LYSO: CENPA Van der Graaf run and upcoming PSI beamtime

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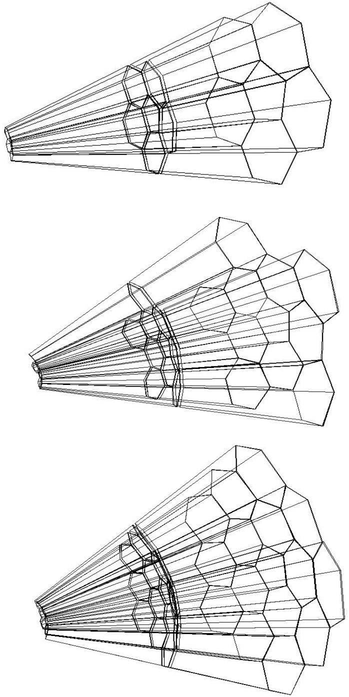
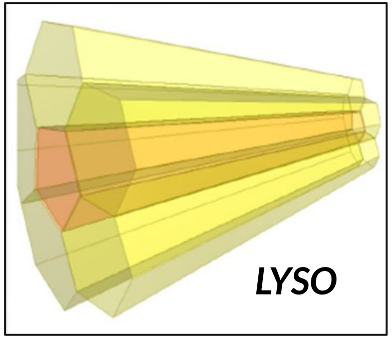
LYSO as a calorimeter option

- Fast (40 ns decay time)
- Bright (30,000 - 40,000 photons/MeV)
- High stopping power
  - Radiation length of 1.14 cm
  - Moliere radius of 2.07 cm
- Intrinsically segmented

BUT

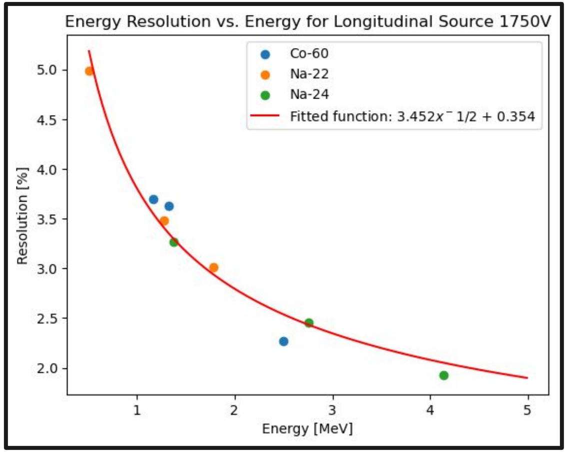
- Resolution better than 4% has not been demonstrated for an array of LYSO crystals at 70 MeV

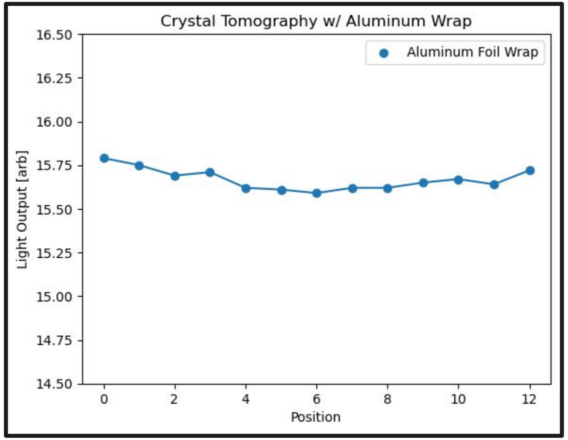




Overview

- We have done a significant amount of testing on single LYSO crystals
  - Energy resolution approaching 1.7 % at 4.14 MeV for a single crystal
  - Strong uniformity – less than 4% variation within a single crystal
- CENPA Van der Graaf test of 2x2 LYSO array at 17.6 MeV done in September
- We will test an array of 10 LYSO crystals at energies ~70 MeV in November at PSI

