Gamma-ray angular correlations with the iThemba LABS segmented clover

Dr. Elena Lawrie
iThemba LABS

What are angular correlations?

Why do we want to measure angular correlations?

How can we measure angular correlations functions?

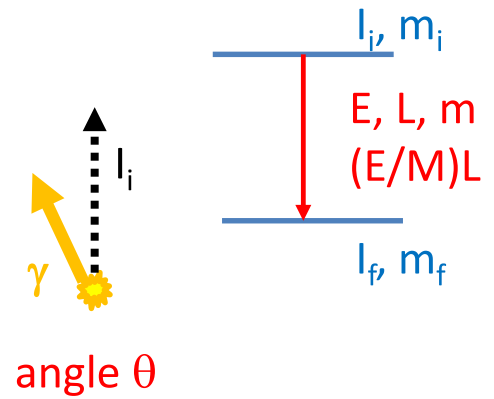
What is the segmented clover detector and why/how do we want to use for angular correlations measurements?

Examples of angular correlations measurements

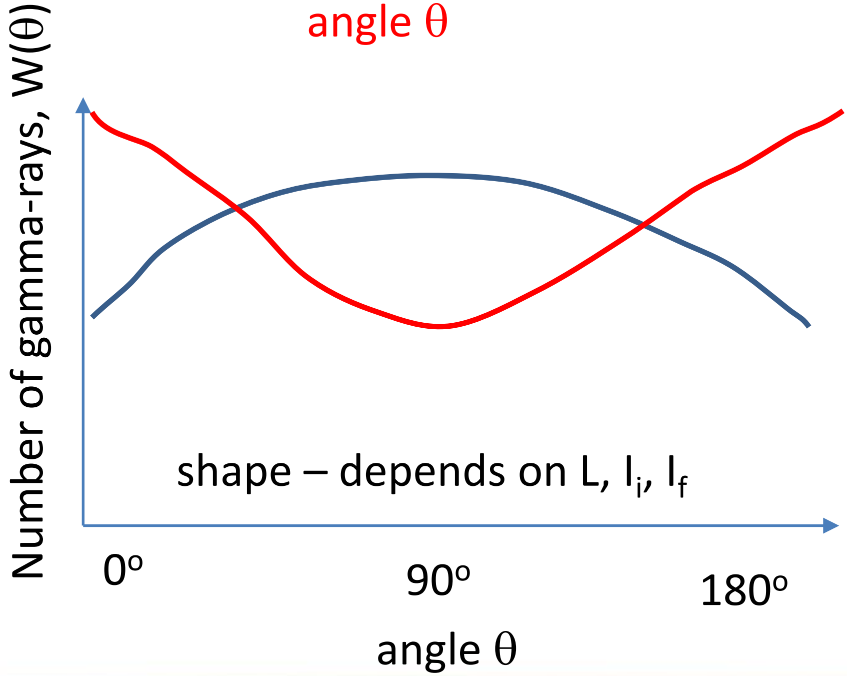
What physics can we do if we can measure precise angular correlations?

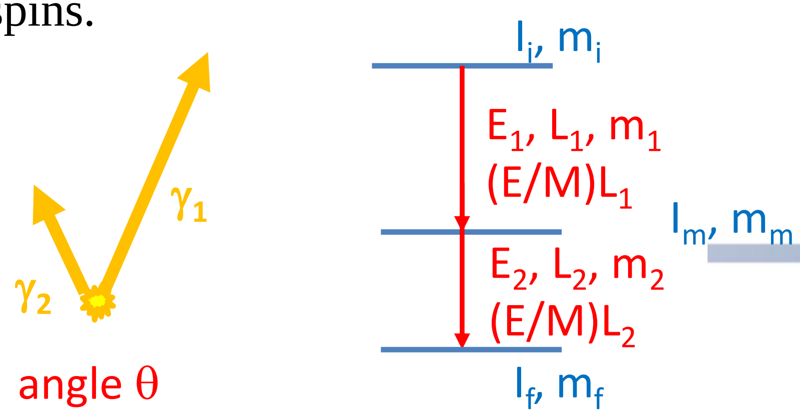
What is a gamma-ray angular correlation function?

Angular distribution of a gamma-ray is the probability for gamma-ray emission as a function of the direction.
It depends on L, I_i, I_f
Needs orientation of the nuclear spins I_i



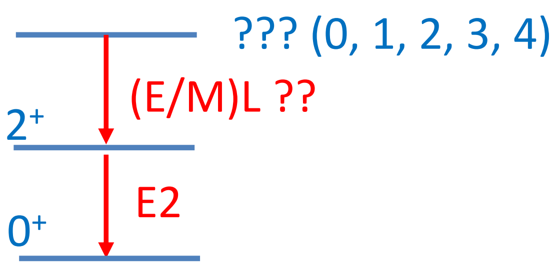
Angular correlation function is the number of emitted gamma-rays as a function of the angle θ, where θ is the angle between the directions of two consecutive gamma-rays.
it depends on L_1, L_2, I_i, I_m, I_f
Works for both, oriented and non-oriented nuclear spins.



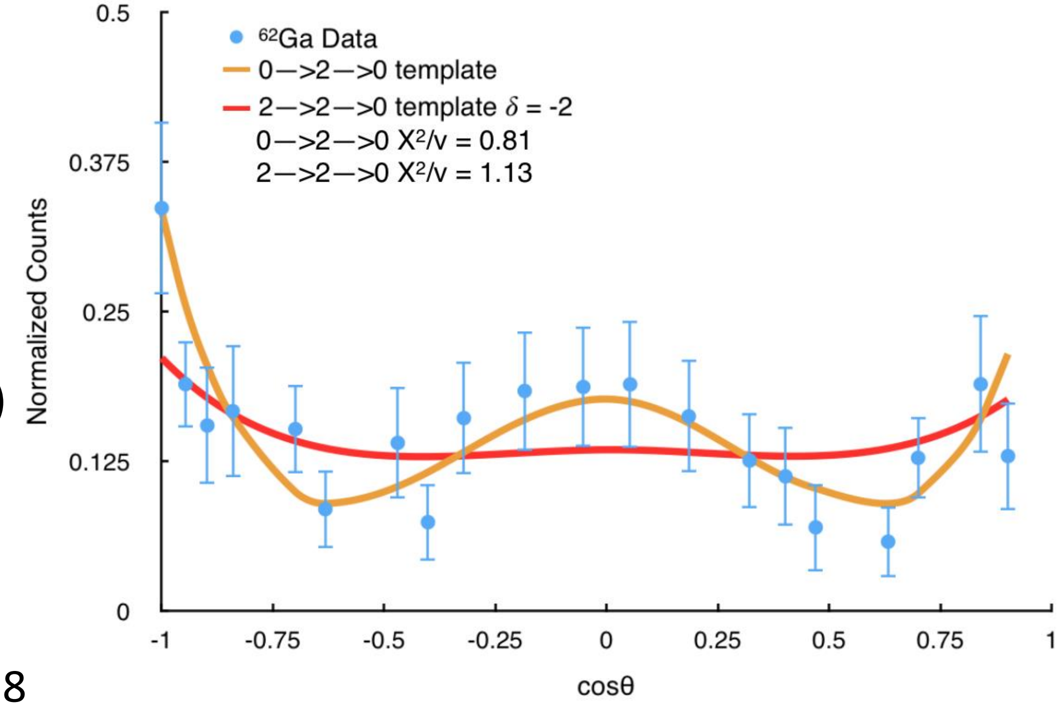


Why do we want to measure angular correlation functions?

The angular distribution/correlation functions carry information about the multipolarity of the emitted gamma rays, and help us to assign spin (and sometimes parity) to new nuclear states.



$$W(\theta) = A_0 \left(1 + a_2 P_2(\cos\theta) + a_4 P_4(\cos\theta)\right)$$



A_0, a_2, a_4… are coefficients

P_2, P_4 -> Legendre polynomials

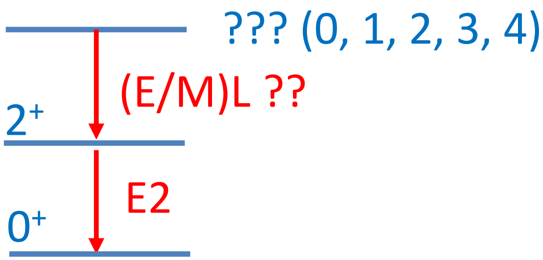
$P_2(\cos\theta) = (3 \cos^2\theta - 1) / 2$

