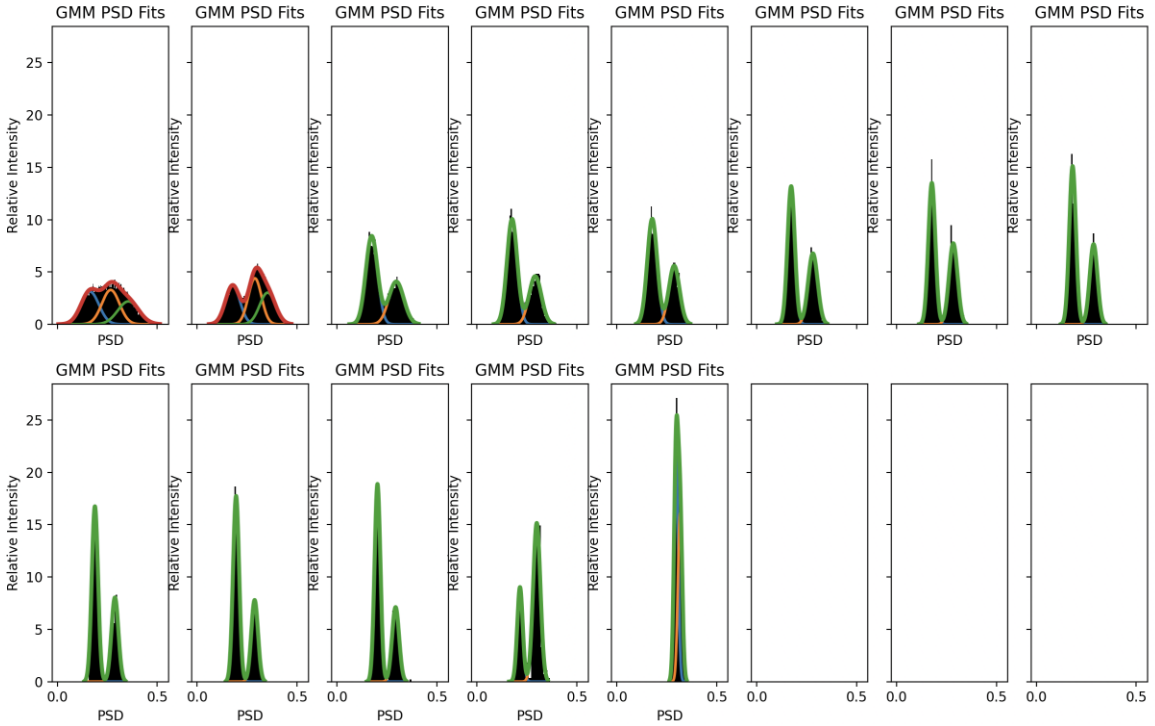


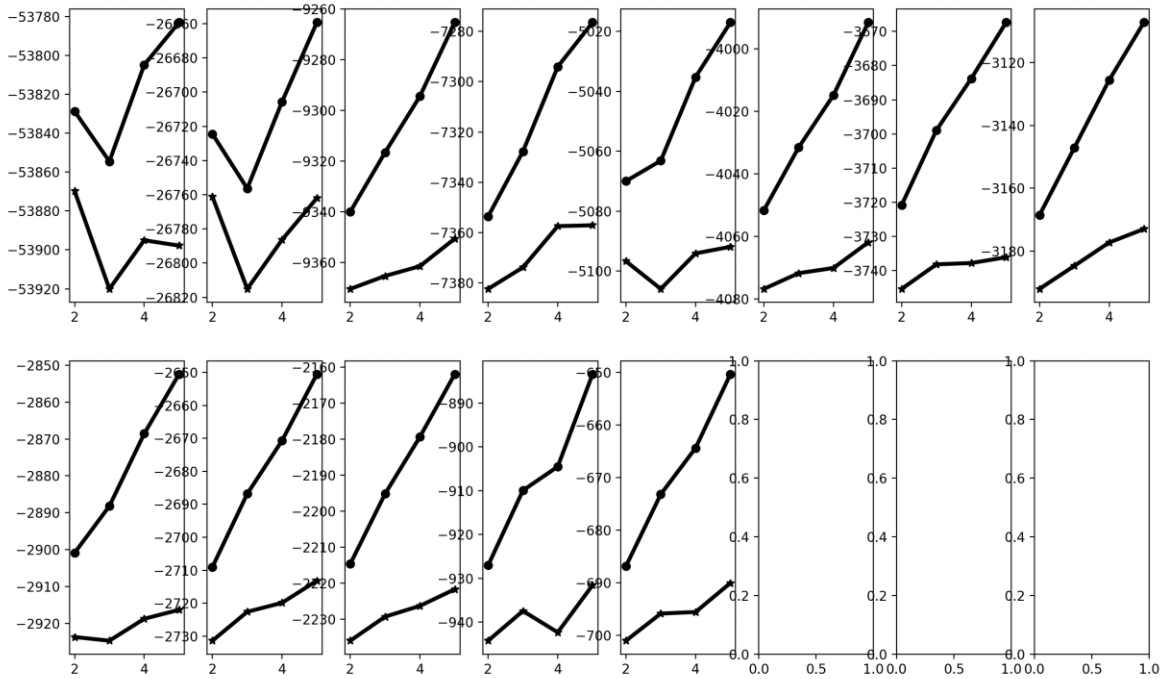


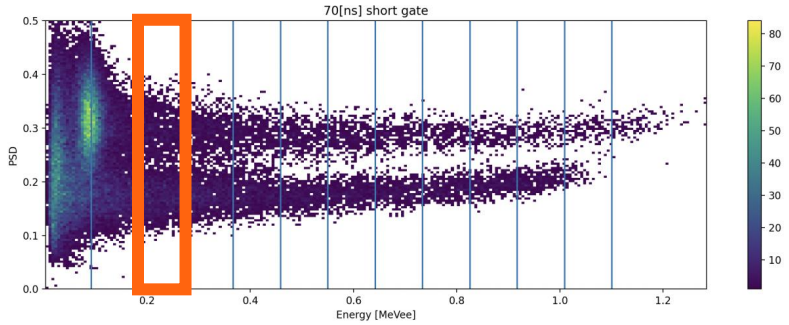
- No pre-labed data required
- Gaussian assumption aligns with data and physics
- Low energy discrimination
- BIC/AIC tests

Blair, B., *Stat. Anal. Data Min.: The ASA Data Science Journal.* 2019, 12 (6) 479-488

