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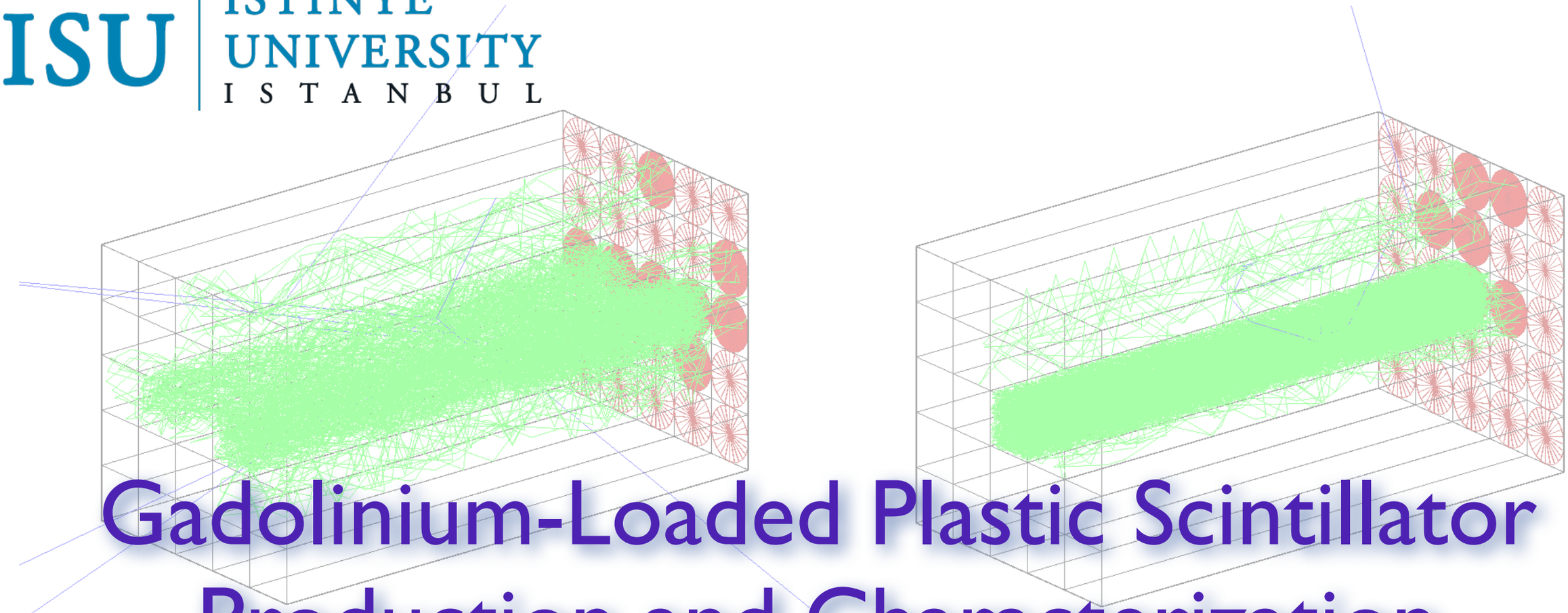

Gadolinium-Loaded Plastic Scintillator Production and Characterization

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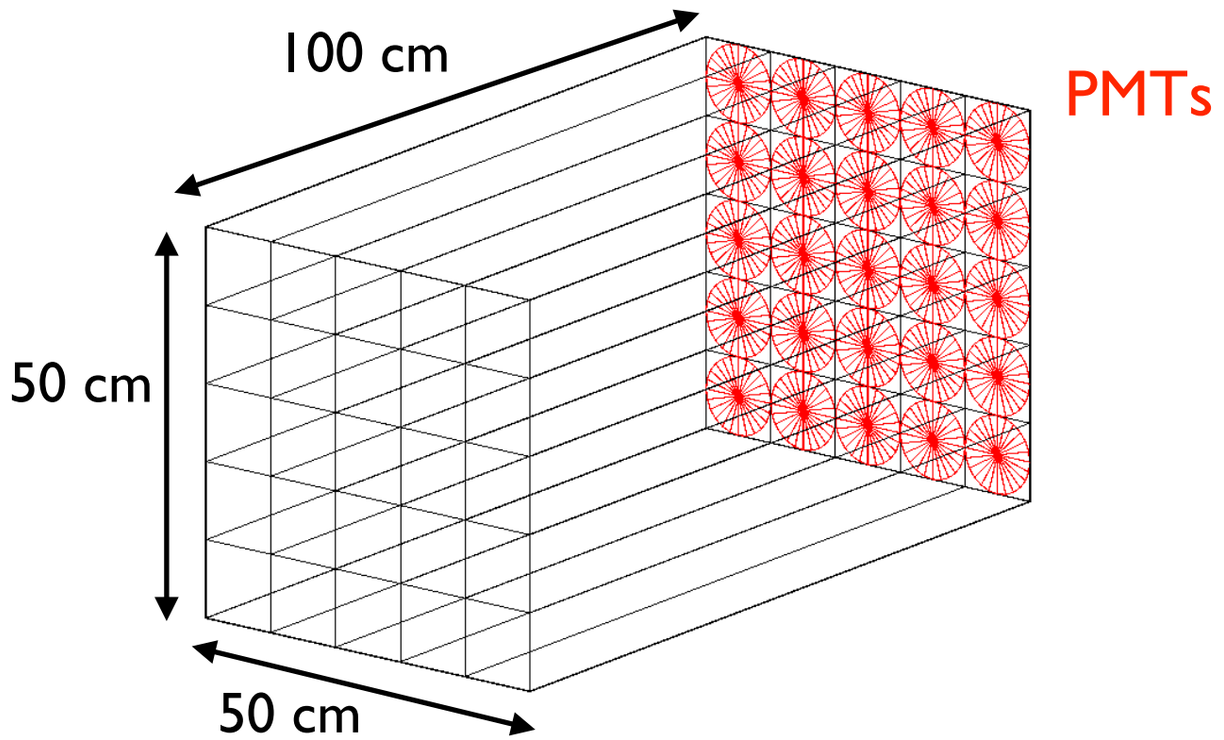
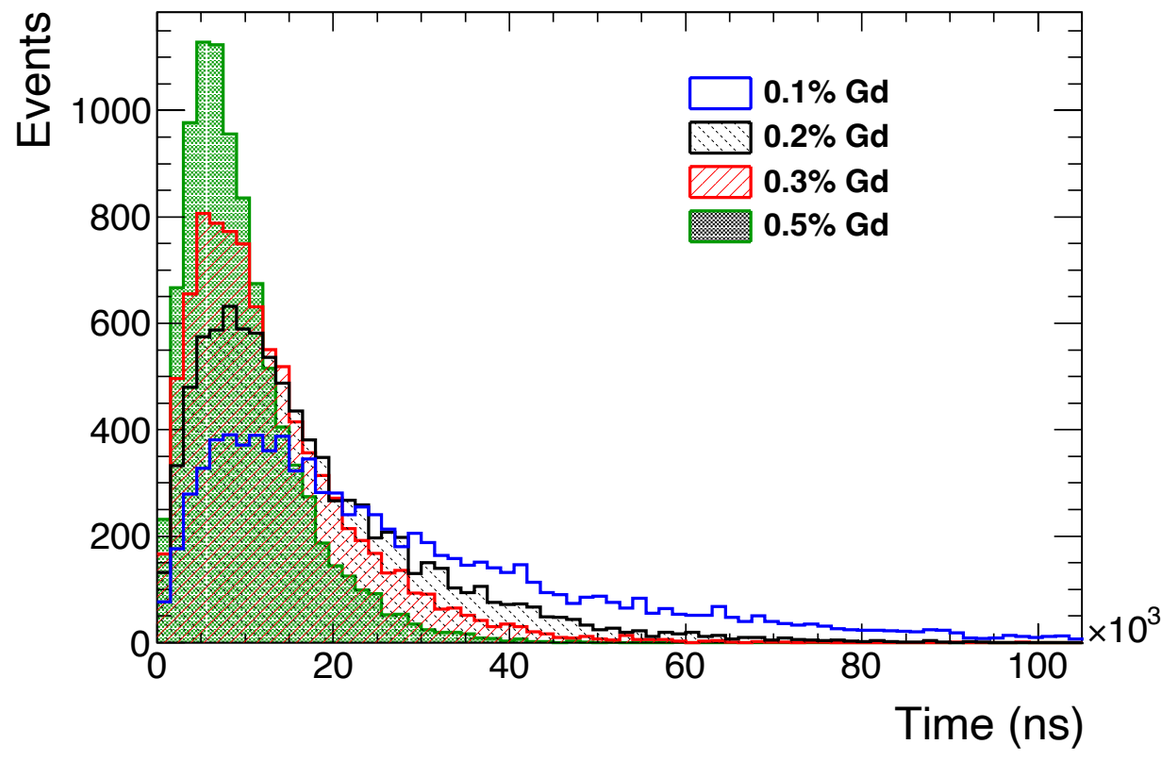
Nuclear Reactors in Turkey

- ☑ The first NPP construction has been recently started at Akkuyu.
  - ✓ It is planed to start operations in 2025-2026.
  - ✓ There will be 4 power units with capacity of 1200 MWe (P_{th} = 3200 MWt) each.
  - ✓ Enriched uranium dioxide is the fuel.
- ☑ Construction of additional NPP in Sinop and İgneada is being planned near future.
- ☑ National and independent safeguard application is very crucial .
- ☑ Monitoring NPP with a compact particle detector is possible.