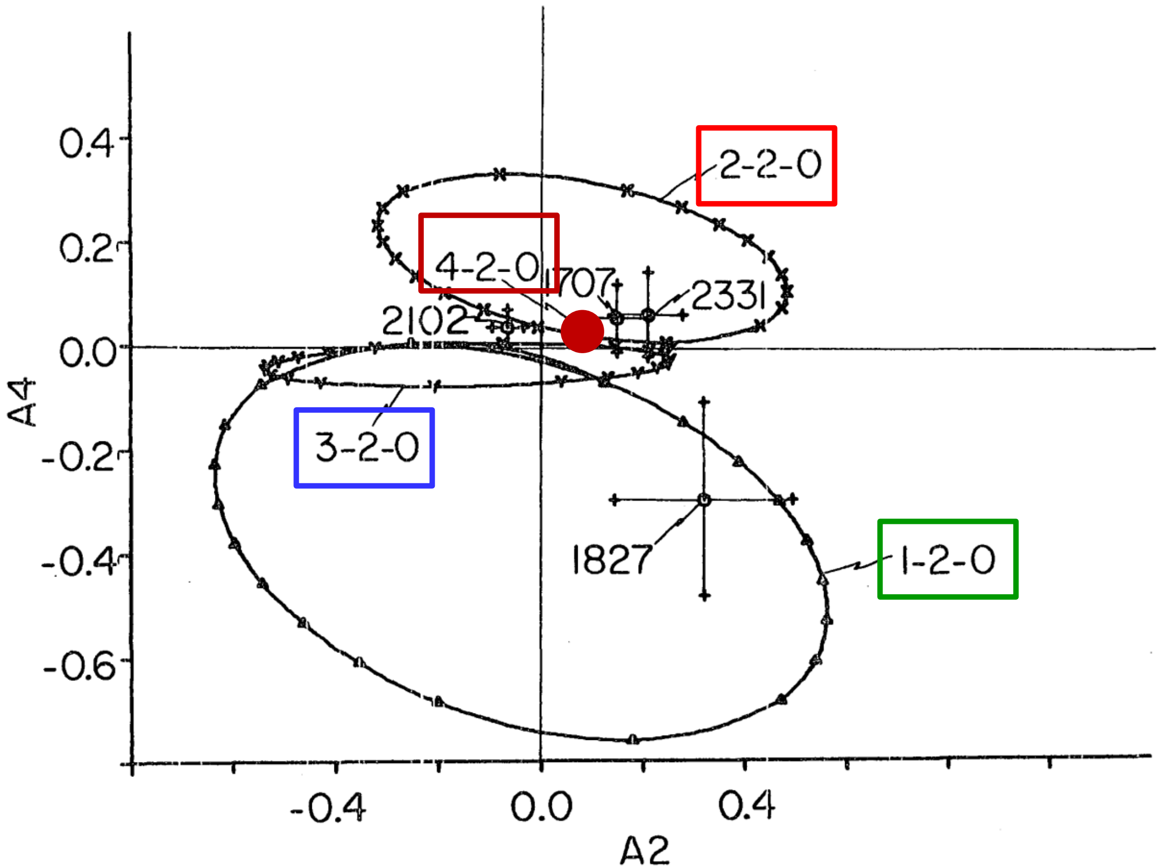
$P_4(\cos\theta) = (35 \cos^4\theta - 30 \cos^2\theta + 3) / 8$

fit experimental data with $W(\theta)$

extract a_2 and a_4

Compare experimental a2 and a4 with theoretical a2 and a4 for different multipolarities





4 → 2 → 0,
multipolarity → L = 2

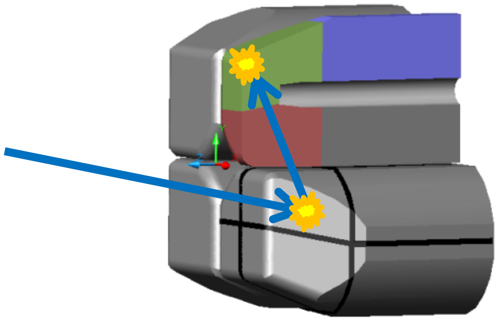
3 → 2 → 0,
multipolarity → could be mixed, e.g. M1 + E2
mixing ratio δ^2 = T(E2)/T(M1)

need good accuracy, particularly for measuring mixing ratios

e.g. many measuring angles
good statistics

iThemba LABS segmented clover

Team:
Dr. E.A. Lawrie,
Dr. T.D. Bucher, Dr. O. Shirinda, D. Duprez (BSc(Hons)), J.L. Easton (PhD), S.P. Noncolela (PhD), S. Mthembu (MSc), W.X. Mtshali (PhD), Dr. T.R.S. Dinoko, N. Erasmus, G. Andrews P. Maleka, P. Beukes, N. Kheswa, colleagues from medical radiations…

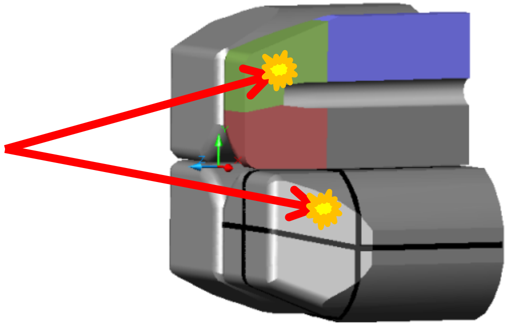


Segmented detector:
- 4 Ge crystals;
- each Ge crystal is 8-fold segmented

The segmentation provides extra capability:

✓ to distinguish Compton scattering of a single gamma ray from coincidence summing of two different gamma rays using **Pulse Shape Analysis and gamma-ray tracking**

✓ to use the segments as individual detectors



The drawback is:

○ needs development – characterization, simulations, etc

Gamma-ray angular correlation measurements with the segmented clover

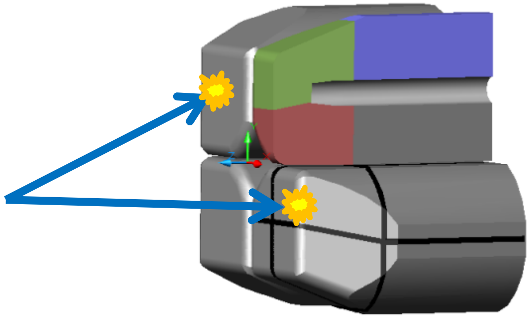
Idea:

- study beta-decaying nuclei
- use the segments as individual detectors (cross talk correction)
- place the source/activated sample at close distance,

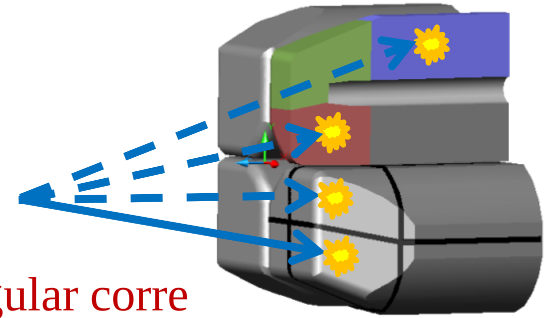
(high statistics, detector subtends ~ $\pi/2$ solid angle, large range for θ of close to 90^{o})

- measure angular correlation for coincident gamma rays detected in any two segments

Use $W(\theta)$ to determine the multipole order and the mixing ratios, etc.

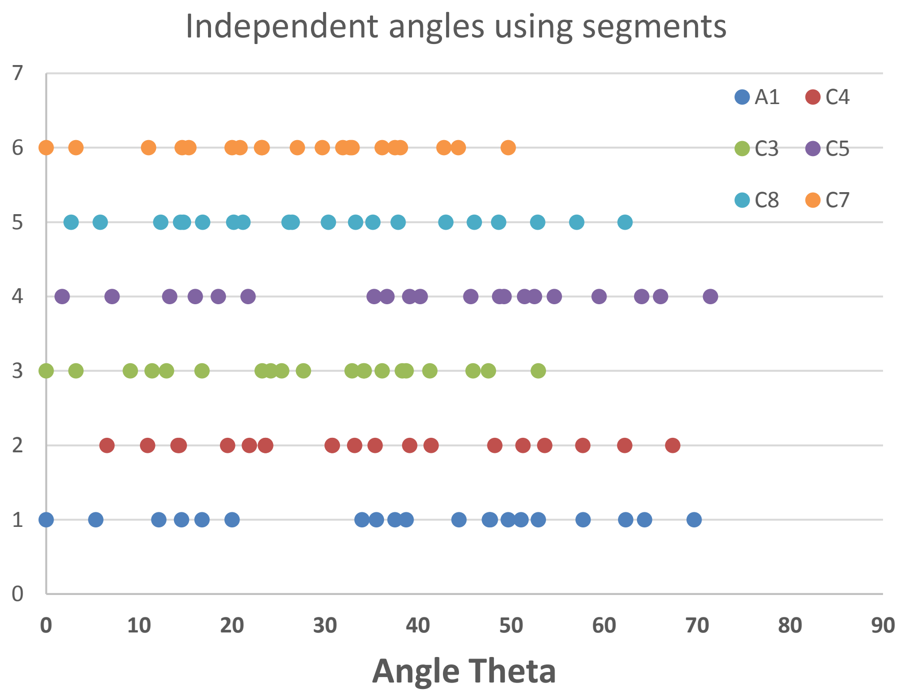


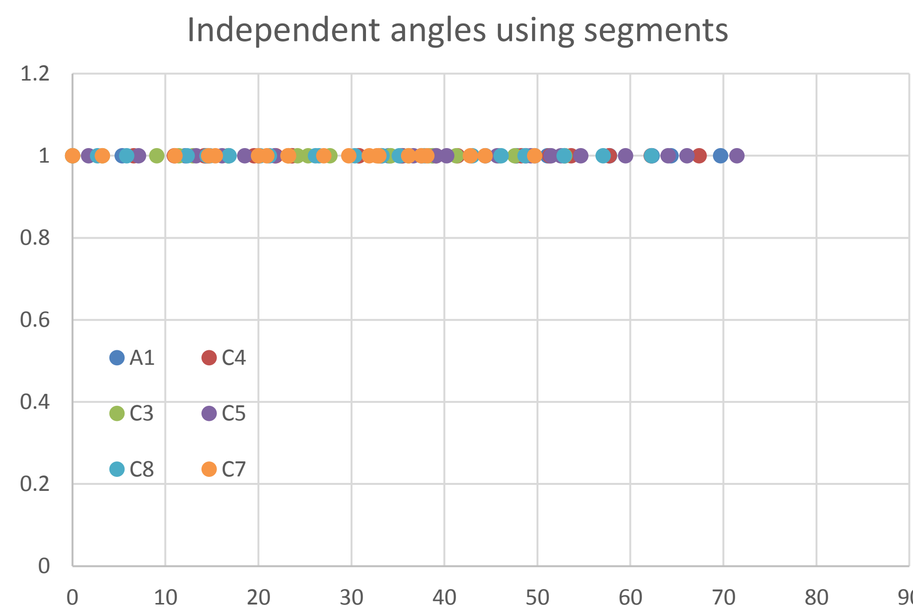
Angular correlations with the segmented clover angles



