NUCLEAR STRUCTURE WITH GAMMA-RAYS
PART II

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Exotic Beam Summer School 2014 – Oak Ridge, TN

THE PLAN

- Yesterday
  - Basics of gamma-rays
  - Interaction of gamma-rays in matter
- Today (Wednesday – July 30)
  - Practical Aspects – detection etc.
    - Types of detectors
    - Characterizing detectors
    - Tracking detectors
  - Experiments with gamma-rays
    - Polarization in Mg, neutron knockout, g-factors and lifetimes

OVERVIEW (II)

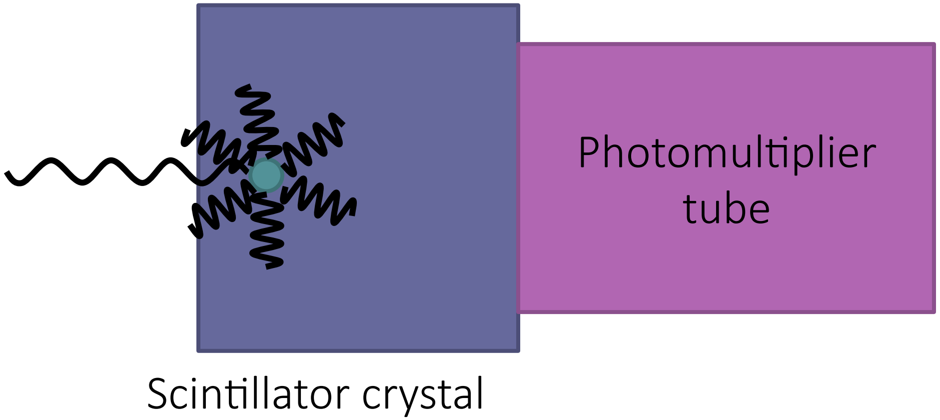
- Basic detector principles
  - Scintillators vs. semiconductors
  - Gamma-ray tracking arrays
- Examples of gamma-ray spectroscopy in nuclear structure
  - ^{24}Mg(p,p’) polarization
  - Neutron knockout
  - g-Factors
  - Lifetimes via the plunger method

GAMMA-RAY DETECTION: BASIC PRINCIPLES

- Fundamentally, we can detect a gamma-ray if it can leave energy in our detector that we can collect
- Gamma-rays primarily interact with electrons – most detectors therefore high *Z*
- Methods for measuring energy transferred to electrons vary… but we worry about 3 basic performance parameters:

- Energy resolution
- Efficiency
- Peak-to-total (P/T) – probability that a *detected* gamma-ray actually makes it into the peak

SCINTILLATORS

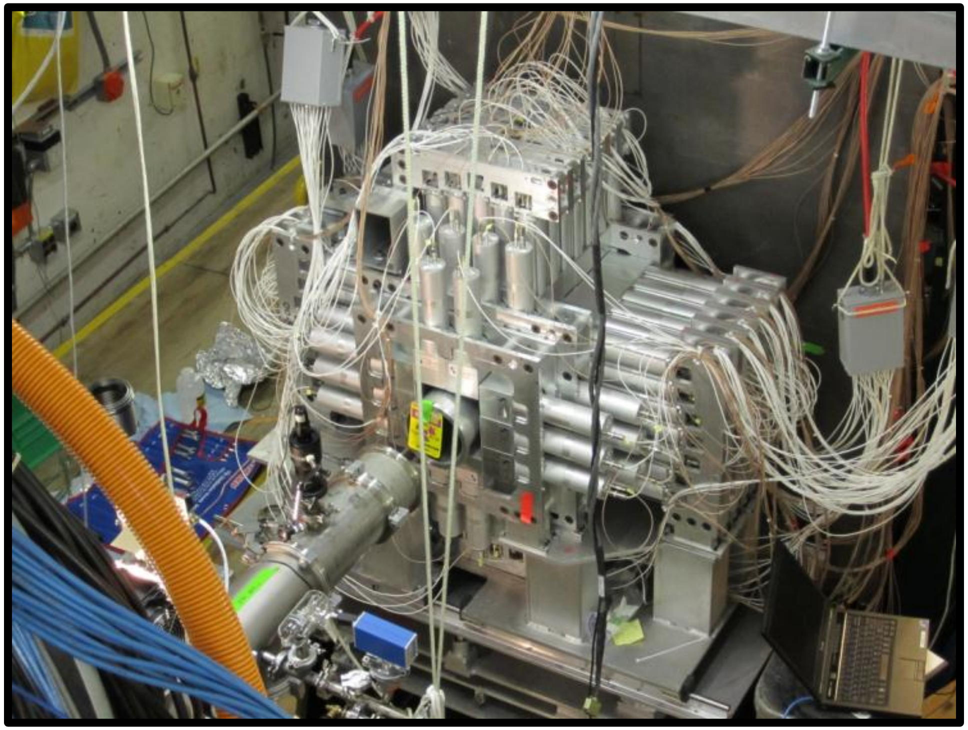


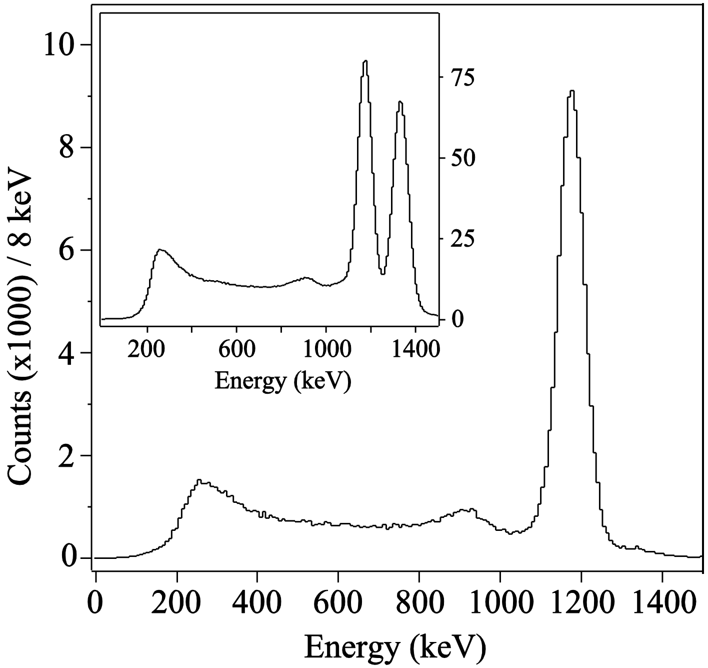
Photomultiplier tube

Scintillator crystal

High efficiency ~ 40%

Intrinsic energy resolution determined by statistics of photoelectrons in the PMT – for scintillators, resolutions ~ 6-7%



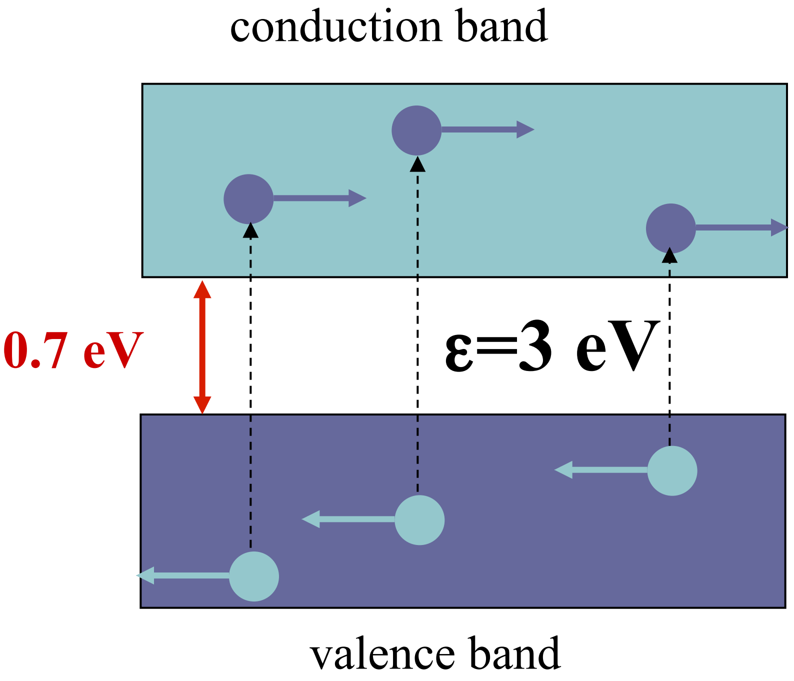


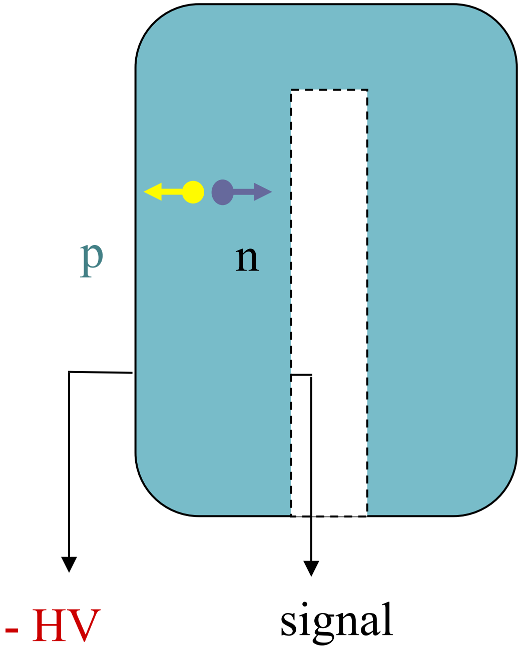
RESOLUTION IN SCINTILLATORS

- Energetic particle traveling through a detector (i.e. electron from gamma-ray interaction). Per length traveled dx, this particle may produce scintillation photon, which may make it to the photo-cathode, be converted to a photo-electron and contribute to a signal
  - CsI(Tl) yields 39,000 photons / 1 MeV gamma
  - Light collection + PMT efficiency = 15%
  - 6000 photons collected on average -- $\sigma = \sqrt{6000} = 77$
  - FWHM = 180 $\rightarrow$ dE/E = 3%

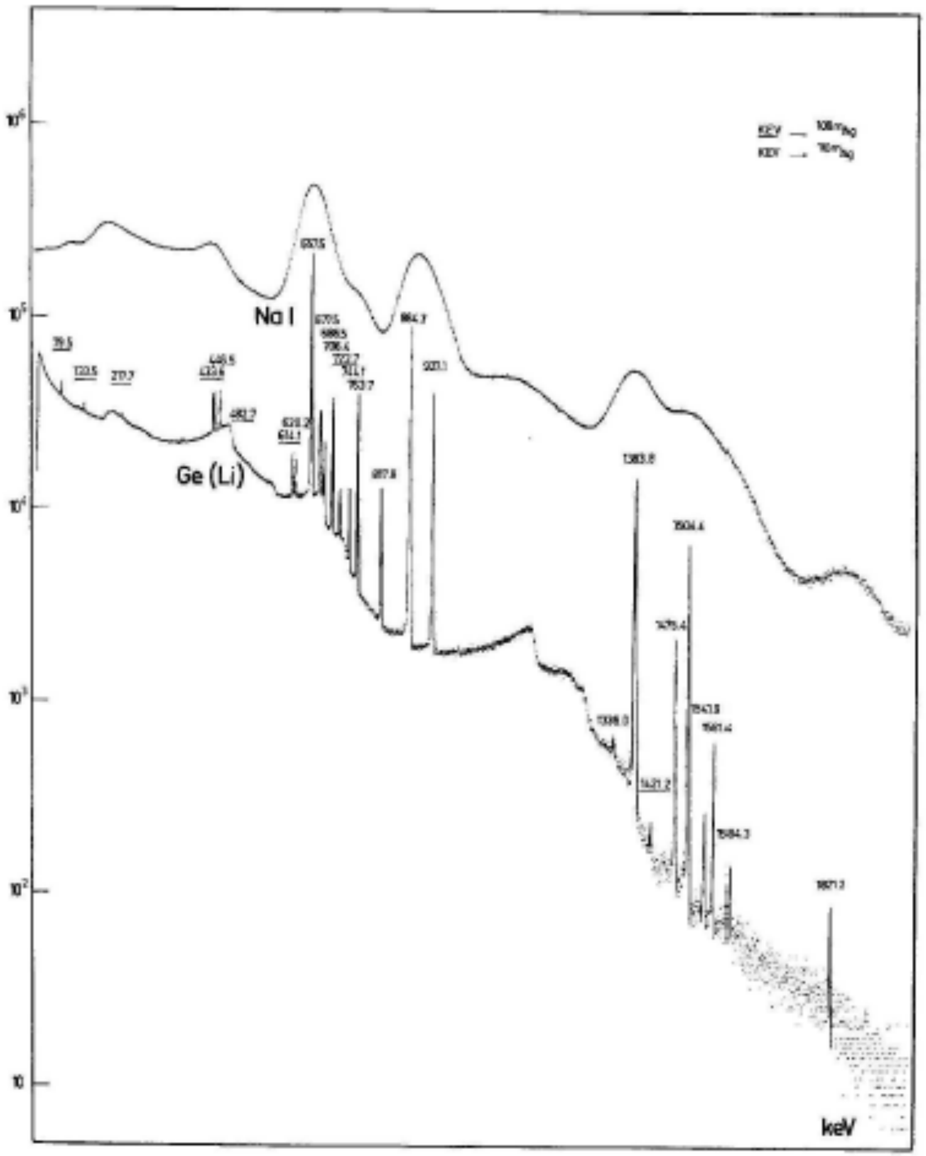
SEMI-CONDUCTORS

- Semiconductors like HPGe provide a gold standard for gamma-ray energy resolution
- Energy required to excite electron into the conduction band ~ 3 eV, many more electron-hole pairs than photons for a scintillator



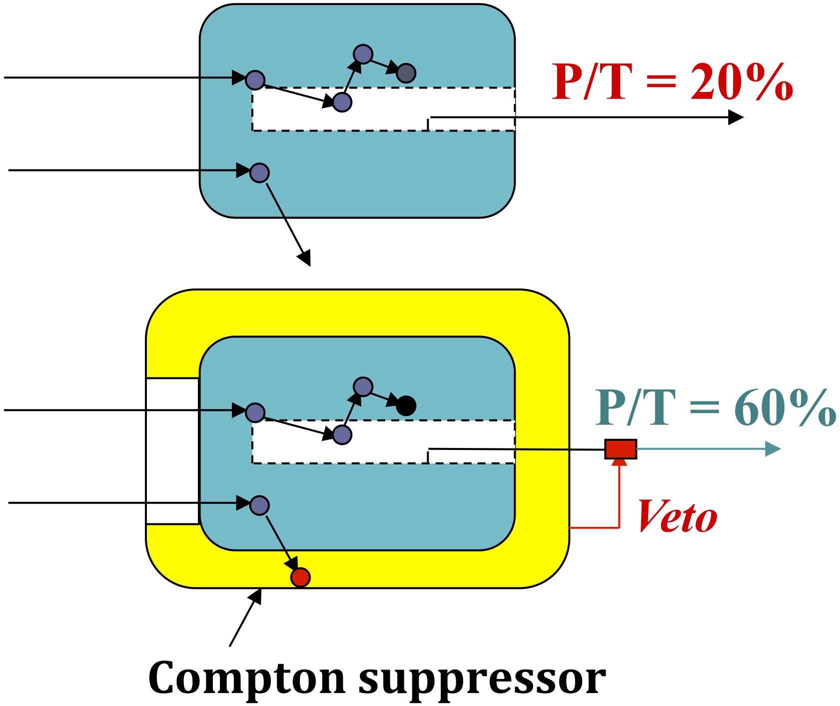


ENERGY RESOLUTION IN HPGe

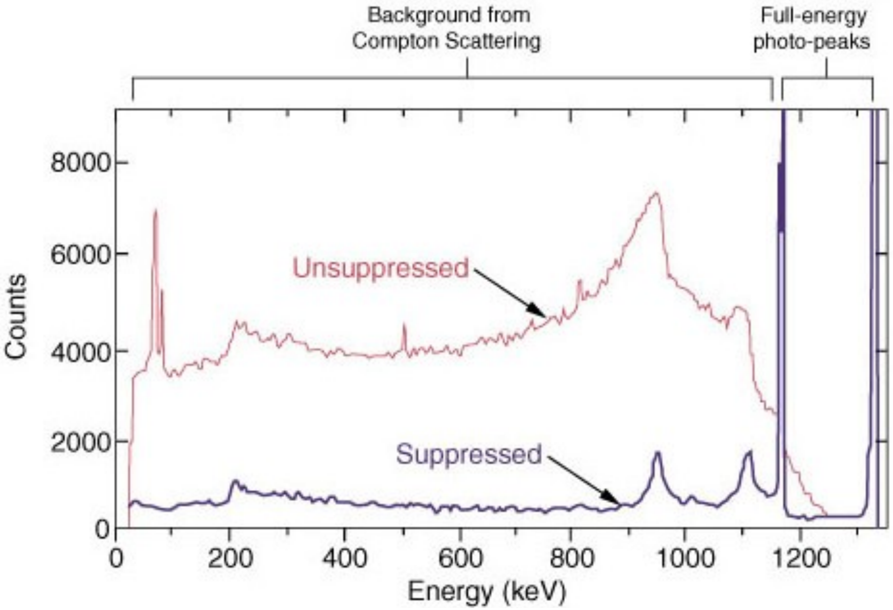


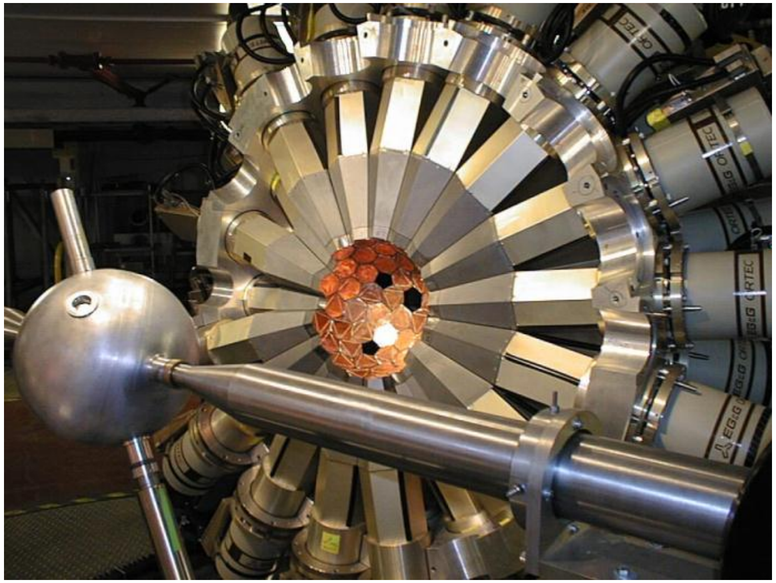
- Energy resolution for Ge is ~ order of magnitude better than scintillators
- So what are the downsides?
  - Very expensive (> $10K)
  - Smaller than scintillator crystals usually
  - Require cooling (LN_2)
  - Slower response (timing Ge 5-10ns; scintillator << 1 ns)

COMPTON SUPPRESSION



- Eliminate Eliminate contribution from Compton-scattered gamma-rays, which contribute to background, by vetoing these events using a high-efficiency scintillator surrounding the Ge crystal





QUESTION!

- Will Compton suppression shields **eliminate** the backscatter peak in a gamma-ray spectrum? What about the Compton edge?
  - (A) No; Yes
  - (B) Yes; No
  - (C) No; No
  - (D) Yes; Yes
  - (E) The backscatter peak and Compton edge are the same thing

QUESTION!

- Will Compton suppression shields completely **eliminate** the backscatter peak in a gamma-ray spectrum? What about the Compton edge?