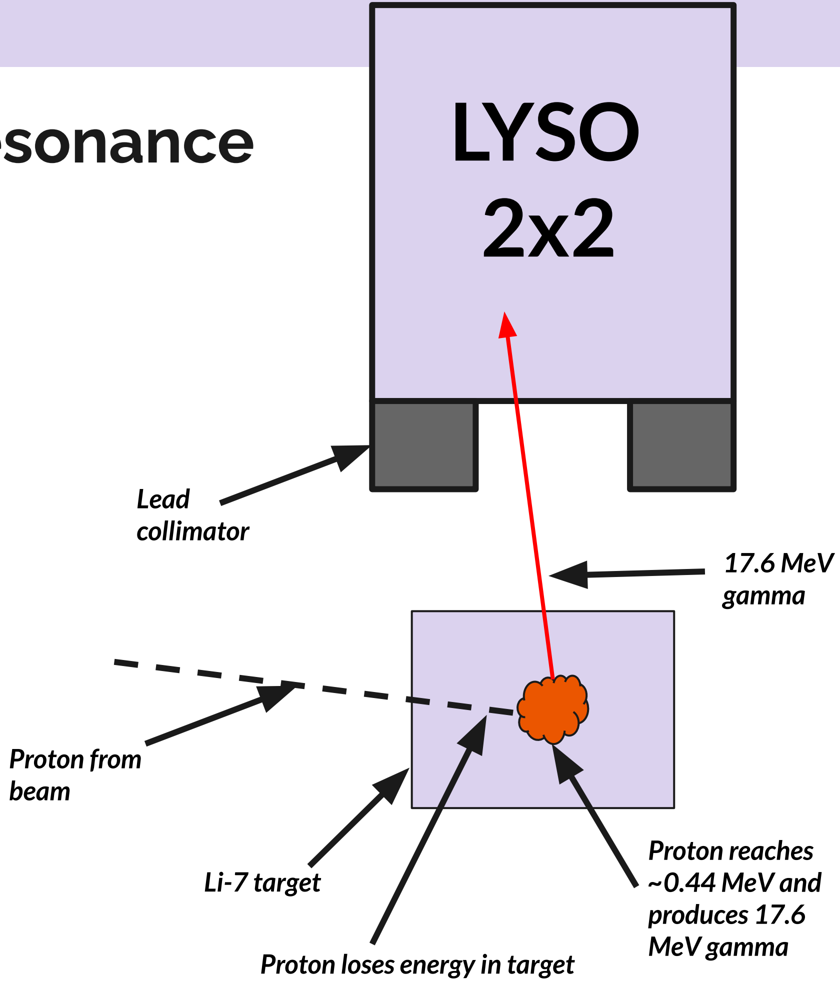




Omar Beesley - University of Washington

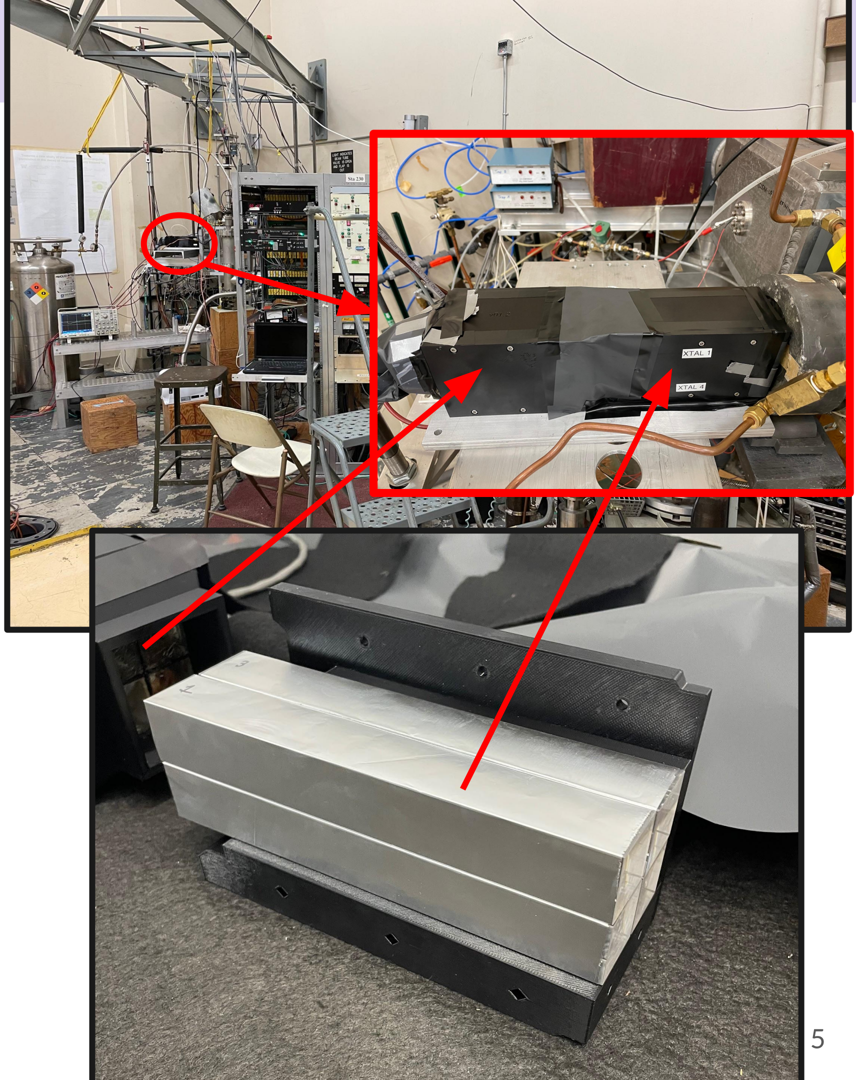
Production of the 17.6 MeV resonance

1. Proton of less than 1 MeV (avoid broad resonance at 1.03 MeV) is shot into a Li-7 target
2. While in the target, the energy of the proton degrades until it reaches a resonance at 0.44 MeV and it captures on a Li-7 to produce Be-8
3. Be-8 quickly de-excites and produces a very sharp 17.6 MeV gamma (and some other broad lines)



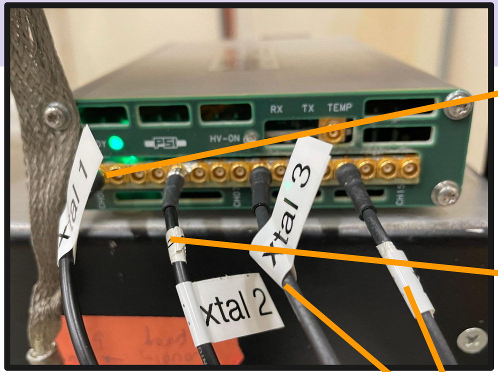
Our LYSO setup

- Light-tight box housing 4 crystals, PMTs and waveguides connecting the crystals to the PMTs
