New spectrometer projects for challenging particle-gamma measurements of nuclear reactions

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collaborations

NUMEN

Nossa Caixa

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Talk summary

- Spectrometer projects and their objectives
  - NC (SP) and
  - GNumen (LNS):
    - Requirements
    - Observational limit model
    - Solutions
    - Preliminary tests (prototypes)
    - Predicted performance
    - Final remarks

Projects and objectives

- Particle gamma coincidence for selection and identification of excited nuclear states
- NC gamma spectrometer (IFUSP)
  - Complimentary system to a near 4π charged particle telescope array
  - Reactions with weakly bound stable and radioactive beams (RIBRAS) to study transfer and break up mechanisms

- GNumen gamma “calorimeter” (LNS)
  - Complimentary system to MAGNEX
  - Measurement of DCE cross sections

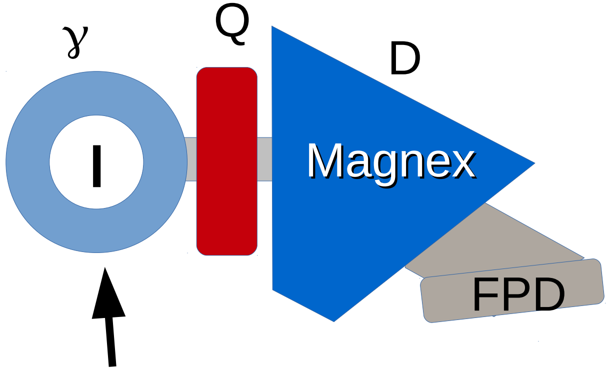
"Easy" and "difficult" DCE experiments

Examples of 2^+ state energies of $\beta\beta$ emitters

Nuclide	$E^*(2^+)$ [keV]
^{48}Ca	**3831.7**
^{82}Se	**654.8**
^{96}Zr	**1750.5**
^{100}Mo	**535.6**
^{110}Pd	**373.8**
^{124}Sn	**1131.7**
^{128}Te	**743.2**
^{130}Te	**839.5**
^{136}Xe	**1313.0**
^{148}Nd	**301.7**
^{150}Nd	**130.2**
^{154}Sm	**82.0**
^{160}Gd	**75.3**
^{198}Pt	**407.2**

Difficult:

- $E(2^+) < 500$ keV (Magnex resolution @ 15*A* MeV)
- ~all cases at ~50*A* MeV



γ calorimeter

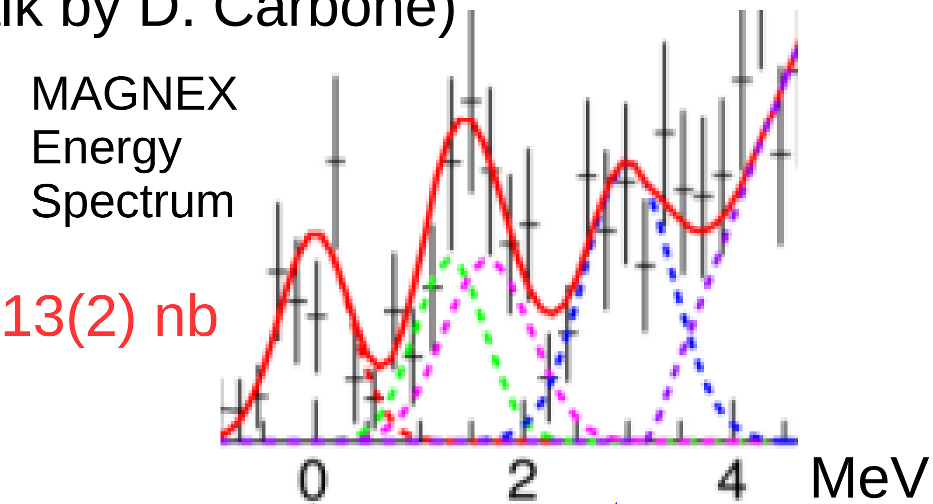
- "veto" 2^+ state decay and measure gs x-section
- measure 2^+ state x-section