Advantages:

- ✓ at 4cm → large efficiency
- ✓ 32 segments → a large number of different angles,
- ✓ opening angle of ~ π/8 → covering the important angles for angular corre





for x0 = 0, y0 = 0, z = -40

xf & yf = 16, zf = 25 xb, yb = 16, 32, zb = 40mm

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allows precise angular correlation functions, important for large multipole order (M4, E5…), mixing ratios for (M1+E2)

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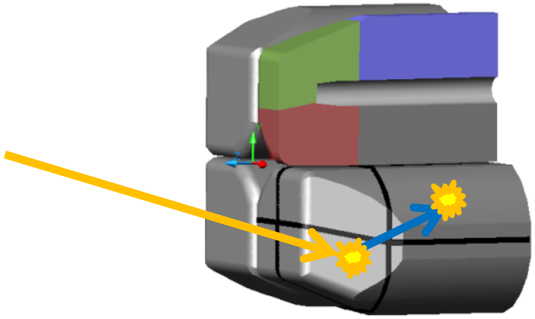
Photopeak efficiency

	Photopeak efficiency at 1.3 MeV addback Exp	Photopeak efficiency at 1.3 MeV segments only Exp
Segmented clover at 4 cm	2.9%	1.0%
AFRODITE 1 clover at 19.6 cm	0.2%	

Complicated analysis

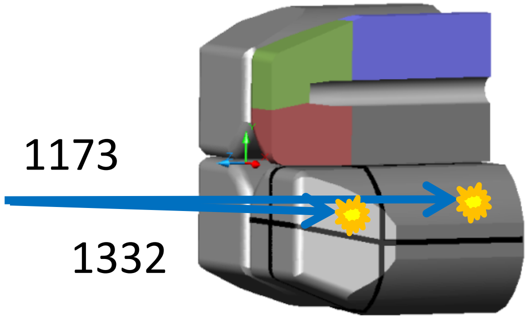
- segmentation produces proportional cross talk
- large probability for Compton scattering producing large Compton background



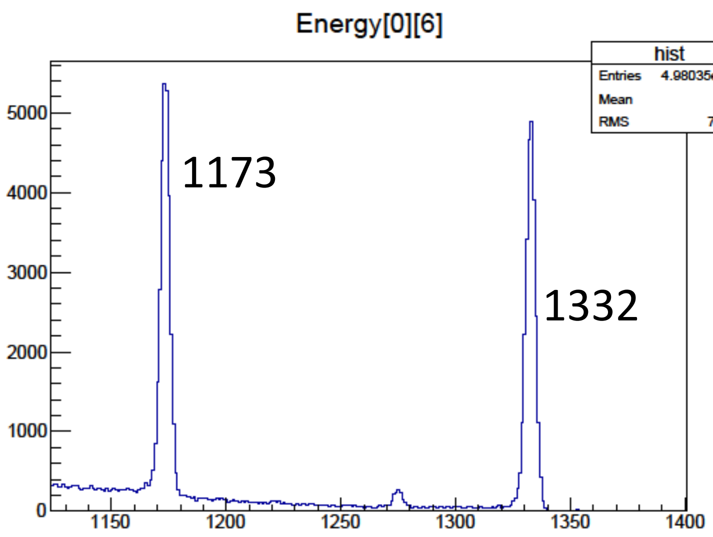
Proportional cross talk

Data analysis:

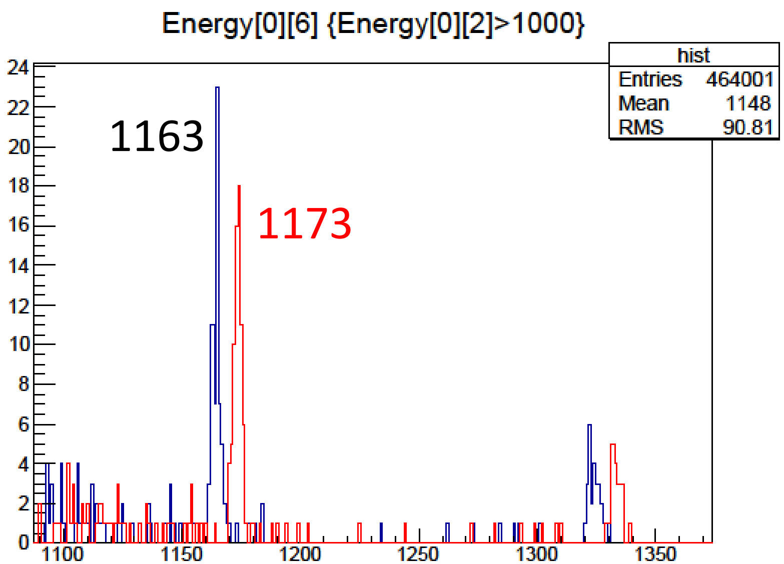
Energy calibration for all segments



single hit in segment 6 of crystal A



double hit – segments 6 and 2 of crystal A



energy shift is caused by proportional cross talk
cross talk correction recovers the correct energy

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S. Noncolela et al., Acta Phys. Pol. B 48 (2017) 347
T.D. Bucher et al., Phys. Scr. 92 (2017) 114004

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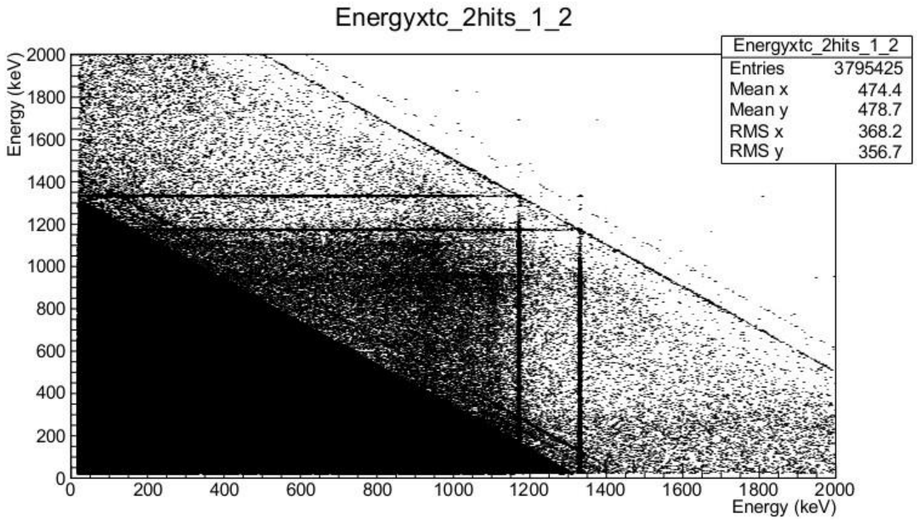
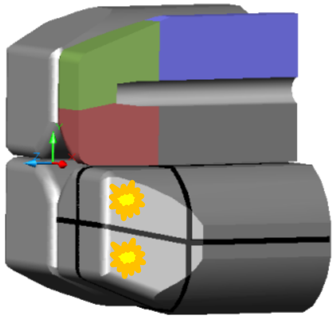
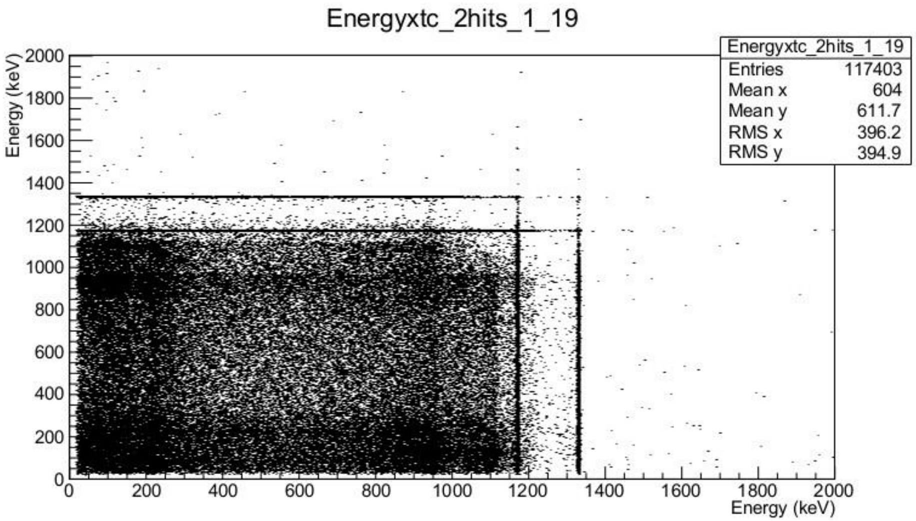
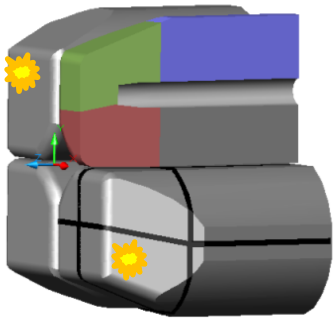
Working with large Compton background