- Crystals were wrapped with smooth aluminum foil, waveguides were wrapped with crinkled aluminum foil, and waveguides were coupled to the crystals and PMTs using EJ-550 optical grease
- Crystal signals were read out by WaveDream DAQ



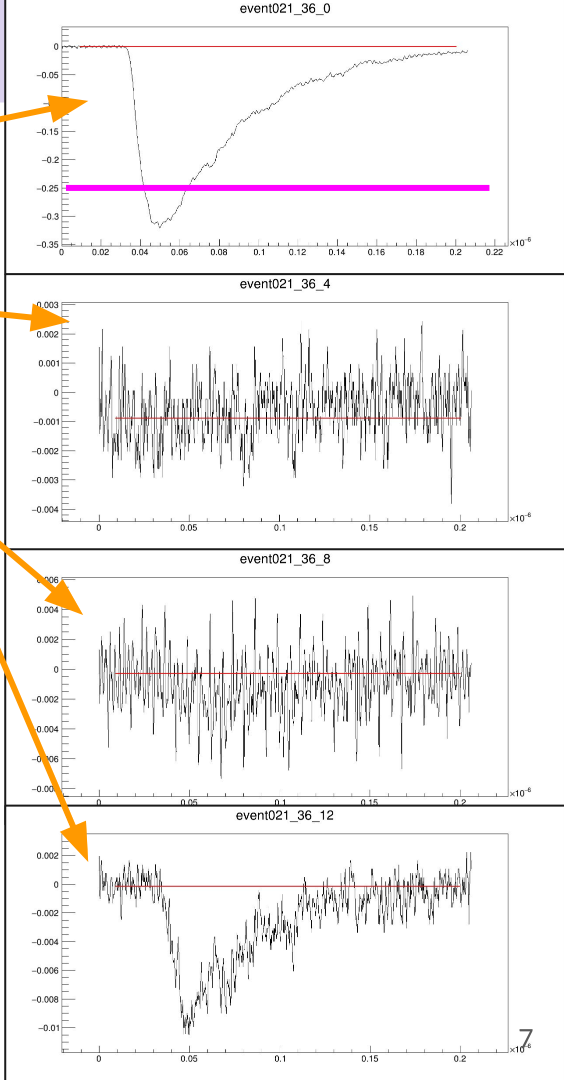
From waveforms to an energy resolution measurement

Waveforms



OR trigger of -250 mV on the 4 LYSO crystals

1. When the system triggers, a pedestal is calculated as an average of the values of the first 20 (out of 1024 bins) of the waveform for each of the 4 waveforms
2. Each of the 4 waveforms is then integrated (channels more than a standard deviation from the pedestal)
3. The final event charge is then the weighted sum of the charges of the 4 waveforms where the weights are calibration constants (calibrations discussed on next slide)