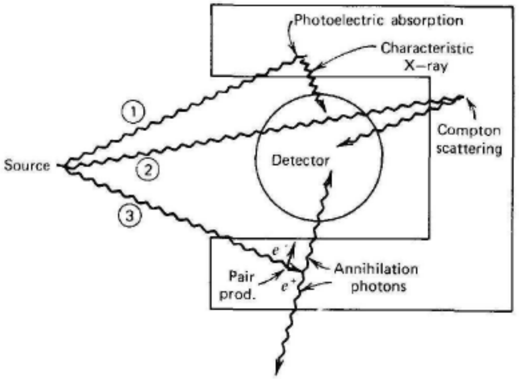
(A) No; Yes

(B) Yes; No

[✓ (C) No; No]

(D) Yes; Yes

(E) The backscatter peak and Compton edge are the same thing

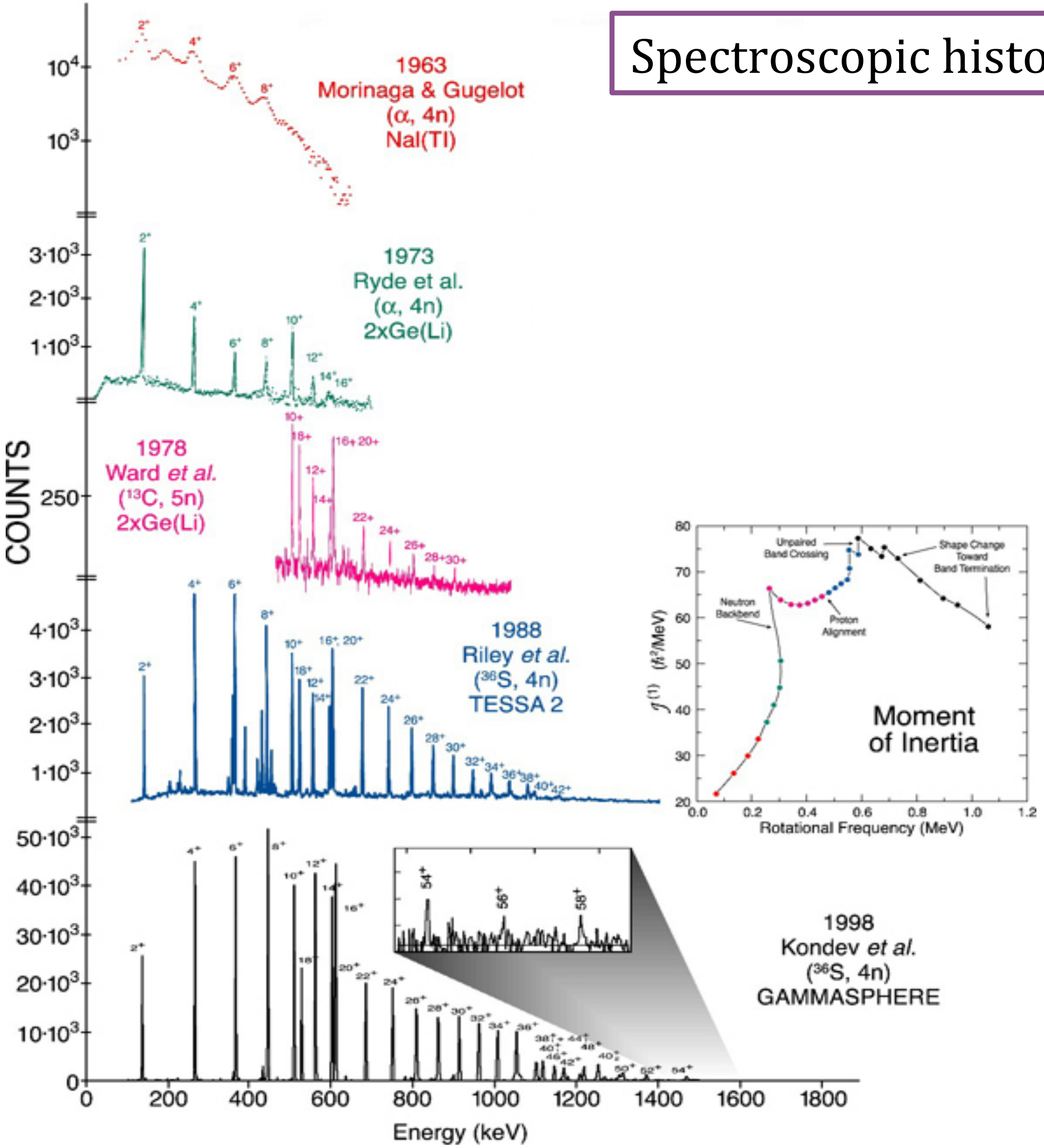


$$E' = \frac{E}{1 + \frac{E}{m_0 c^2}\,(1 - \cos\theta)}$$

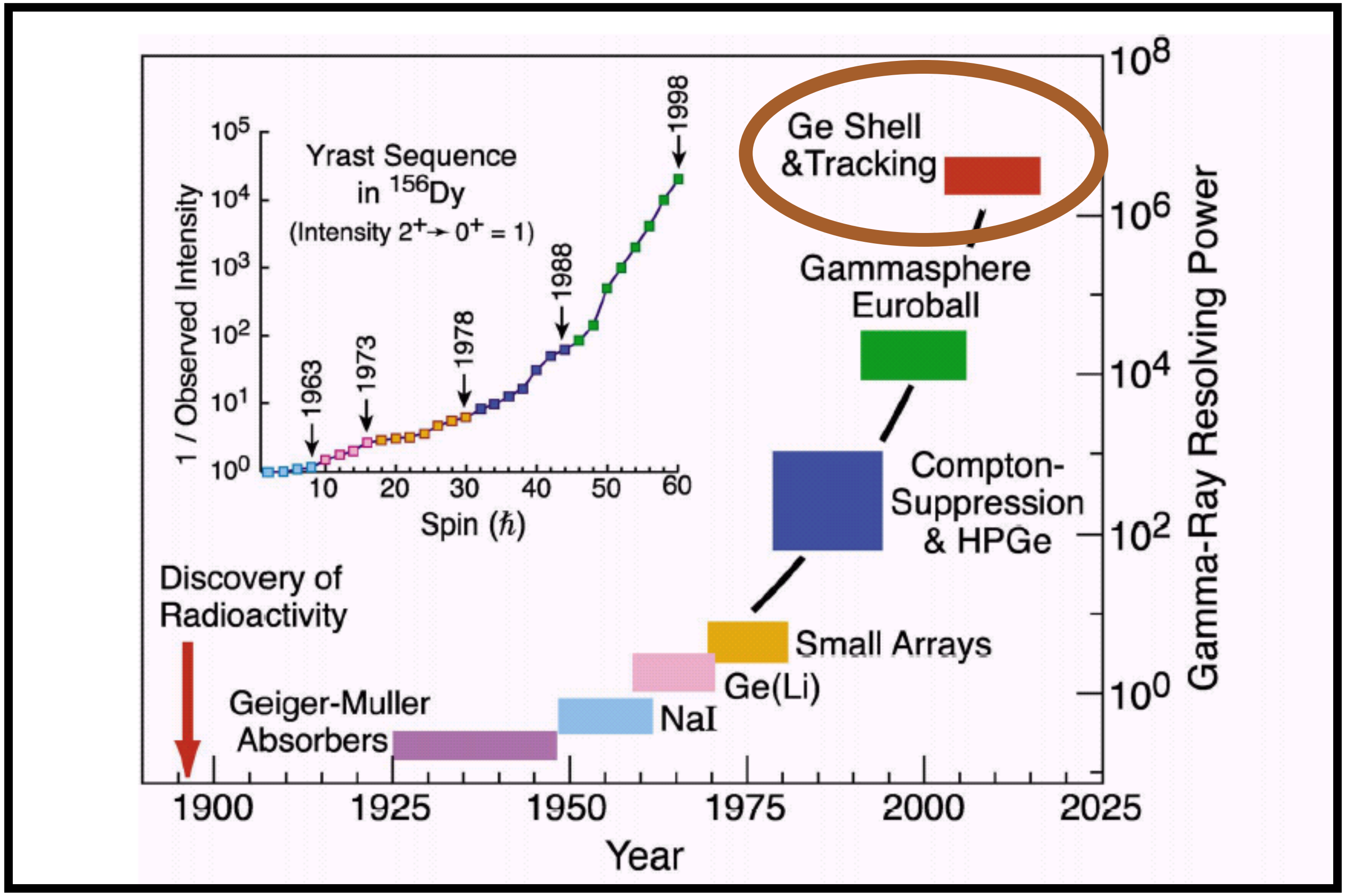
Compton edge when E’ is as small as possible – amount deposited in detector is large – corresponds to θ = 180°

TIMELINE OF γ-RAY SPECTROSCOPY

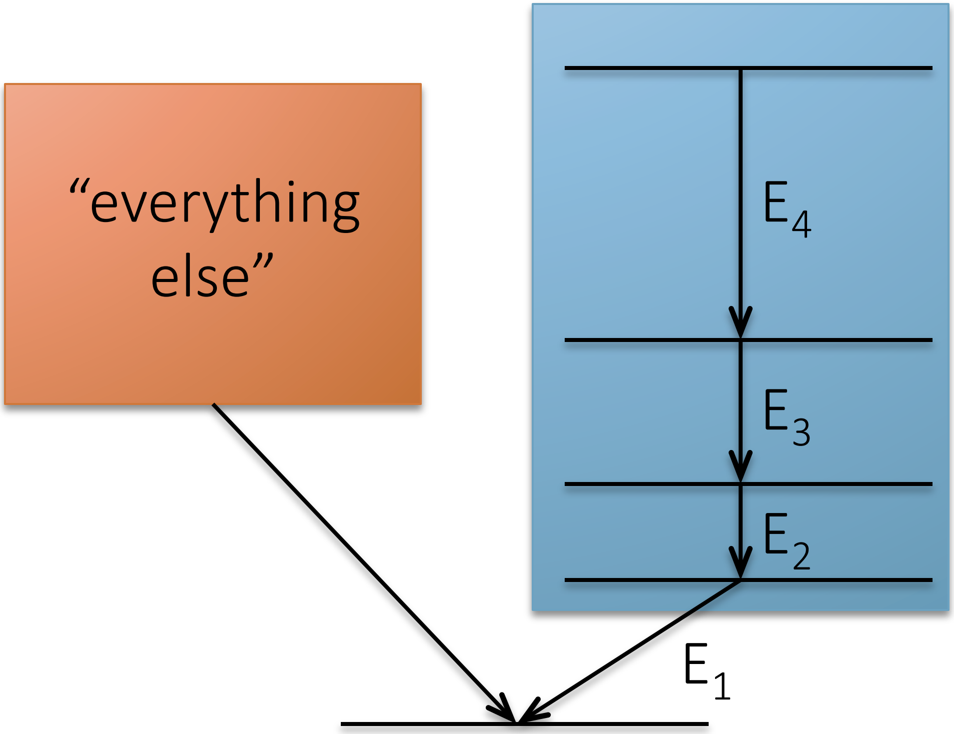
Spectroscopic history of ^{156}Dy



TIMELINE OF γ-RAY SPECTROSCOPY



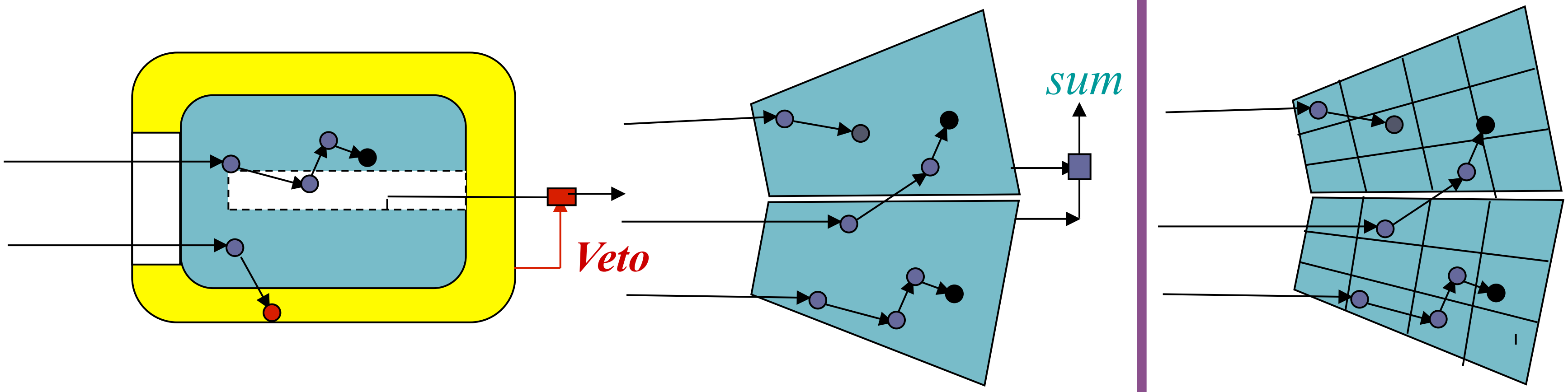
BENCHMARK: RESOLVING POWER



“everything else”

Gamma-Ray Energy Tracking Array

- Compton Suppressed Ge
- Ge Sphere
- Gamma Ray Tracking



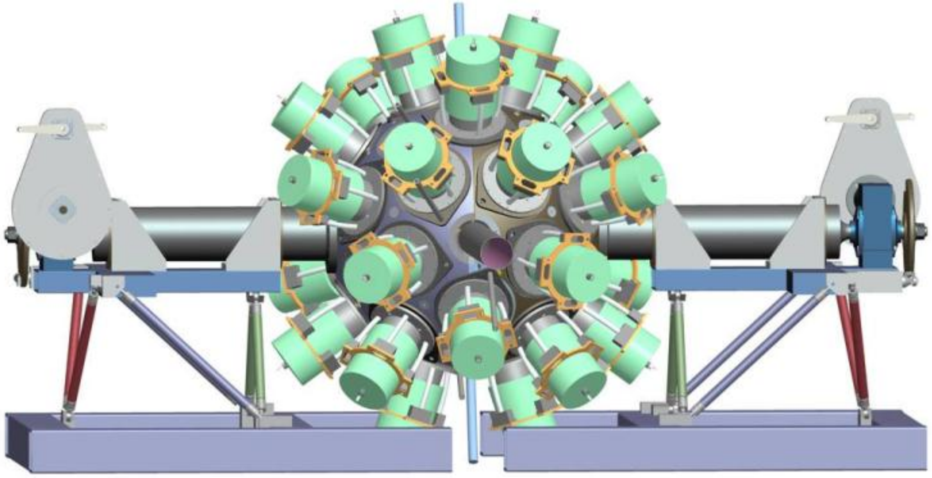
N = 100
NΩ e = 0.1
Efficiency limited

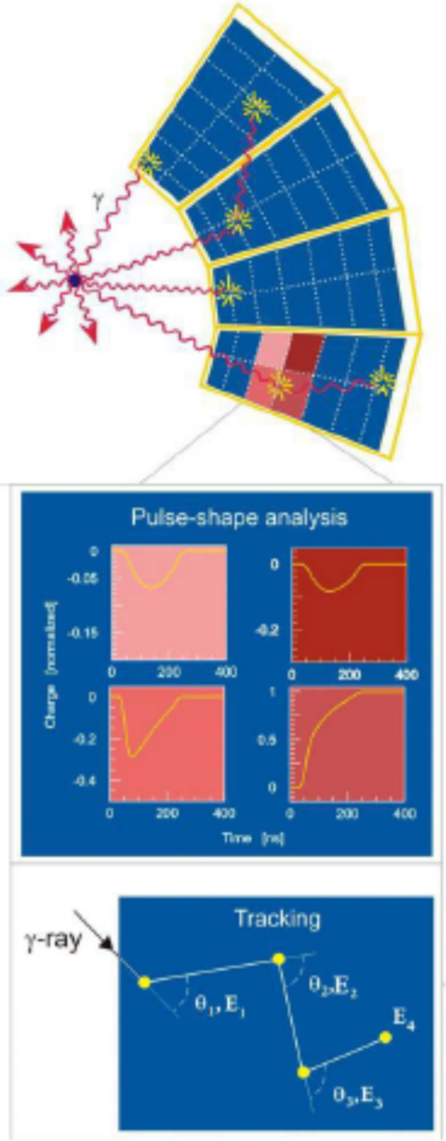
N = 1000 (summing)
NΩ e = 0.6
Too many detectors

N = 100
NΩ e = 0.6
Segmentation

Build a 4π sphere of Ge, using highly-segmented detectors
Gamma-ray tracking allows rejection of Compton scattering events,
Signal decomposition allows sub-segment position resolution

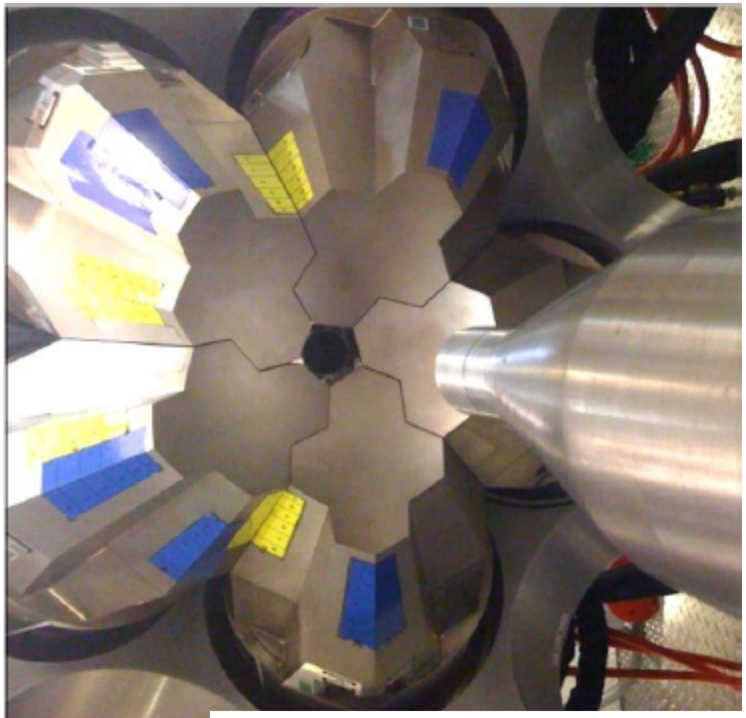
GRETA





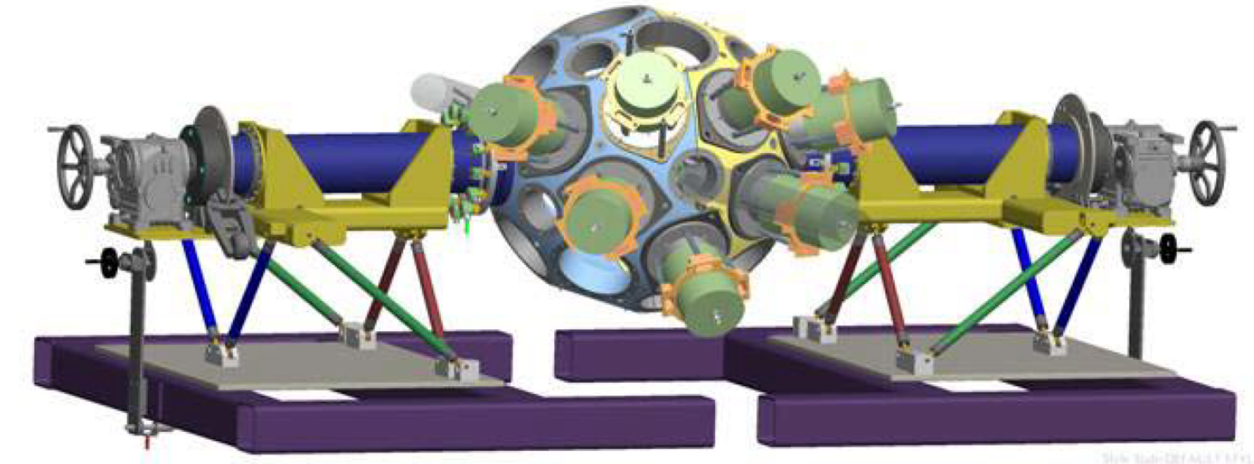
- GRETA will be a 4π solid sphere of HPGe, composed of 120 individual crystals, housed as quads
- Array will be self-shielding, signal decomposition and tracking allows for Compton rejection, and sub-segment first-hit localization for Doppler correction

GRETINA: ¼ OF GRETA (SORT OF)

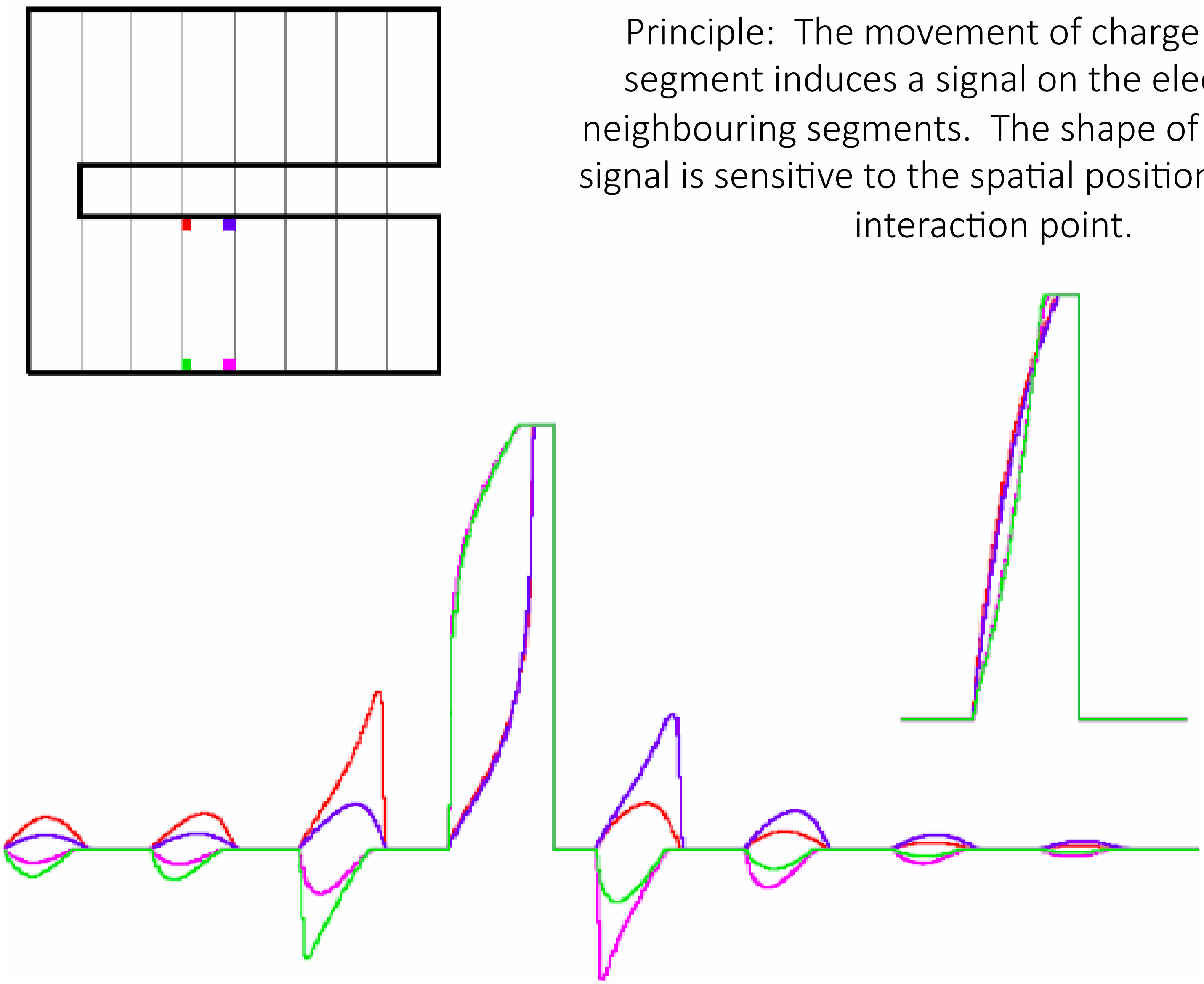


- GRETINA is the first-stage of GRETA, an array covering ¼ of 4π, consisting of 28 individual crystals in 7 quads
- Something to consider: ¼ of a full HPGe sphere is no longer self-shielding

Construction started at LBL in 2005
Commissioning runs at LBL finished in March, 2012

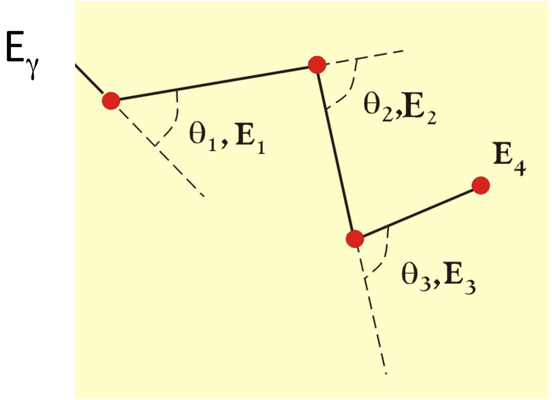


SIGNAL DECOMPOSITION

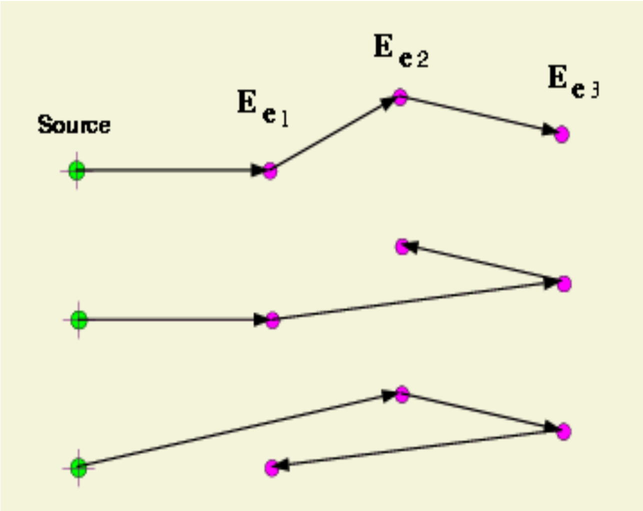


Principle: The movement of charge in a given segment induces a signal on the electrodes of neighbouring segments. The shape of this induced signal is sensitive to the spatial position of the γ-ray interaction point.