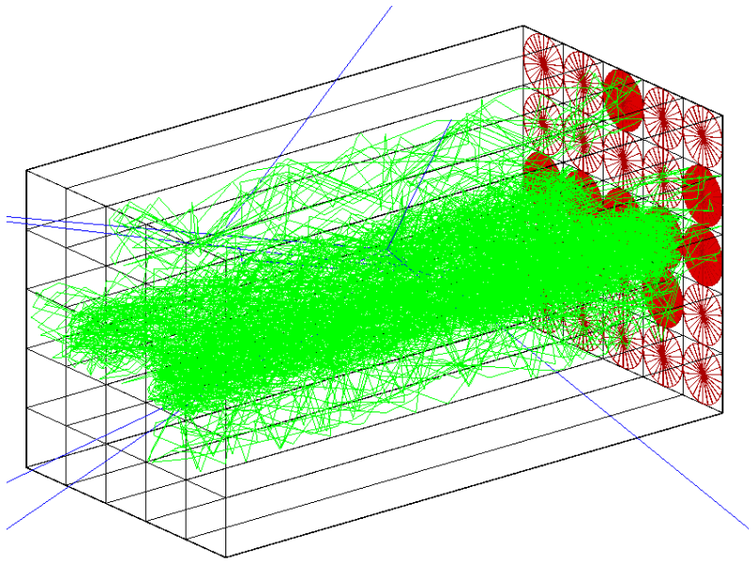
Segmented Plastic Scintillator Detector

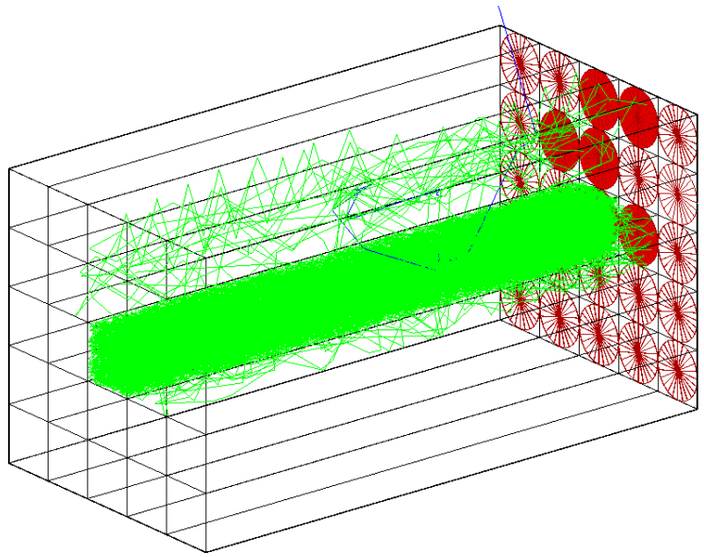
- Gadolinium-loaded segmented plastic scintillator modules for antineutrino detection.
- There are 25 identical 10x10x100 cm gadolinium-loaded polyvinyltoluene based plastic scintillators.
- It is about 250 kg and about 1185 antineutrino events can be observed per a day when it is placed 50 m away from the 3.2 GWt reactor core.

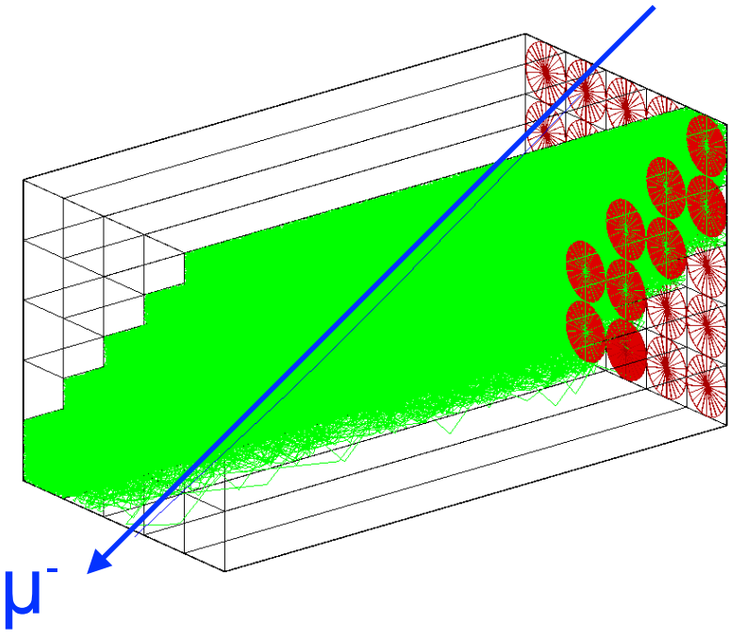




Event Topologies and Machine Learning



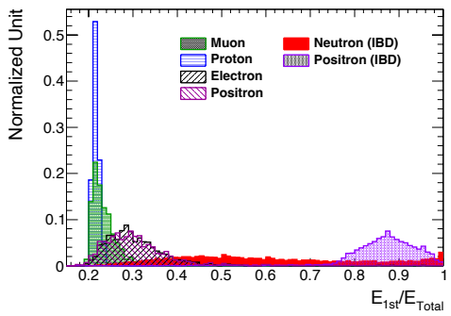


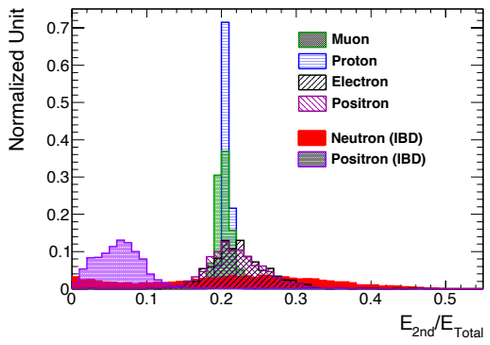


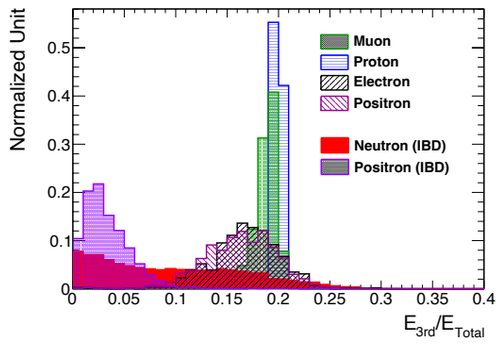
10 keV neutron

3 MeV positron

1 GeV/c muon

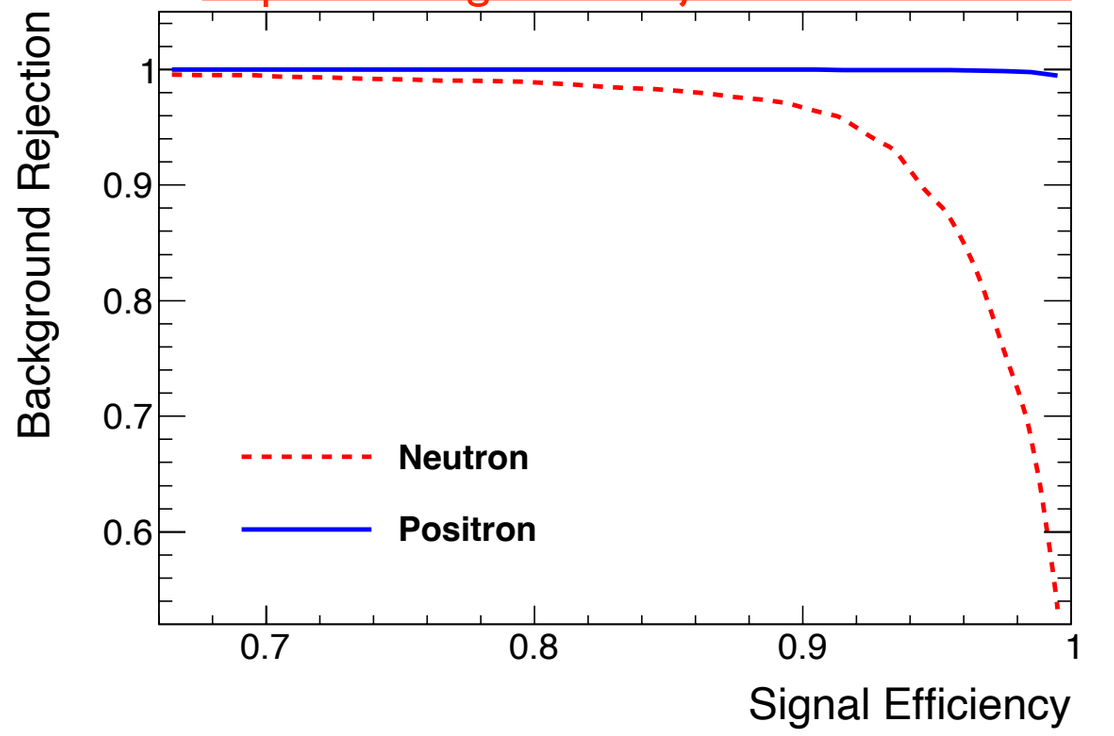






TMVA

https://doi.org/10.1016/j.nima.2019.163314



Synthesis of Plastic Scintillators

- ☑ A typical plastic scintillator consists of three components:
  - ✓ polymer base, primary fluor (first additive), and wavelength shifter (second additive).
- ☑ Gd additive could be salt, organometallic or nanoparticles.
  - ✓ Transparency problem for nanoparticles
- ☑ The plastic scintillator samples are produced using the thermal bulk polymerization technique.
  - ✓ Size and shape limitation

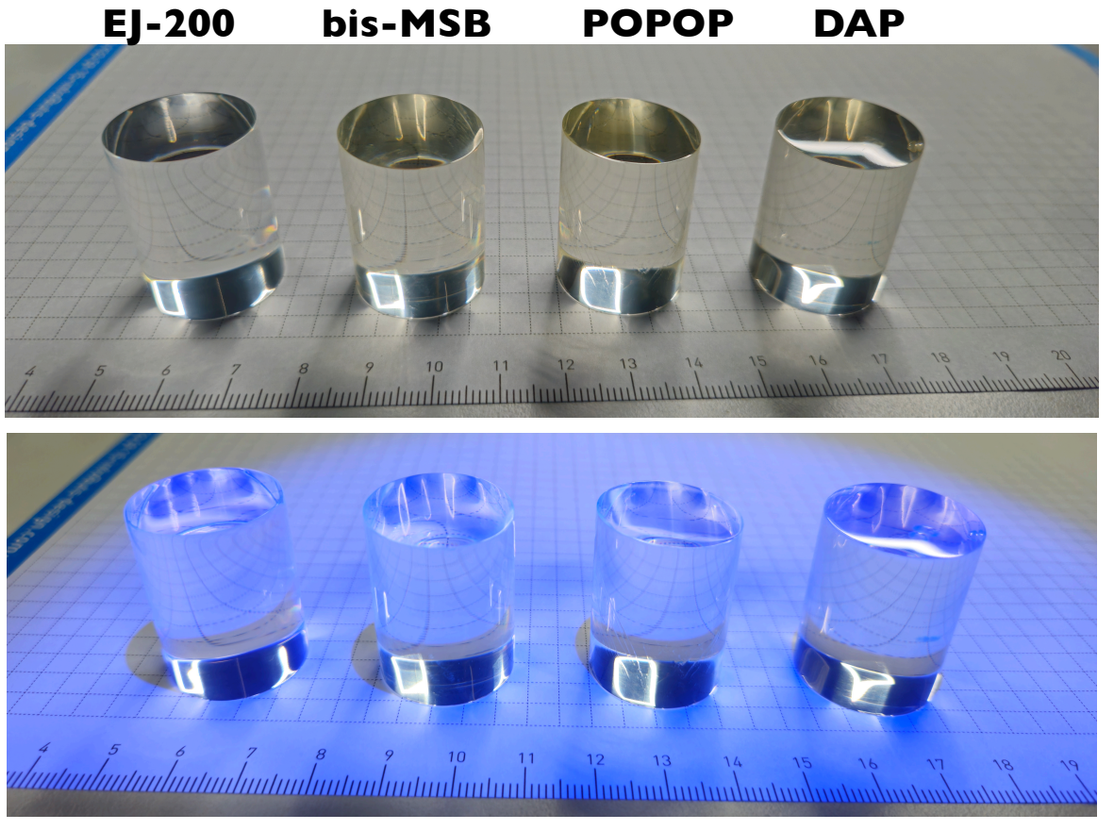
Name	T_g (°C)	d (g/cm^3)	n	λ_{em} (nm)
Polyvinyltoluene (*PVT*)	93-118	1.02	1.59	315
Polystyrene (PS)	100	1.04-1.065	1.59	310