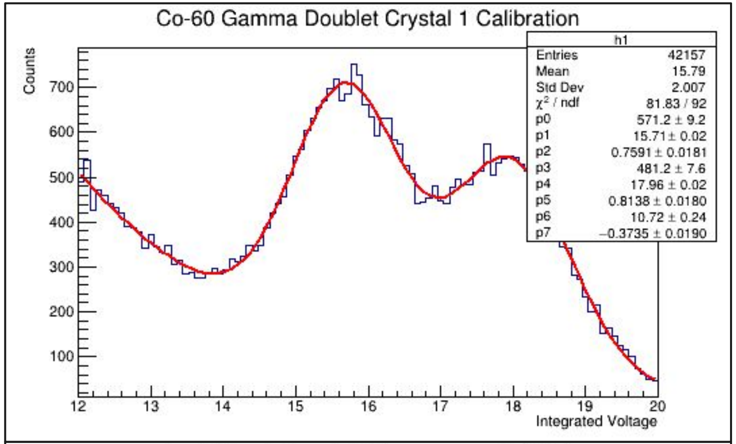
Calibrations

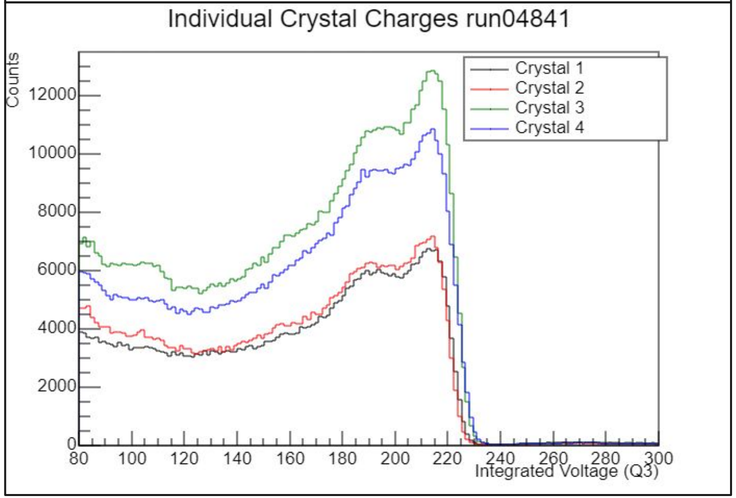
Two calibrations were done for each of the 4 channels

1. Co-60 calibration on each of the xtals. The double peak from the Co-60 was fit and the difference in light output was determined for each crystal.
2. Calibration constants from the Co-60 tests are applied, the highest energy peak for each crystal is measured. Calibration constants are adjusted using the position of this peak.

Calibration constants were small – largest dataset had calibration constants of [1, 0.99187, 1.03036, 1.03502]

$$Q3_{Total} = c_1{*}Q3_{xtal1} + c_2{*}Q3_{xtal2} + c_3{*}Q3_{xtal3} + c_4{*}Q3_{xtal4}$$

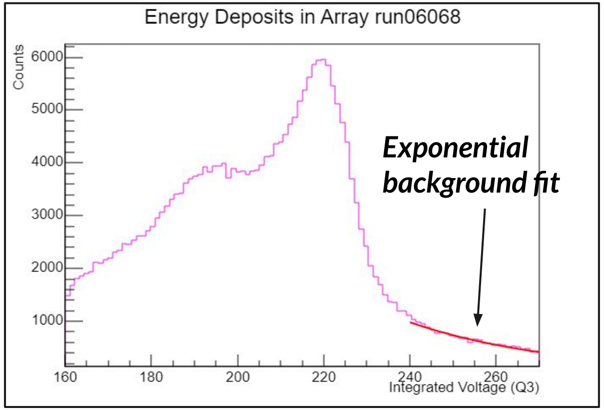


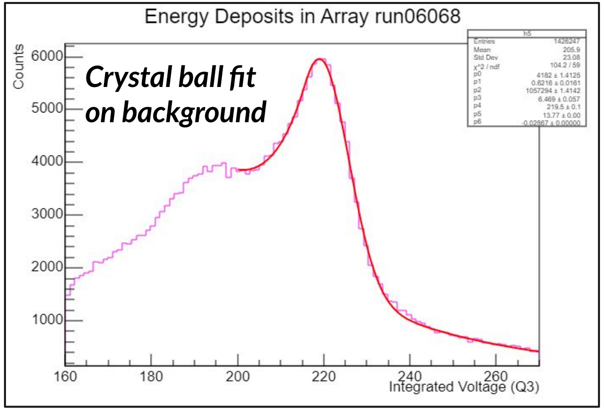


Fitting the resulting distribution

We are interested in the Gaussian core of this peak – core captures the imperfect energy resolution of LYSO

1. First, an exponential is fit to the background region away from the gaussian core
2. This background fit is extended to the signal region and fixed
3. A crystal ball function (Gaussian core, power law tail) is fit on top of this background
4. The σ/E resolution at 17.6 MeV is then extracted to be 2.95% (Gaussian on exponential gives 2.93%)