COMPTON TRACKING



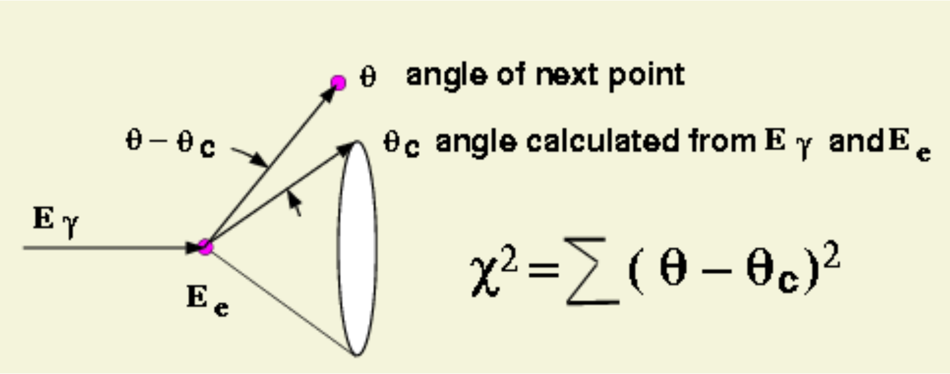
Problem: 3!=6 possible sequences



$$E_e = E_\gamma\left(1-\frac{1}{1+\frac{E_\gamma}{0.511}(1-\cos\theta)}\right)$$

Assume:

- $E_g = E_{e1} + E_{e2} + E_{e3}$
- γ-ray from the source



Sequence with the minimum $\chi^2 < \chi^2_{max}$
→ correct scattering sequence
→ rejects Compton and wrong direction

→ Low-energy single interaction point γ-rays don't track

SO WHAT DO WE GET FROM GRETINA?

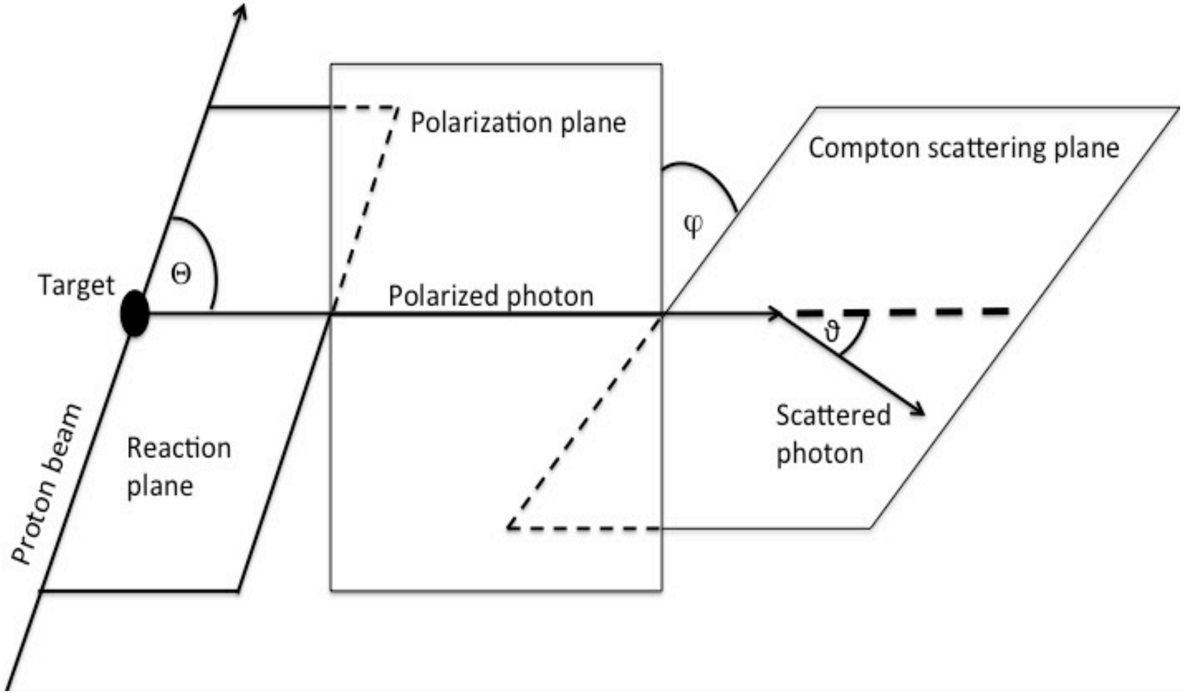
- GRETINA (GRETA) provides us the benefits of Ge resolution, the background reduction of suppression and the maximum efficiency by allowing the most detector material to be in place
    - More resolving power than any previous array

- Do we gain anything else?

POLARIZATION IN GRETINA

^{24}Mg(p,p'g)^{24}Mg, E_p = 2.6 and 6 MeV

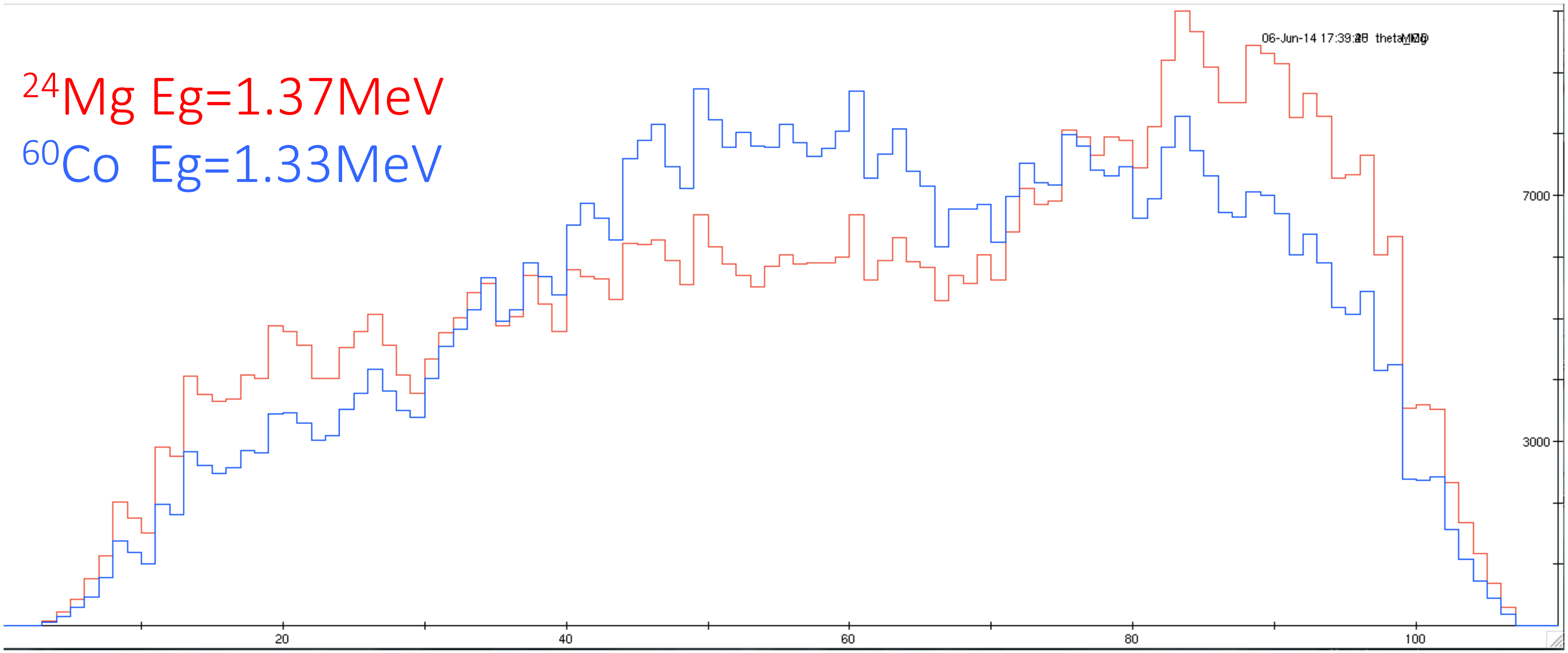
P(2^+,M=0) $\sim$ 100% P(M=1) $\sim$ few %



$$\frac{d\sigma}{d\Omega}(\vartheta,\varphi) = \frac{r_0^2}{2}\left(\frac{E_{\gamma'}}{E_\gamma}\right)^2\left[\frac{E_{\gamma'}}{E_\gamma} + \frac{E_\gamma}{E_{\gamma'}} - 2\sin^2\vartheta\cos^2\varphi\right]$$

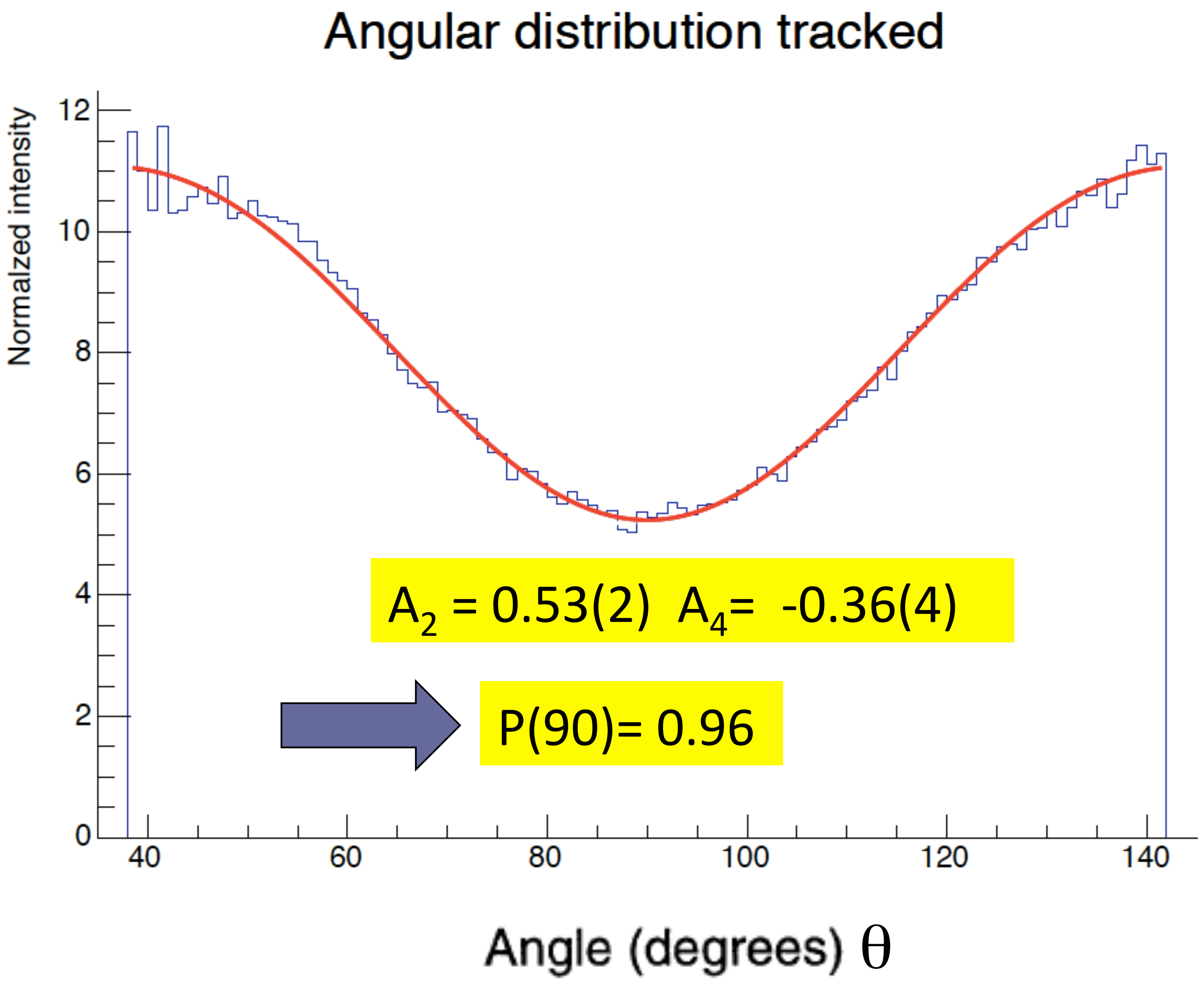
A. Wiens, LBNL

POLARIZATION IN GRETINA



θ Angle (Channels)

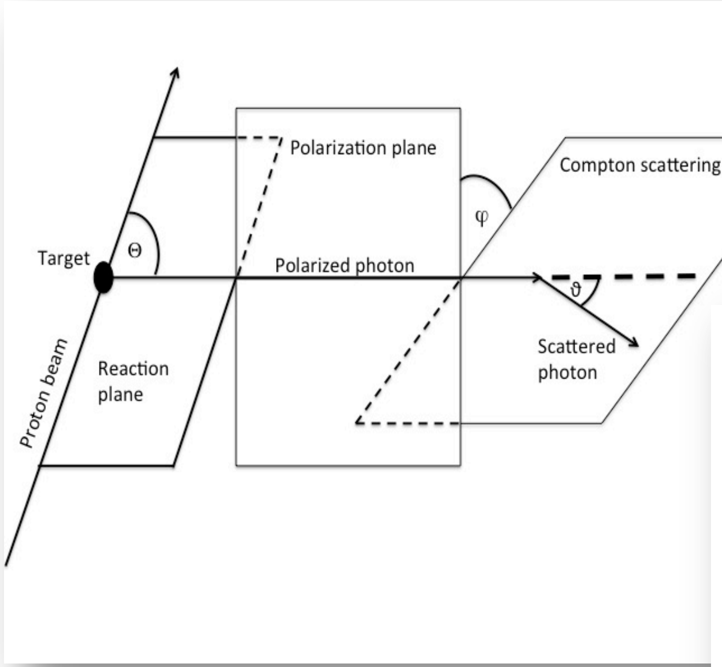
POLARIZATION IN GRETINA

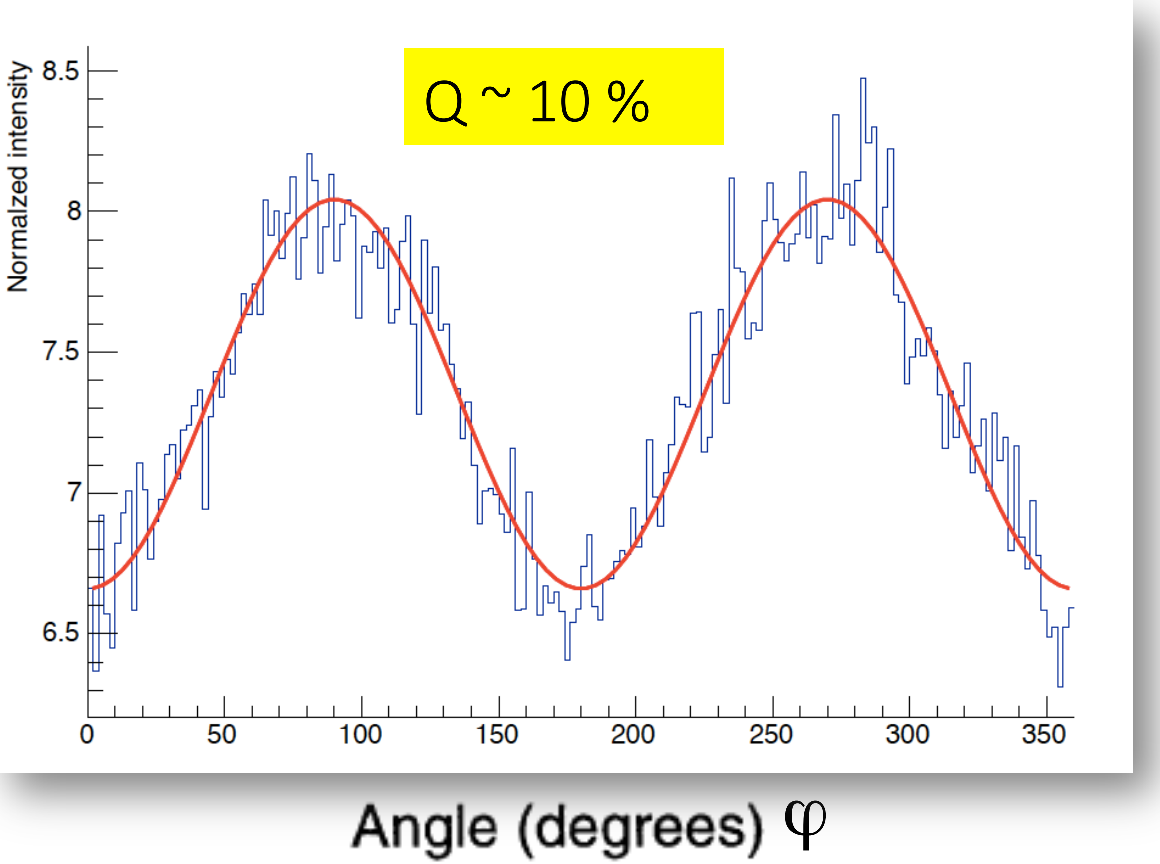


$A_2 = 0.53(2)$ $A_4 = -0.36(4)$

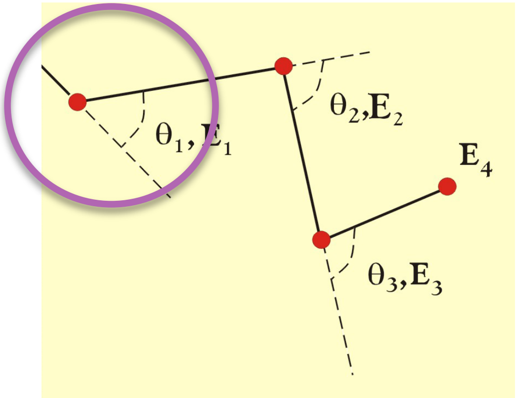
P(90)= 0.96

POLARIZATION IN GRETINA



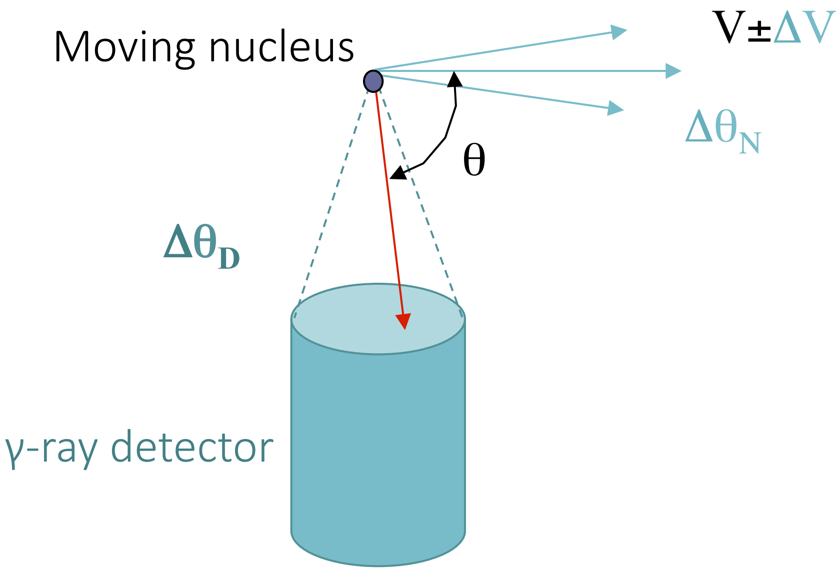


Q ~ 10 %



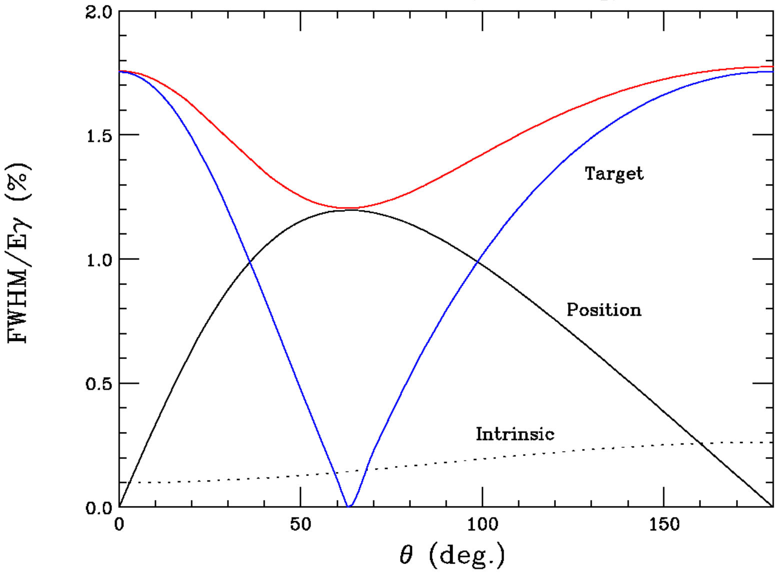
A. Wiens, LBNL

DOPPLER CORRECTION



Doppler shift

$$E_\gamma = E_\gamma^0 \frac{\sqrt{1-\frac{V^2}{c^2}}}{1-\frac{V}{c}\cos\theta}$$