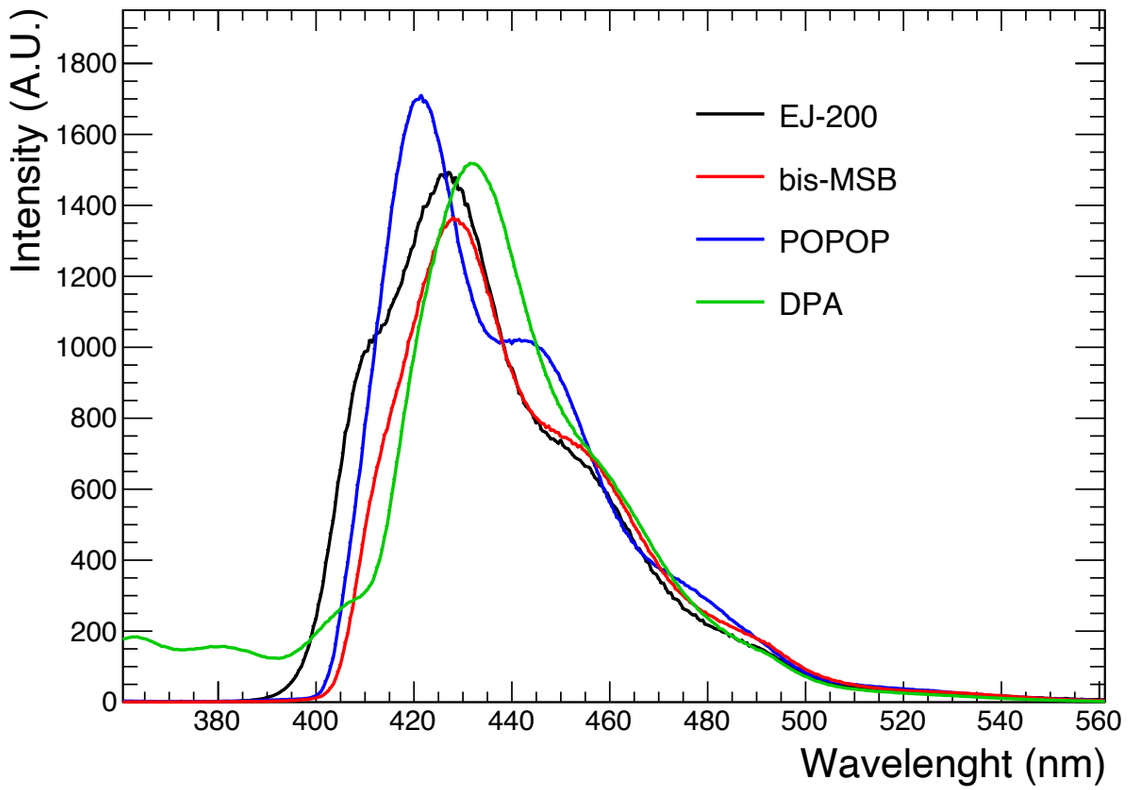
Name	Abbrev.	λ_{abs} (nm)	λ_{em} (nm)	ϕ	T (ns)
p-Terphenyl	PTP	288;276	335;339	0.85	1.2
2,5-Diphenyloxazole	PPO	303;308	365;375	0.8	1.6
2-phenyl-5-(4-biphenylyl)-1,3,4- oxadiazole	PBD	305;302	360;365	0.8	1.2

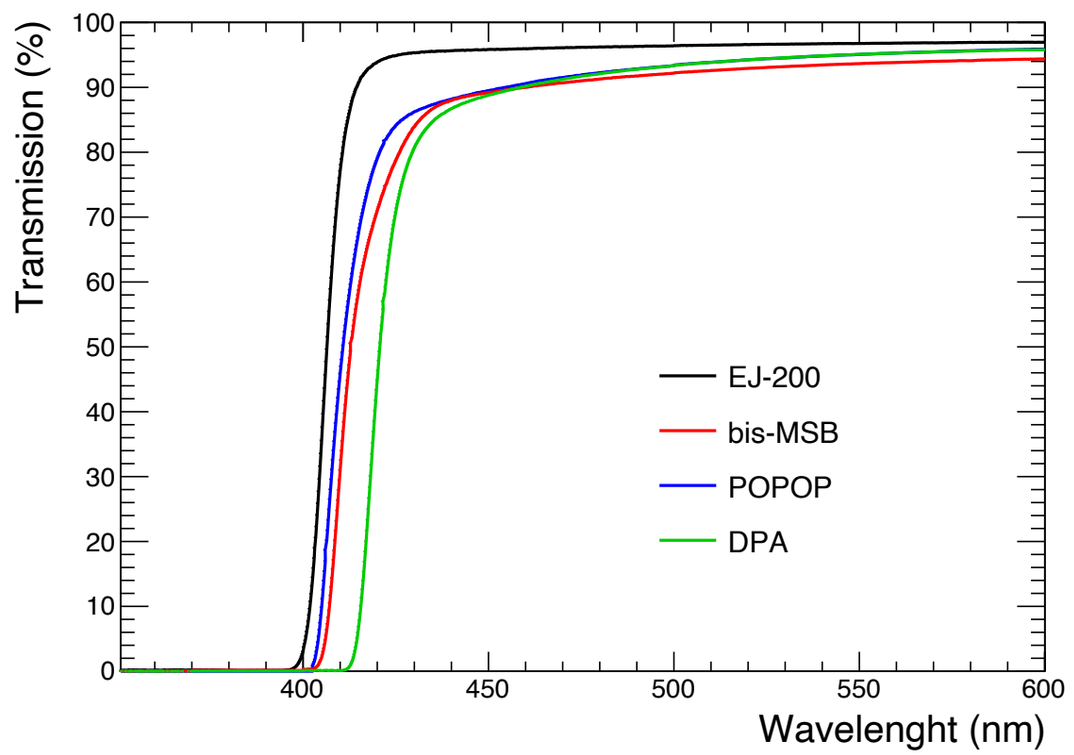
Name	Abbrev.	λ_{abs} (nm)	λ_{em} (nm)	ϕ	T (ns)
1,4-bis(5-phenyl-2-oxazolyl)benzene	POPOP	365	415-417	0.85	1.3
1,4-bis(2-methylstyryl)benzene	Bis-MSB	347-350	420	0.96	1.6
9,10-diphenylanthracene	DAP	366-375	430	0.95-1.0	7.3

Gd Loaded Plastic Scintillator

- ☑ 3 different types plastic scintillator samples are produced to determine optimal content.
  - ✓ Polyvinyltoulene as polimer base
  - ✓ PPO as primary flour (1.5%)
  - ✓ POPOP, bis-MSB and DAP as secondary flour (%0.08)
  - ✓ $Gd(TMHD)_3$ as Gd additive (%0.2)
  - ✓ ϕ=2.2 cm, h=3 cm
- ☑ Transmission rates in 1 cm length are around 85%.