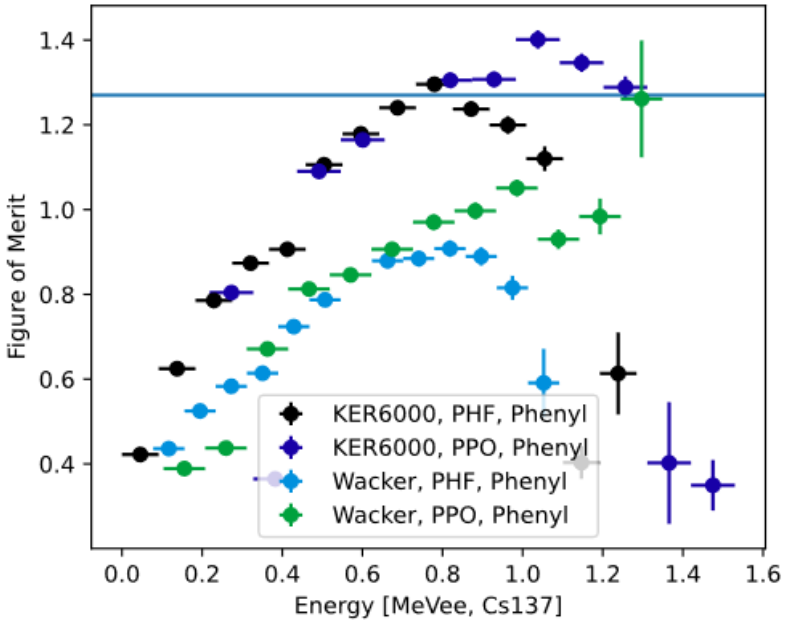
GMM Applied to Full Dataset

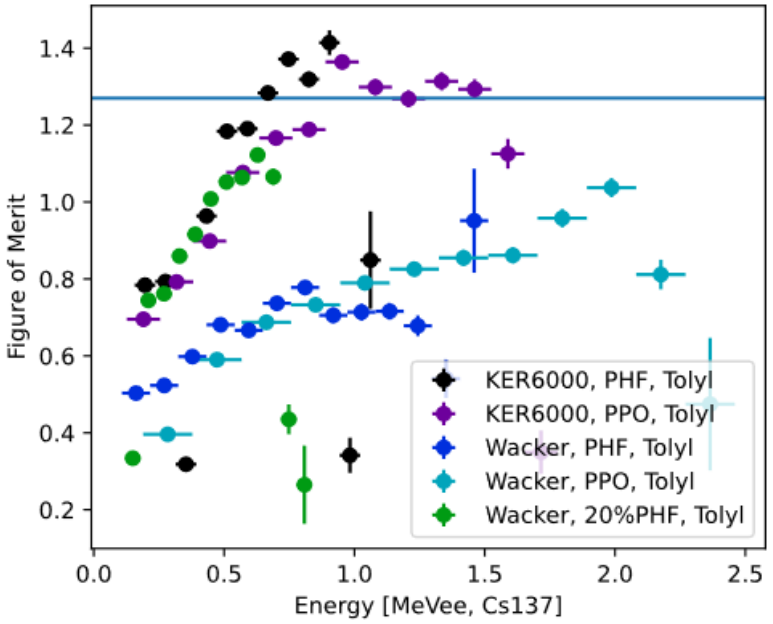


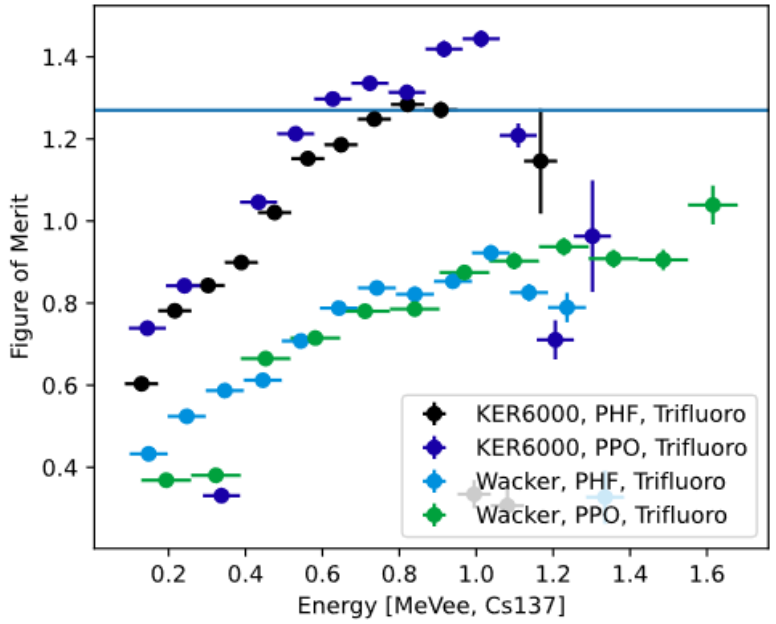




Unsupervised Gaussian Mixture Model for FOM

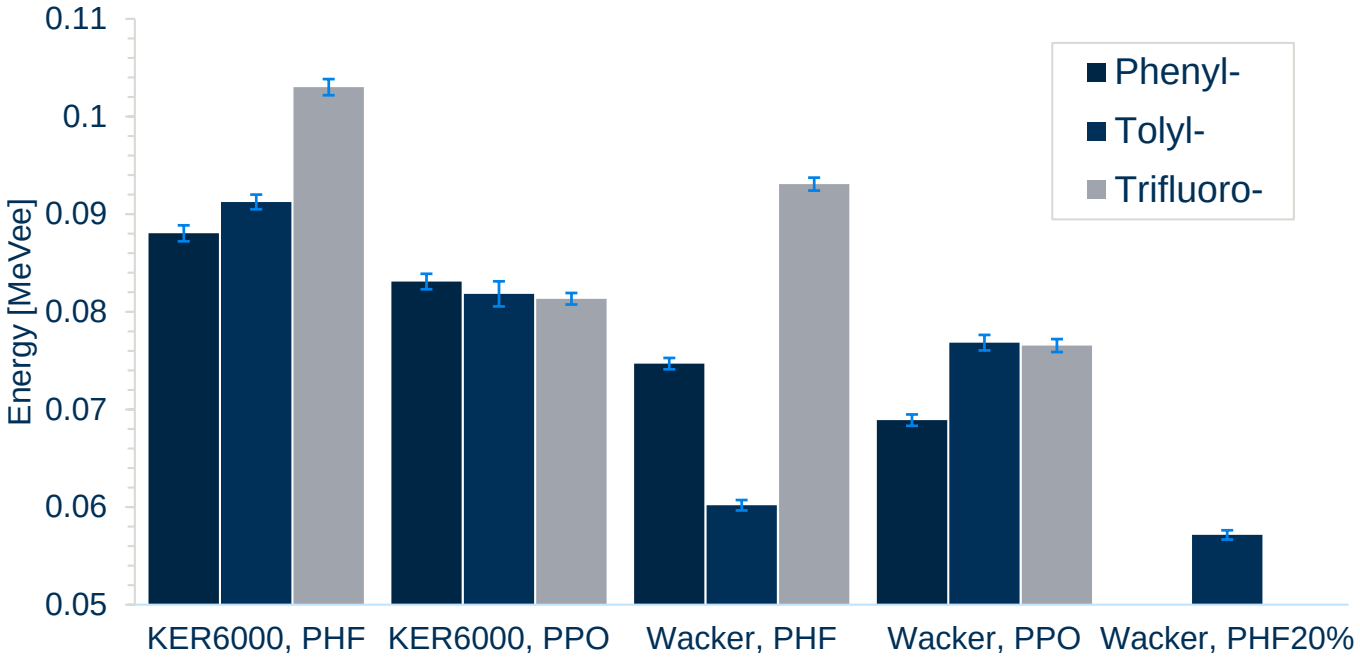


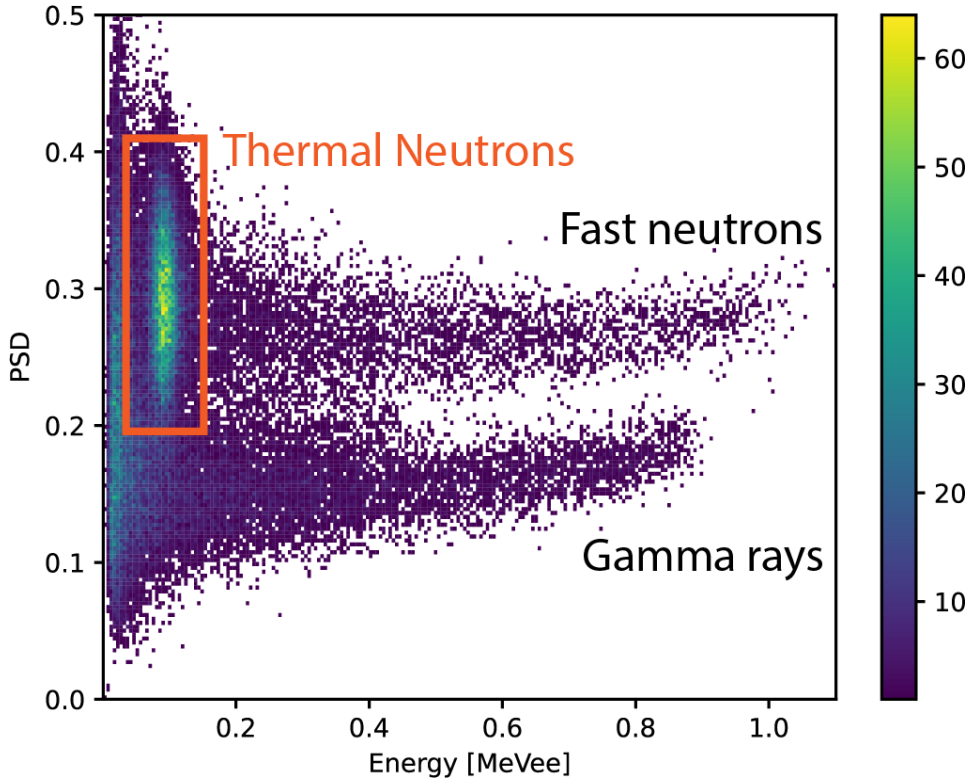