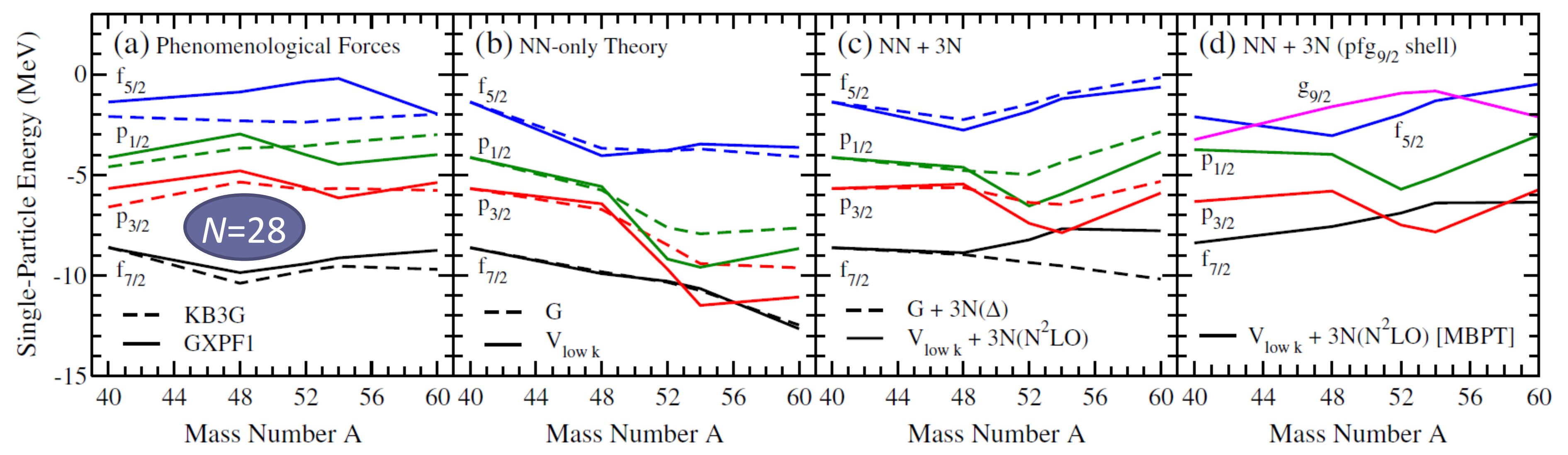


Broadening of detected gamma-ray energy due to:

- Spread in speed Δ V
- Distribution in direction of velocity $\Delta\,\theta_N$
- Detector opening angle $\Delta\,\theta_D$

NUCLEON KNOCKOUT REACTIONS

STRUCTURE OF NEUTRON-RICH Ca ISOTOPES



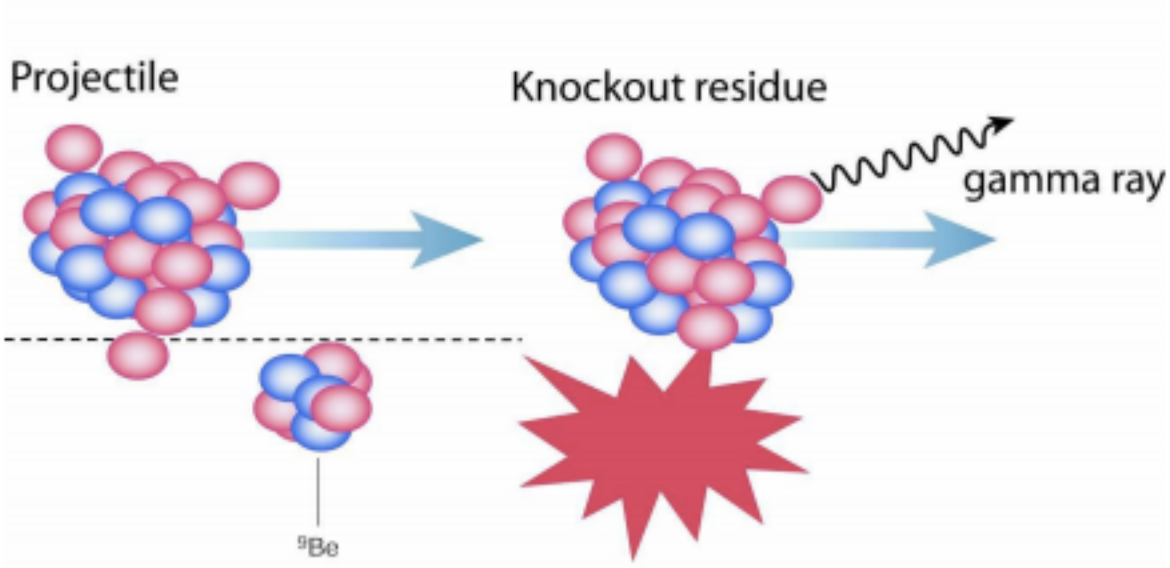
- Microscopic calculations including 3N forces make predictions for excitation energies, and for the evolution of the neutron SPEs in the neutron-rich Ca isotopes

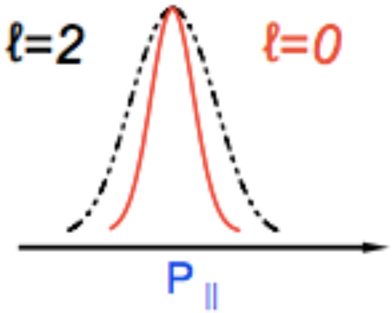
  ⇒ Opportunity exists to test these most advanced calculations

J.D. Holt *et al.*, J. Phys. G: Nucl. Part. Phys. **39**, 085111 (2012).

Knockout Reactions

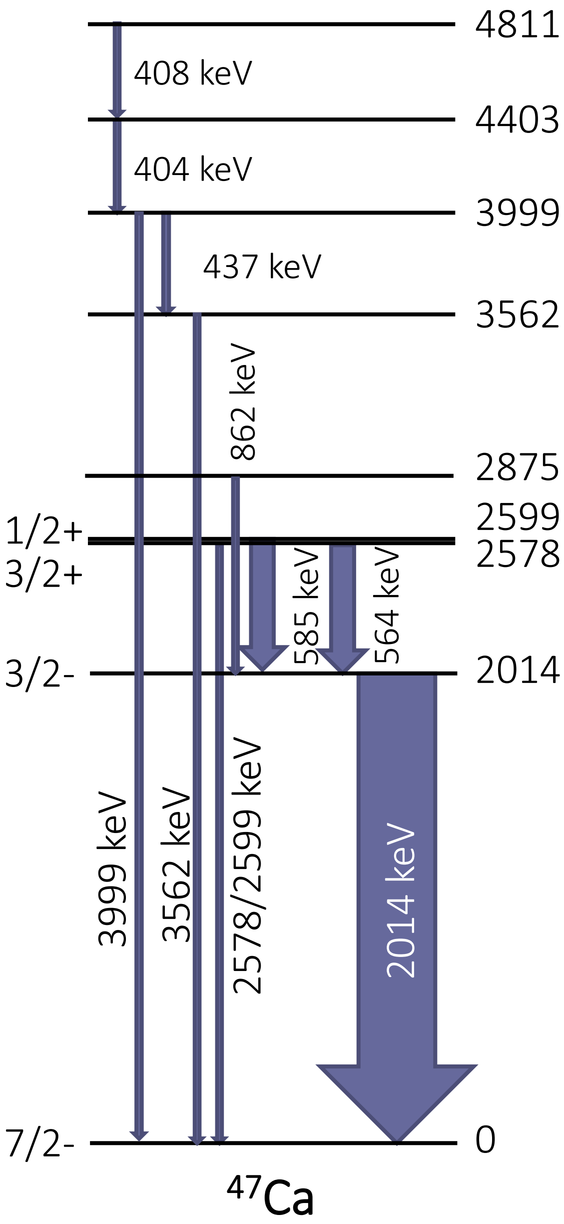
- Intermediate energy beams (> 50 MeV/nucleon)
  - Sudden approximation + eikonal approach for reaction theory
- Spectroscopic strengths
  - Populated states in A-1 residue provide detailed measure of beam structure