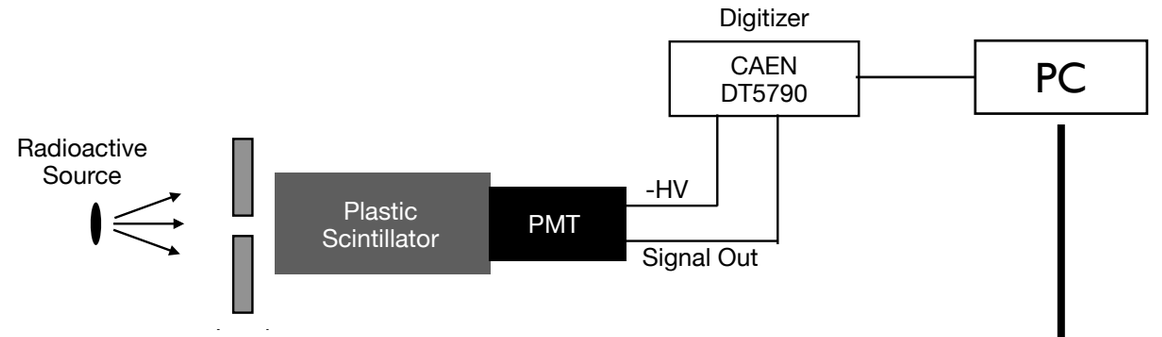


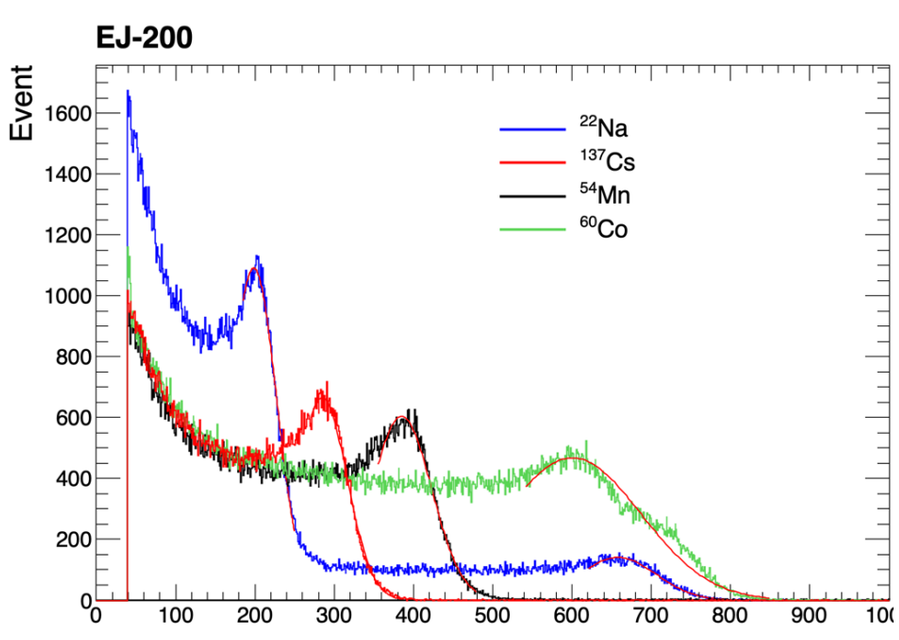


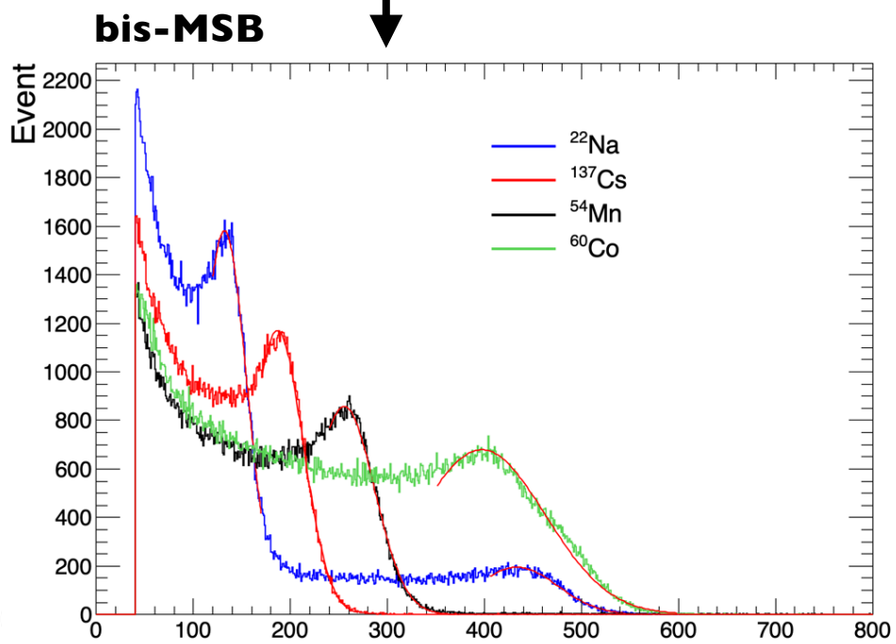


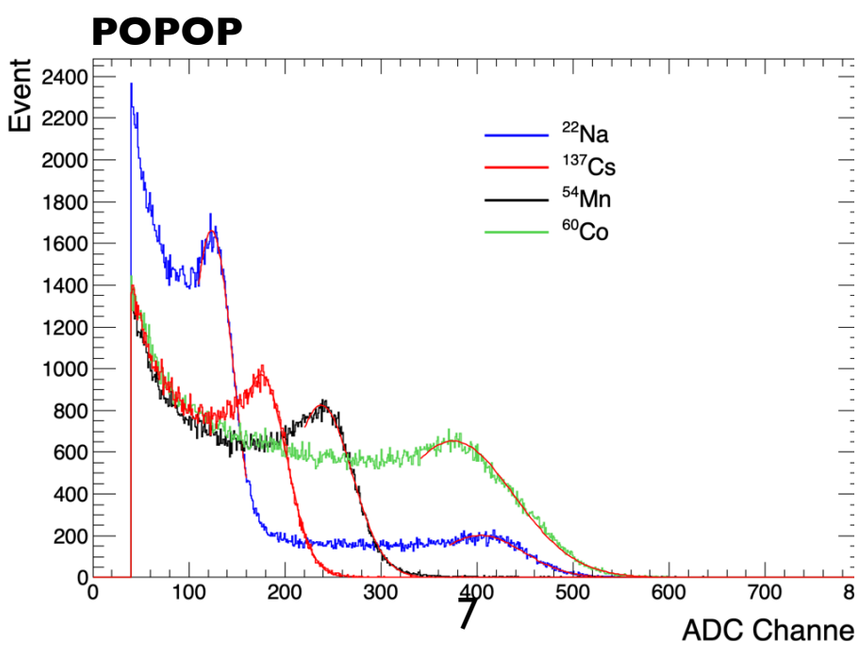
Light Yield Measurement

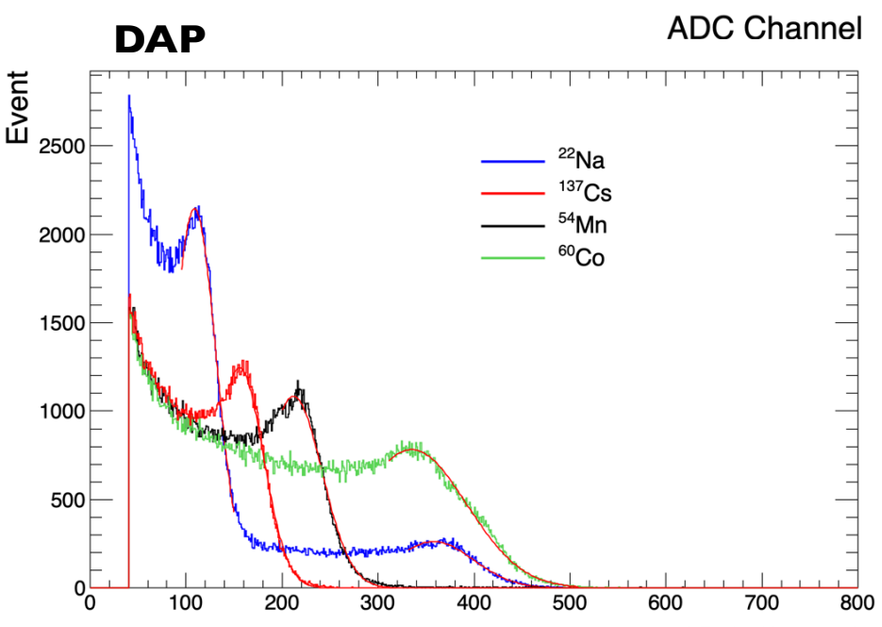
- Second additive that gives the highest light yield is used in the detector.
- The measurements were done using 4 different gamma sources.
- The compton- edge region in the energy distribution is fit with the Gaussian function and 80% values in the energy tail of the peak are taken.