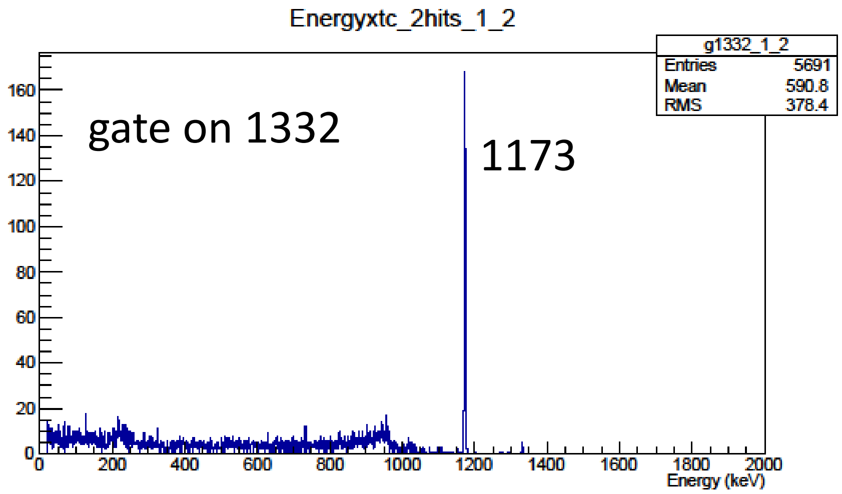


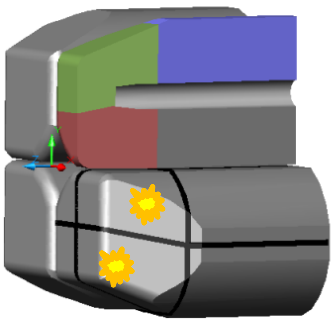


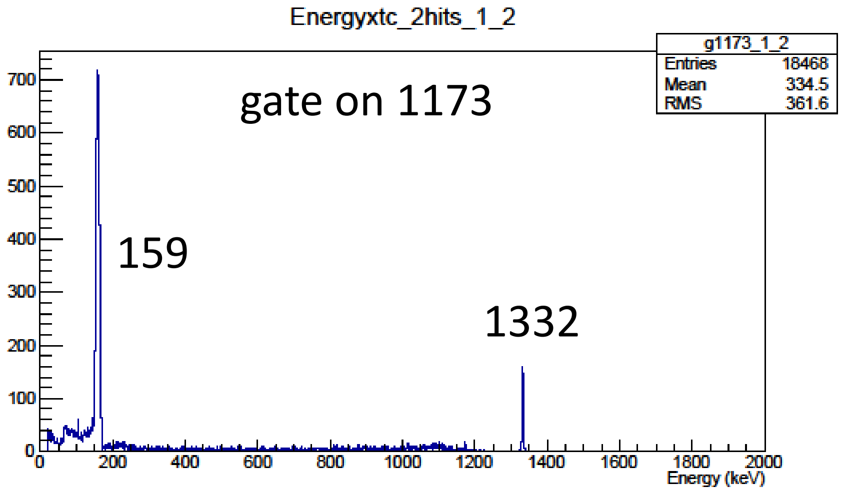




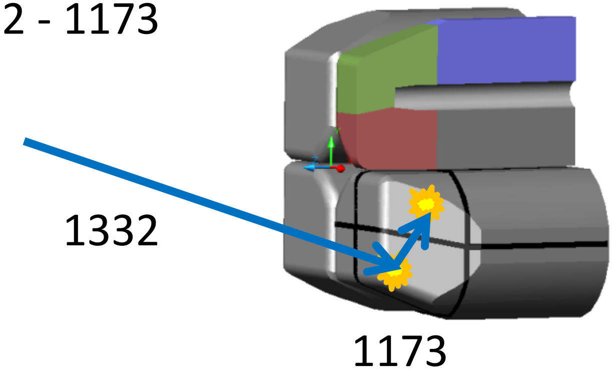
Gating in a matrix with large Compton background







Compton scatter peak
159 = 1332 - 1173



Examples of angular correlation measurements:

- for radioactive nuclei with long lifetime, months and years : ^{60}Co, ^{207}Bi, ^{133}Ba

- radioactive nuclei with medium lifetime, like days.

Produced, transported and measured with the segmented clover…

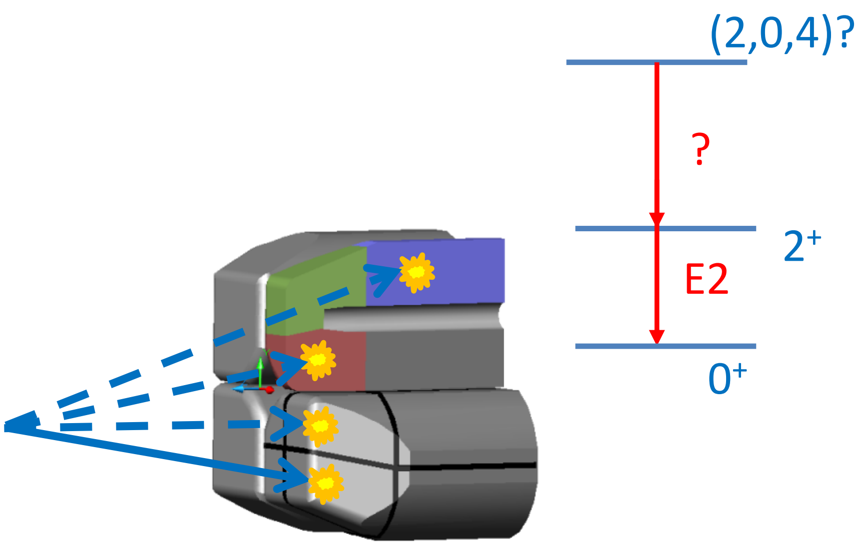
- radioactive nuclei with short lifetime, a few seconds or minutes.

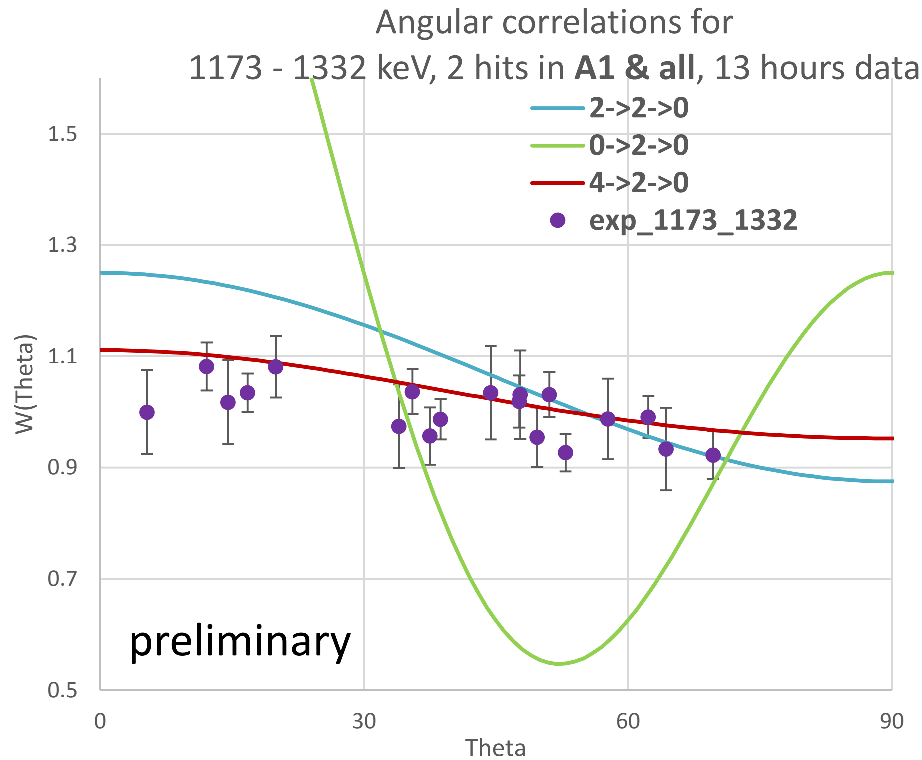
Produced, transported with a tape station, measured…

Angular correlations with the segmented clover long lifetimes ^{60}Co

16 hours of ^{60}Co data
angular correlations for 1173_1332 cascade
angular correlation matrices → Seg_i vs Seg_j

Partial data: 1332 is detected in seg1 of crystal A
(one out of 32 segments)