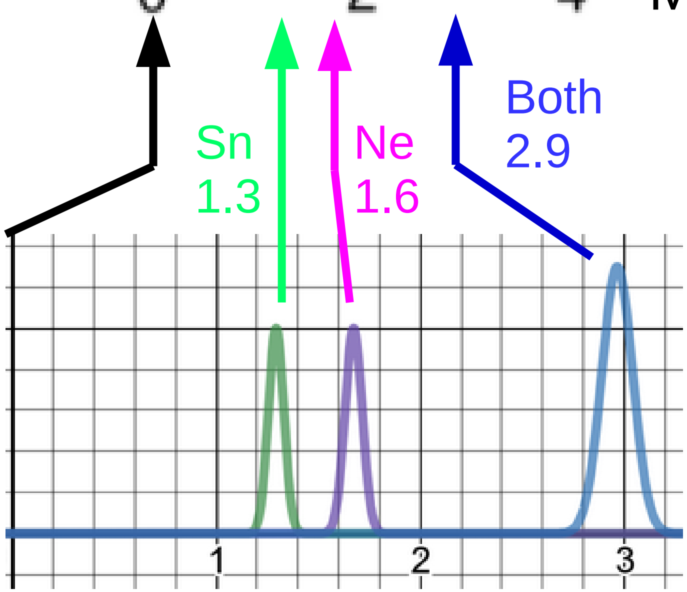
GNumen project

Requirement: Sufficient energy resolution

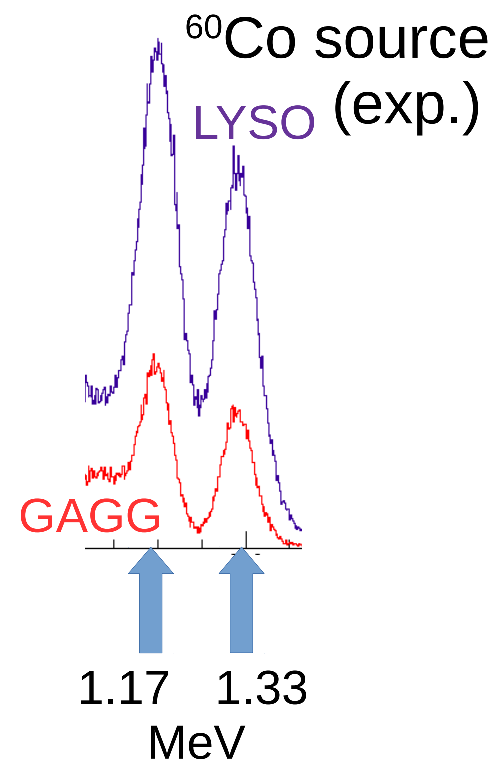
$^{116}Cd(^{18}O, ^{20}Ne)^{116}Sn$ @15MeV/nucleon
(talk by D. Carbone)

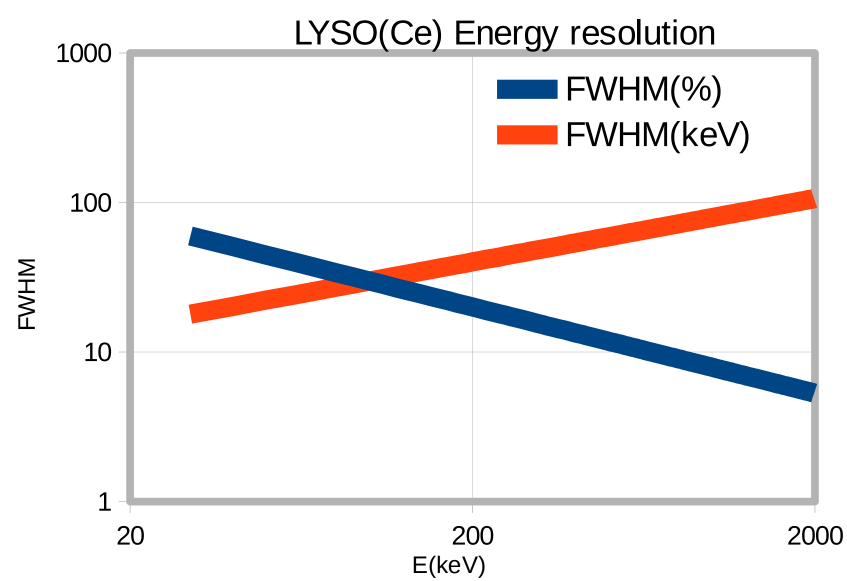
gs: 13(2) nb





Gamma spectrum
LYSO(Ce) typical resolution





Requirement: High efficiency

- Angular distribution data point: 12 pb → 100 counts after 1 week @ 6 x 10^{12} pps beam on 600 μg/cm² A~150 target

→ High photopeak efficiency (high density+high effective *Z*)

→ High geometric efficiency (→ 4π)

Requirement: Tolerance to high rates

- Gamma multiplicity: M_γ~3-30, R_γ → 1 GHz!

→ High granularity (~2000 detectors)

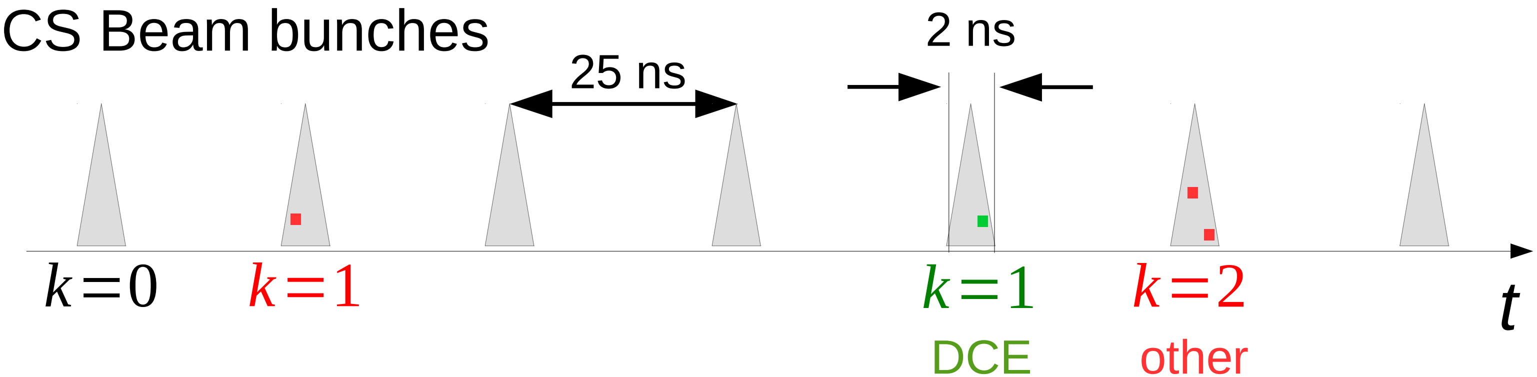
→ Small opening detectors

- High radiation hardness (n,γ) – inorganic scintillators

Requirement: Good timing resolution

- → reduce random coincidence BG at high rates

CS Beam bunches



Average number of reactions per beam bunch

$$\bar{k} = \frac{R_R}{f_c}$$

Poisson statistics:

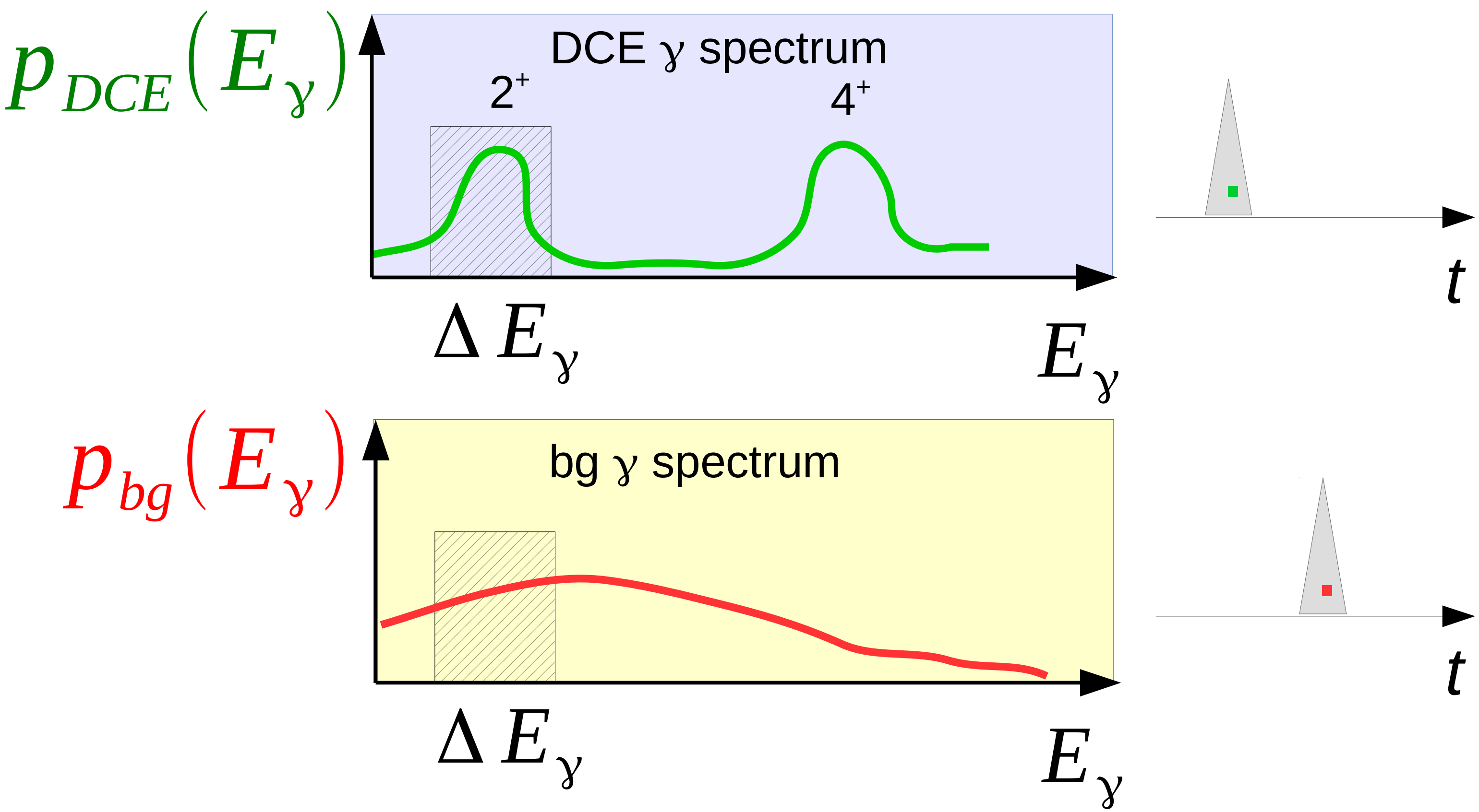
$$P(k=0) = e^{-\bar{k}}$$

$$P(k>0) = 1 - P(0)$$

→ Observational limit: $\alpha_{\mathrm{lim}} = \frac{\sigma_{\mathrm{min}}^{\mathrm{DCE}}(u)}{\sigma_{\mathrm{TOT}}}$

With some model assumptions, it can be predicted analytically:

O.L. model: BG count probability



$$P_F = 1 - e^{-\bar{k}\, p_{bg}(E_\gamma)\, \Delta E_\gamma\, \varepsilon}$$

Probability of 1 bg count (or more) within the 2^+ window range

O.L. model: 2 event types

- Both with a DCE reaction product identified in the FPD
- Composed of experimentally undistinguishable events

- 0^+-like

  (no γ)

true 0^+ · no bg · 2^+ · not detected · no bg

$$A_0 = N_0 \widetilde{P}_F + N_2 \widetilde{\varepsilon}\, \widetilde{P}_F$$

- 2^+-like

  (1 γ or more in ΔE_γ)