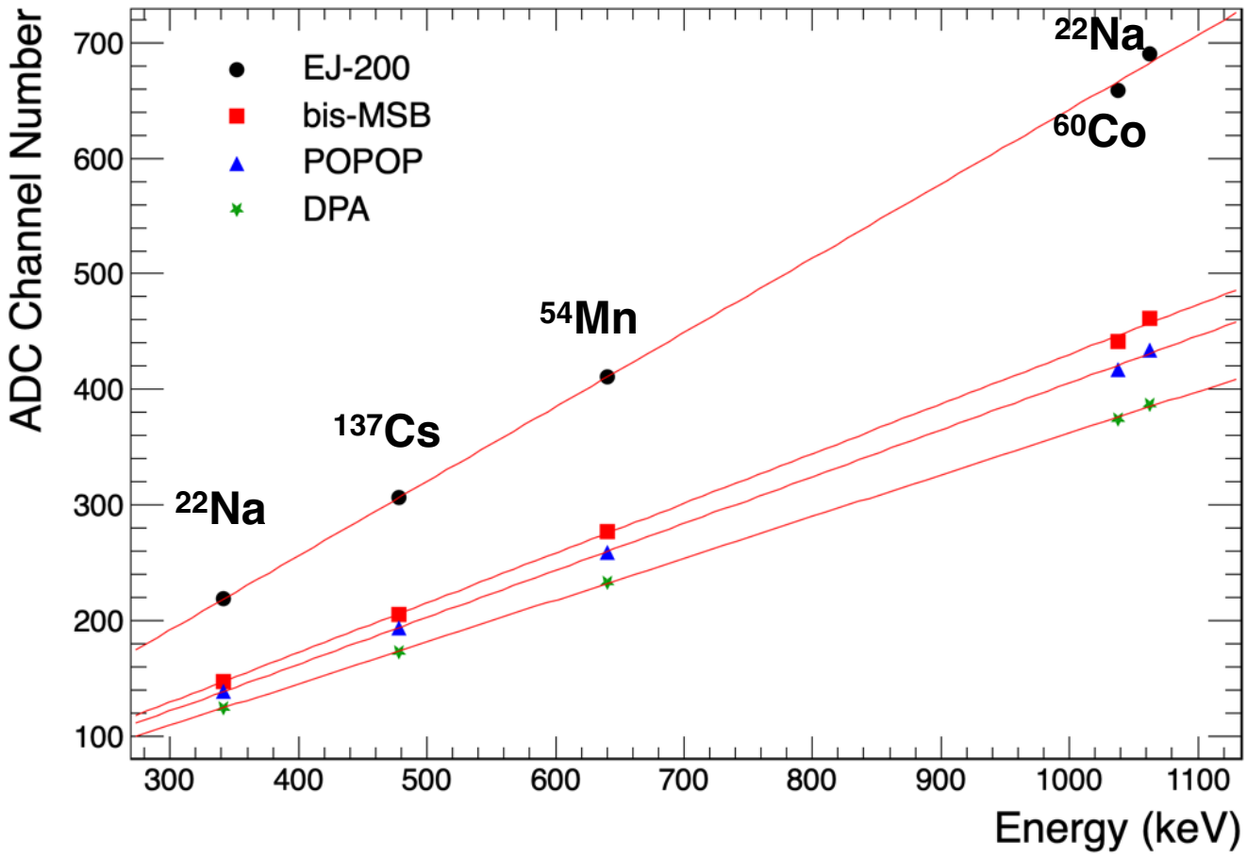








Linearity of Gd Loaded PS

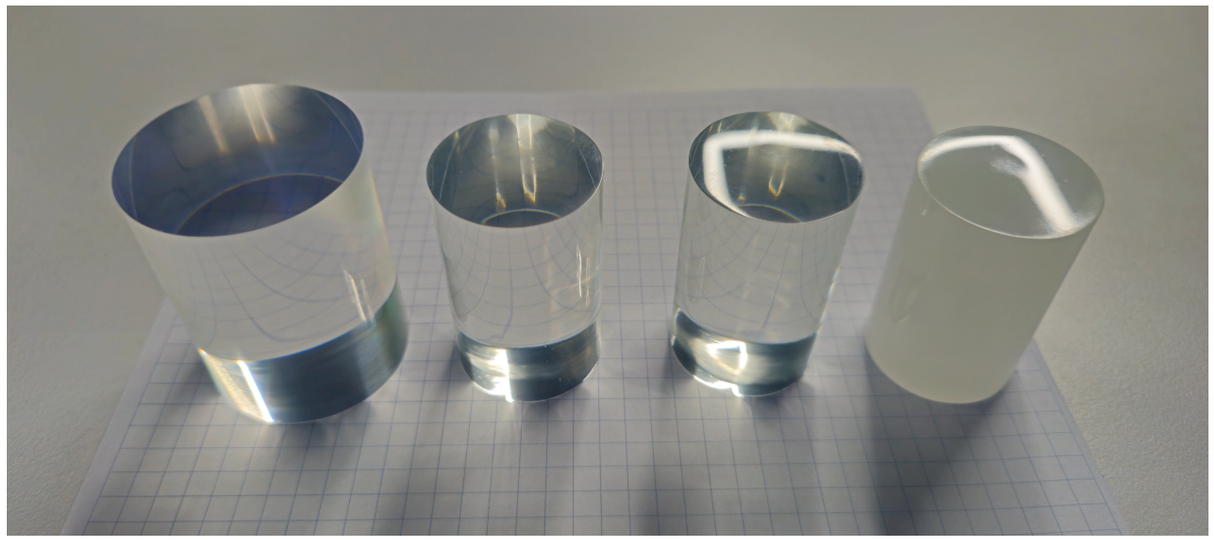


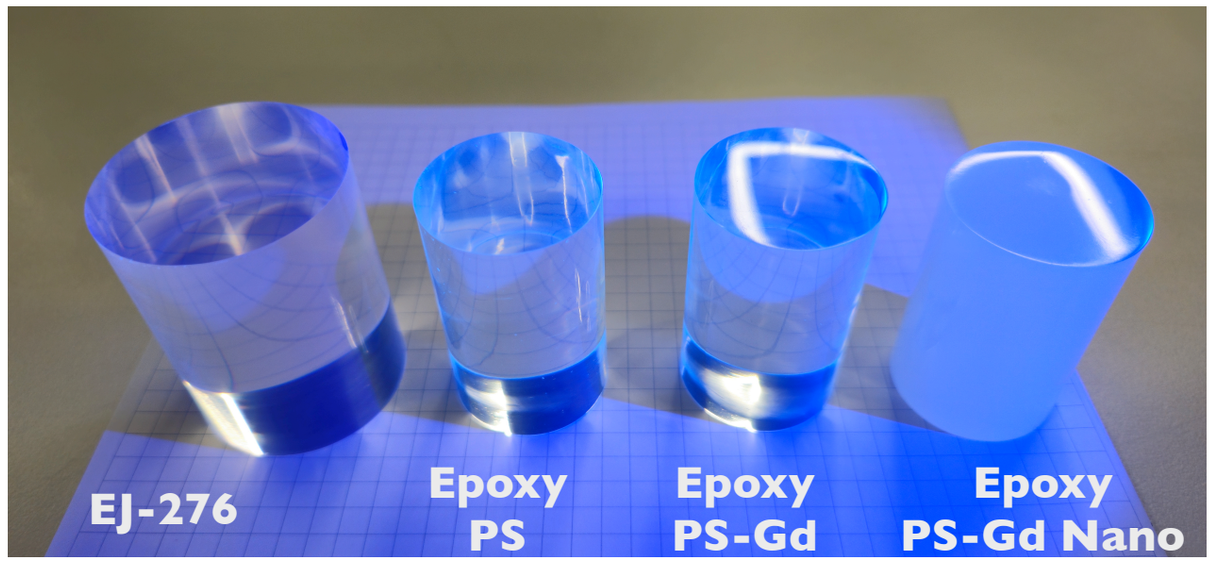
- PS samples have a good energy linearity.
- Relative light yield values are acceptable.
- bis-MSB has the highest LY.

$$R_{sample} = R_{EJ-200} \times V_{CE,sample} / V_{CE,EJ-200}$$

Samples	^{22}Na	^{137}Cs	^{54}Mn	^{60}Co	^{22}Na	Rel. LY @ 80%
EJ-200	100	100	100	100	100	100
bis-MSB	67.63	66.86	67.33	67.03	66.84	67.14 ± 0.14
POPOP	63.77	63.06	63.14	63.35	62.84	63.23 ± 0.14
DAP	57.00	56.29	56.51	56.72	55.88	56.48 ± 0.17