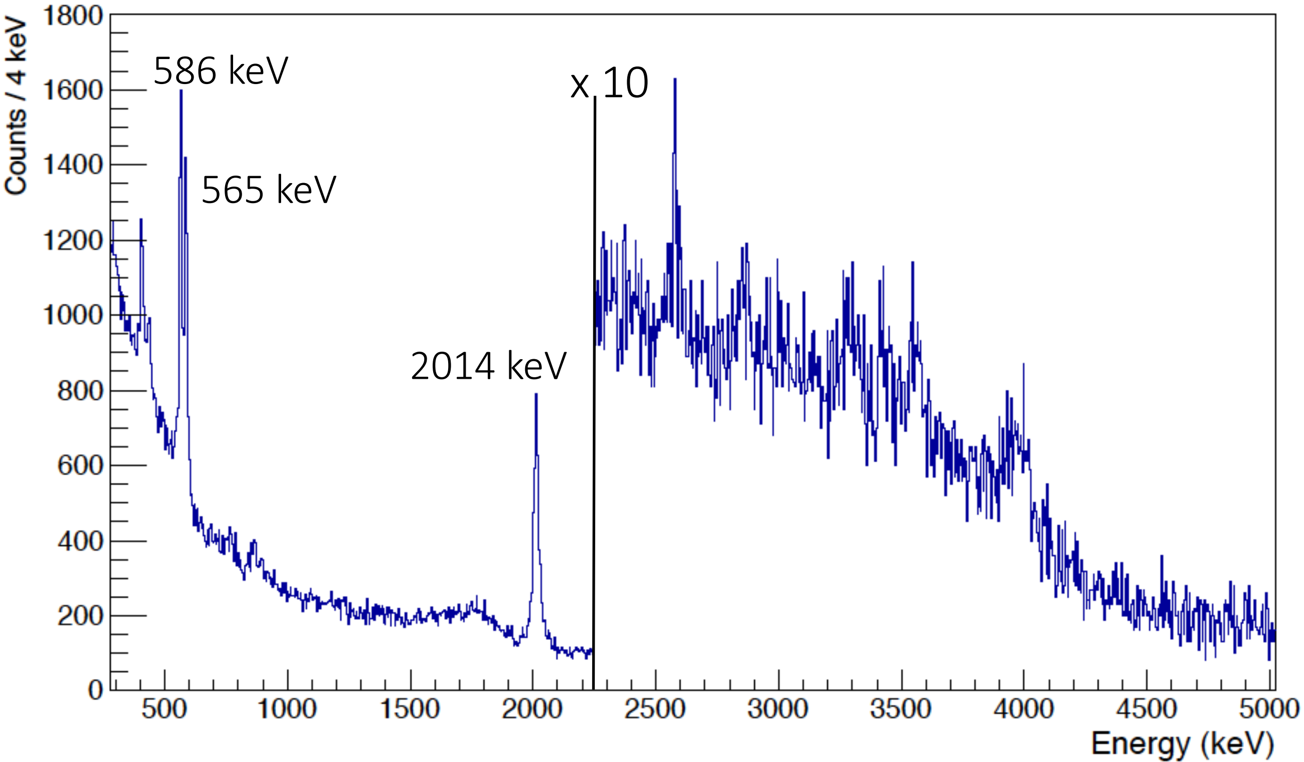


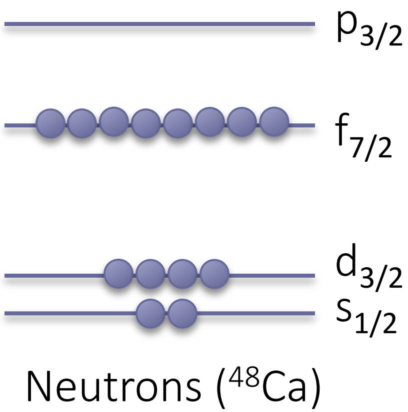


residue moment distribution
→ ℓ-value of knocked-out n

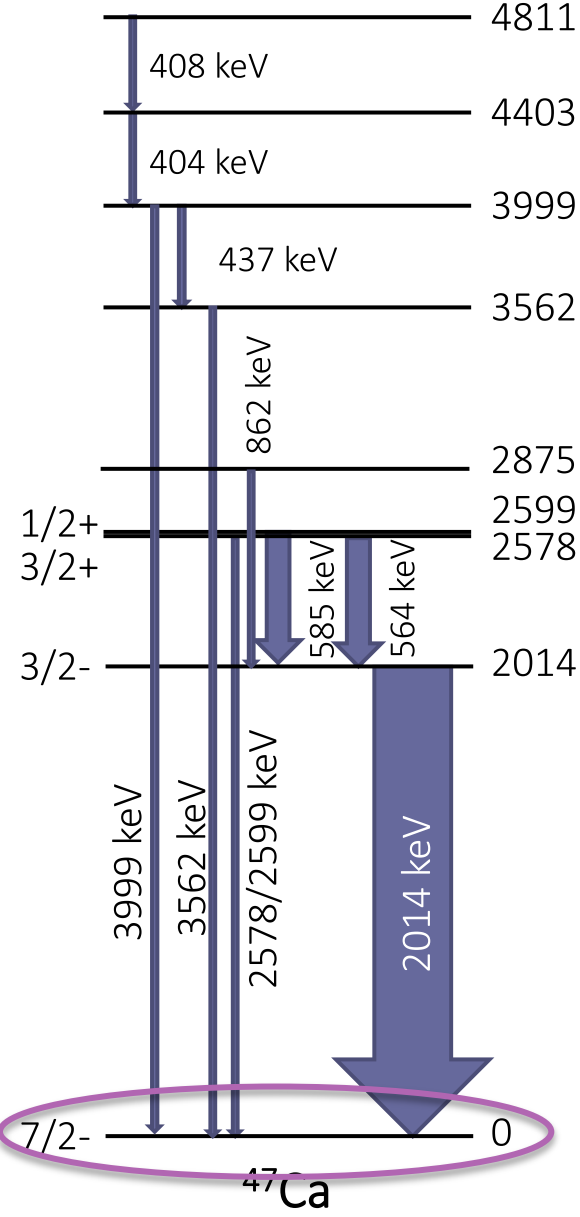
BENCHMARK AGAINST ^{48}Ca(p,d)^{47}Ca

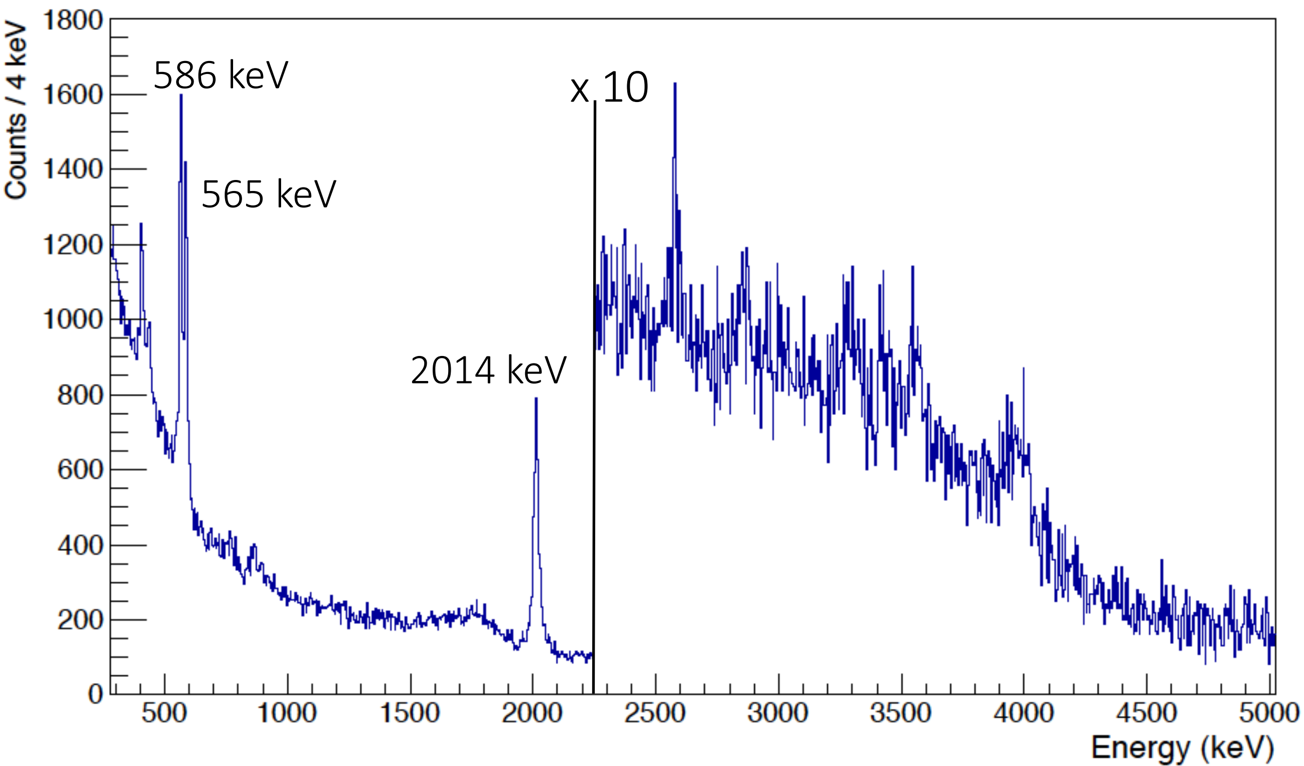


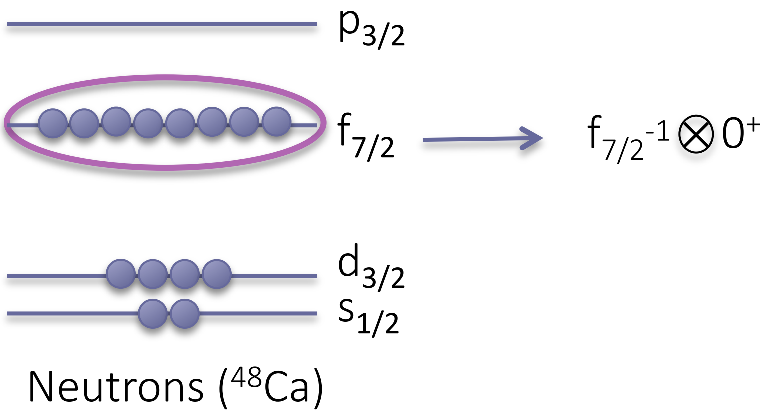




BENCHMARK AGAINST $^{48}Ca(p,d)^{47}Ca$







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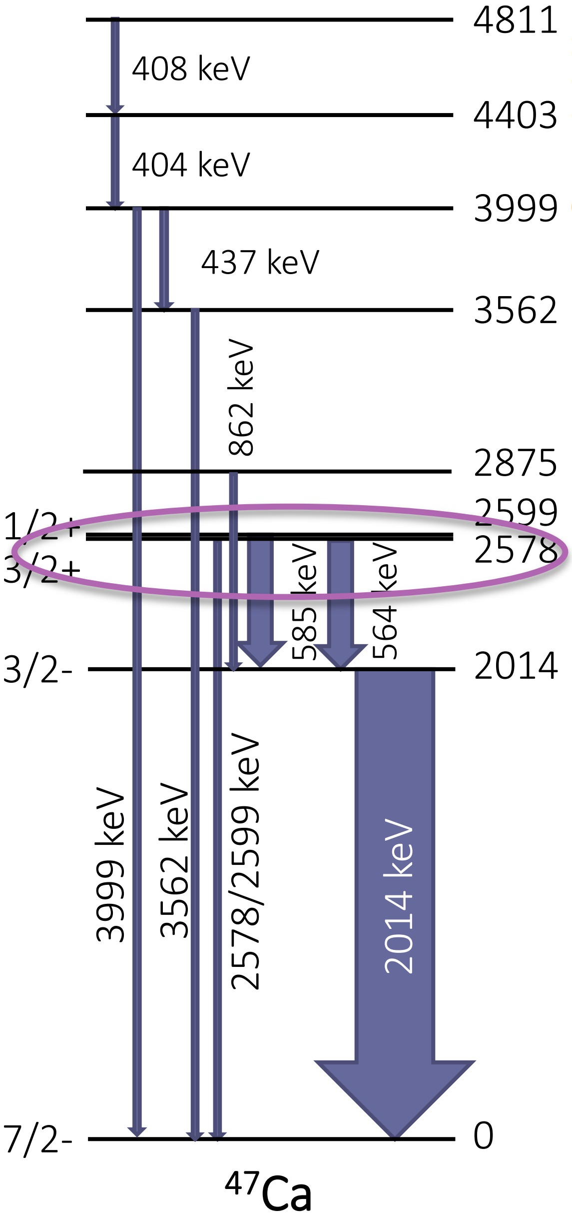
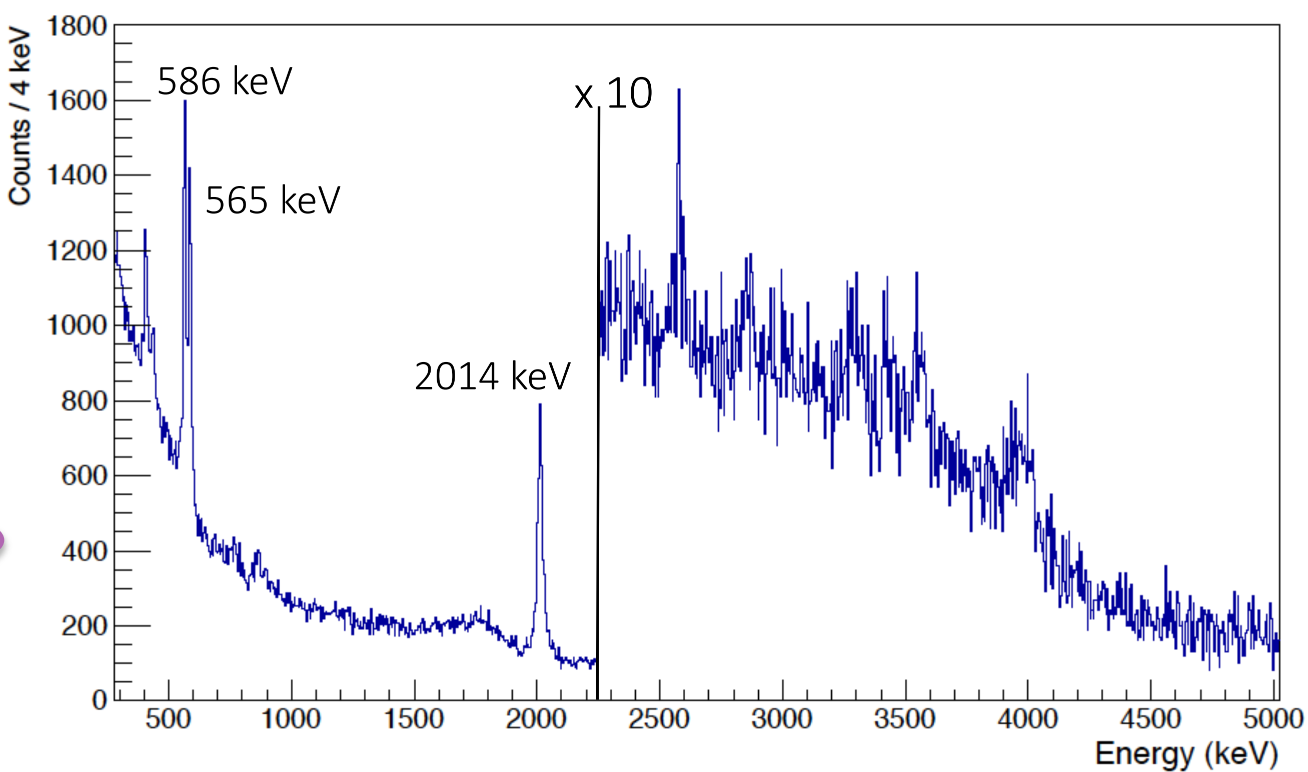
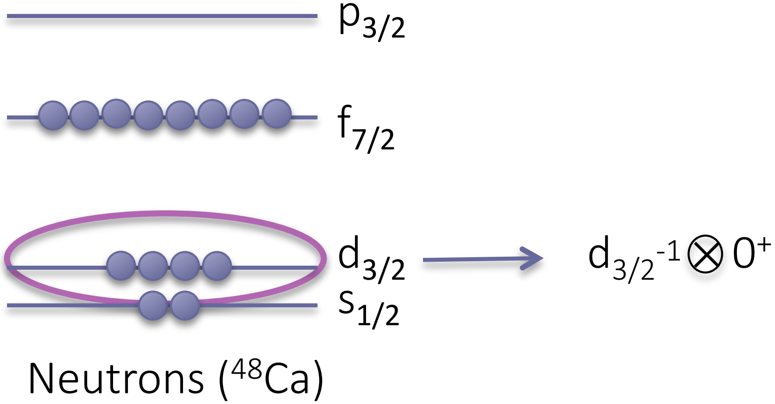
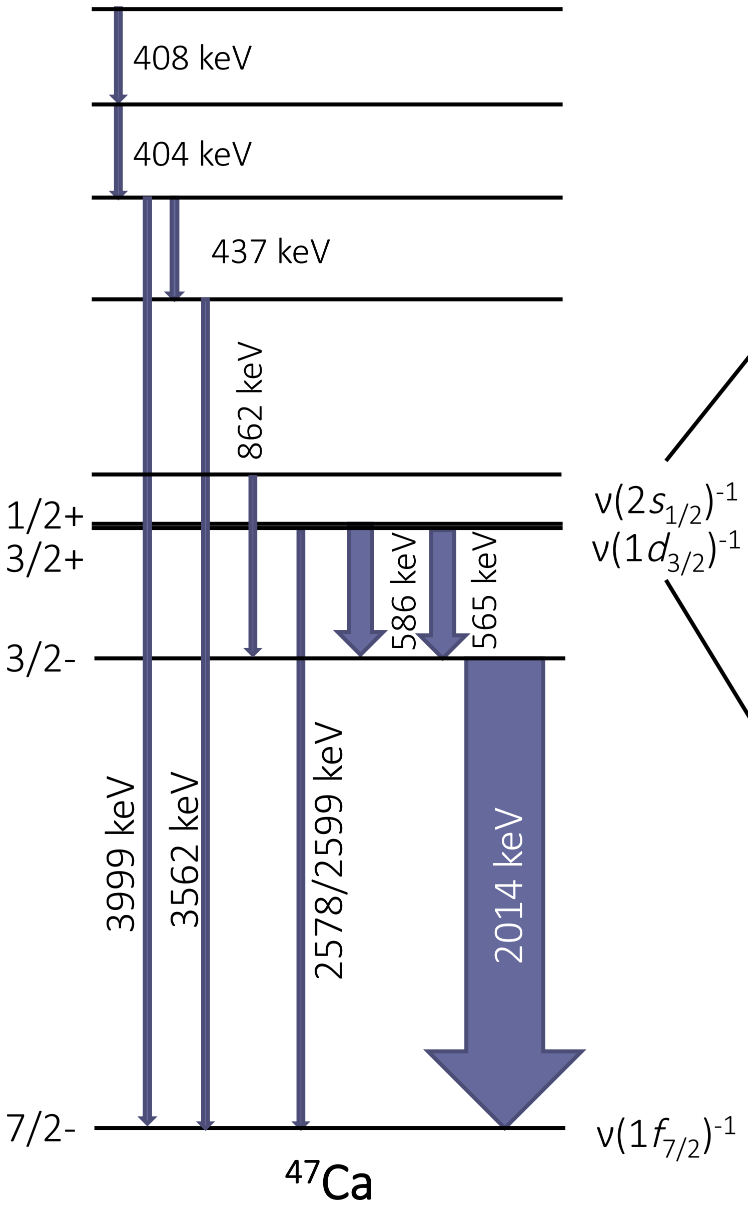
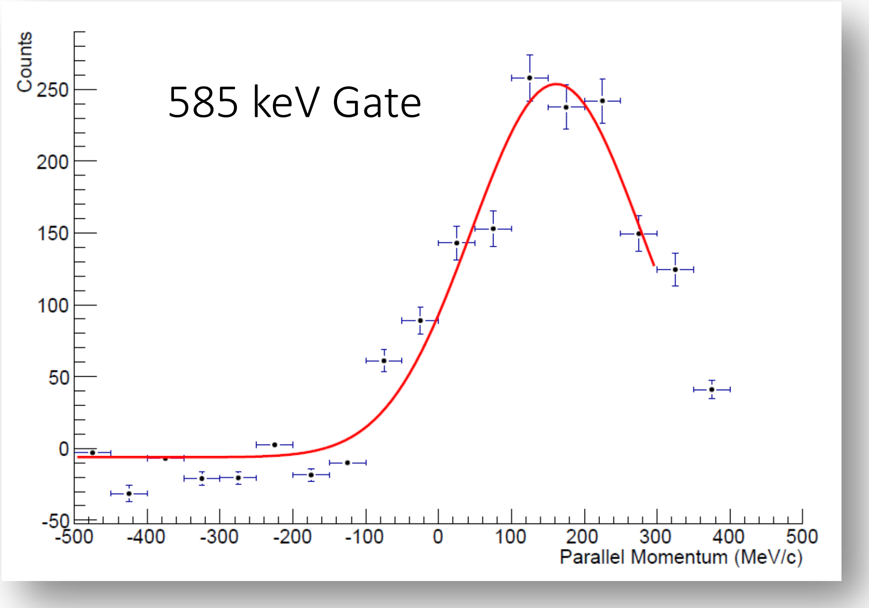


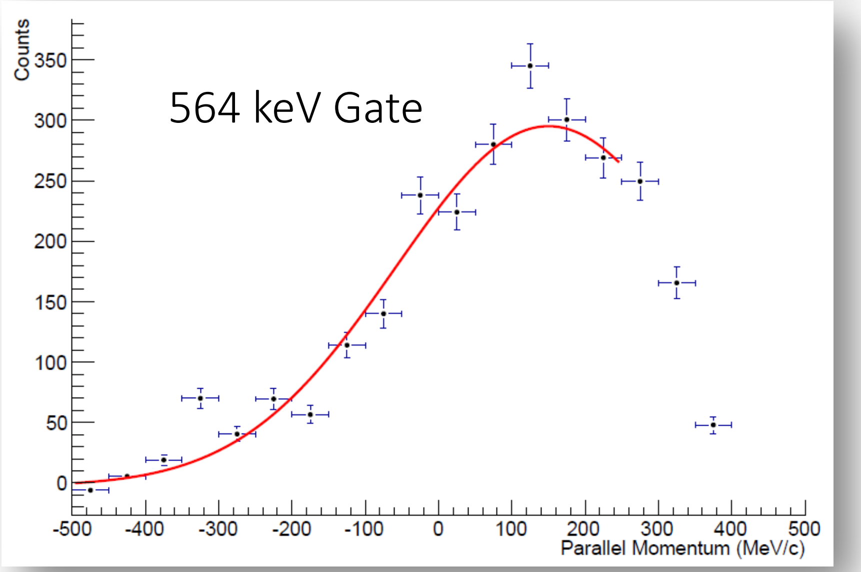




Exclusive Momentum Distributions in ^{47}Ca

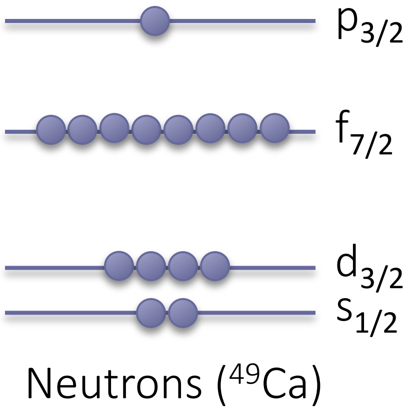






QUESTION!

- In neutron knockout from ^{49}Ca to ^{48}Ca, should you expect to populate a 6^+ state?
  (A) No
  (B) Yes



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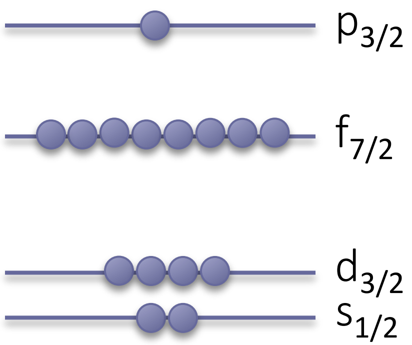


Neutrons (^{49}Ca)

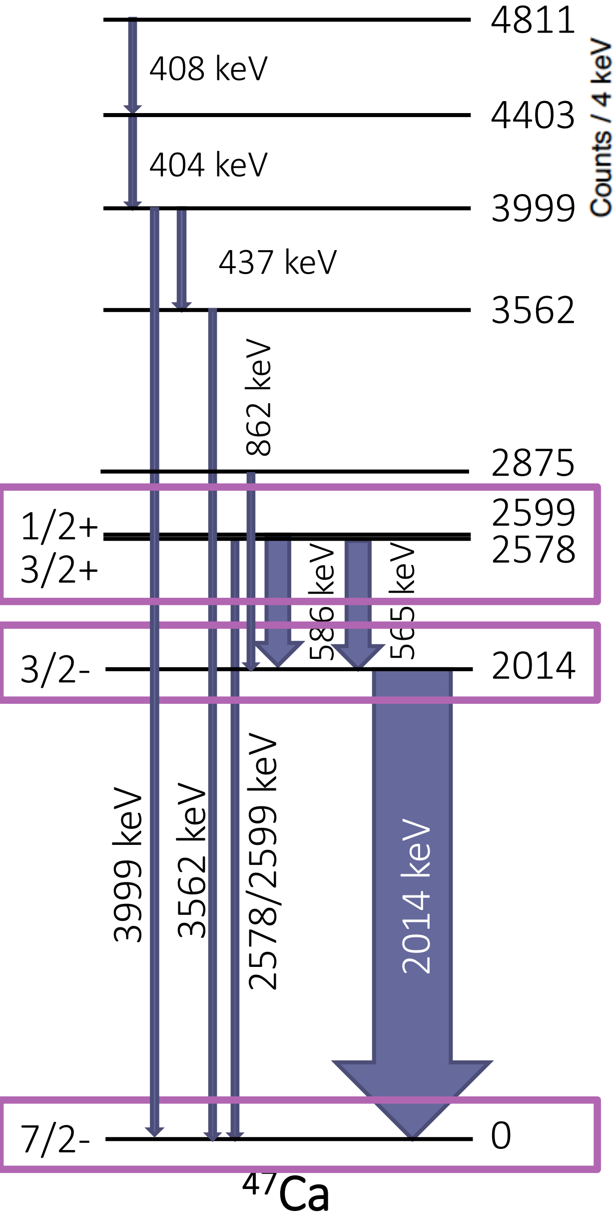
$(p_{3/2})^0(f_{7/2})^8\ldots \rightarrow 0^+$

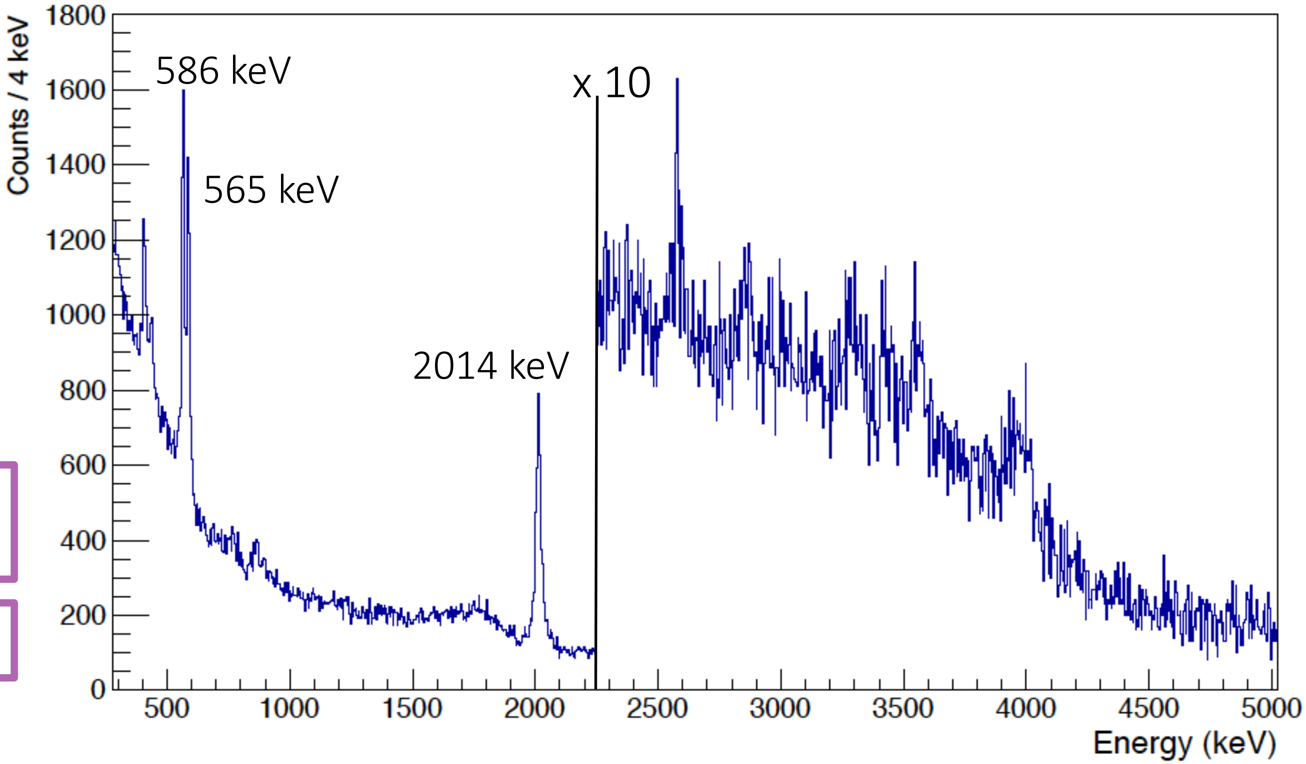
$(p_{3/2})^1(f_{7/2})^{-1}\ldots \rightarrow 2^+, 3^+, 4^+, 5^+$