B-10	Matrix	5% PHF	5% PPO
5% Phenyl	KER6000	1.09	0.81
	Wacker	0.69	
4% Tolyl	KER6000	1.17	0.78
	Wacker	0.64	0.62
5% Trifluoro	KER6000	1.10	1.21
	Wacker	0.56	0.69

Thermal Neutron Island Evaluation

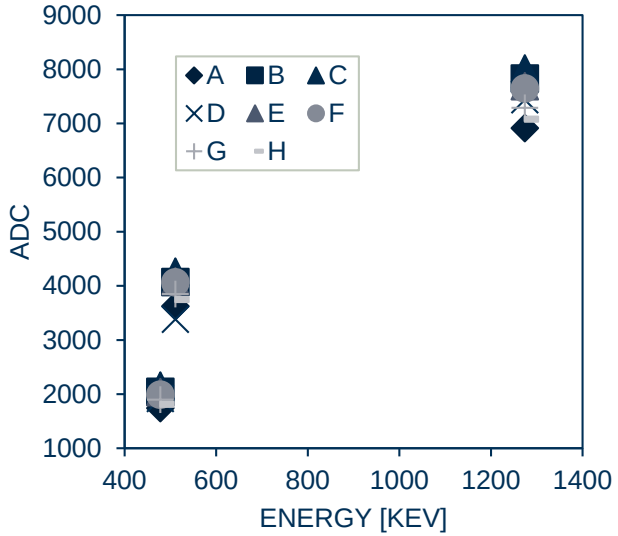


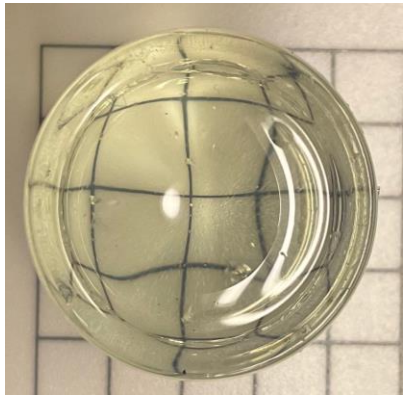