0^+ · bg · true 2^+ · detected · not detected · bg

$$A_2 = N_0 P_F + N_2 \left(\varepsilon + \widetilde{\varepsilon}\, P_F \right)$$

$$\left(\widetilde{P}_F = 1 - P_F ,\ \widetilde{\varepsilon} = 1 - \varepsilon \right)$$

O.L. predictions, as a function of $\bar{k}$

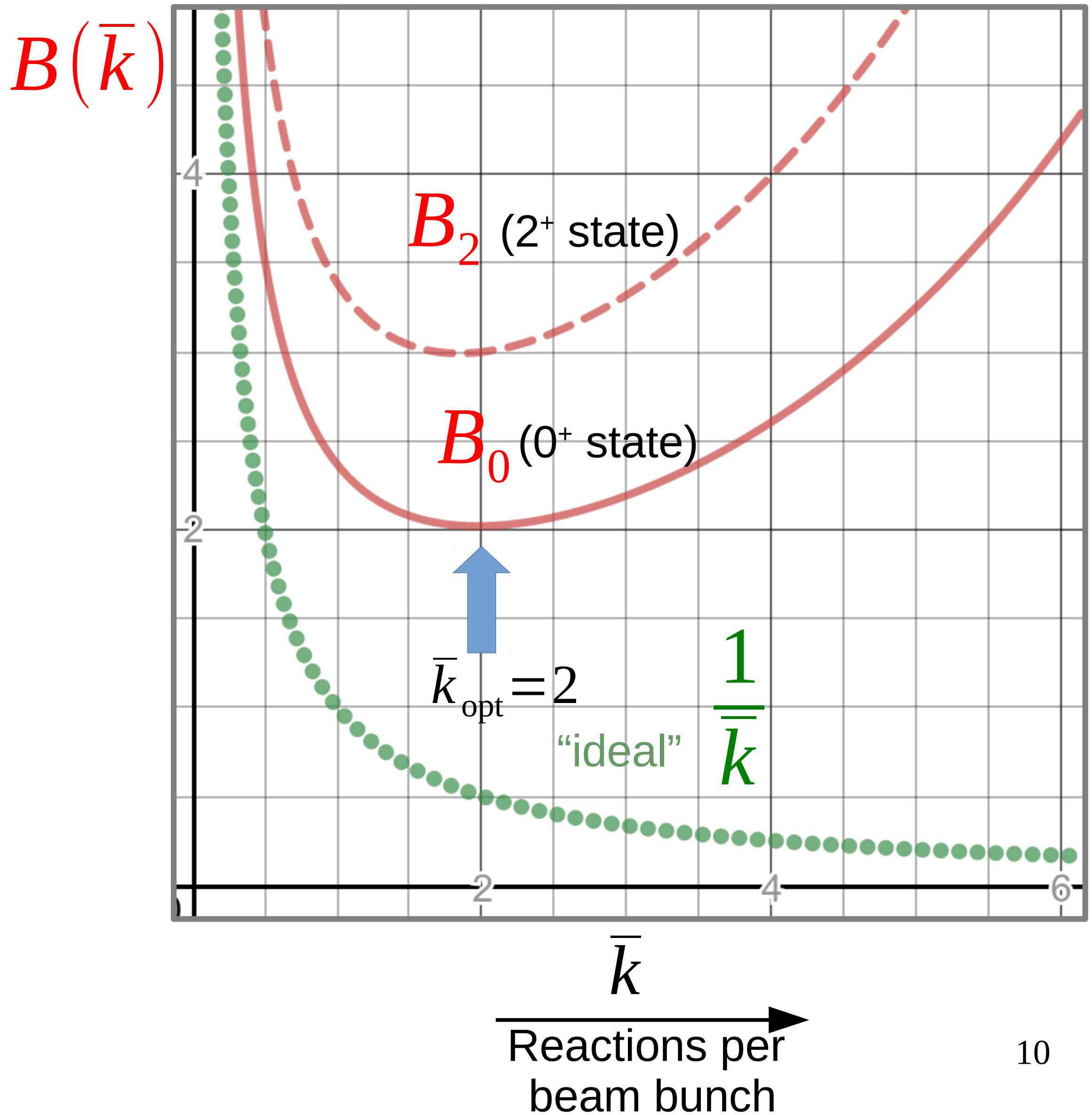
$$\alpha_{\lim} = \frac{B(\varepsilon, \Delta E_\gamma, p_{bg}, f, \bar{k})}{T f_c u^2}$$

Parameter	Value
ε	75%
ΔE_γ	25 keV
$p_{bg}(E_\gamma)$	1.5%/keV
$f = \sigma_{2^+}/\sigma_{0^+}$	0.8
T	1 week
f_c	40 MHz
u	10%

$B = 2 \Rightarrow \alpha = 8 \times 10^{-12}$

$\sigma_{min} \approx 22\,\text{pb}$ (if $\sigma_R = 2.8\,\text{b}$)

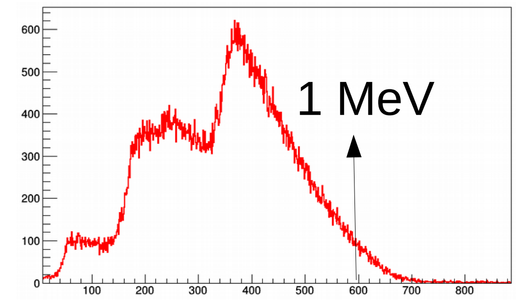
“Reduced” O.L. function B



Solutions - Detector crystals

- Inorganic scintillators:

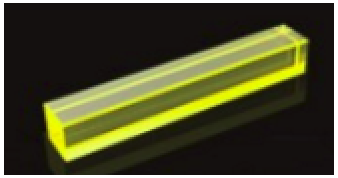
Type	Dens. g/cm³	Zeff	Decay const., ns	Res. @662keV	Higrosc.
NaI(Tl)	3.8	50	250	7%	yes
$LaBr_3$(Ce)	5.1	44.1	30	2.6%	yes
LYSO(Ce)	7.1	66	40	10%	No
GAGG(Ce)	6.6	54.4	80 (70%)* 280 (30%)	5%	No



LYSO intrinsic radiation ~ 300 Hz/cm³

LYSO

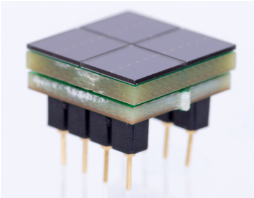
Rad. Hard. γ >10^6Gy



GAGG
No bg

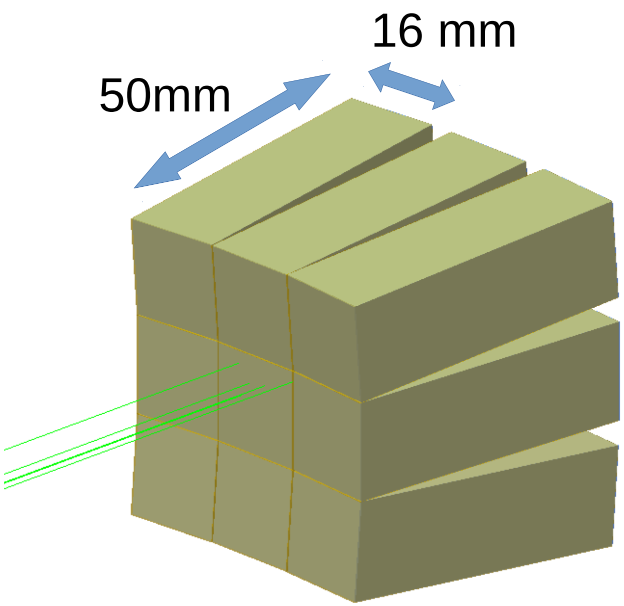
Improves (!) with γ radiation >10Gy-800Gy

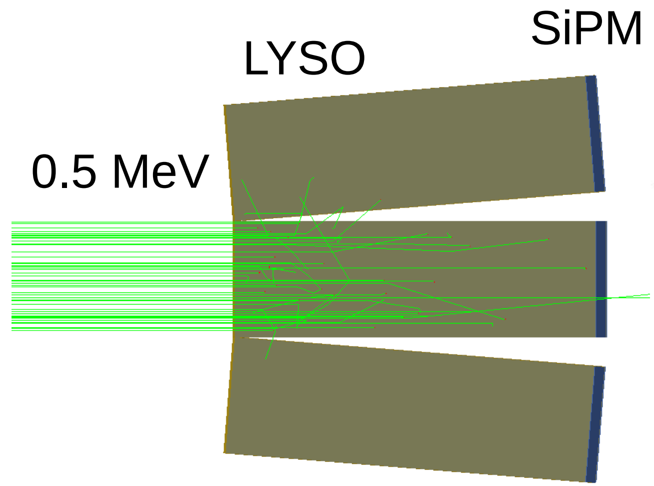
- SiPM (Sensl)
  - Tolerance to magnetic fields