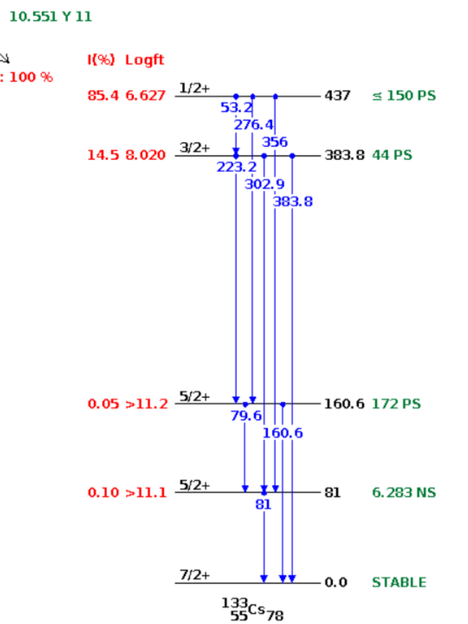


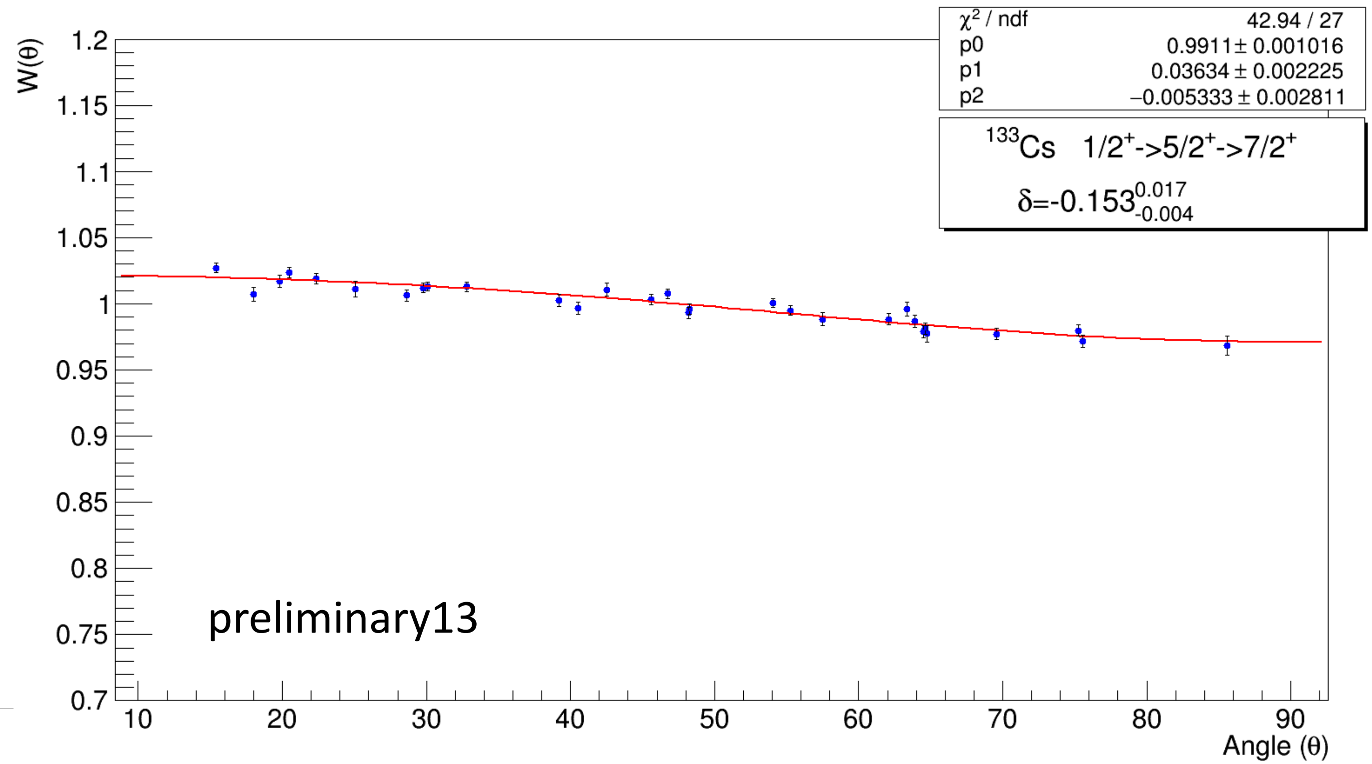


can distinguish unstretched dipole from stretched quadrupole

Angular correlations with the segmented clover
long lifetimes
^{133}Ba

12 hours of ^{133}Ba data, ^{133}Ba → ^{133}Cs
angular correlations for 356-81 cascade
which is E2 → M1+E2, δ = 0.158(5)
angular correlation matrices → Seg_i vs Seg_j





$\delta = -0.153\ ^{+0.017}\ _{-0.004}$

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analysis S.H. Mthembu

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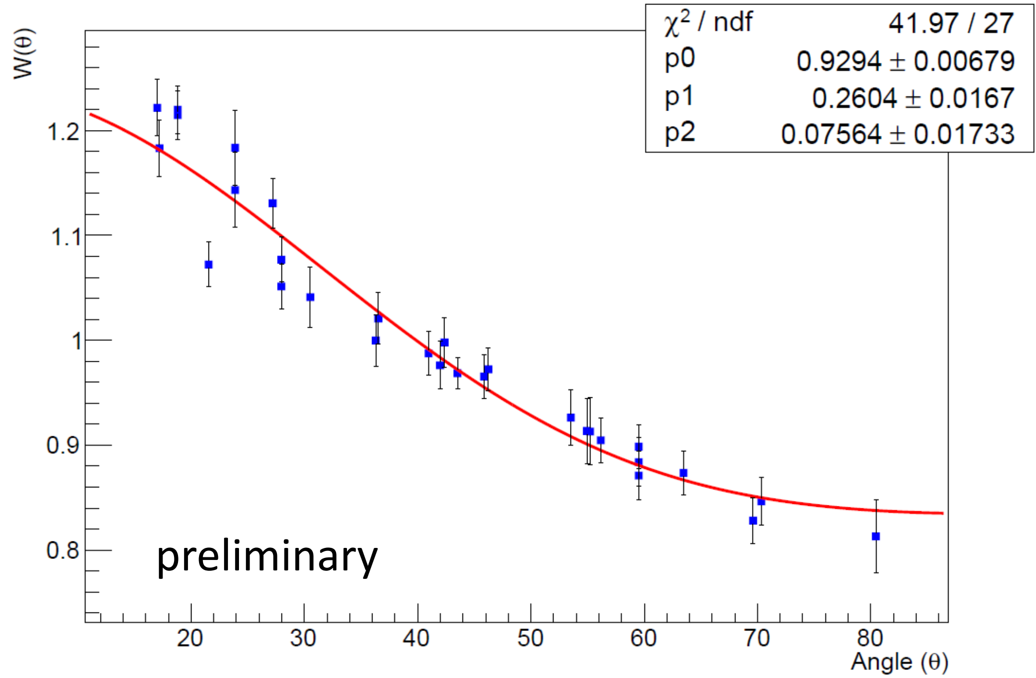
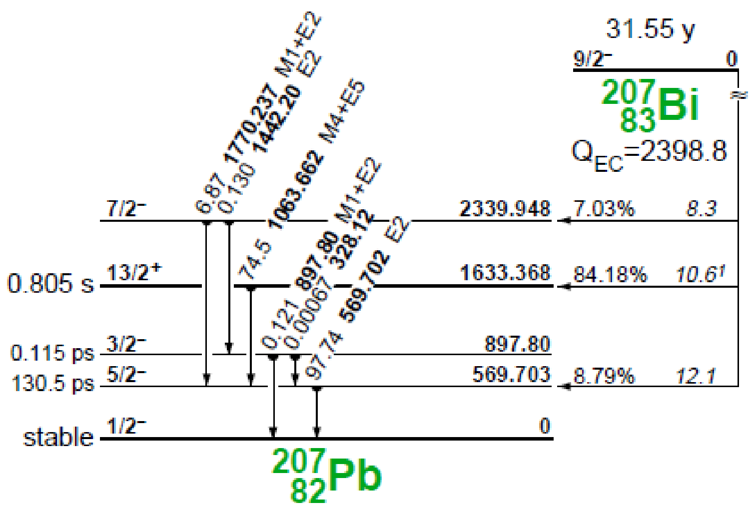
Angular correlations with the segmented clover
long lifetimes
^{207}Bi

24 hours of ^{207}Bi data
angular correlations for 570_1064 cascade
which is M4 + E5, δ = +0.02(1)
angular correlation matrices





Analysis of data → T.D. Bucher

Angular correlations with the segmented clover
medium lifetimes
Mo data

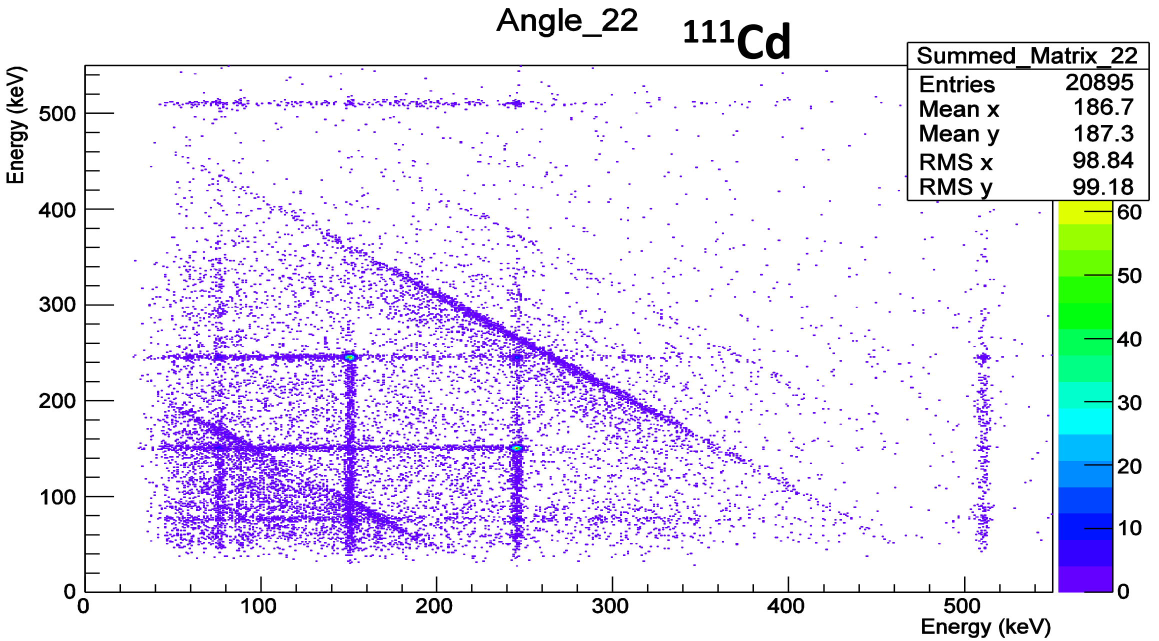
Targets : natural materials: Cd, Pd, Mo, Au, Ta, of 0.5 – 1 gr

irradiated the targets with neutron beam at up to 66 MeV in the neutron therapy vault