Array Fabrication & Characterization

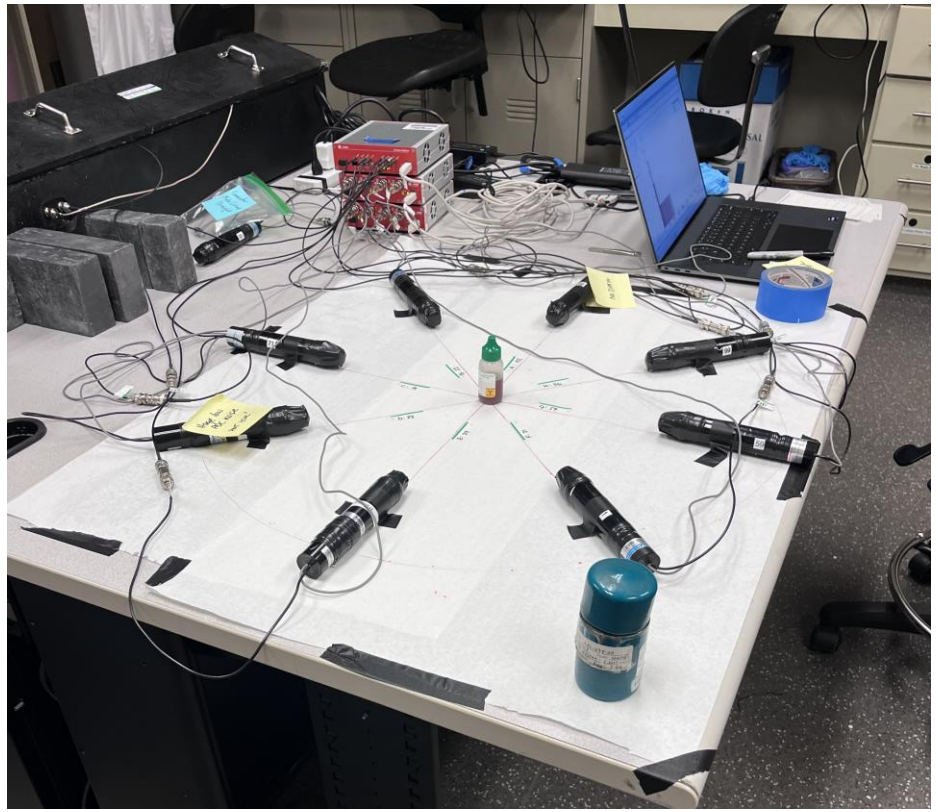
- Boron-enriched molecule doped did not diminish FOM(n,γ) from previous polysiloxane trials
- Best **FOM$(n_{th},\gamma) = \mathbf{0.54}$** 83% of EJ309-B
- Best **light yield 62%** of EJ200
- **-26% LY reduction** over 1 year