Epoxy Resin Based Gd Loaded PS

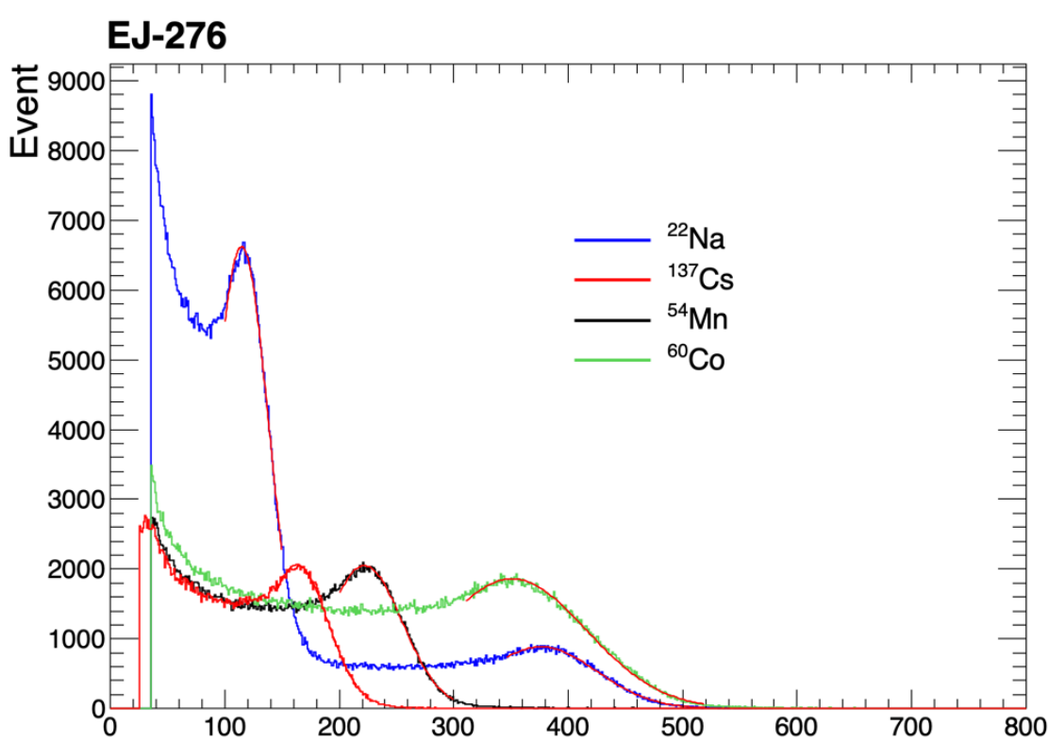


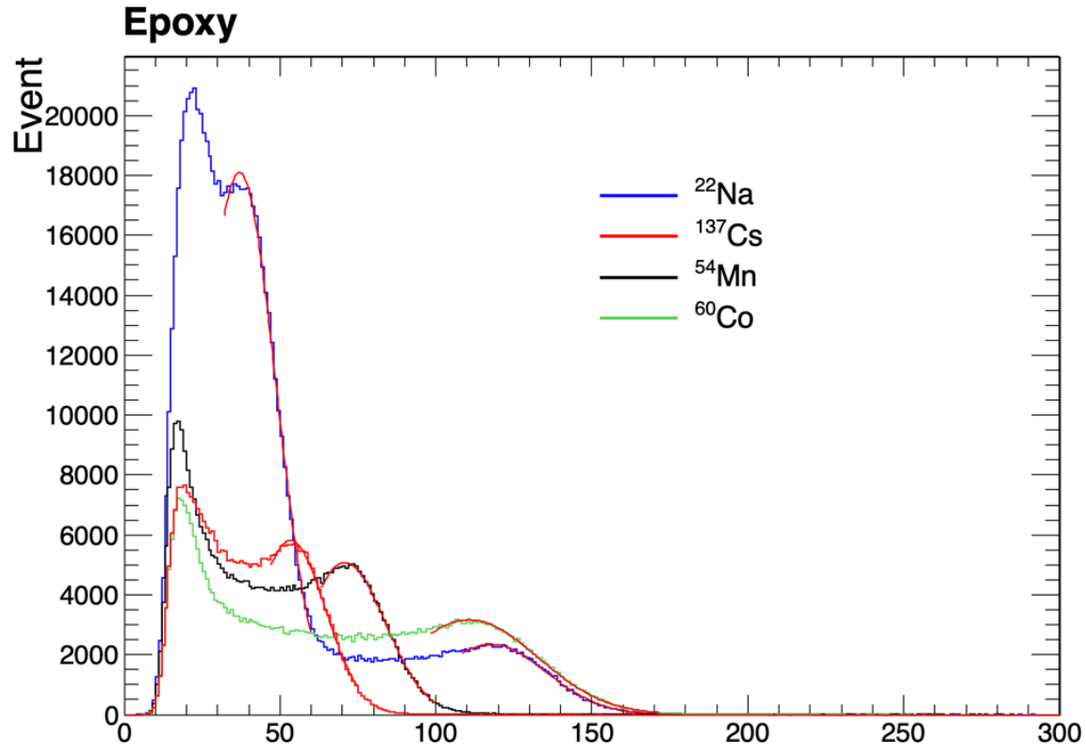


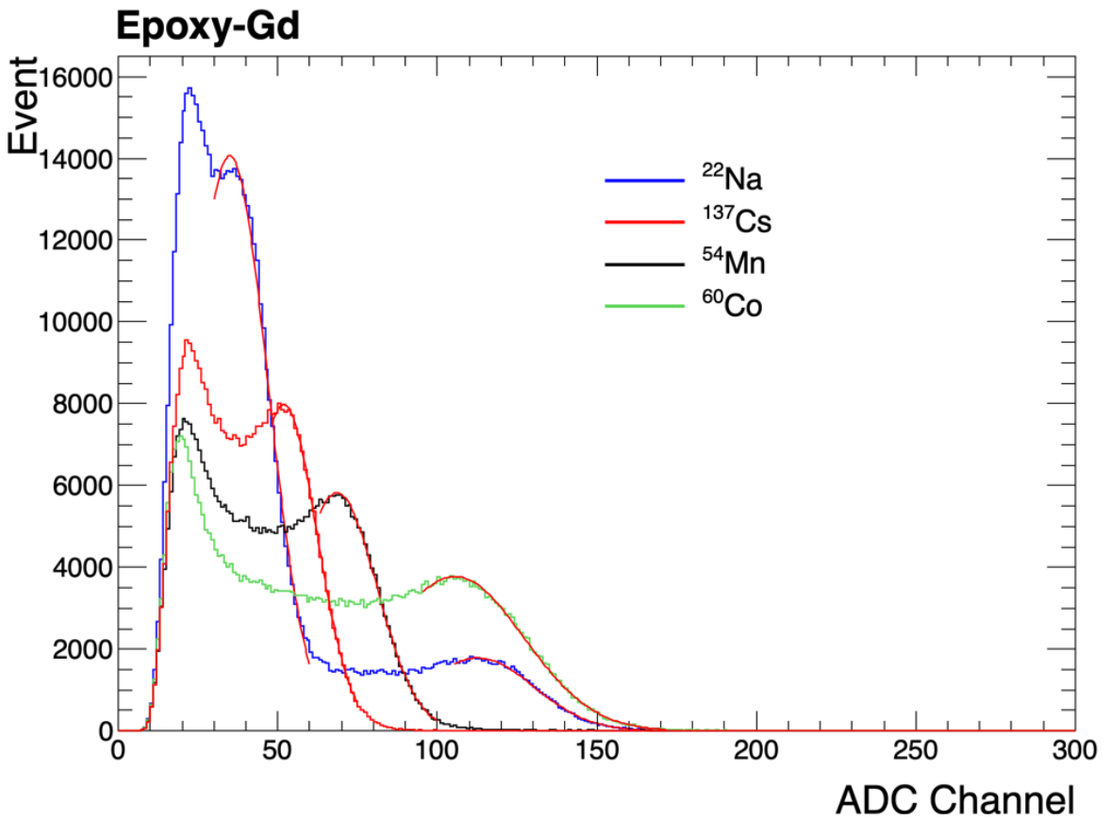
$$T = \frac{I}{I_0} = exp\left\{-\frac{32\pi^4 V_p x r^3 n_m^4}{\lambda^4}\left[\frac{\left({}^{n_p}/_{n_m}\right)^2 - 1}{\left({}^{n_p}/_{n_m}\right)^2 + 1}\right]^2\right\}$$

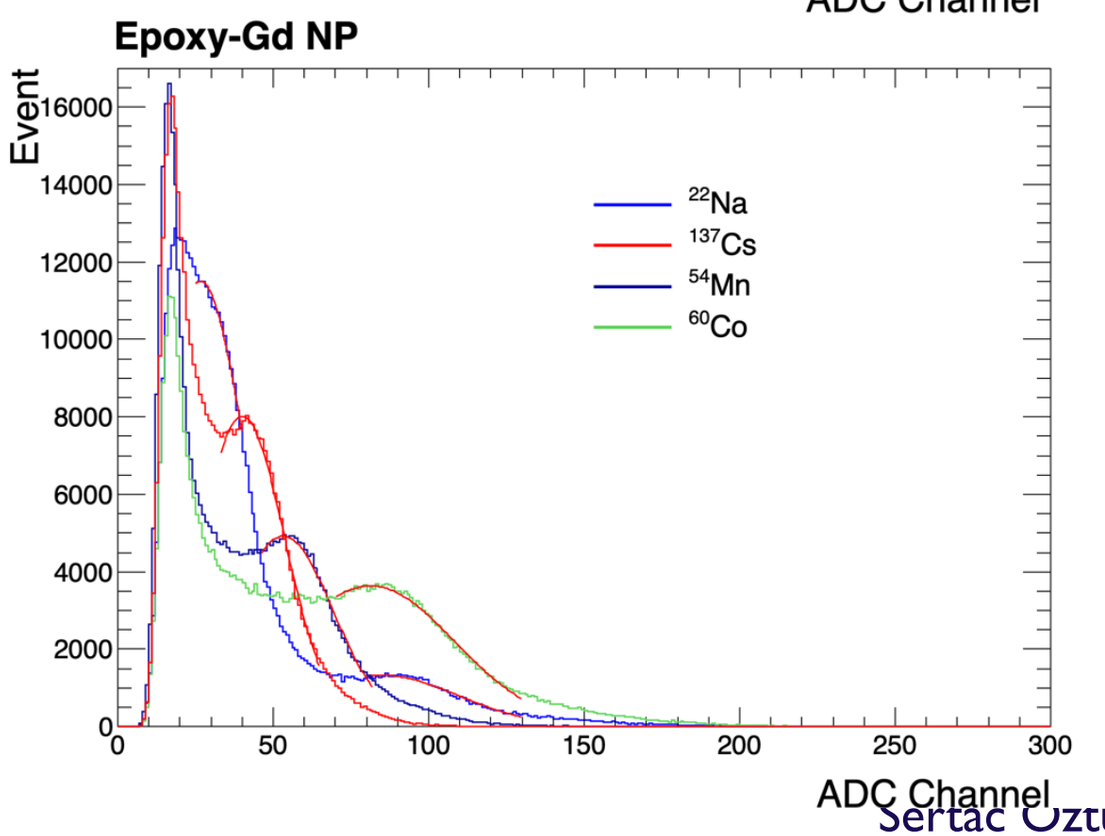
- ☑ Size of PS is limited with size of the oven.
- ☑ Epoxy resin base could be a good option for Gd loaded PS production.
  - ✓ Size of silicon mold
  - ✓ Ready in two days
  - ✓ Cheaper
- ☑ High viscosity is better for nanoparticle loading.
  - ✓ Nanoparticles tend to have higher thermal and air stabilities than the organometallics.
  - ✓ The transmittance loss of nanoparticle embedded polymer as a result of Rayleigh scattering.
- ☑ 3 epoxy resin based PS were produced.
  - ✓ 1.5% PPO and 0.08% bis-MSB
  - ✓ 0.2% $Gd(TMHD)_3$ and Gd nanoparticle (particle size:13-95 nm)
  - ✓ ϕ=3 cm, h=4.5 cm
- ☑ No yellowish in epoxy resin based with Gd organometallic loading.

Light Yield of Epoxy PS

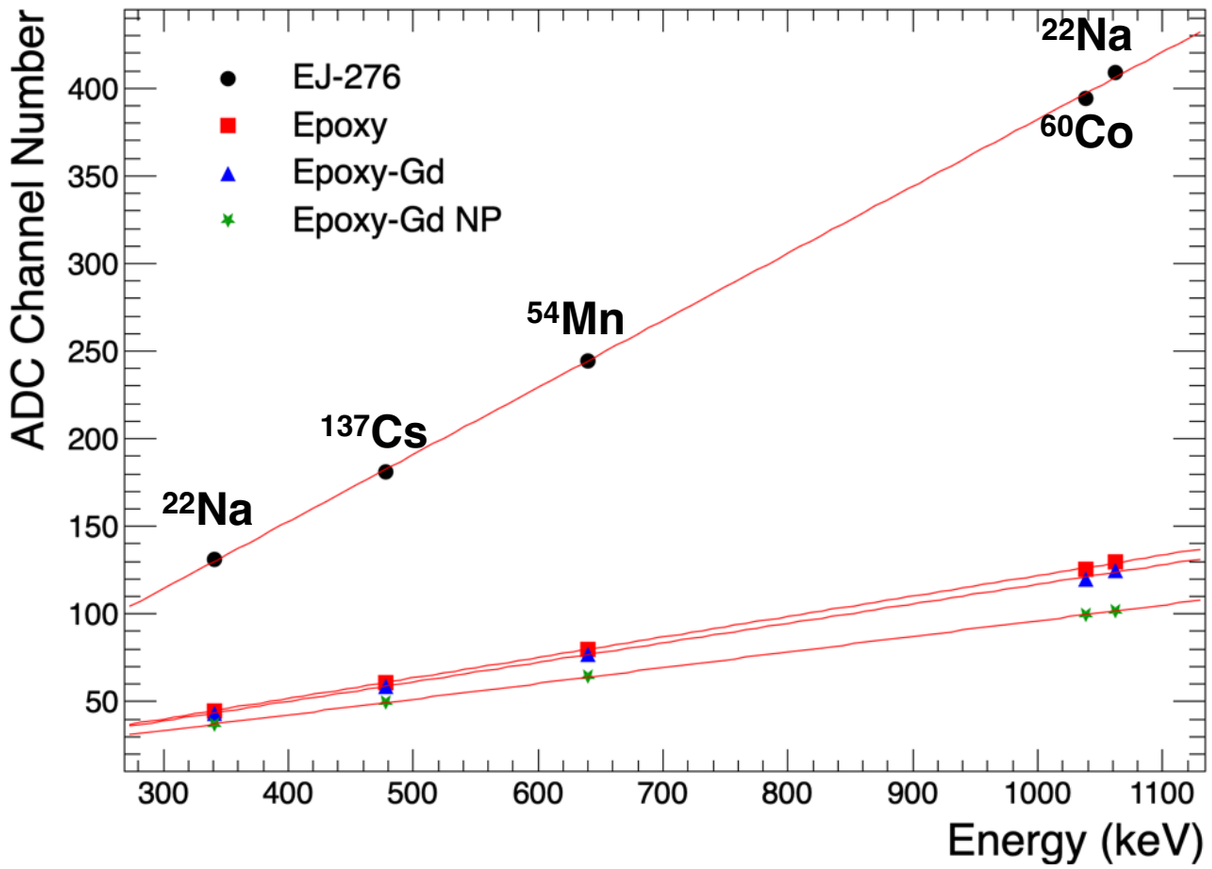








Linearity of Epoxy Based PS

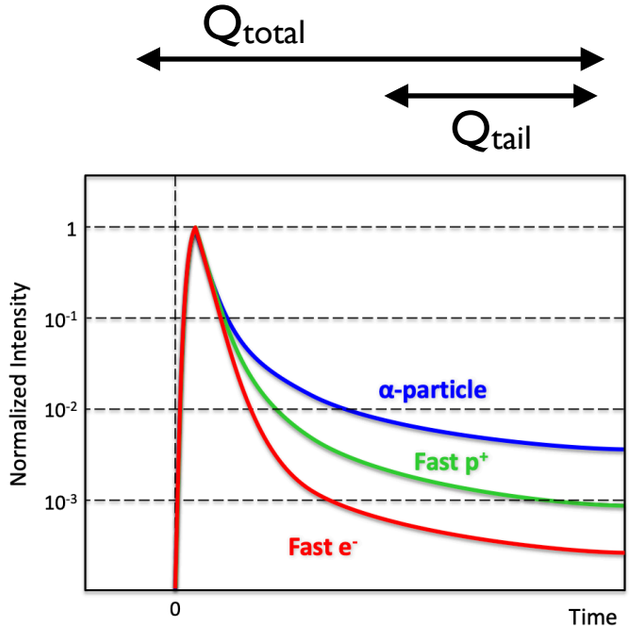


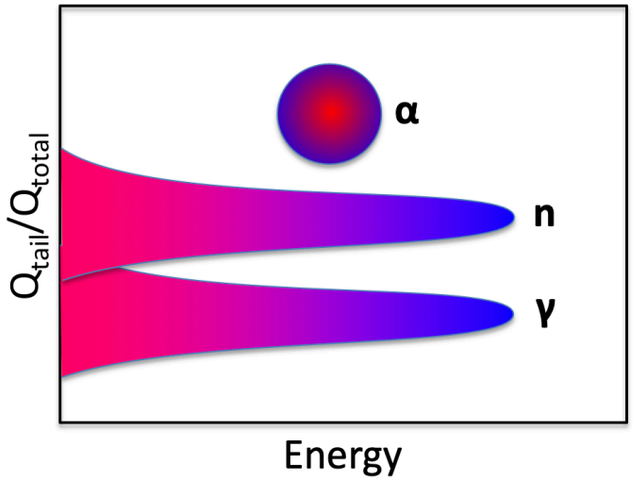
- Epoxy resin based PS samples have a good energy linearity.
- Relative light yield values are about 30% of EJ-276
- Despite its opaque structure, the nanoparticle additive does not reduce the light efficiency much.