MEG 17.6 MeV test

- MEG performed a similar 17.6 MeV gamma test of their LXe calorimeter using a Cockcroft-Walton proton accelerator and a Lithium target
- Their LXe calorimeter measured a 3.85% resolution at 17.6 MeV

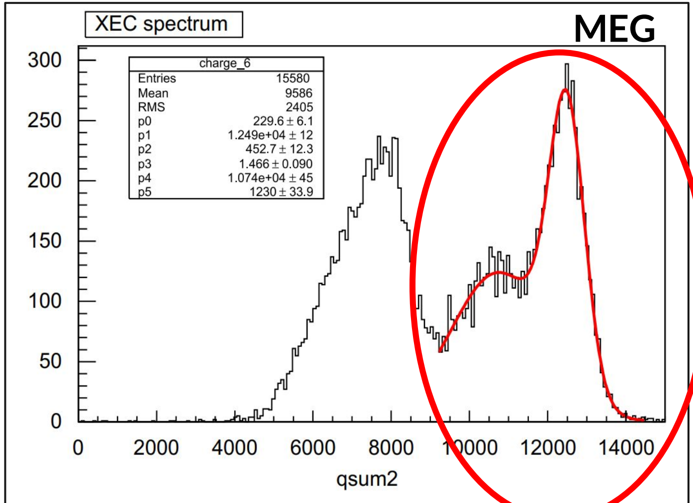


Fig. 24. LXe calorimeter resolution at the 17.6 MeV γ-line. The events in the 5000–9000 region are due to the α-particles from the calibration wire sources.

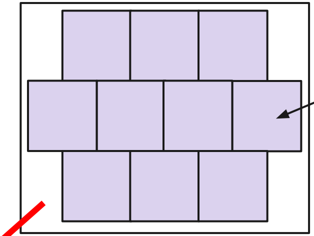
https://www.sciencedirect.com/science/article/abs/pii/S0168900211006875?via%3Dihub

LYSO beamtime at PSI

Primary goals for the PSI LYSO beamtime

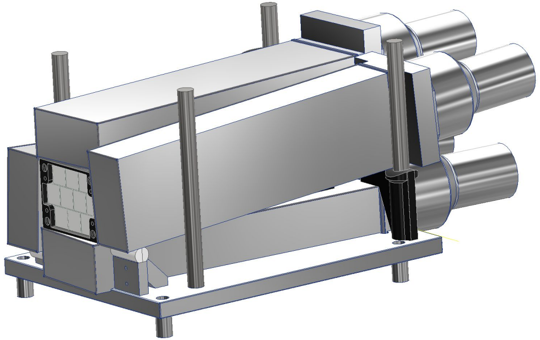
1. Determine the energy resolution of an array of LYSO crystals at the PIONEER energy scale
2. Determine the losses in the calorimeter at the boundaries between crystals
3. Identify the electromagnetic physics list that most accurately describes albedo