- Successful triple particle detection!

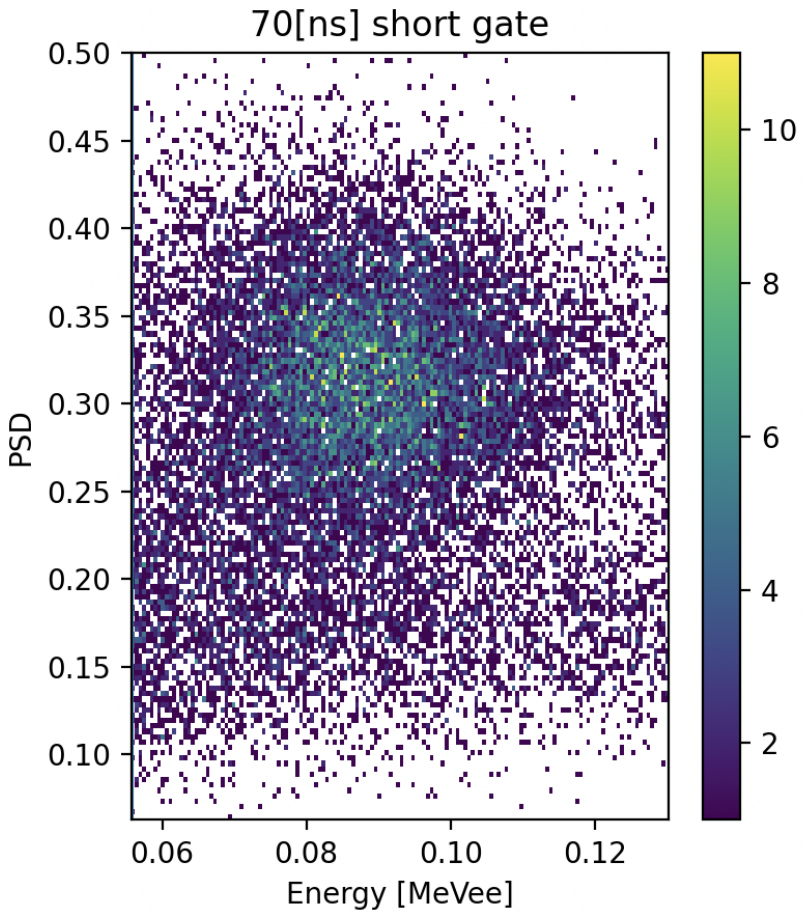




4% Tolyl-, 5% PHF, KER6000



Separating Thermal Neutron Contributions