$(p_{3/2})^1(d_{3/2})^{-1}\ldots \rightarrow 0^+, 1^+, 2^+, 3^+$

$(p_{3/2})^1(s_{1/2})^{-1}\ldots \rightarrow 1^+, 2^+$

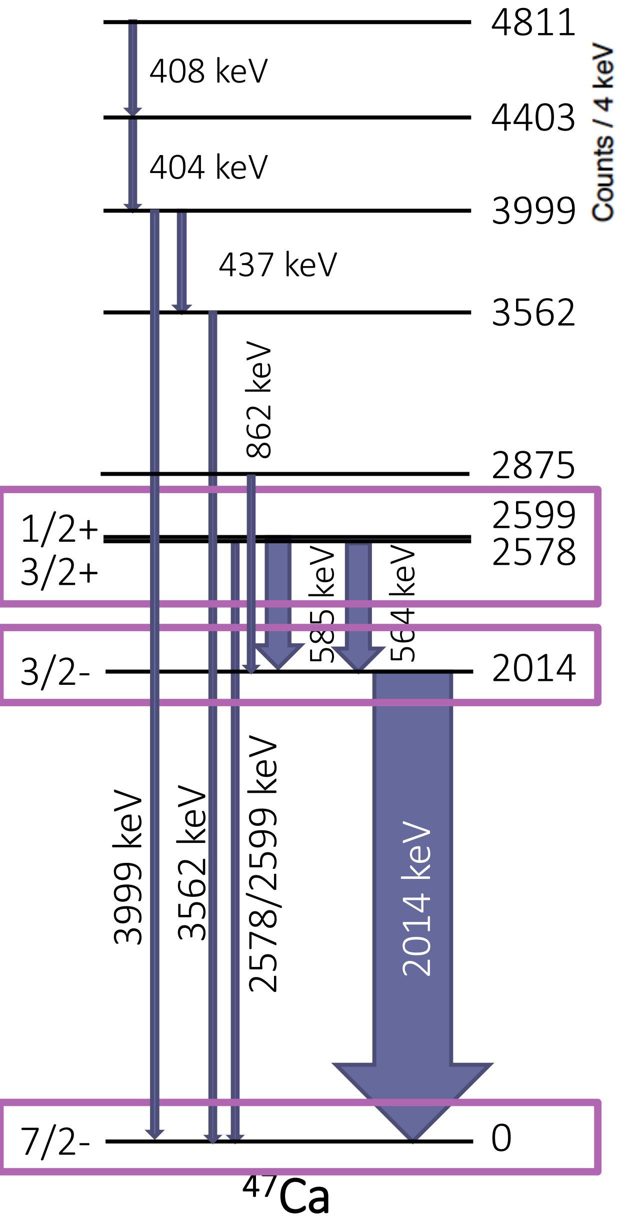
BENCHMARK AGAINST ^{48}Ca(p,d)^{47}Ca

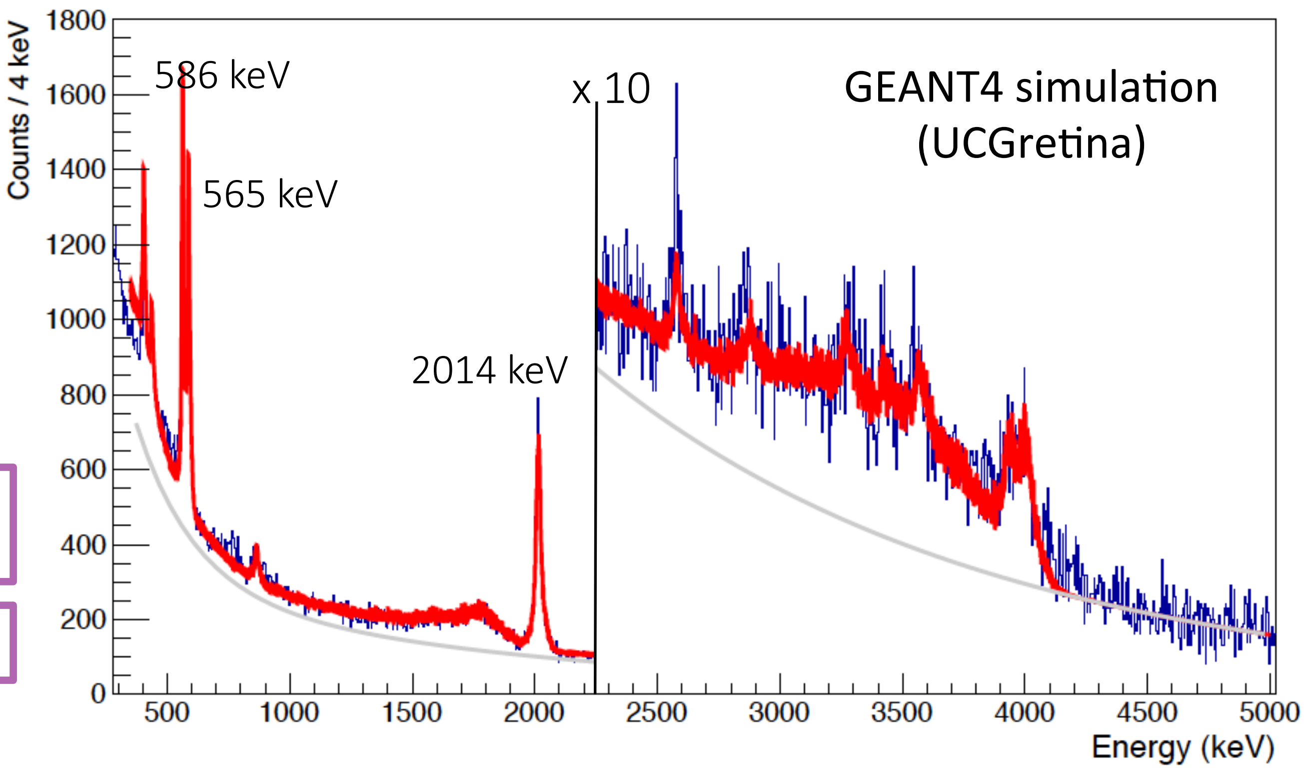




Energy (keV)	Jπ	Configuration	C^{2}S^a	C^{2}S^b
0 (g.s)	7/2-	$(1f_{7/2})^{-1}$	6.7	6.22
2014	3/2-	$[(1f_{7/2})^{-2}(2p_{3/2})^{1}]_{3/2-}$	0.02	0.10
2578	3/2+	$(1d_{3/2})^{-1}$	3.6	1.18
2599	1/2+	$(2s_{1/2})^{-1}$	1.8	1.28

BENCHMARK AGAINST $^{48}Ca(p,d)^{47}Ca$





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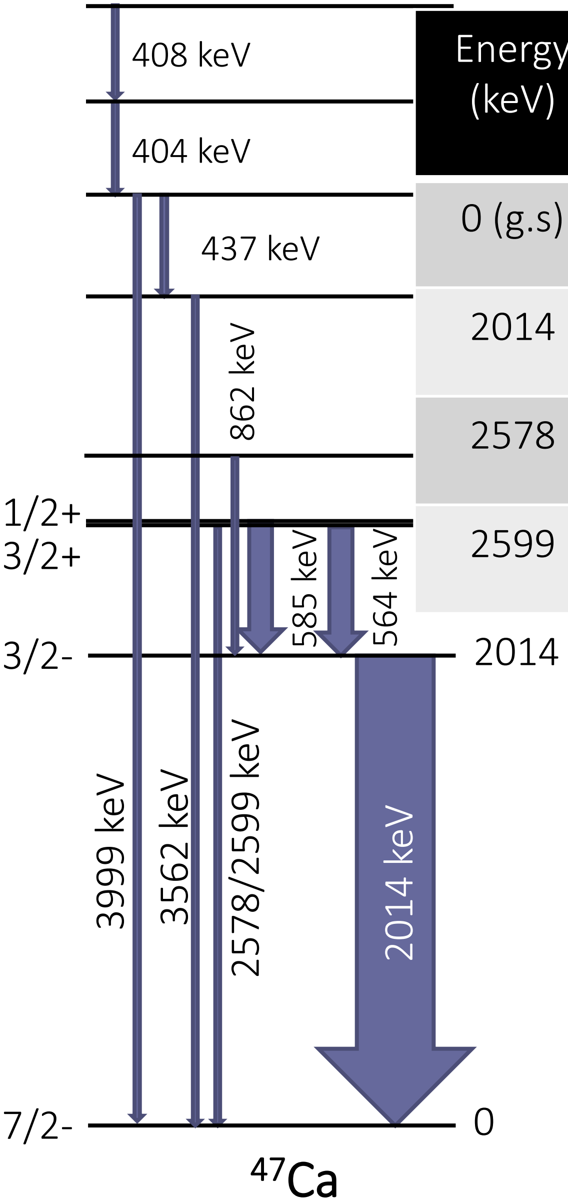
2599	1/2+	$(2s_{1/2})^{-1}$	1.8	1.28

BENCHMARK AGAINST $^{48}Ca(p,d)^{47}Ca$



Energy (keV)	J^π	Configuration	C^2S^a	C^2S^b	σ (mb)	C^2S
0 (g.s)	7/2-	$(1f_{7/2})^{-1}$	6.7	6.22	76.2±4.0	6.9±0.4
2014	3/2-	$[(1f_{7/2})^{-2}(2p_{3/2})^{1}]_{3/2-}$	0.02	0.10	6.9±1.6	0.6±0.1
2578	3/2+	$(1d_{3/2})^{-1}$	3.6	1.18	9.7±1.8	1.3±0.2
2599	1/2+	$(2s_{1/2})^{-1}$	1.8	1.28	11.1±2.0	0.9±0.2

- Cross-sections to individual states tell us about the occupancy (number of nucleons in a given single particle state)
- Transfer reactions (lower beam energies) provide similar information

(a) P. Martin et al., Nuclear Physics A185, 465 (1972). -- (p,d)
(b) M.E. Williams-Norton and R. Abegg, Nuclear Physics A291, 429 (1977). – (d,t)

MAGNETIC MOMENTS

MAGNETIC MOMENTS

- Magnetic dipole moment has contributions from spin and angular momenta of protons and neutrons
- Single-particle state (Schmidt limits)

$$\mu = \frac{1}{j+1}\langle j, m = j|\vec{\mu}\cdot\vec{j}|j, m = j\rangle = g_l\langle l_z\rangle + g_s\langle s_z\rangle$$

g-factor	g_l	g_s
	(μ_n)	
Proton	1	5.5858
neutron	0	-3.8263

$\mu_n = e\hbar / 2m_p = 5.05\ 10^{-27}$ J/T

MEASUREMENT OF MAGNETIC MOMENT

- Produce a nucleus with spin alignment
  - Coulomb excitation, transfer reaction, fission, etc…
- Magnetic moment will precess in magnetic field (B), according to Larmor frequency

$$\omega = \frac{\mu B}{J} = gB\frac{\mu_N}{\hbar} \longrightarrow g = \frac{\frac{\mu}{\mu_N}}{\frac{J}{\hbar}}$$

- Measure the angular distribution (of gamma ray!)

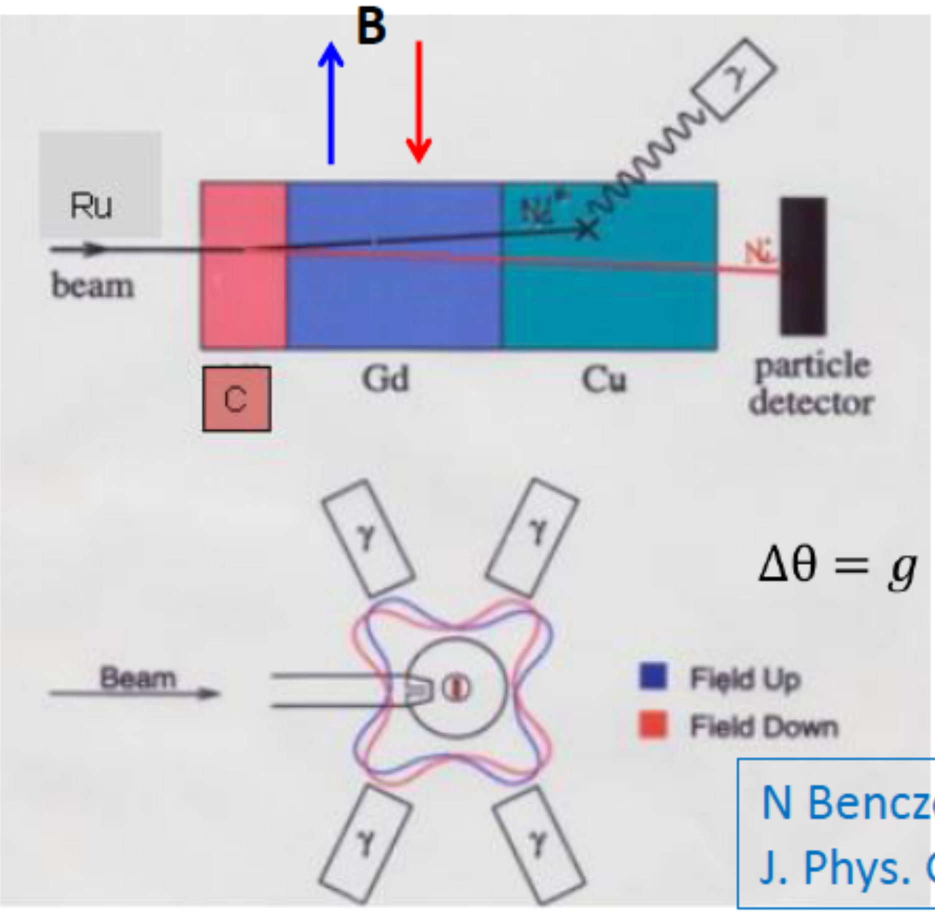
$$W(\theta, t) = 1 + \sum_k A_k P_k(cos(\theta + \omega t))$$

  - States with shorter lifetimes (τ) need faster ω (stronger B field) to produce measurable precession angle

g = 1	ωτ=10°
τ	B
1 µsec	0.0036 T
1 nsec	3.6 T
1 psec	3644 T

TRANSIENT FIELD METHOD

- Nucleus moves through magnetized material (e.g. Fe, Gd)
- Precesses in transient magnetic field B (≈100 Z T)
- Measure angular distribution of decay gamma ray



$$\Delta\theta = g\,\frac{\mu_n}{\hbar}\int_0^T B\,e^{-t/\tau}\,dt$$

N Benczer-Koller and G J Kumbartzki
J. Phys. G: Nucl. Part. Phys. 34 (2007) R321–R358

QUESTION!

- Where should we place the detectors to maximize the sensitivity of transient field magnetic moment measurements?

$$W(\theta) = 1 + \sum_k A_k P_k(cos\theta)$$

(A) Maximum of W(θ)
(B) 45°
(C) Maximum of dW(θ)/dθ
(D) Maximum of |dW(θ)/dθ|
(E) 60°

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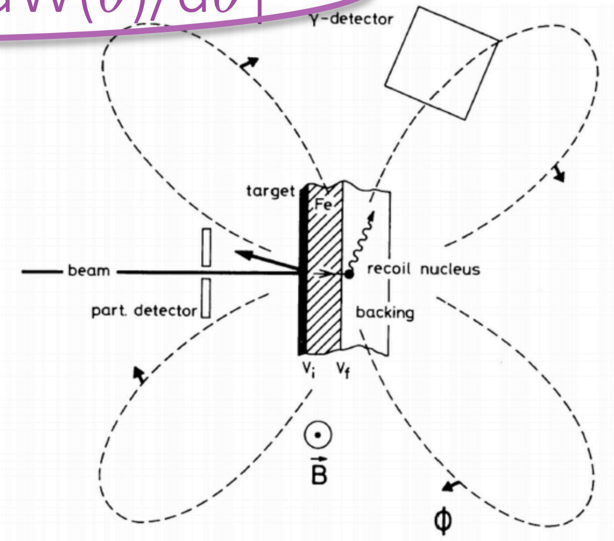
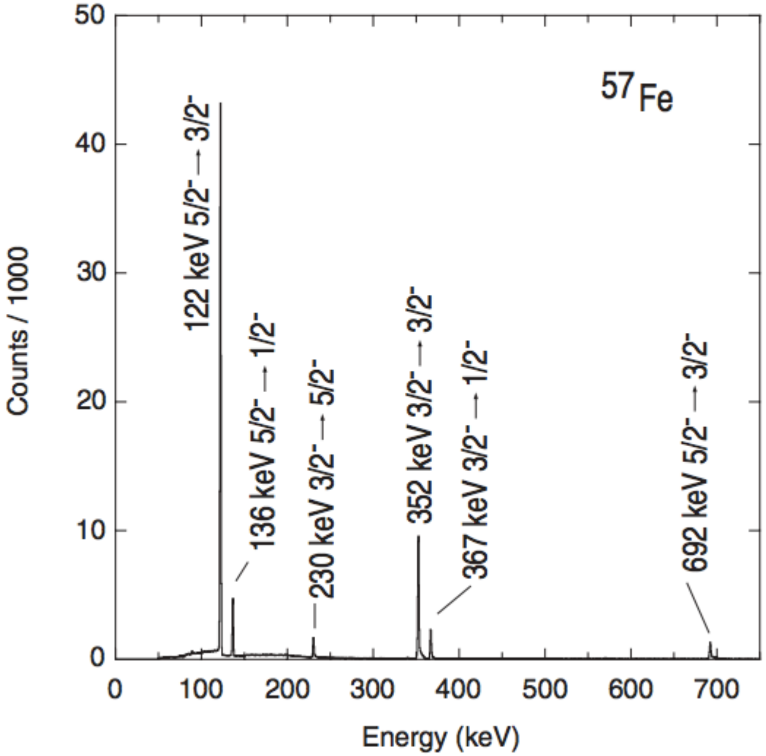
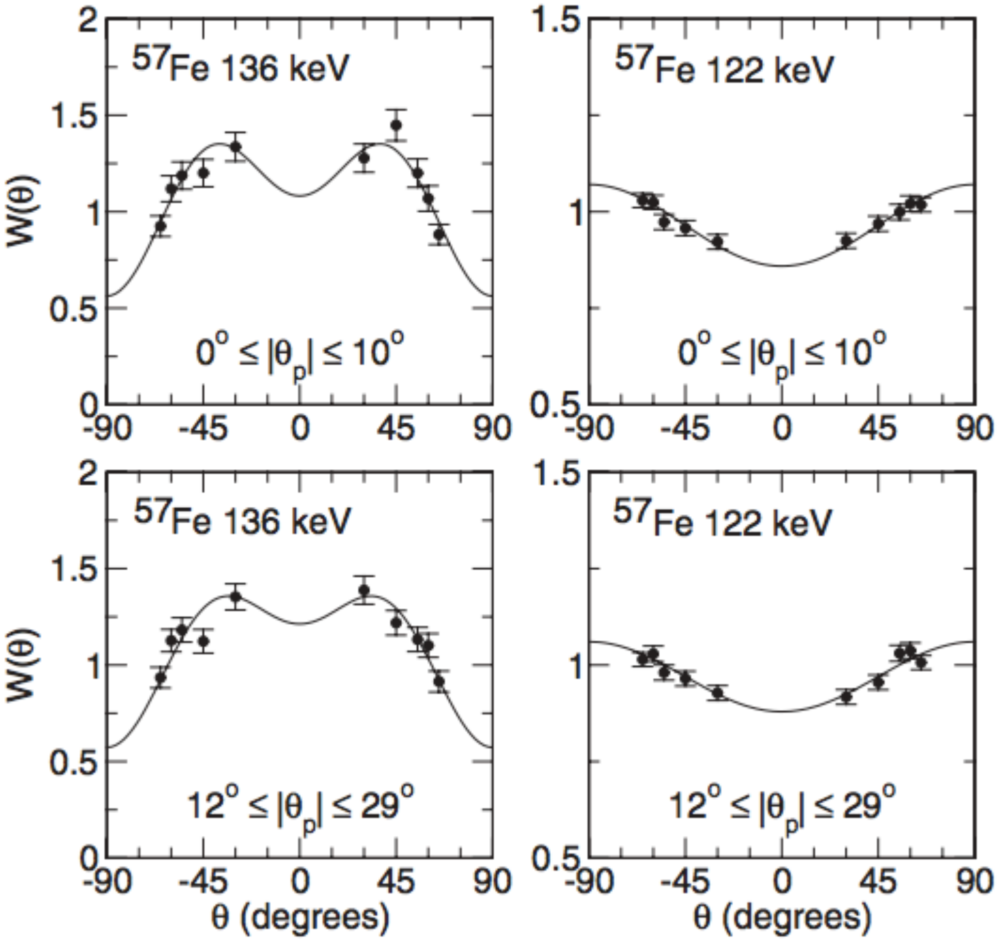


MAGNETIC MOMENT

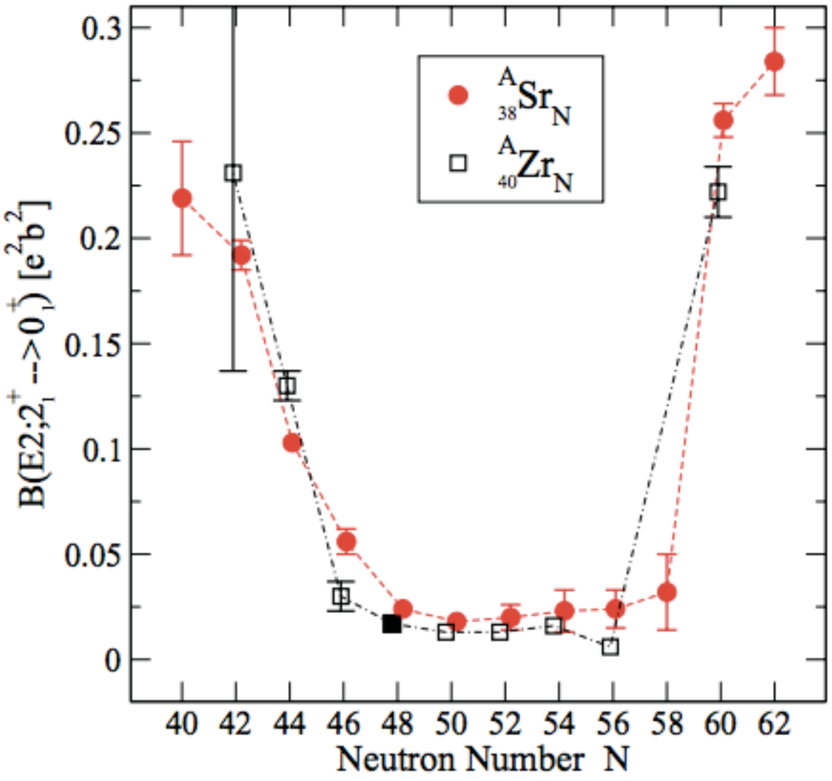
- Example of ^{57}Fe g-factor measurement measured at ANU – 5/2^{-} state at 136 keV
- Measurement used as relative point for ^{56}Fe 2^{+}