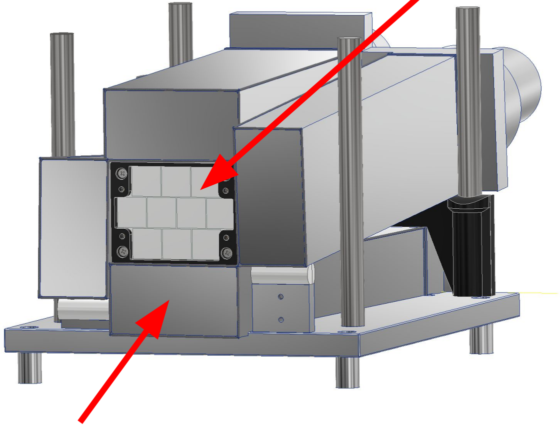
General detector setup

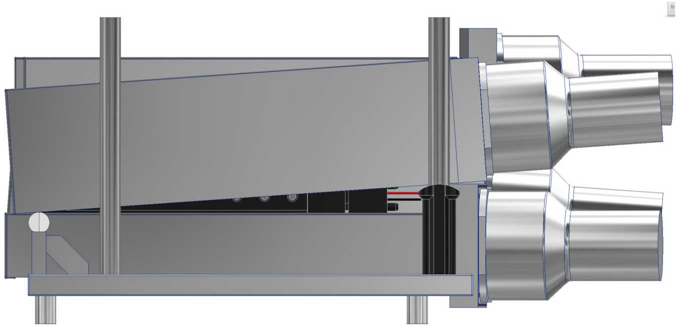


Individual LYSO is 2.5 x 2.5 x 18 cm

3-4-3 LYSO array





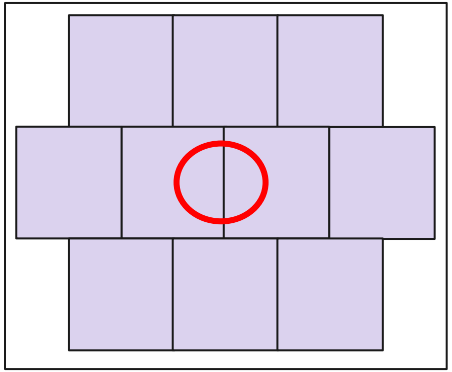


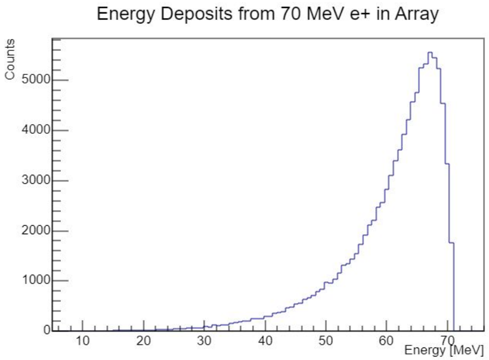
NaI(Tl) ~5 x 11 cm front

Drawings by Ryan Roehnelt

LYSO energy resolution measurement

- Use hodoscope to select events hitting center of LYSO array
- Walk beam energy from 50 to 150 MeV in 10 MeV steps
  - Make energy resolution measurement at each beam configuration
  - Understand "constant" contribution to energy resolution by analyzing energy resolution as a function of energy
- Repeat energy resolution measurement for different wraps/filter configuration
  - Unwrapped/ESR/Aluminum Foil

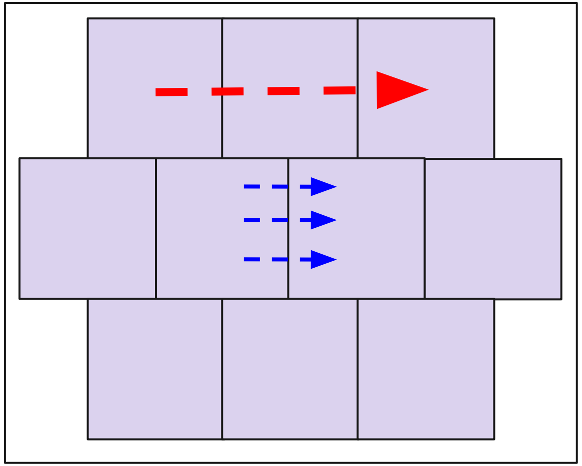




Tests of losses at boundaries between crystals

In each measurement, we look at how the peak position changes in each step with beam at 70 MeV

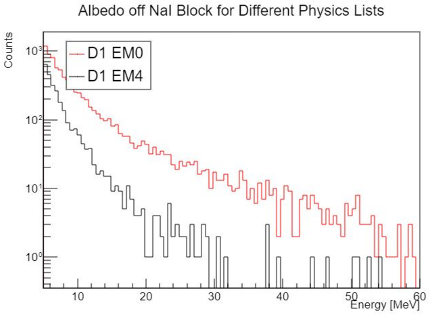
1. Measure horizontal slices of the array with small steps
2. Slowly move beam over central boundary at multiple vertical positions

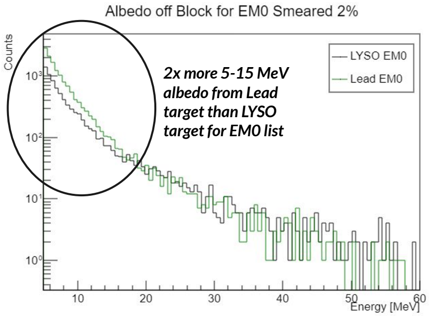


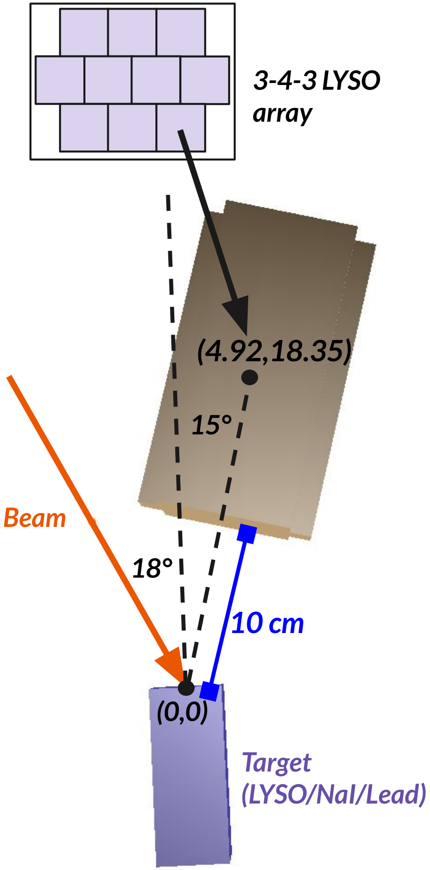
Albedo will be measured during LYSO beam tests and EM lists will be validated