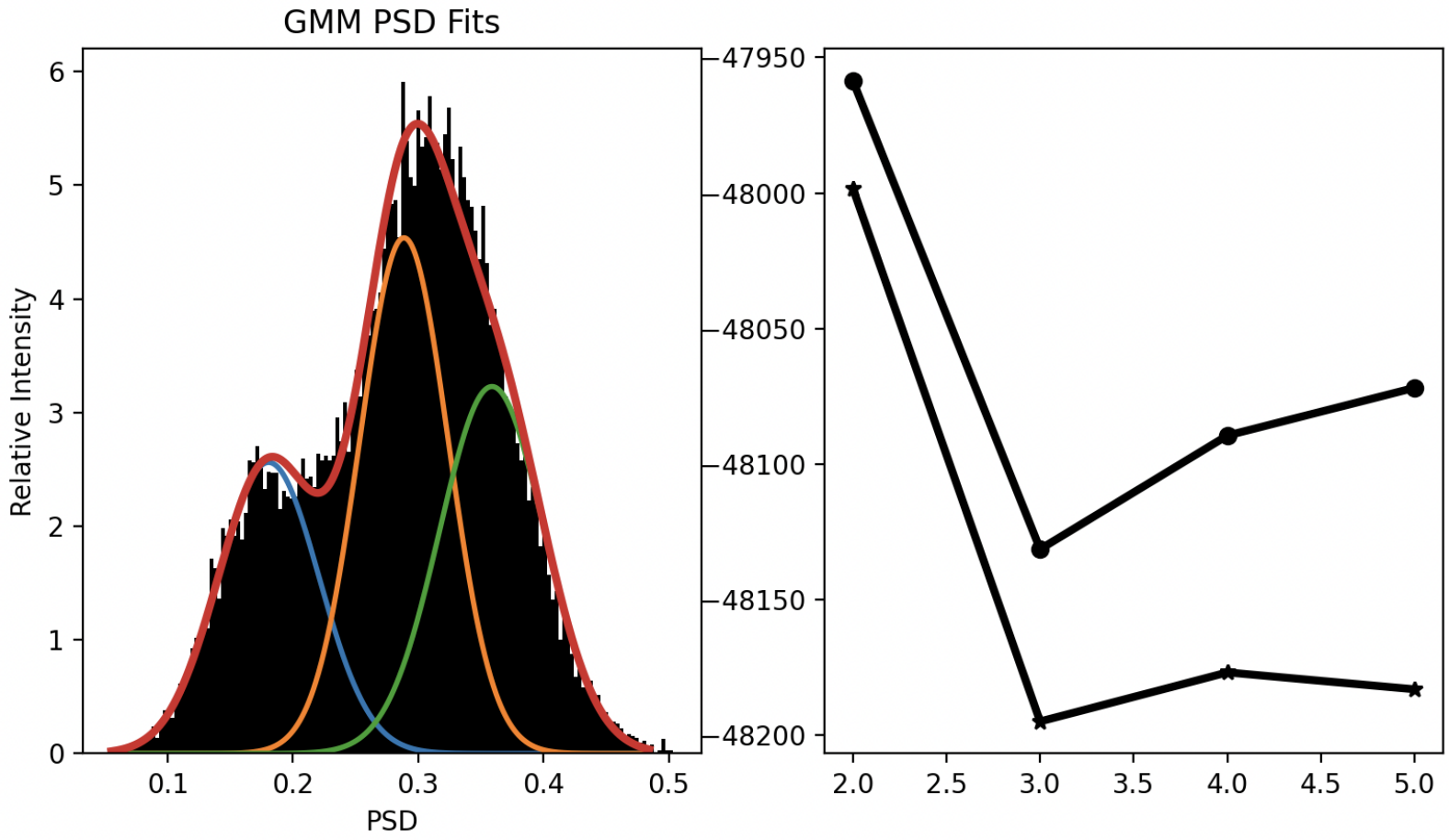
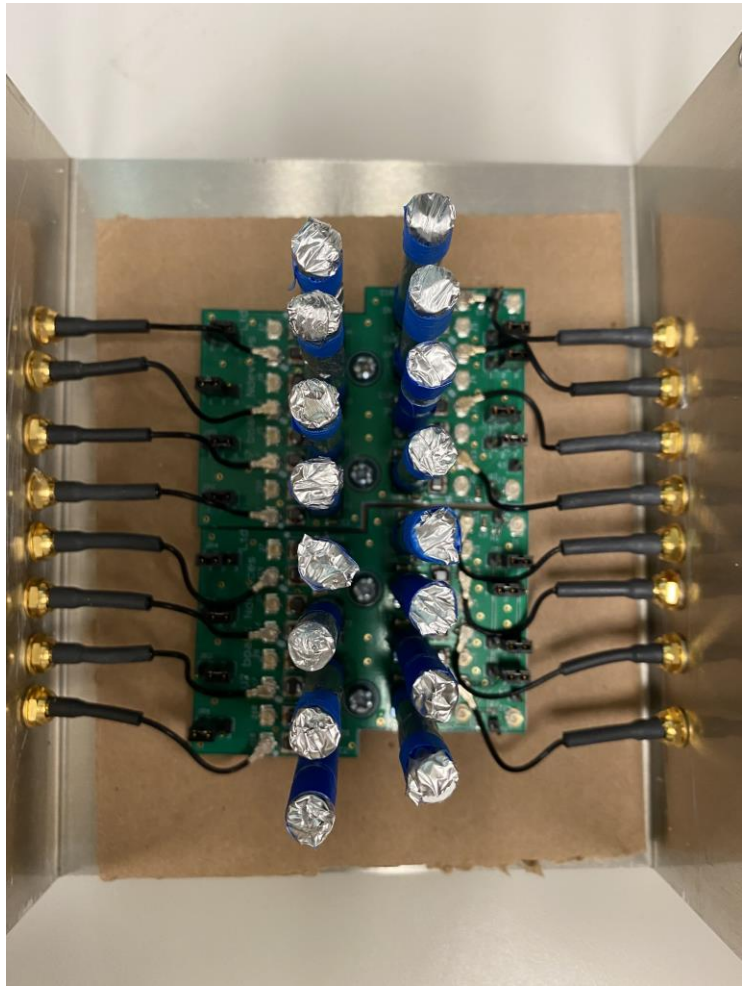
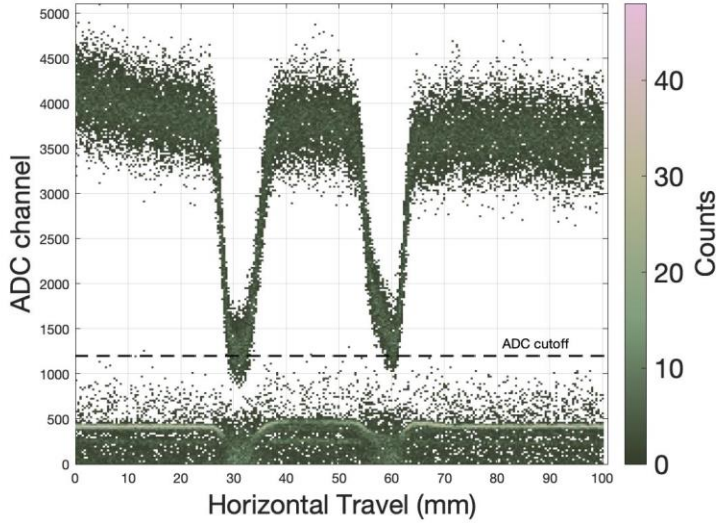
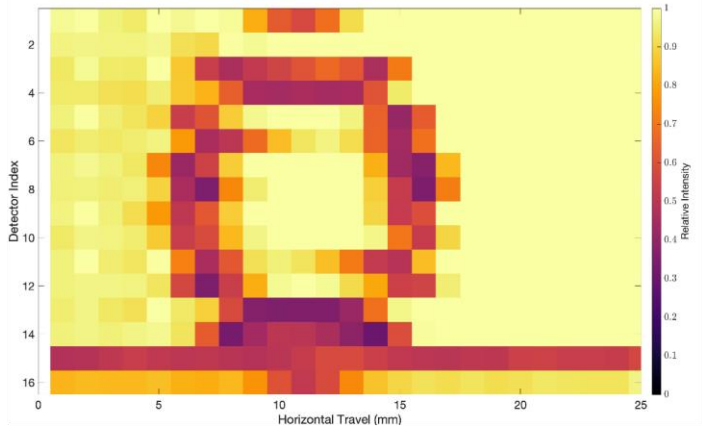