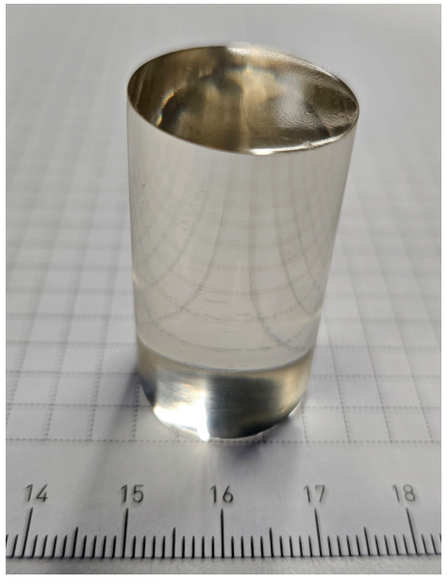
Samples	^{22}Na	^{137}Cs	^{54}Mn	^{60}Co	^{22}Na	Rel. LY @ 80%
EJ-276	100	100	100	100	100	100
Epoxy	34.29	33.58	32.68	31.86	31.70	32.83 ± 0.44
Epoxy-Gd	33.12	32.47	31.52	30.44	30.49	31.61 ± 0.48
Epoxy-Gd NP	27.87	27.32	26.27	25.31	24.77	26.31 ± 0.52

$Li_2B_4O_7$ NP Loaded PSD PS

- ☑ Detecting thermal neutrons and fast neutrons with a NP loading plastic scintillator becomes emerging field.
- ☑ Thermal neutron detection with ^{6}Li, ^{10}B, ^{113}Cd and $^{155,157}Gd$.
- ☑ Fast neutron detection with plastic scintillator containing high concentration of primary flor using pulse shape discrimination (PSD) technique.
- ☑ PSD sensitive PS with $Li_2B_4O_7$ nanoparticles could be great option for neutrino detectors.
- ☑ Project has just funded and $Li_2B_4O_7$ nanoparticles synthesis has started.





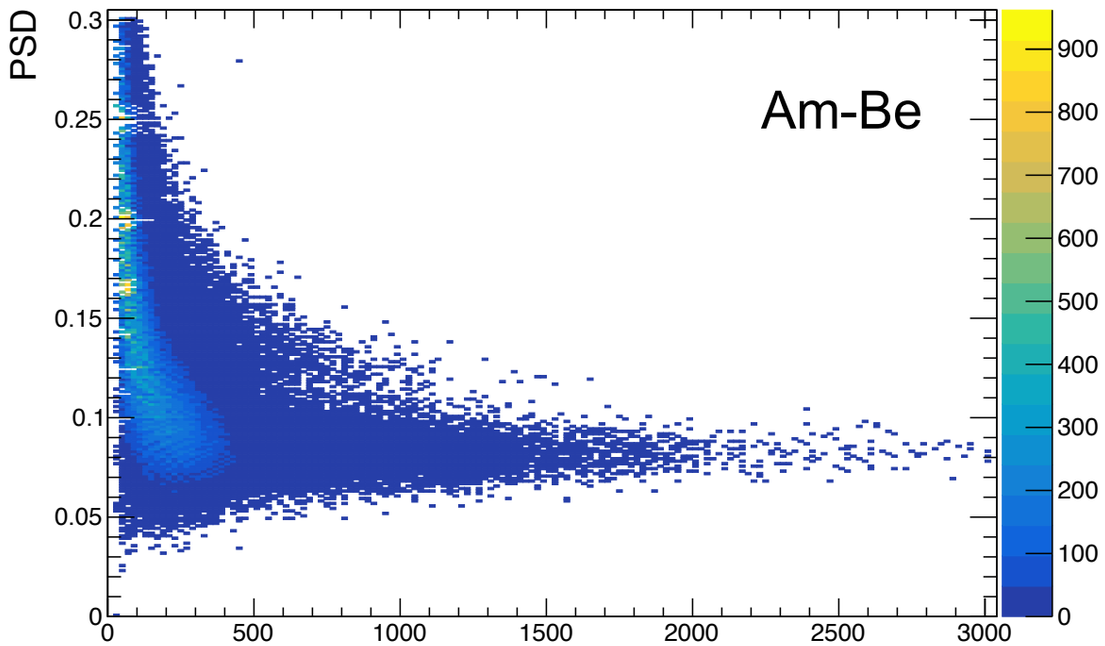


PV base, 30% PPO, 0.2% DAP and 3% polymer cross linker. ϕ=2.2 cm, h=4 cm

Isotope	Thermal neutron capture reaction	25 meV cross section (Barns)	Natural isotopic abundance (%)
^{3}He	${}^{3}_{2}He + n \rightarrow {}^{3}_{1}H + {}^{1}_{1}p$	5,330	0.000137
^{6}Li	${}^{6}Li + n \rightarrow {}^{3}H(2.73\ \text{MeV}) + \alpha(2.05\ \text{MeV})$	940	7.5
^{10}B	${}^{10}B + n \rightarrow {}^{7}Li^{*} + \alpha(1.47\ \text{MeV}) \rightarrow {}^{7}Li + \alpha(1.8\ \text{MeV}) + \gamma\ (0.48\ \text{MeV})$	3,840	19.9
^{113}Cd	${}^{113}Cd + n \rightarrow {}^{114}Cd + \gamma's\ (9\ \text{MeV})$	20,600	12.2
^{155}Gd	${}^{155.157}Gd + n \rightarrow {}^{156.158}Gd^{*} \rightarrow {}^{156.158}Gd + e^{-} + \gamma's\ (8\ \text{MeV})$	60,900	14.7
^{157}Gd		254,000	15.7