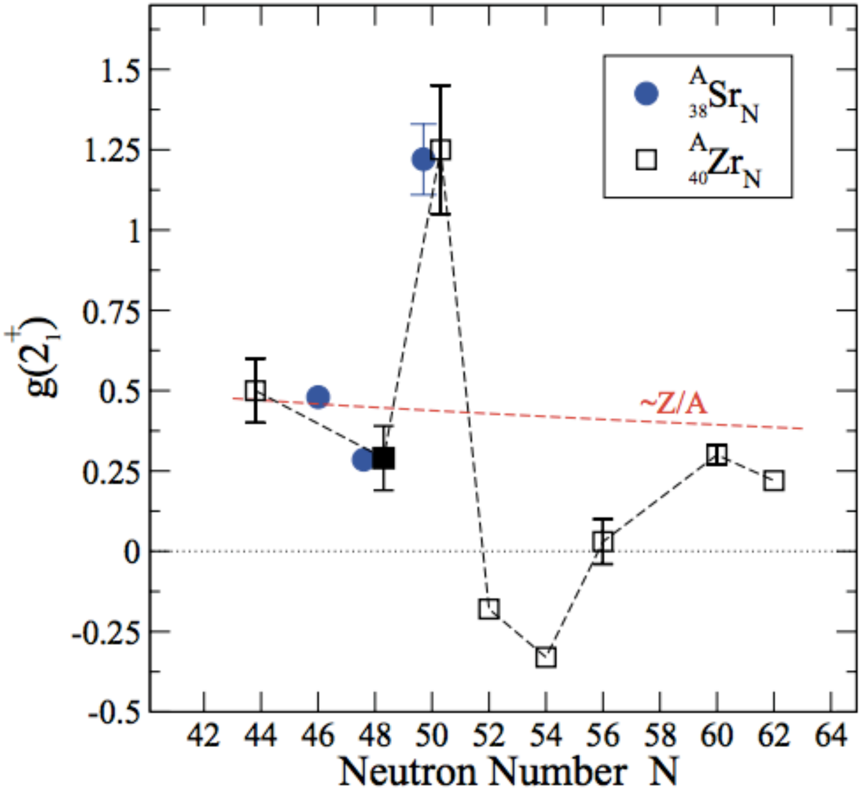




M. East *et al.*, Phys. Rev. C **79**, 024303 (2009).

PHYSICS OF MAGNETIC MOMENTS





- g-factors are sensitive to proton/neutron contributions to nuclear states – where collective properties may vary smoothly, proton and neutron contributions can vary substantially

G. J. Kumbartzki *et al.*, Phys. Rev. C **85**, 044322 (2012).

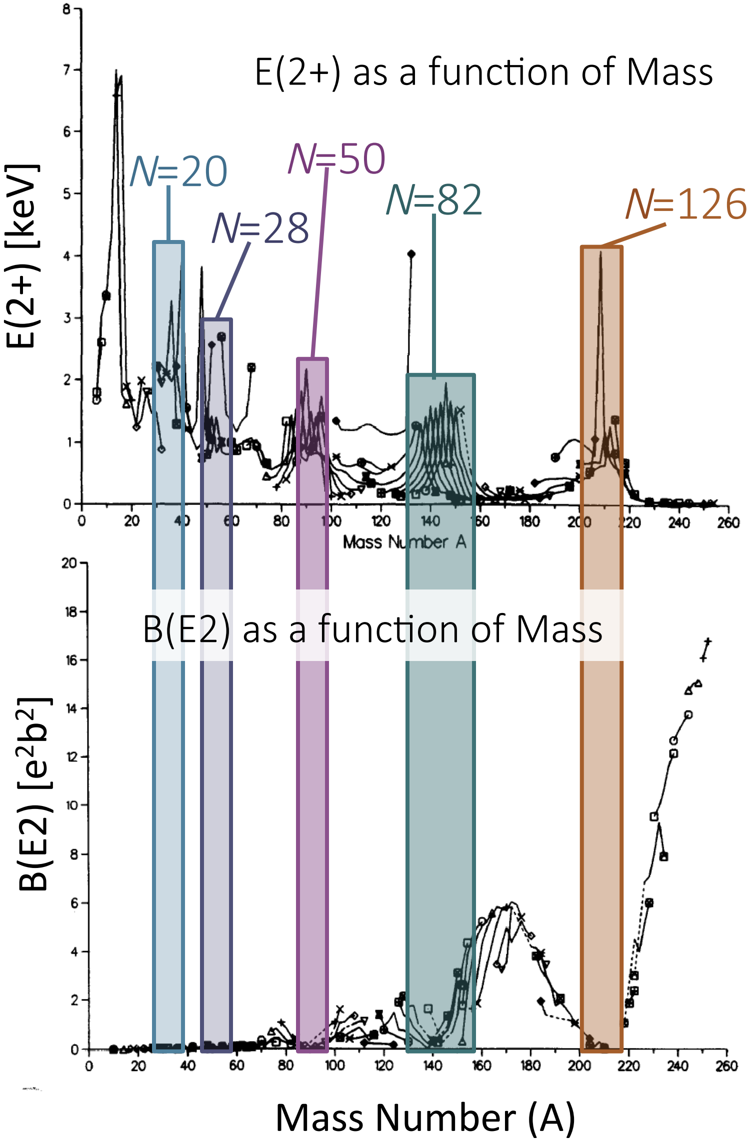
LIFETIMES

LIFETIME MEASUREMENTS AND STRUCTURE

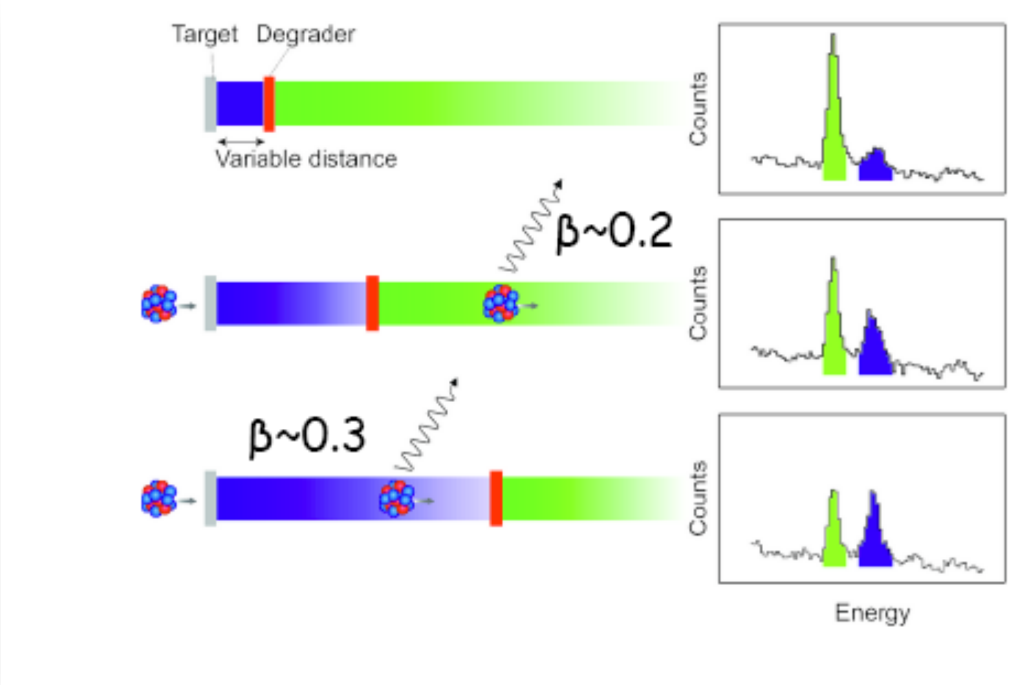
- Gamma transition lifetimes related to transition matrix elements – direct method to determine B(E2)

$$T_{fi}(\lambda L) = \frac{8\pi(L+1)}{\hbar L((2L+1)!!)^2}\left(\frac{E_\gamma}{\hbar c}\right)^{2L+1} B(\lambda L : J_i \to J_f)$$

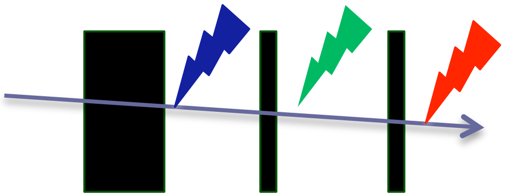
- First characterization of collectivity (deformation) often comes from transition probabilities – collective structures will have higher transition probabilities



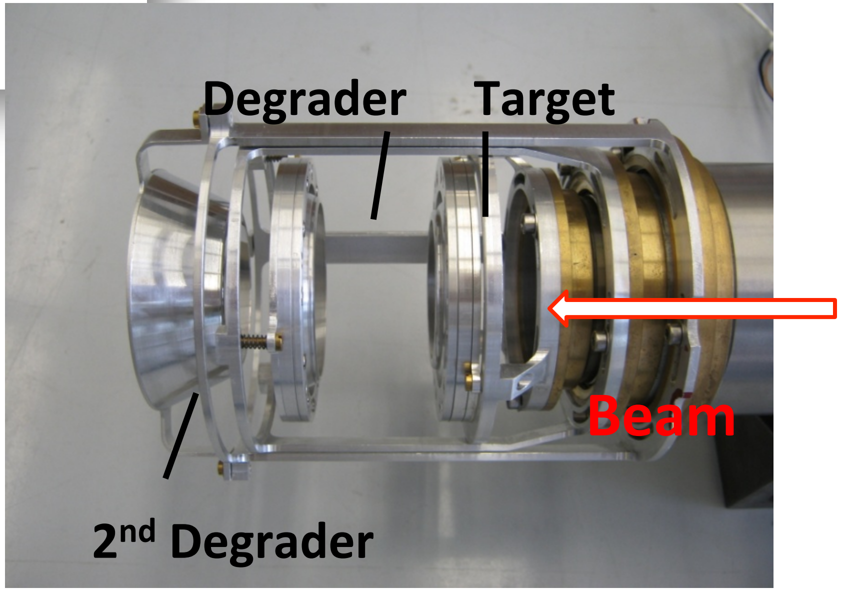
LIFETIME MEASUREMENTS WITH PLUNGER



TRI-foil Plunger for EXotic beams

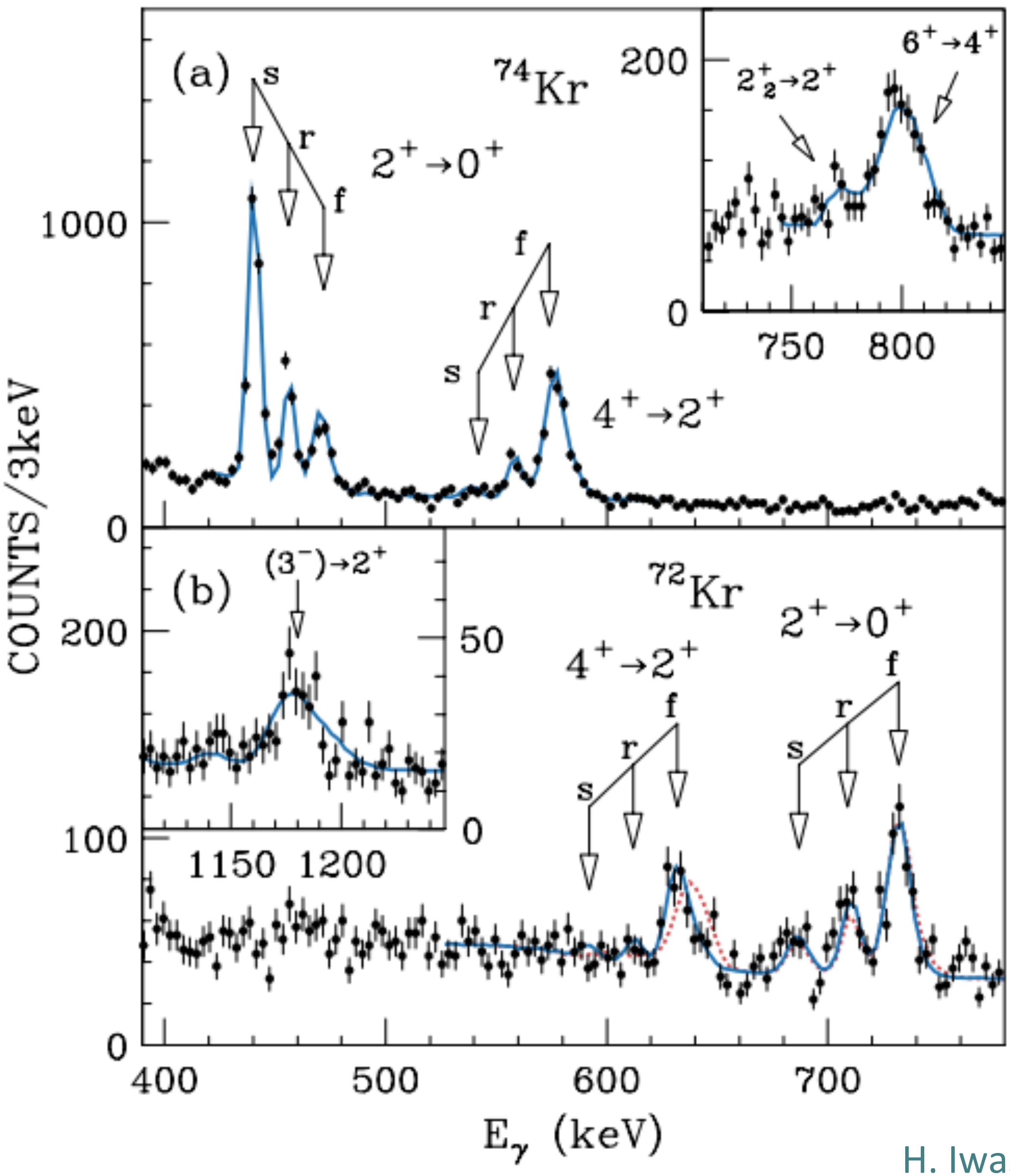


Target	**Degrader**	**Degrader**
Be	**Ta**	**Ta**
0.75mm	**0.125mm**	**0.1mm**



H. Iwasaki *et al.*

LIFETIMES IN ^{72,74}Kr



H. Iwasaki *et al.*, Phys. Rev. Lett. **112**, 142502 (2014).

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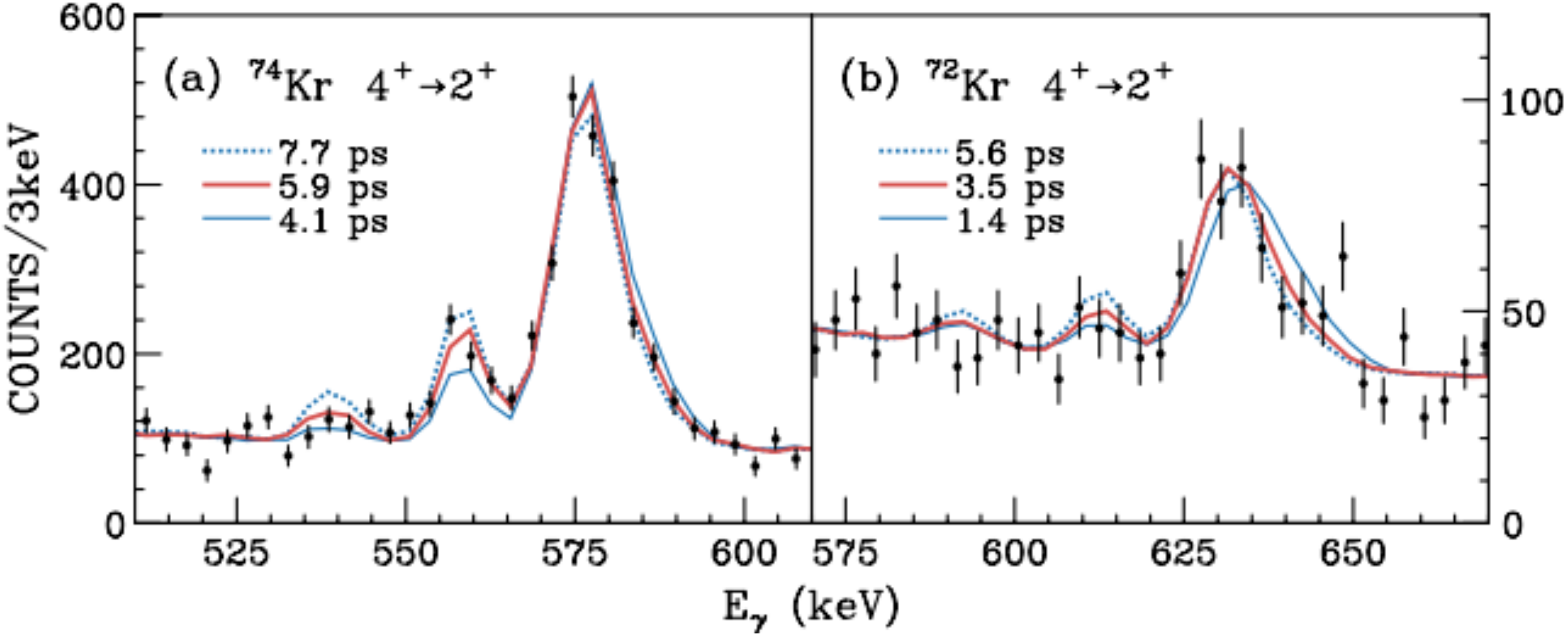

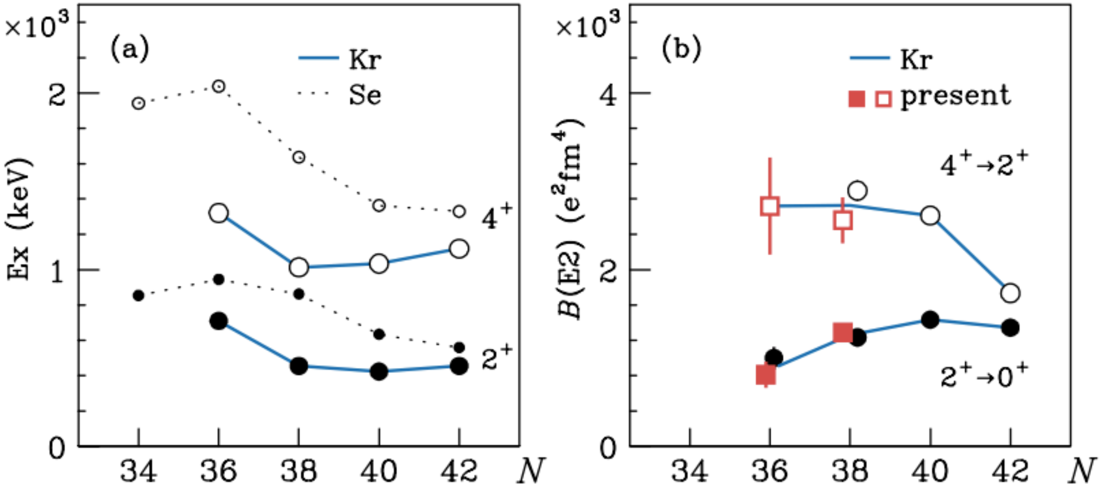

Lifetimes for 2+ and 4+ states tell us about transition probabilities – high value of B(E2) for 4+ → 2+ is first evidence for shape transition

H. Iwasaki *et al*., Phys. Rev. Lett. **112**, 142502 (2014).

SUMMARY

- What should you take home:
  - Gamma spectroscopy can provide important details about nuclear levels – energy separations, spin information, etc.
  - Detectors for gamma spectroscopy are of two main types – scintillators and Ge
  - Next generation spectrometers (GRETA) provide unparalleled performance (resolving power) and may open new experimental opportunities
  - Experiments including gamma spectroscopy are wide ranging, addressing many physics questions in our field

THANK YOU TO A.O. MACCHIAVELLI, I.Y. LEE AND D. WEISSHAAR FOR SLIDE MATERIAL!

Questions?

POISSON (COUNTING) STATISTICS

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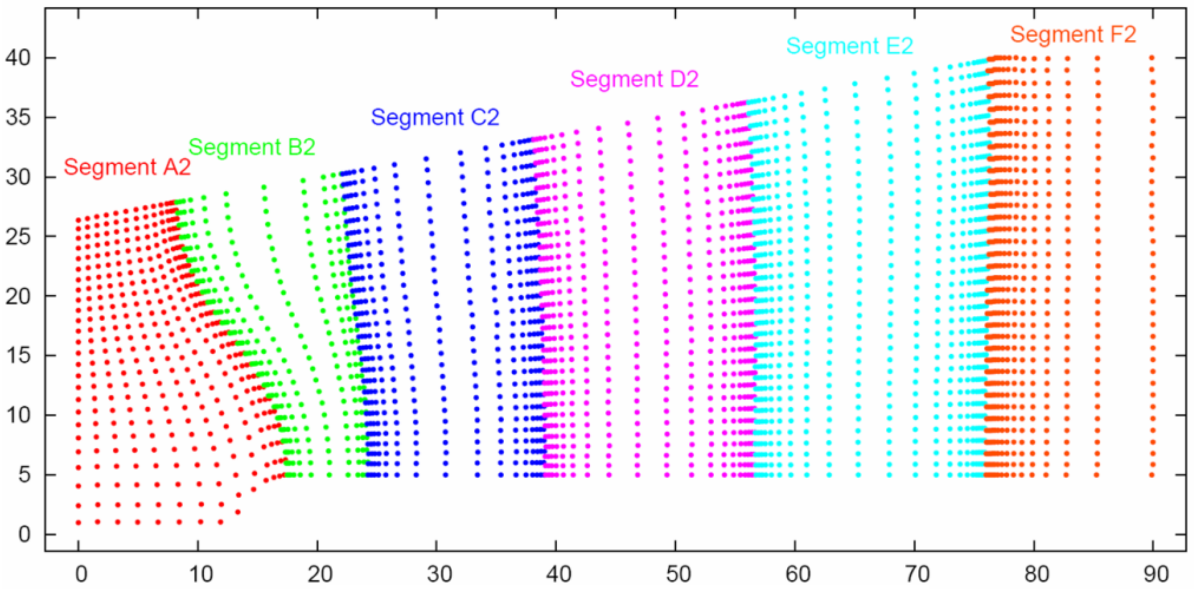
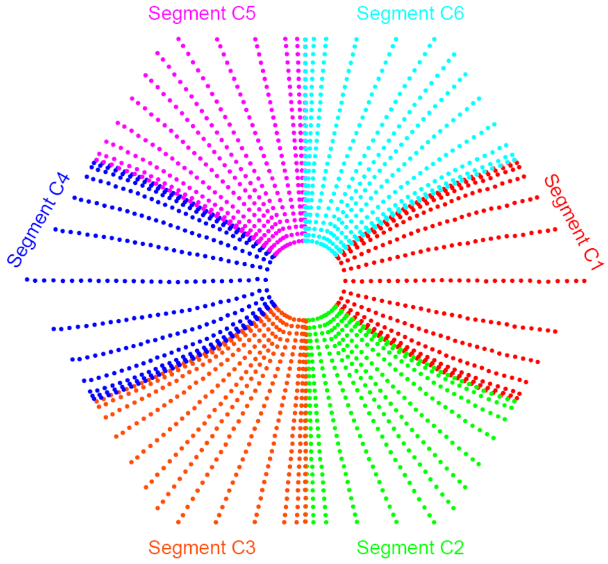
ADAPTIVE GRID SEARCH

Adaptive Grid Search algorithm:

Start on a course grid, to roughly localize the interactions, then refine the grid close by.