Activity after 2 hours of irradiation
5 – 23 μSv/h
Counting rate per crystal :
400 up to 6000 /s
Background rate : 100 /s

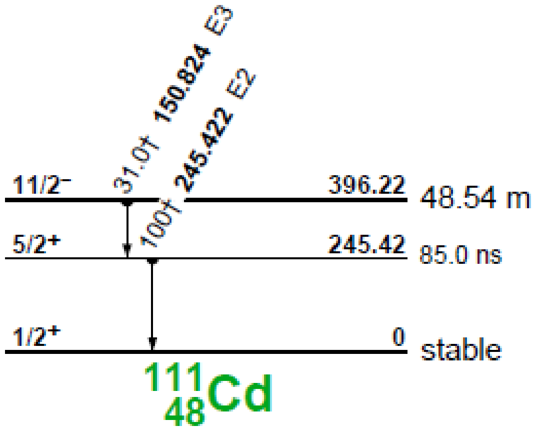
Angular correlations with the segmented clover
Cd data

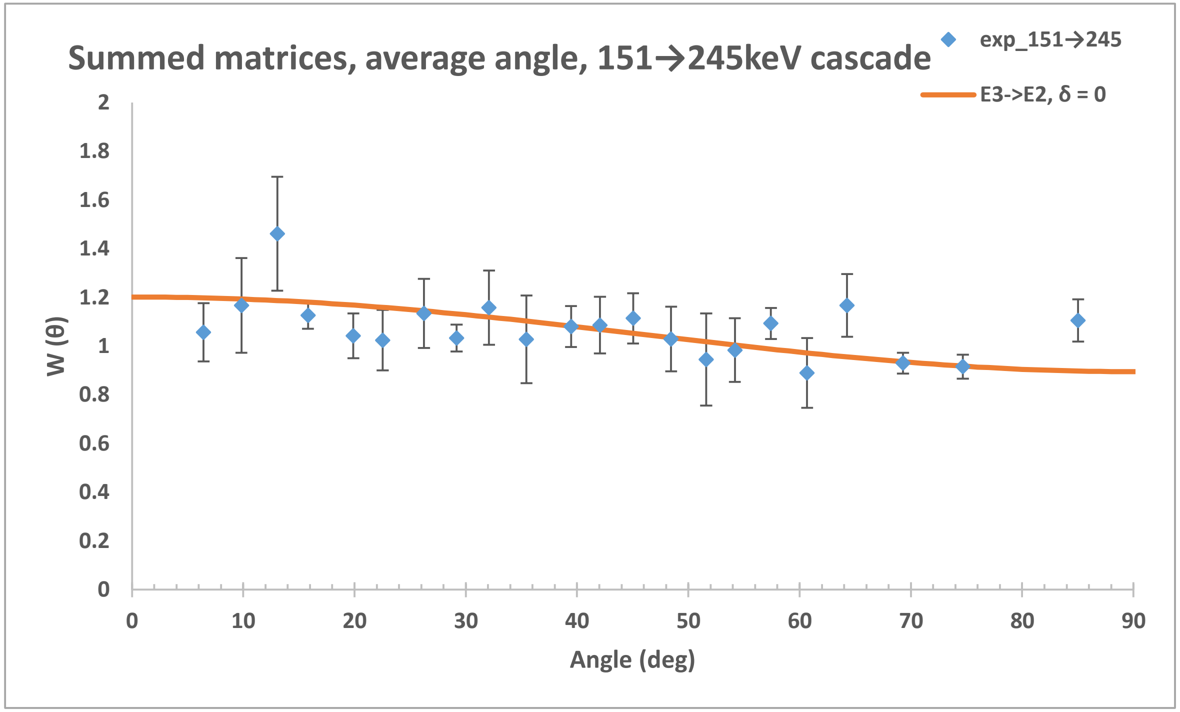
- Measurement took 14 minutes of ^{111}Cd data (IT decay, $T_{1/2}$ = 48.54 minutes)
- Count rate: 2.5kHz, background count rate of 100Hz
- To measure angular correlations for 151→245 keV cascade
- Sorted summed angular correlation matrices → Seg_i vs Seg_j



Analysis by O. Shirinda

Angular correlations with the segmented clover
^{111}Cd data





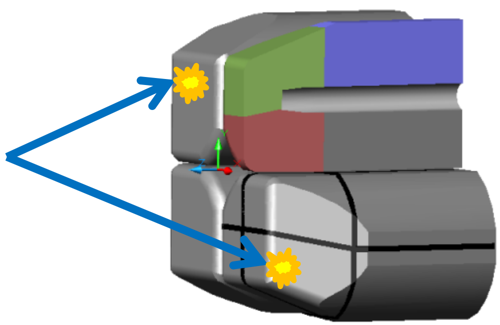
Analysis by O. Shirinda

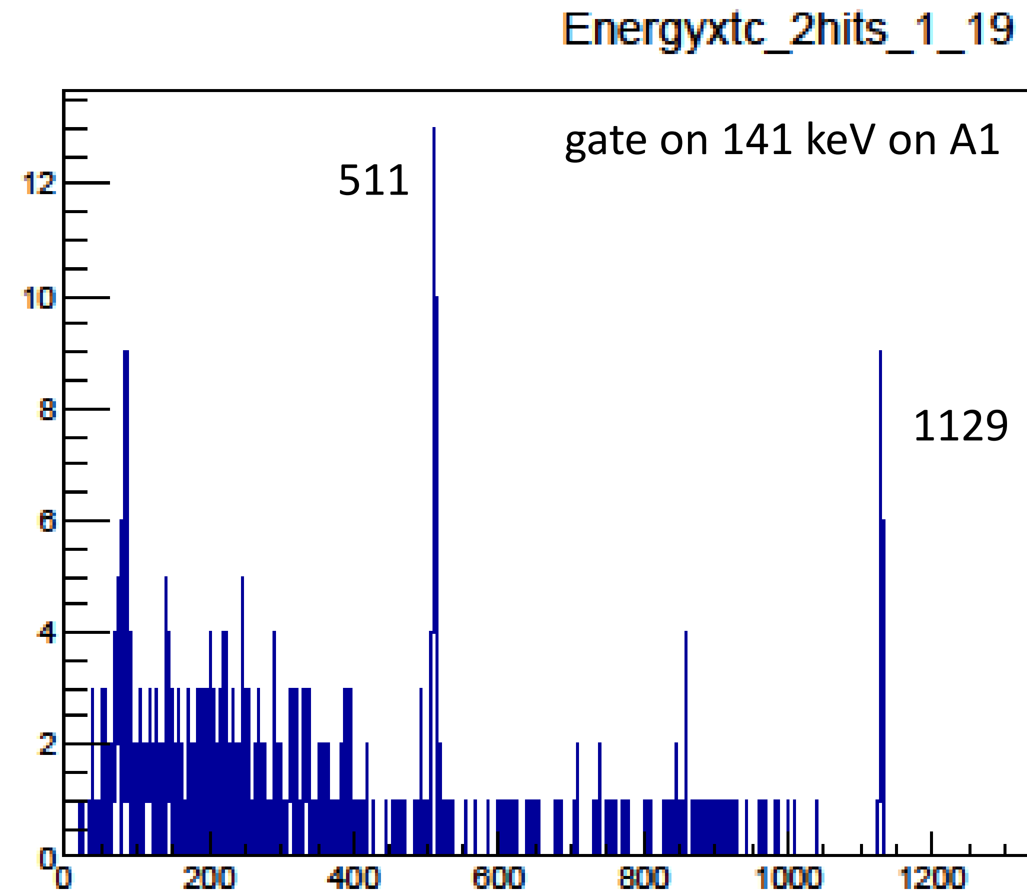
Angular correlations with the segmented clover
Mo data