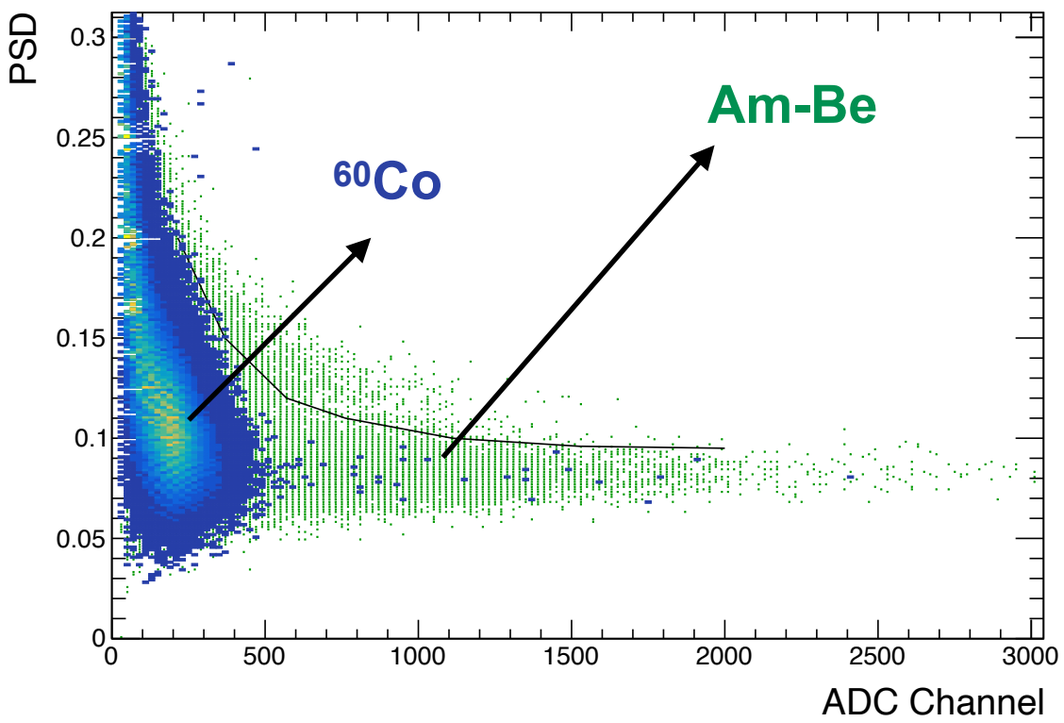
Pulse Shape Discrimination

PS-PSD

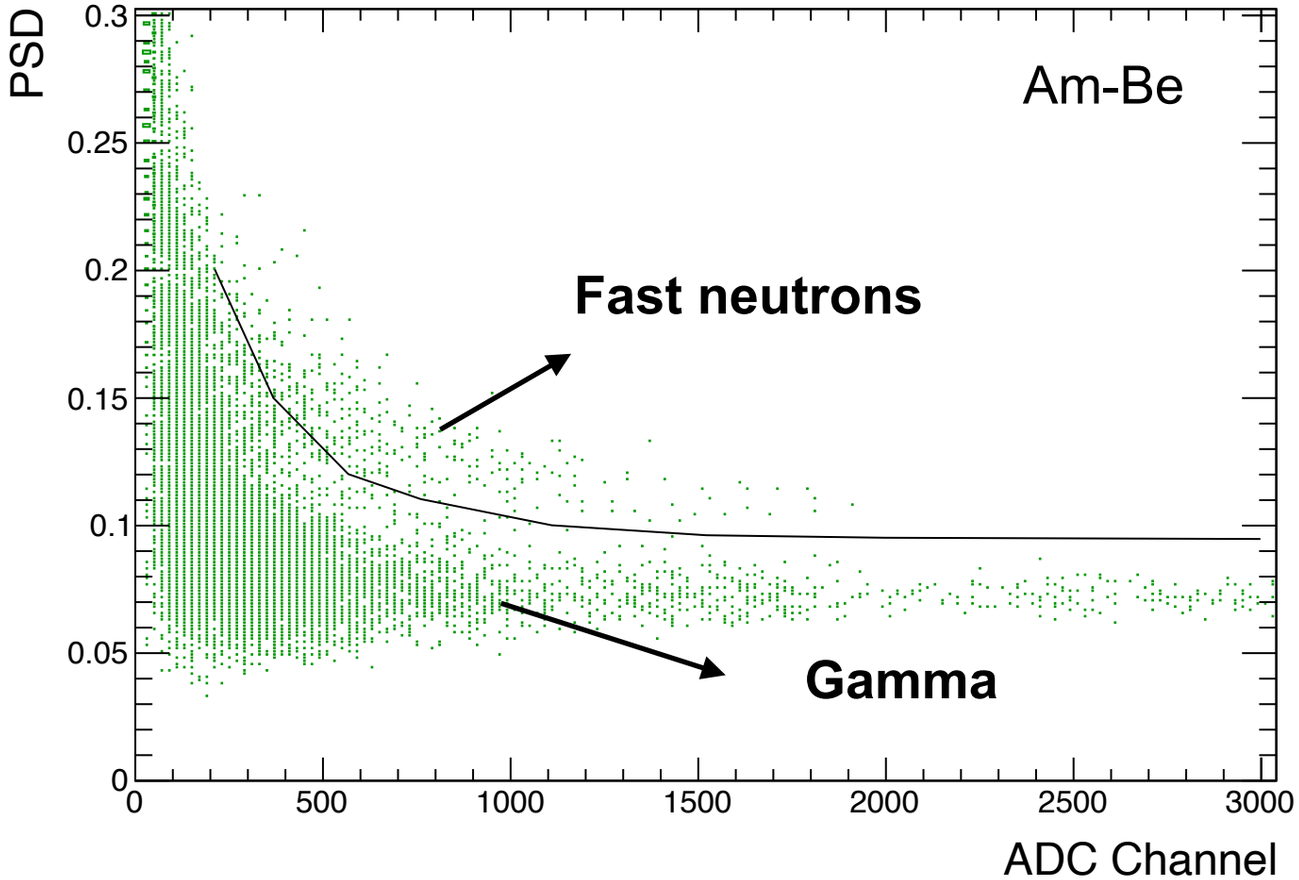


- Am-Be as a neutron source.
- Q_{tail}/Q_{total} vs energy histograms for PS-PSD and EJ-276 are shown.
- The PS-PSD shows the same behavior as EJ-276.

PS-PSD

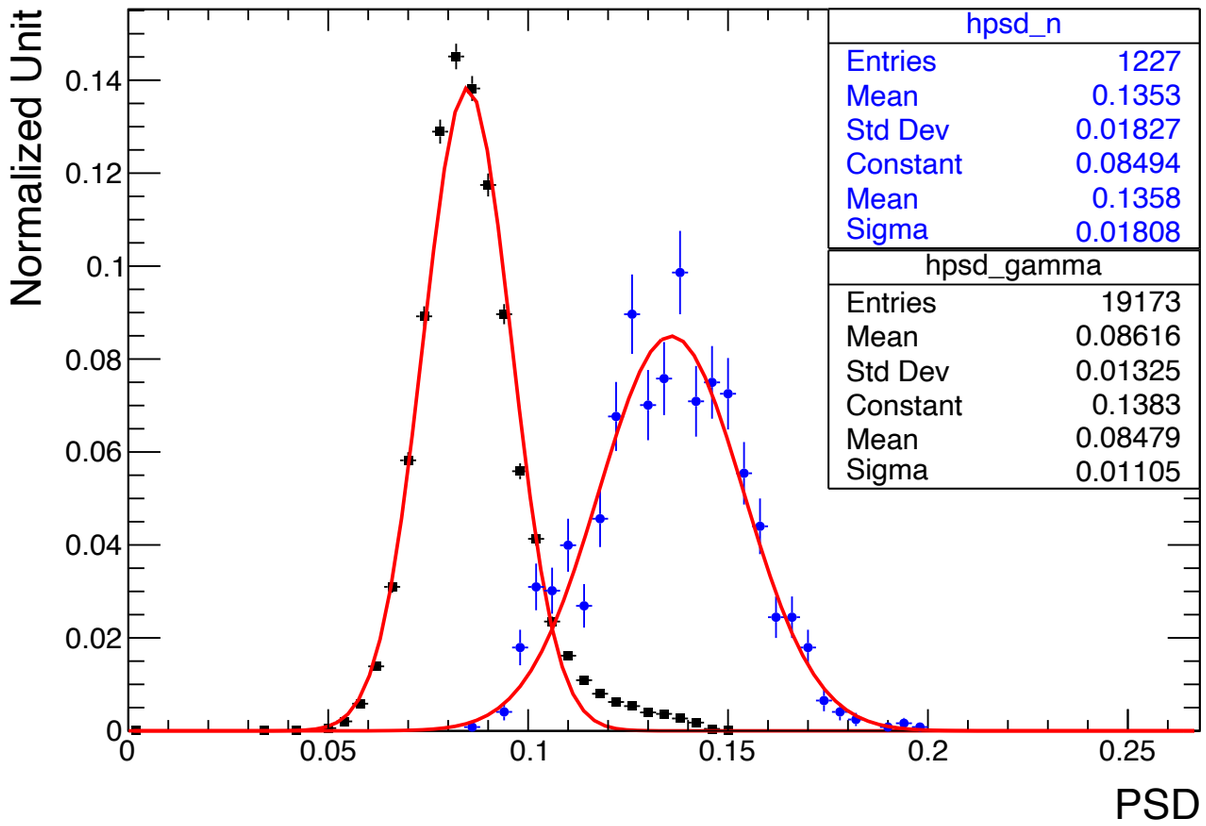


EJ-276



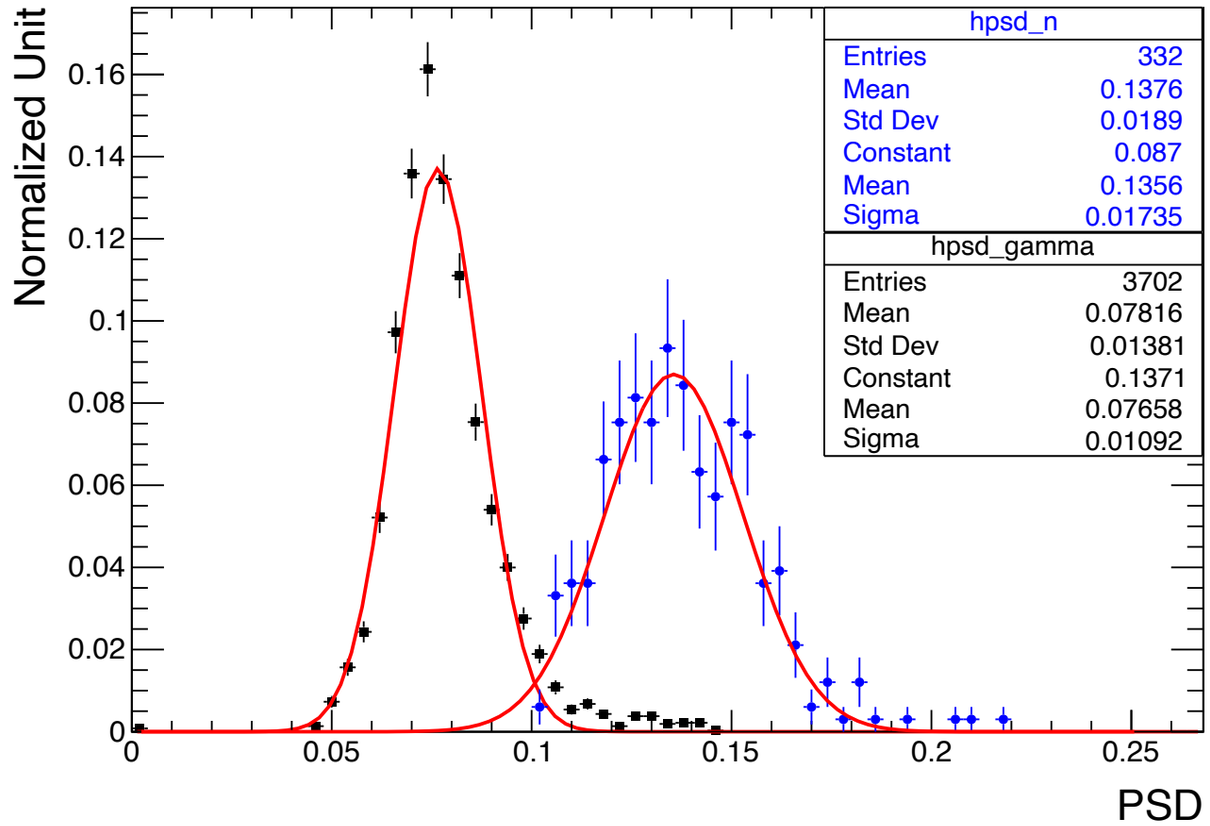
FoM for n/γ Separation

PS-PSD



FoM=0.745

EJ-276



FoM=0.889

- ☑ The quality of the PSD was quantitatively estimated from the calculation of the Figure of Merit (FoM).
- ☑ PS-PSD has a comparable FoM value with EJ-276.

$$FoM = \frac{\left|\mu_n - \mu_\gamma\right|}{2.35(\sigma_n + \sigma_\gamma)}$$

Prospects and Conclusion

- ☑ Nuclear reactors and nuclear technology will be active in Turkey in the next years.
- ☑ Monitoring these reactors independently and reactor antineutrino energy spectrum measurements are the main purposes.
- ☑ The effort for production and characterization of gadolinium loaded plastic scintillator has been started.
  - ✓ Gd-loaded plastic scintillator blocks with the content of PPO (1.5%) + bis-MSB (%0.08) + $Gd(TMHD)_3$ (%0.2)
- ☑ The project proposal has been submitted to the funding agency and a response is awaited.
- ☑ Gd loaded and $Li_2B_4O_7$ nanoparticles loaded epoxy based scintillator are also in consideration.
- ☑ Work on improving the PSD-enabled plastic scintillator will continue.
- ☑ Collaborating and contributing to other groups are highly welcome.