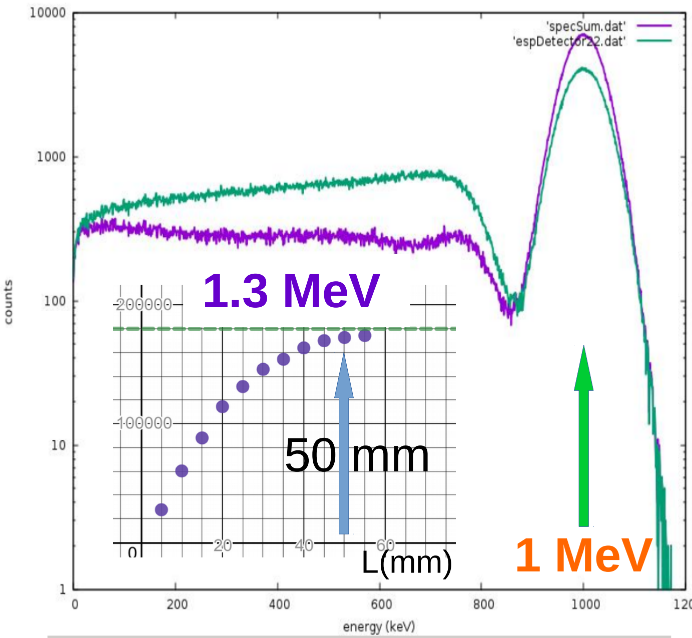


Models:
1.6 cm: 16x3mm pixels
1.2 cm: 4x6 mm pixels

Solutions: Crystal “Pixel” modules

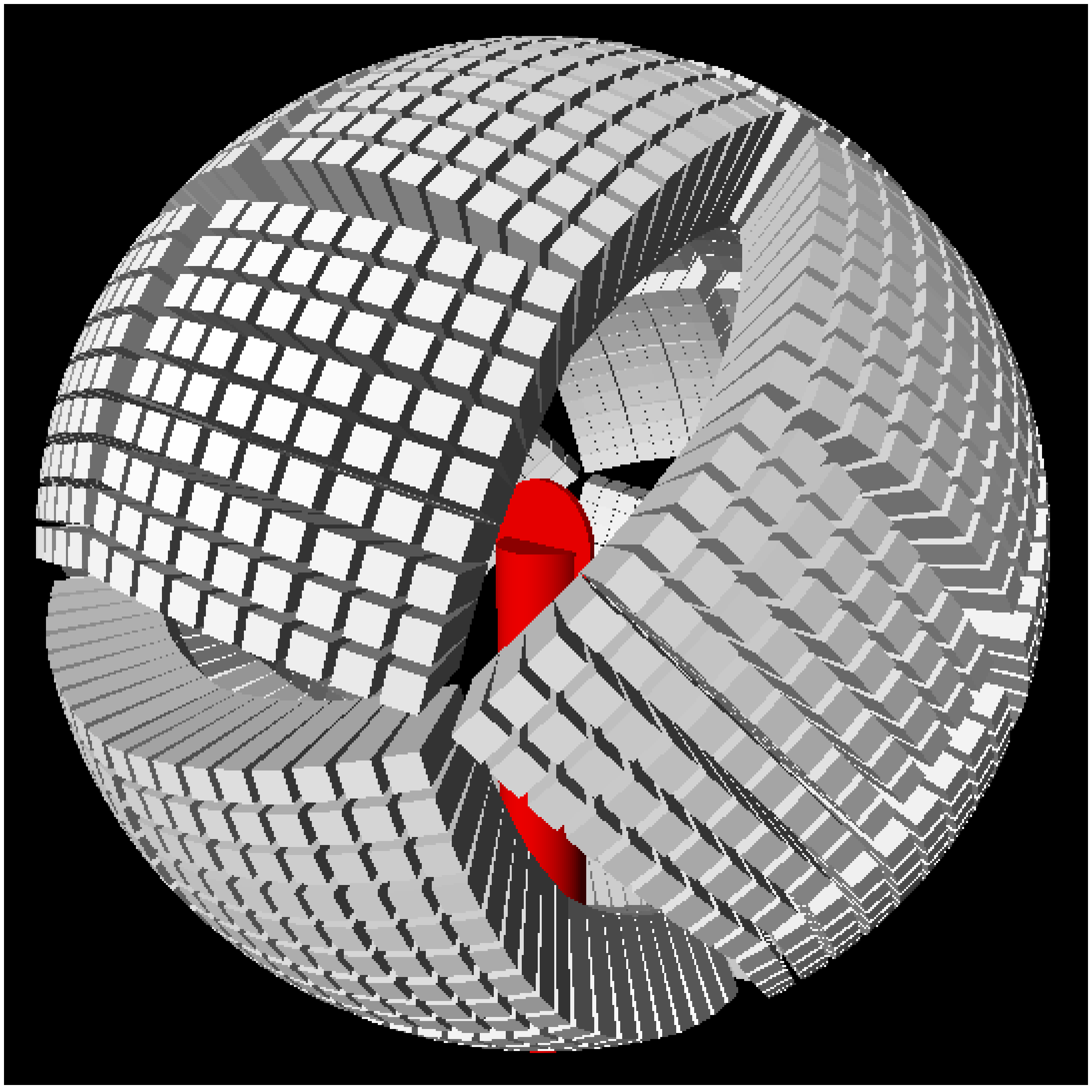


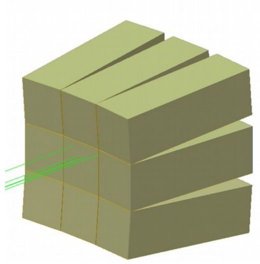




- Parallel section of crystals → best light collection in SiPM of same size
- GEANT simulations for 1 MeV gamma rays:
  - Intrinsic photopeak efficiency: Sum 65%; Central 42%.
  - Compton continuum around 400 keV: reduced by a factor of 2.
  - Total rate increases by 40% due to Compton cross-talk, but is reduced by 6.4 times compared to a monolithic piece of same total size.
  - Pile-up reduced to a few % (at 6 x 10^{12} pps or $\bar{k} \approx 1$)