beta-decay of Mo target, data taken for 11 hours

^{90}Nb → ^{90}Zr, 14.6h,
populating 8^+ state in ^{90}Zr,
half-life of 809ms

141 keV – 1129 keV cascade at large angle





141 keV is E2 (+M3)
1129 keV is E1 (+M2) according to nndc

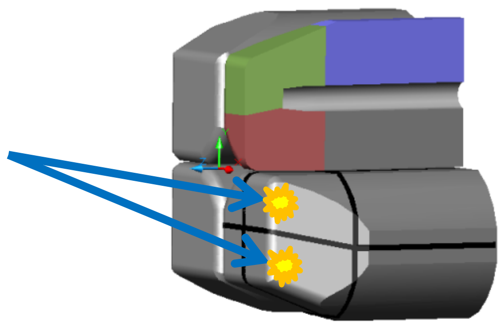
Analysis by J.L. Easton

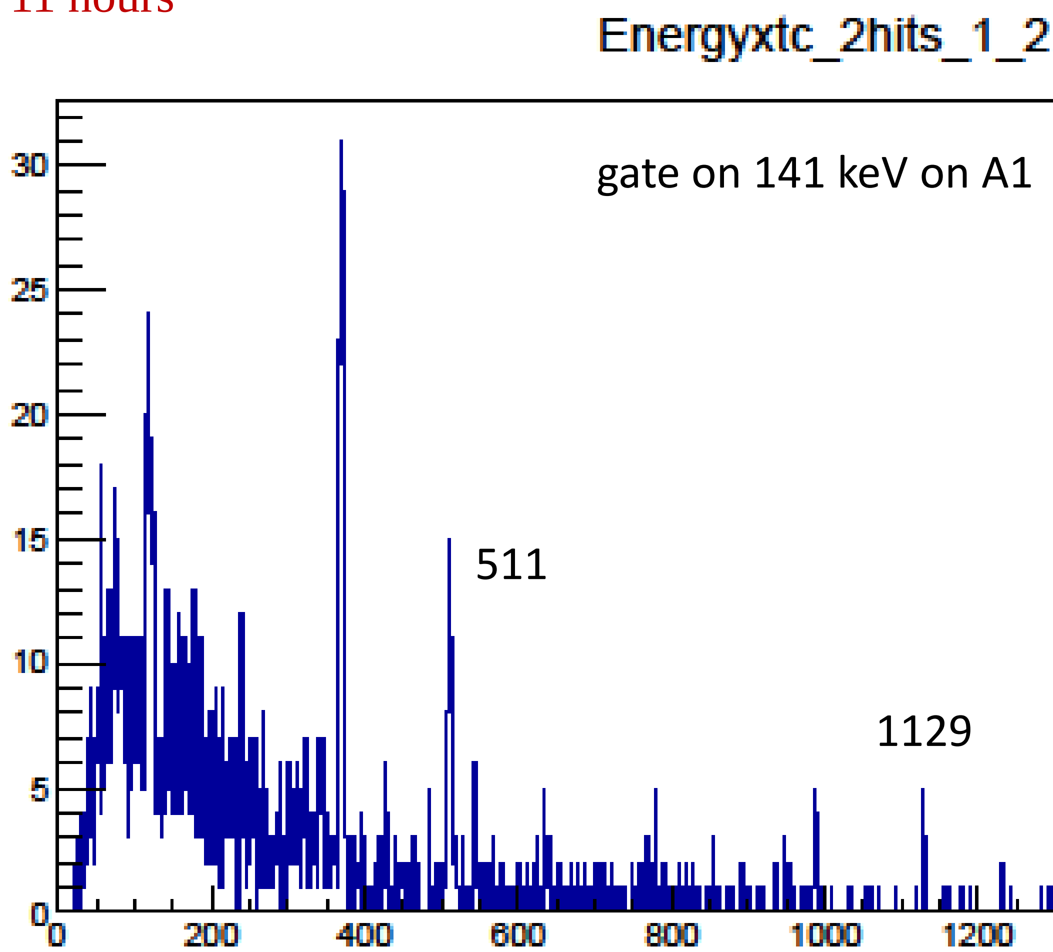
Angular correlations with the segmented clover
Mo data

beta-decay of Mo target, data taken for 11 hours

$^{90}Nb \rightarrow ^{90}Zr$, 14.6h,
populating 8^+ state in ^{90}Zr,
half-life of 809ms

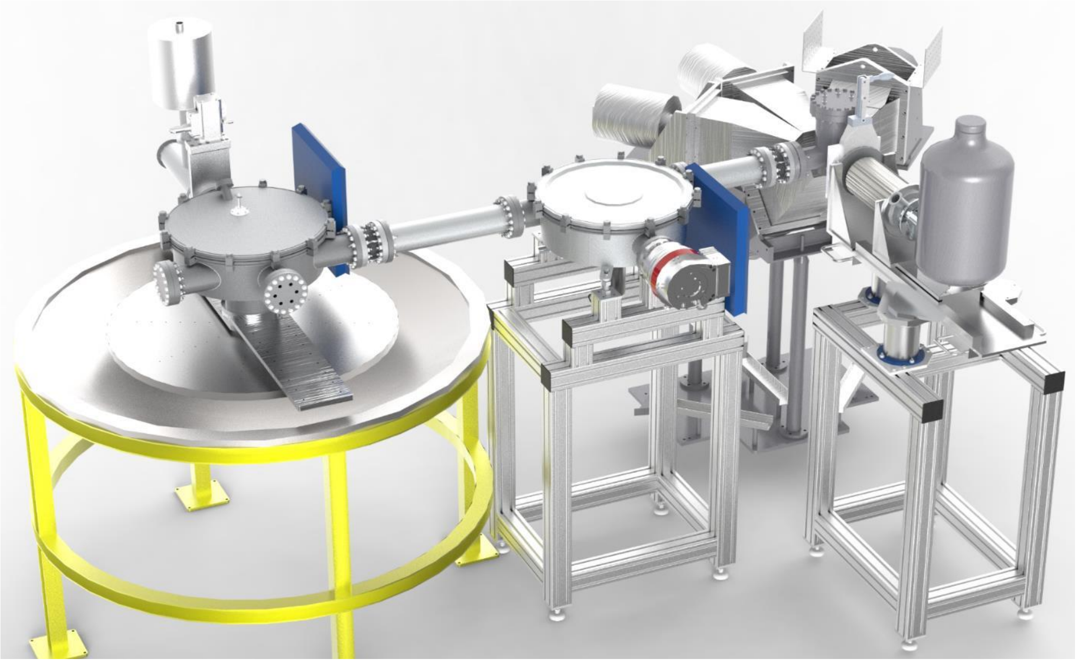
141 keV – 1129 keV cascade
at small angle





Analysis by J.L. Easton

Angular correlations with the segmented clover short lifetimes with tape station setup



tape station setup
by R.A. Bark and L. Makhatini

3 clovers
1 TIGRESS segmented clover
SiLi detector for conversion electrons

Two experiments carried out already

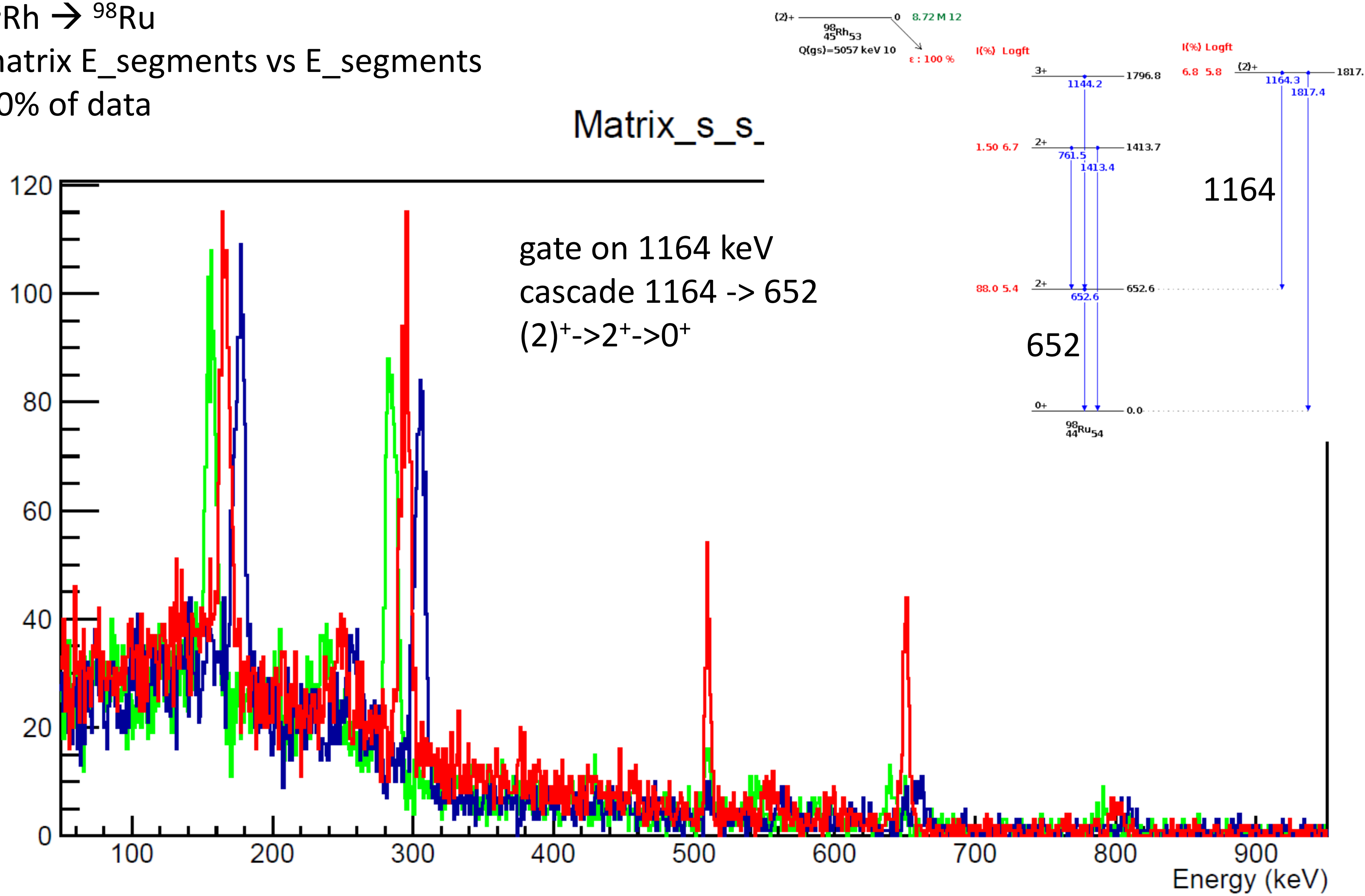
Clovers are at ~ 20cm, opening angle similar to that at Afrodite;
angles between segments → $5^o – 15^o$
small angles → very important for angular correlations

Angular correlations with the segmented clover
Ru data, spokesperson P. Garrett

$^{98}Rh \rightarrow {}^{98}Ru$

matrix E_segments vs E_segments

10% of data



What physics needs accurate angular correlations?