Image Reconstruction Algorithm Development







Maloney, Luke et al. "Assessment of image reconstruction algorithm coupled with fine-resolution array of Cherenkov detectors." Scientific Reports 12 (2022)

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Acknowledgement

This work is supported by the Department of Energy / National Nuclear Security Administration under Award Number(s) DE-NA0003921.

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Thank you

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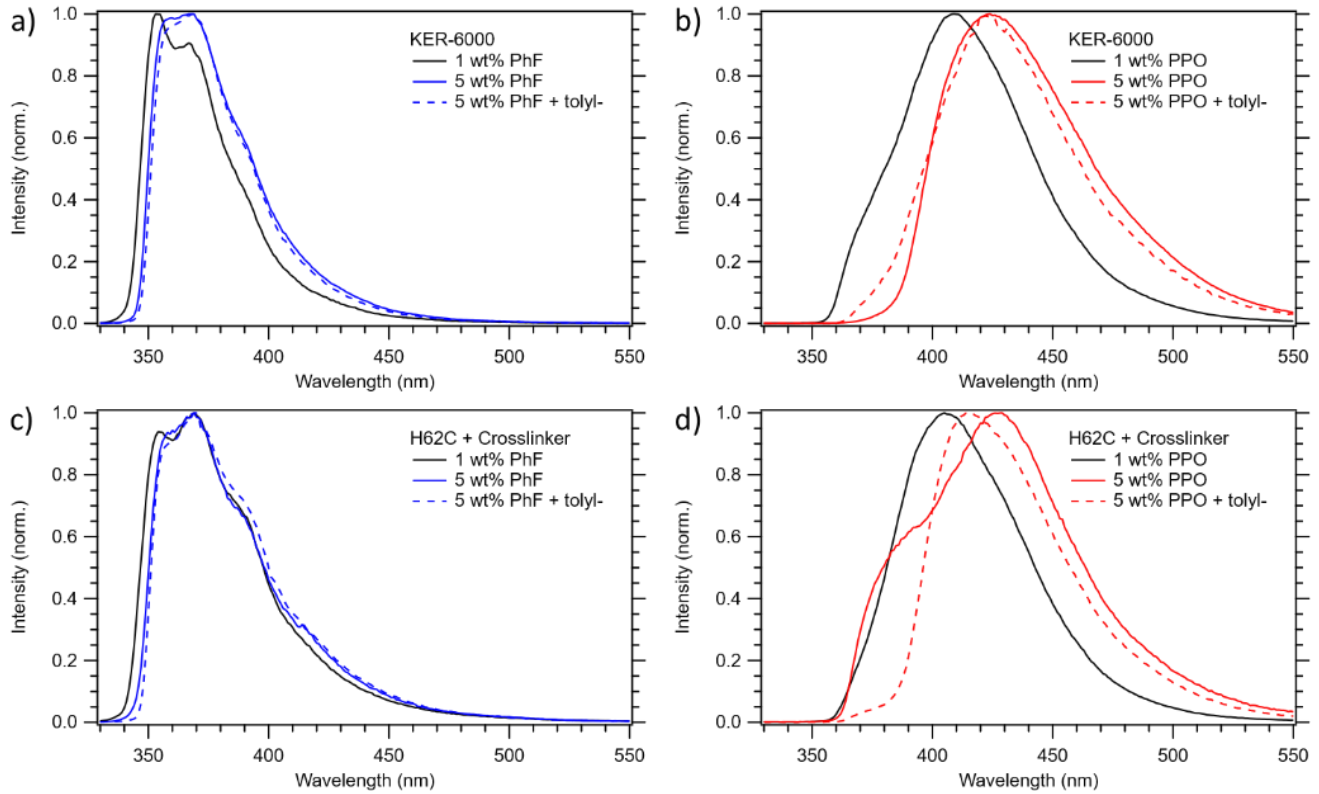