- Shoot 70 MeV e+ beam at target of various materials (LYSO/NaI/Lead) and measure the albedo in our LYSO array
  - Energy deposits in LYSO array primarily from albedo
  - OR trigger on hodoscope and clock will be used to measure the background distribution

- Additional validation tests
  - Angular distribution of albedo
  - Test ~1/r^2 dependence
  - Vary beam energy







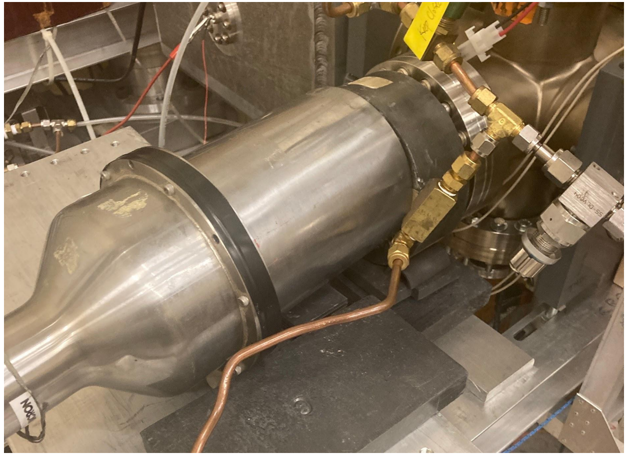
Discussion

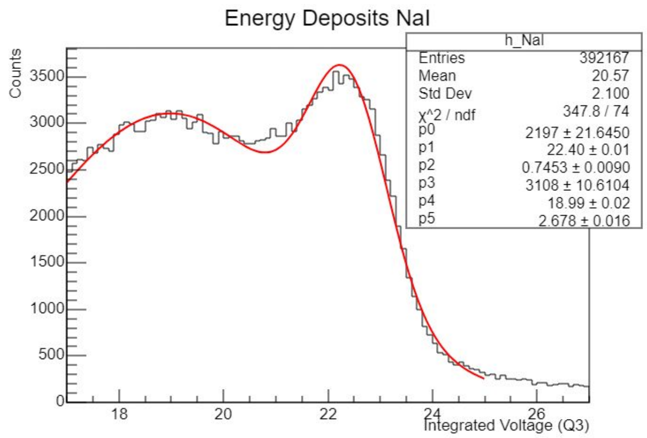
- We have measured an energy resolution of 2.95% at 17.6 MeV using a 2x2 array of LYSO crystals
- Previous MEG tests measured a resolution of 3.85% with their calorimeter using the same 17.6 MeV gamma
- In our upcoming beam test at PSI, we plan to test
  - The energy resolution of LYSO at energies around 70 MeV
  - The losses at the boundaries of LYSO crystals in an array
  - The albedo reflecting back from different targets in various configurations

Backup

Validation with a NaI detector

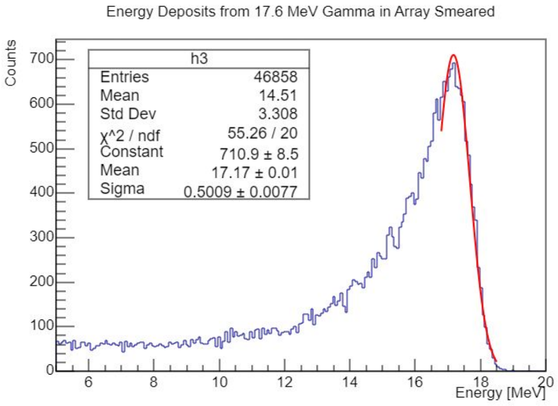
- A single NaI detector was placed in the same position as the LYSO array to validate our results
- This detector was only ~4-5 radiation lengths deep, which adversely affected resolution, but the same resonance was observed in this detector