1. Testing vibrational models, need mixing ratios $\delta(E2,M1)$, spin/parity assignments

2. Testing for (transverse/longitudinal) wobbling, need $\delta(E2,M1)$

3. Testing shape co-existence, to deduce E0 in a E0+M1+E2 transition, need $\delta(E2,M1)$

4. Measuring deformation using Coulomb excitation, need $\delta(E2,M1)$

5. In rotational bands g-factors are related to $\delta(E2,M1)$

Summary

Current data on mixing ratios – scarce for the majority of nuclei, mostly determined in the 70s with much inferior detectors

Segmented clover – sensitive, powerful detector for angular correlations

Upgraded AFRODITE (through the GAMKA project) – will have 4 independent angles (31, 45, 71, 90), sufficient for accurate mixing ratios and angular correlation measurements

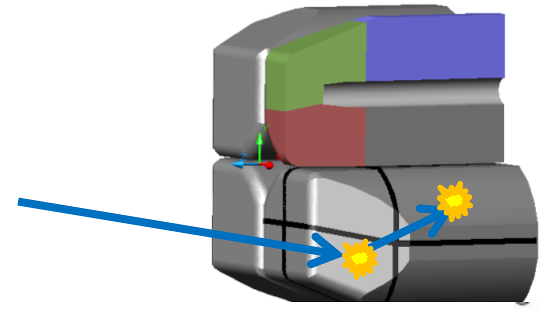
Angular correlations

a very interesting and promising area of research,

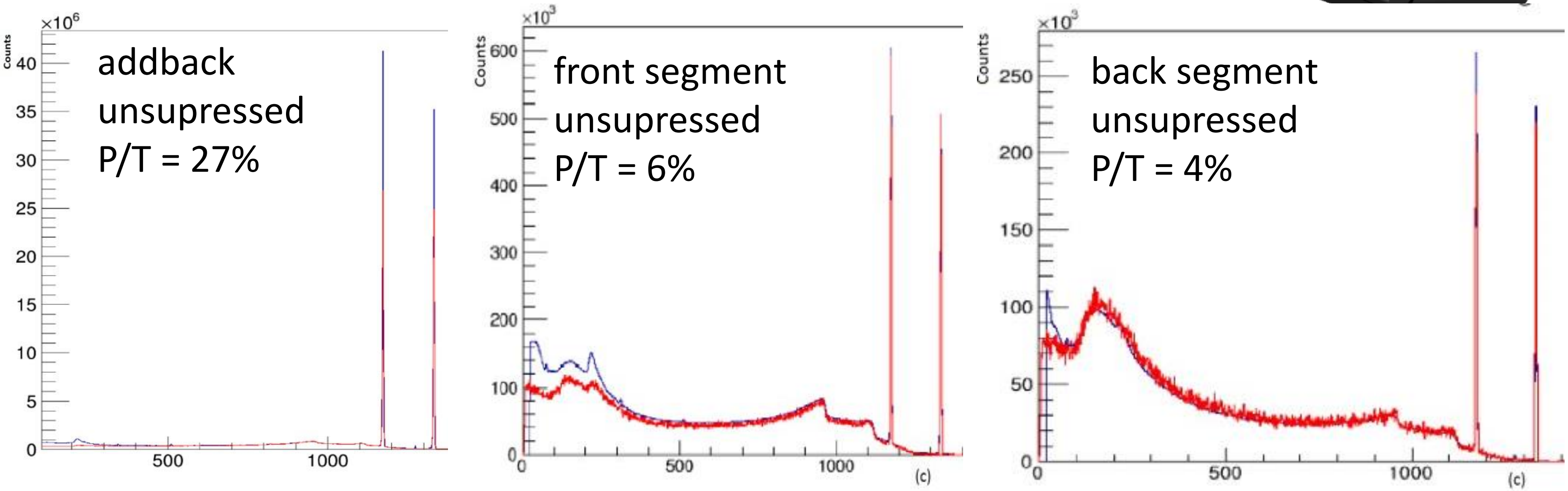
volunteers are very welcome

Disadvantages - large probability for Compton scattering

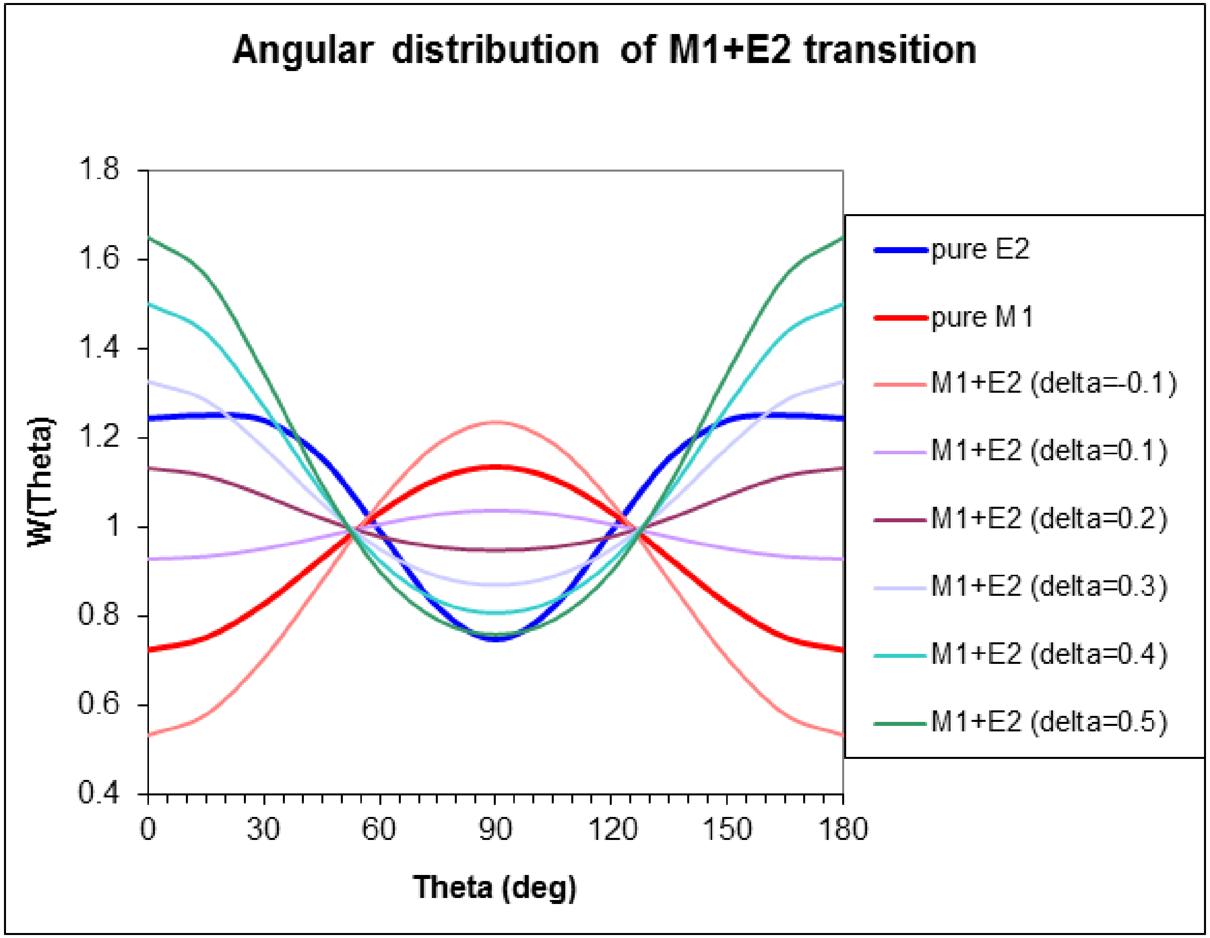
1 MeV gamma ray needs on average three interactions
in Ge medium to be absorbed



→ considerable addback between segments
large Compton continuum background



solution : gamma-ray tracking
recovers addback events without mistaking them with coincidence gamma rays


Angular distribution of M1+E2 transition
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
W(Theta)
0
30
60
90
120
150
180
Theta (deg)
pure E2
pure M 1
M1+E2 (delta=-0.1)
M1+E2 (delta=0.1)
M1+E2 (delta=0.2)
M1+E2 (delta=0.3)
M1+E2 (delta=0.4)
M1+E2 (delta=0.5)