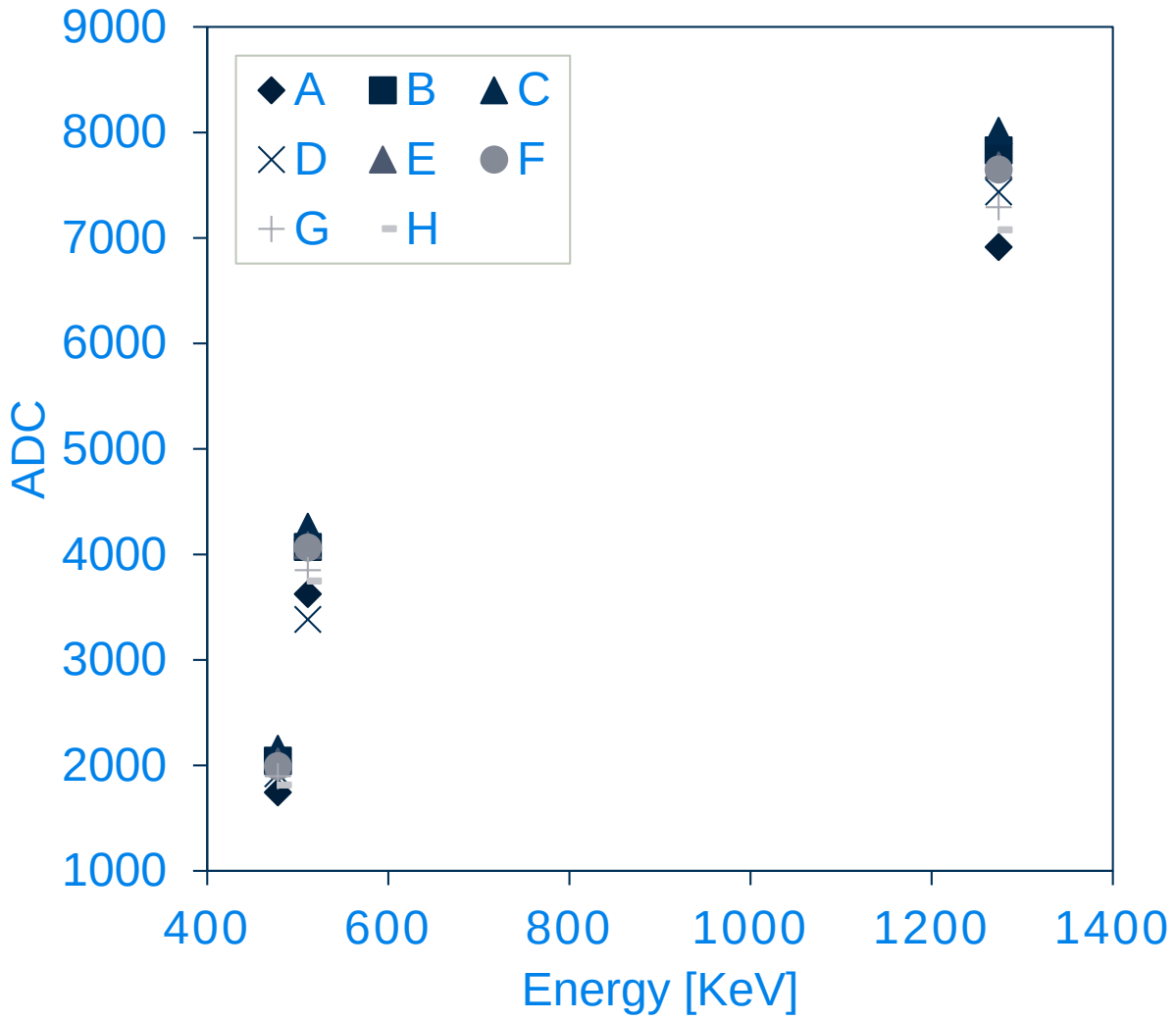
Polysiloxanes as alternative to PVT matrices

- Internship at LBL supporting the EOS demonstrator
- Presentation at IEEE MIC/NSS 2022
  - Arrue, J., Chandler, C., Duce, M., Sellinger, A., Erickson, A., “Boron Doped Polysiloxane Organic Scintillators for Thermal and Fast Neutron Detection Via Pulse Shape Discrimination”
- Collaboration with Colorado School of Mines
- Ex-Core measurements with Texas A&M

PSD Capable Polysiloxane-based Scintillators



Fluorescence emission, samples excited at 290 nm



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