Solutions: Modular geometry → 4π

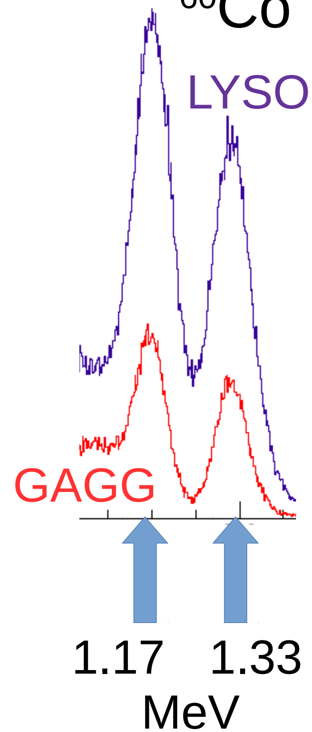




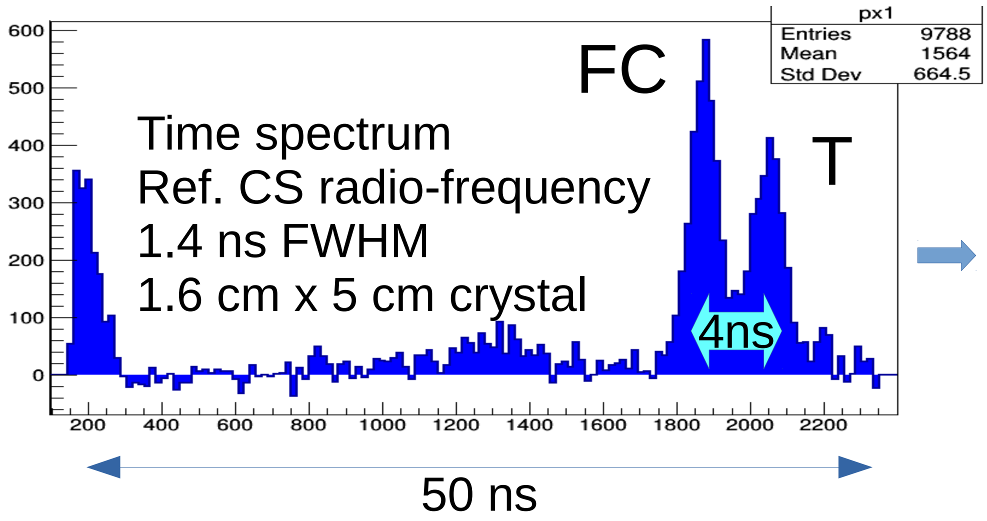
- 3 x 3 pixel modules
- "square" walls with 9 (3 x 3) modules each
- 6 sides x 4 = 24 "squares"
- Total: 1944 crystals
- $\Omega_\gamma \sim$ 60% of 4π
- Openings for target post, beam entrance and exit, vacuum pumping and/or additional detectors.
- Circumscribes a sphere of ~25 cm radius

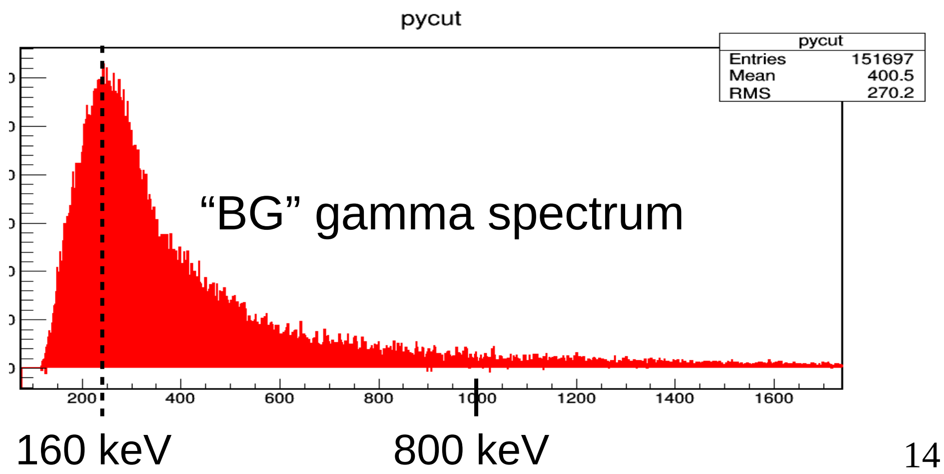
Preliminary tests - prototypes

- Energy and Time resolutions with 1.2 cm side x 4 cm length crystals (NC project, phase 1):
  - LYSO + SiPM → OK for both, full energy range
  - GAGG + SiPM → OK for both at gamma energies above ~250 keV. Bad below ~100 keV (SiPM spectral match)



- LYSO in beam $^{116}Cd(^{20}Ne, ^{20}Ne)^{116}Sn$ @15MeV/nucleon:

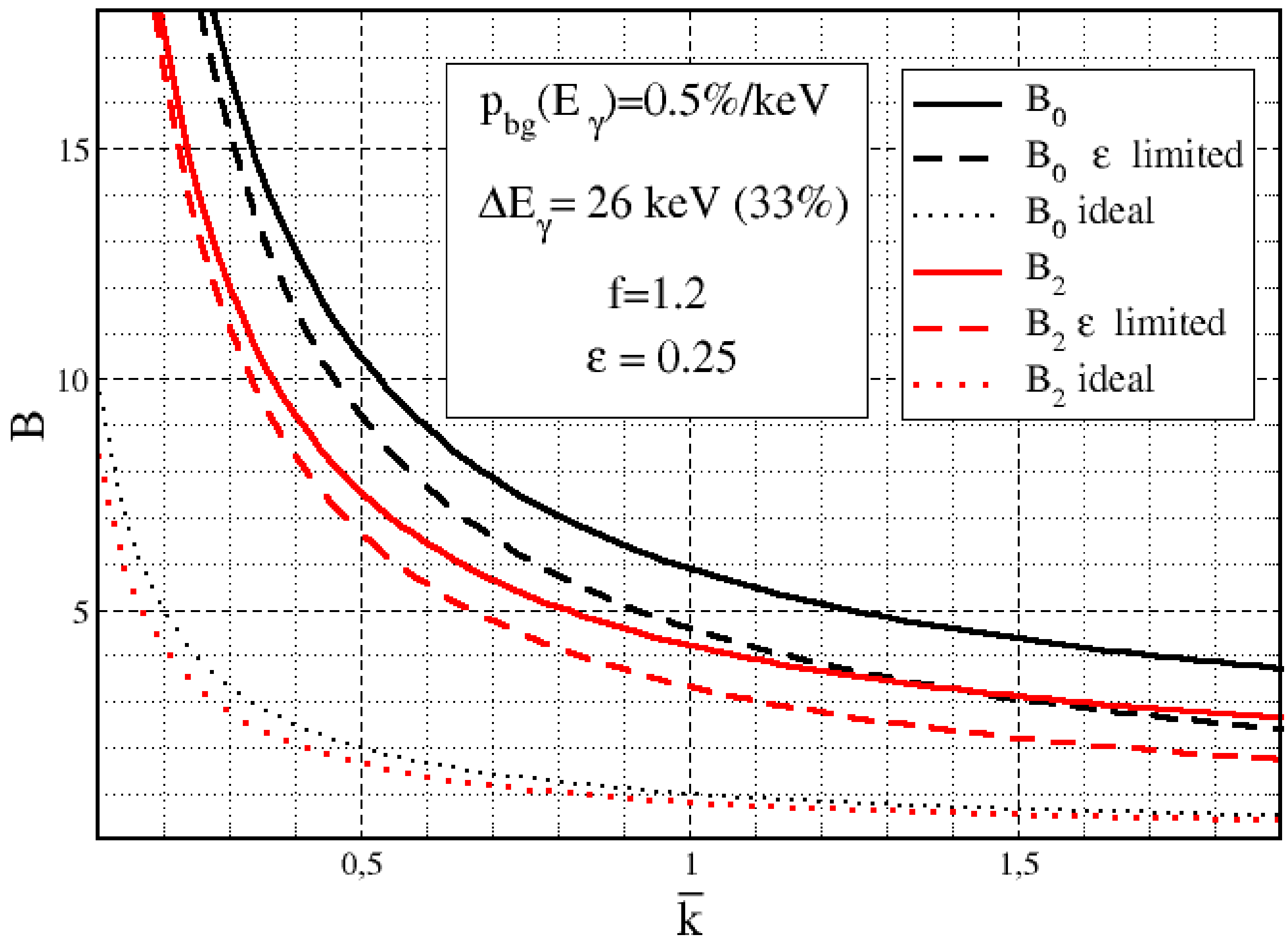


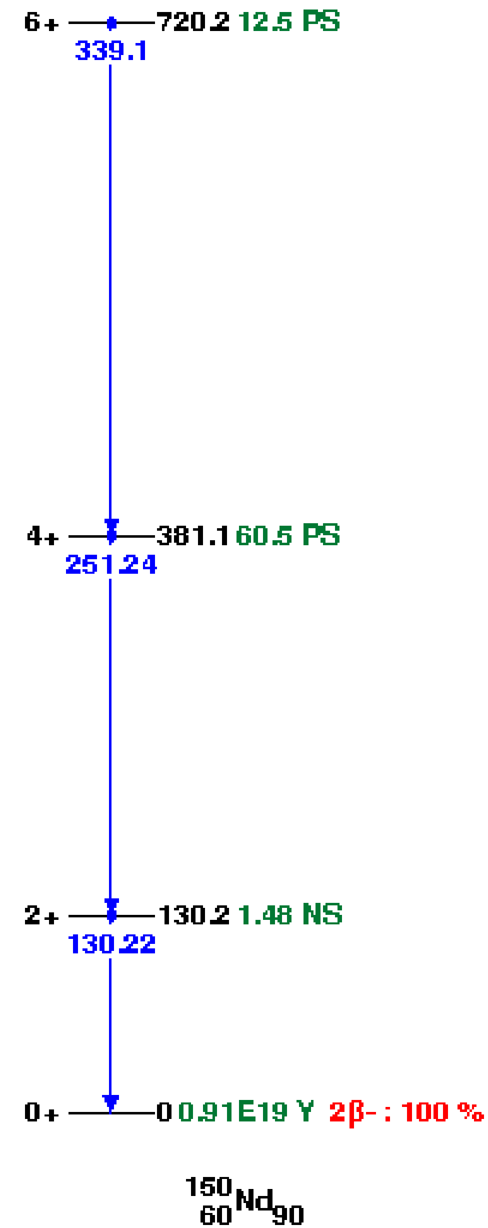


Expected performance

"Difficult case": $^{150}Sm(^{18}O,^{18}Ne)^{150}Nd$ @ 270 MeV

$$E_\gamma(2^+ \rightarrow 0^+) = 130\,\mathrm{keV}, \alpha_{tot}^{ec} = 0.86, I_\gamma = 54\,\%$$





Conclusion → Mostly **efficiency** limited

Final remarks

- Looks challenging but feasible
- Next steps:
  - Detailed GEANT4 simulations
  - Detailed tests of prototypes (LNS & IFUSP – NC1)
    - With radioactive sources
    - In beam
  - Electronics tests
  - Measurement of in-beam bg and gamma multiplicity
  - Detailed design of array and electronics
  - Building in steps as experiments/techniques advance

Collaborators

NC1:

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… and the other NUMEN WP's

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