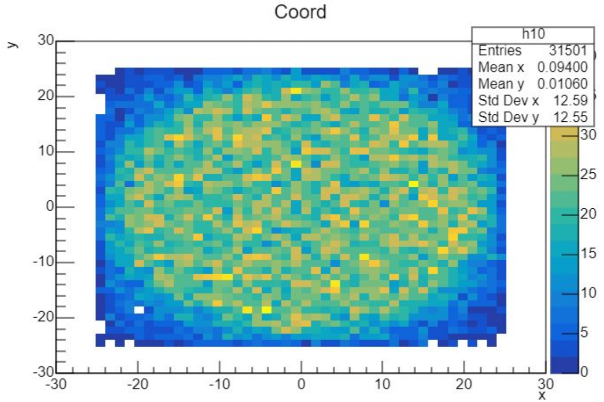




Simulation of 17.6 MeV test in Geant4

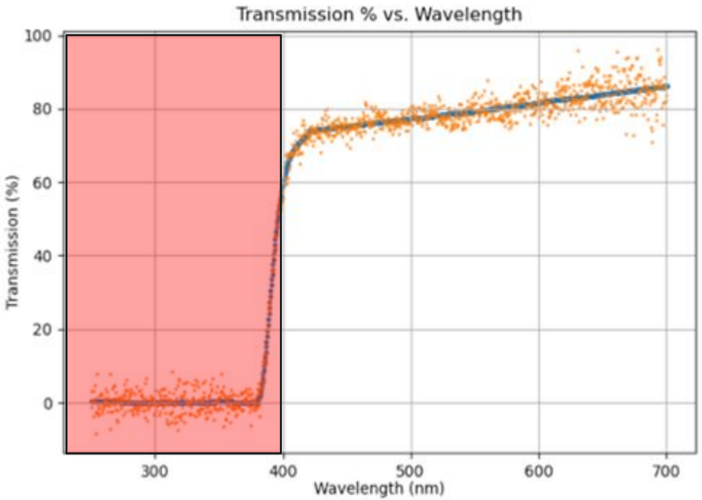
- In Geant4, our CENPA test setup was simulated using an isotropic 17.6 MeV gamma source emitting 10 cm from the front face of our crystal array. A lead collimator similar to the one use in our CENPA runs is added
- We then smear the energy deposits in the LYSO array with 2% Gaussian smearing and fit the resulting distribution to obtain the resolution one might measure
- We measure a σ/E resolution at 17.6 MeV of 2.90% and the peak position is located at 17.2 MeV – this suggests that our energy resolution from the Van der Graaf test has been smeared due to leakage from the LYSO array (primarily a loss of 511 keV gammas)





Importance of testing the yellow filter

- Rectangular crystals demonstrate great uniformity (less than 4% variation within a crystal)
- Tapered crystals will have a focusing effect causing worse uniformity
- Light at wavelengths with short absorption lengths is the root of this effect
  - Idea: Use filter to only accept light that has a long absorption length
  - Test energy resolution with filter



Crystals with Mass Production Capability

Crystal	NaI:Tl	CsI:Tl	CsI	BaF_2	CeF_3	PbF_2	BGO	BSO	$PbWO_4$	LYSO:Ce	AFO Glasses	Sapphire:Ti
Density (g/cm^3)	3.67	4.51	4.51	4.89	6.16	7.77	7.13	6.8	8.3	7.40	4.6	3.98
Melting points (°C)	651	621	621	1280	1460	824	1050	1030	1123	2050	\	2040
X_0 (cm)	2.59	1.86	1.86	2.03	1.65	0.94	1.12	1.15	0.89	1.14	2.96	7.02
R_M (cm)	4.13	3.57	3.57	3.10	2.39	2.18	2.23	2.33	2.00	2.07	2.89	2.88
λ_I (cm)	42.9	39.3	39.3	30.7	23.2	22.4	22.7	23.4	20.7	20.9	26.4	24.2
Z_{eff}	50.1	54.0	54.0	51.6	51.7	77.4	72.9	75.3	74.5	64.8	42.8	11.2
dE/dX (MeV/cm)	4.79	5.56	5.56	6.52	8.40	9.42	8.99	8.59	10.1	9.55	6.84	6.75
$\lambda_{peak}{}^{a}$ (nm)	410	560	420 310	300 220	340 300	\	480	470	425 420	420	365	750
Refractive Index[b]	1.85	1.79	1.95	1.50	1.62	1.82	2.15	2.68	2.20	1.82	\	1.76
Normalized Light Yield[a,c]	120	190	4.2 1.3	42 4.8	8.6	\	25	5	0.4 0.1	100	1.5	\
Total Light yield (ph/MeV)	35,000	58,000	1700	13,000	2,600	\	7,400	1,500	130	30,000	450	\
Decay time[a] (ns)	245	1220	30 6	600 0.5	30	\	300	100	30 10	40	40	3200
Hygroscopic	Yes	Slight	Slight	No	No	No	No	No	No	No	No	No