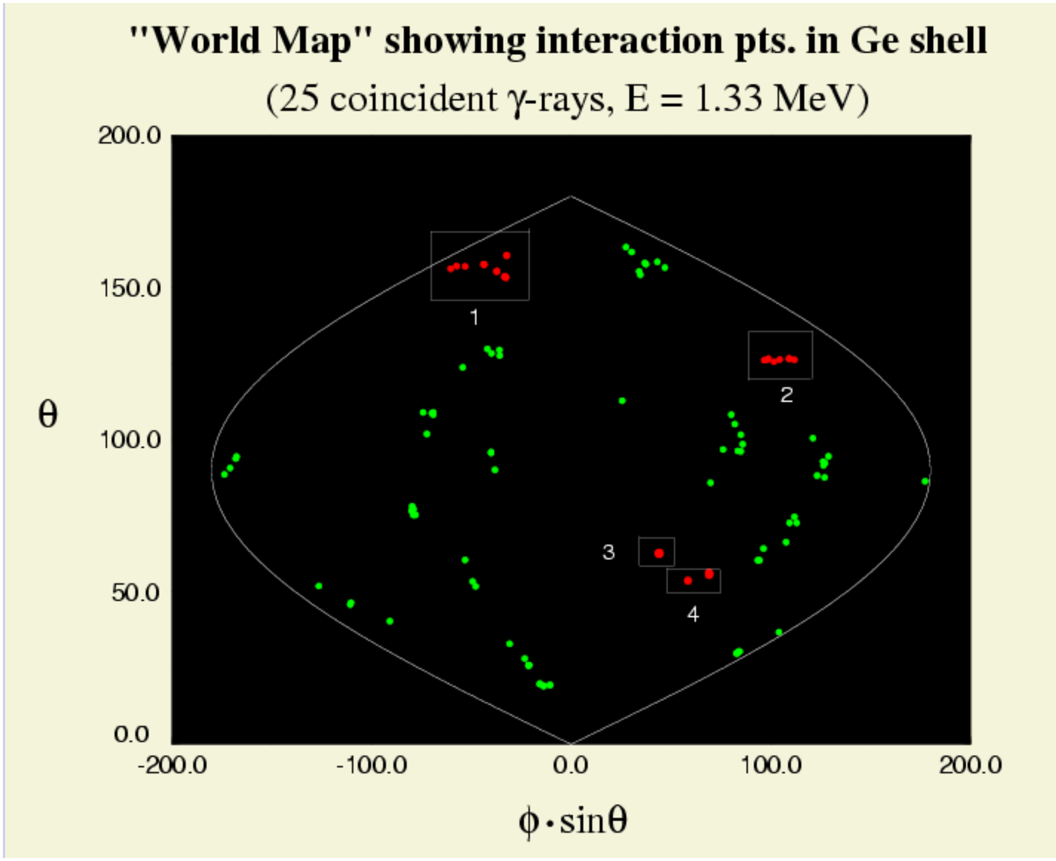
Pristine basis (set of signals at grid points) is calculated based on simulation; measurements are made to correct for effects such as segment cross-talk, etc.

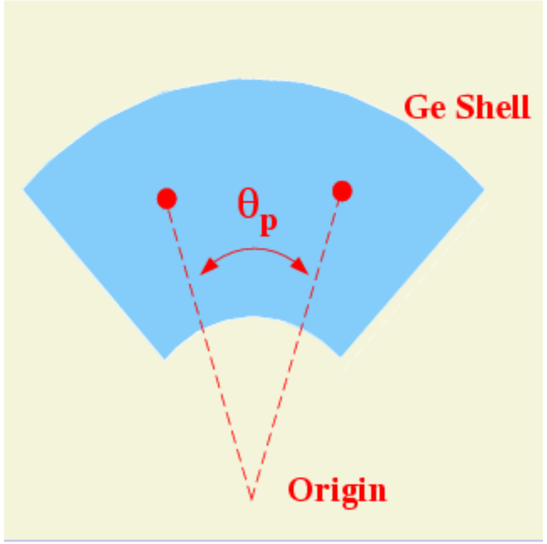




TRACKING: CLUSTERING

First step in tracking is to find clusters of interaction points which likely belong to a single γ-ray scattering in the detector – based on opening angle into the Ge shell





Any two points with $\theta < \theta p$ are grouped into the same cluster

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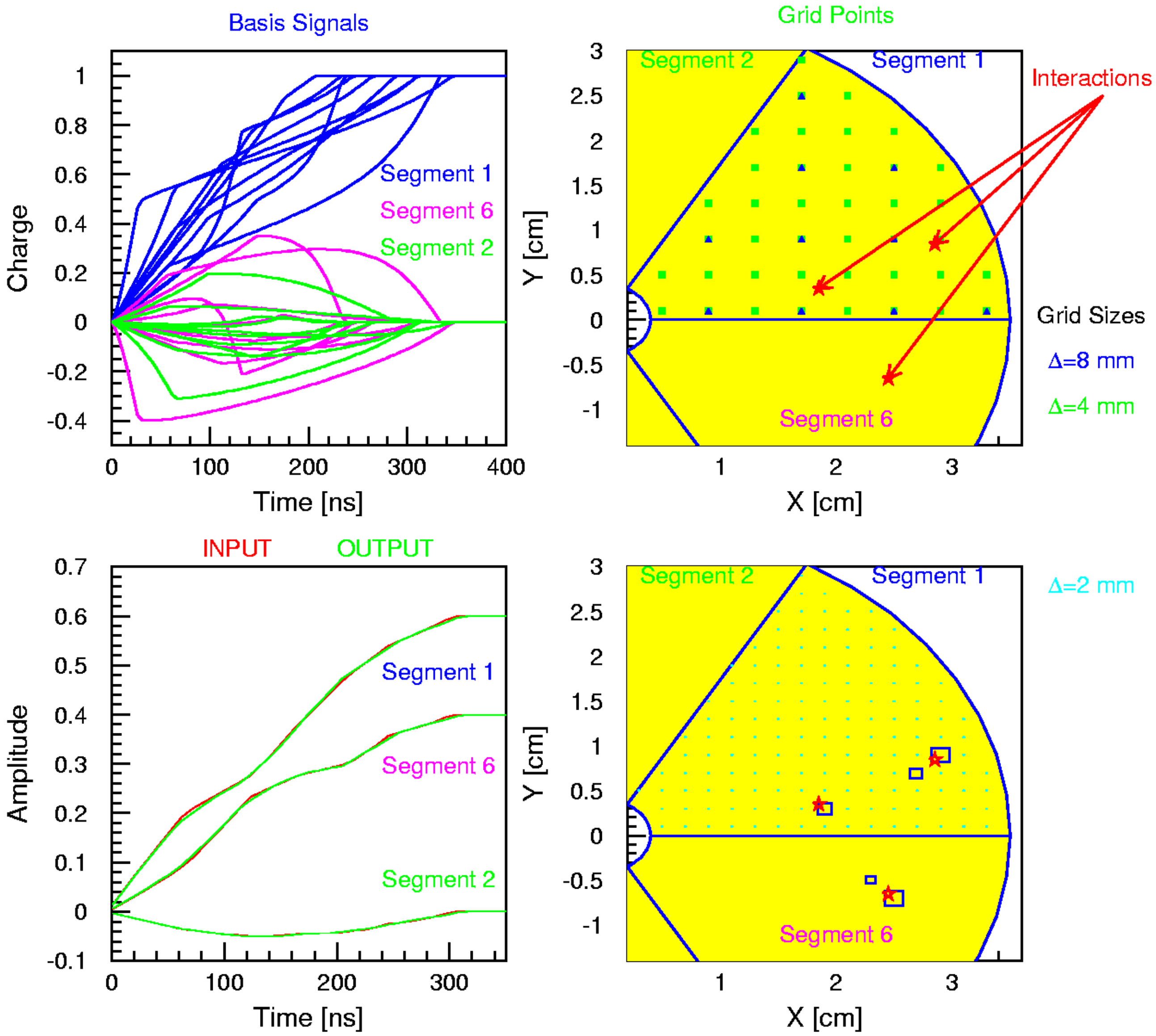
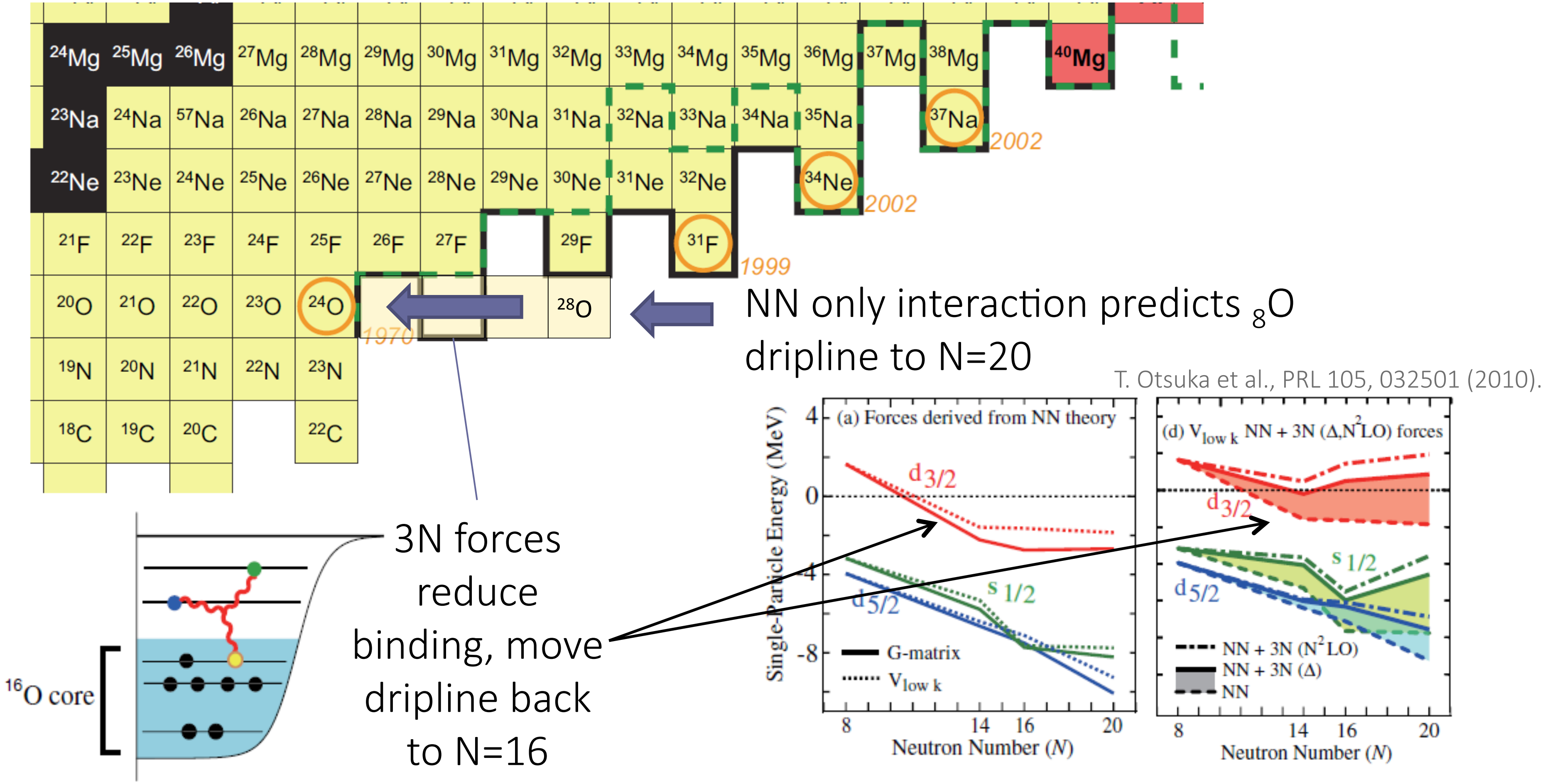


3N FORCES: THE OXYGEN ANOMALY

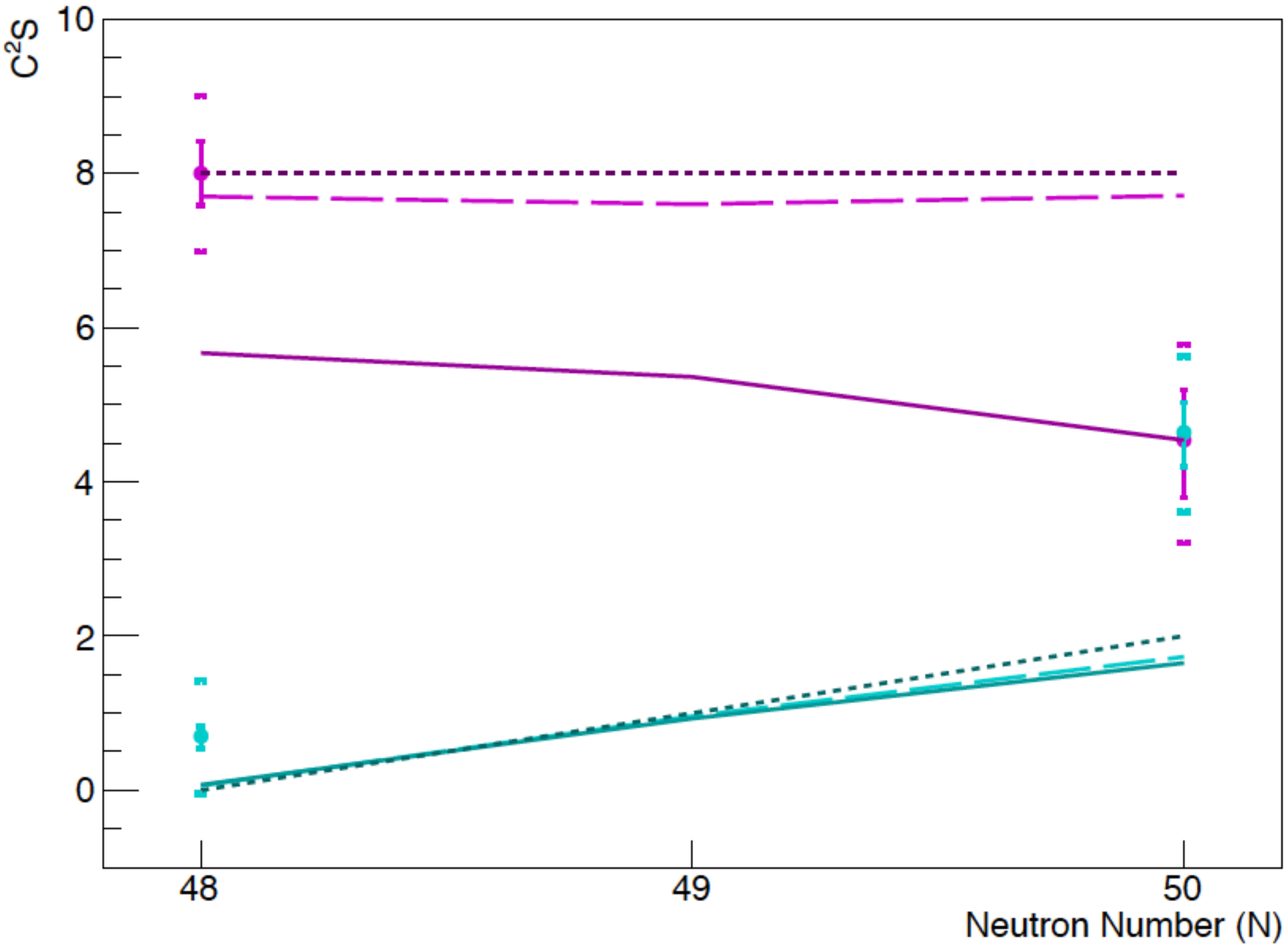
- Many body theory based on NN-only forces places the position of the dripline for Z=8 at A=28, rather than the experimentally observed A=24
- Without 3N forces, the NN interaction is too attractive



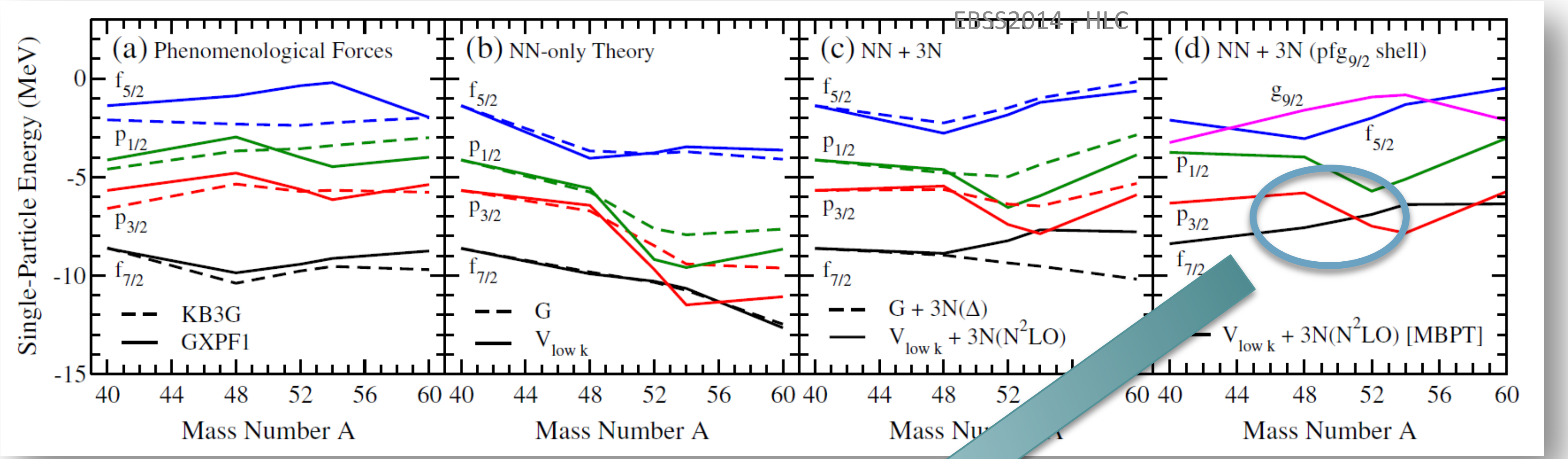
NN only interaction predicts $_8$O dripline to N=20

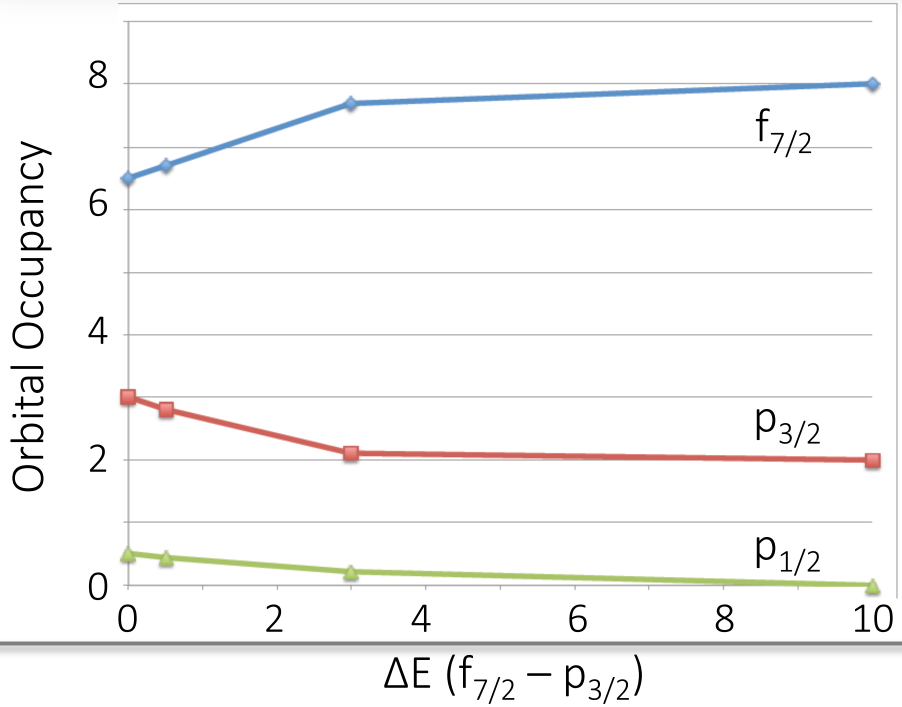
T. Otsuka et al., PRL 105, 032501 (2010).

3N forces reduce binding, move dripline back to N=16


C^2S
10
8
6
4
2
0
48
49
50
Neutron Number (N)

MIXING OF THE $f_{7/2}$ AND $p_{3/2}$?





Mixing may provide at least a partial explanation for depletion of the $f_{7/2}$ strength and enhancement of the $p_{3/2}$ occupancy

Reduction of the $f_{7/2}$ strength in the $7/2_1$- state may also be related to fragmentation of strength to higher states as predicted by the microscopic calculations

^{47}Ca: GAMMA-GAMMA AND LEVEL SCHEME