Nuclear Structure Studies with High-Resolution In-Beam γ-Spectroscopy

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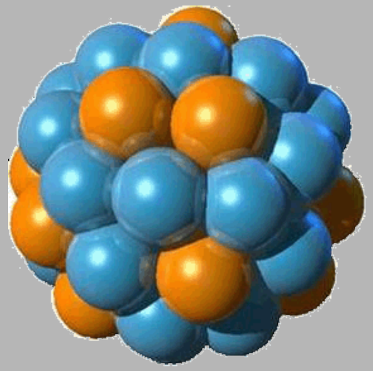


- Introduction to the physics
  Introduction to the in-beam technique
- Reactions for the Spectroscopy
- Measurement capabilities
- Instrumentation

The Atomic Nucleus

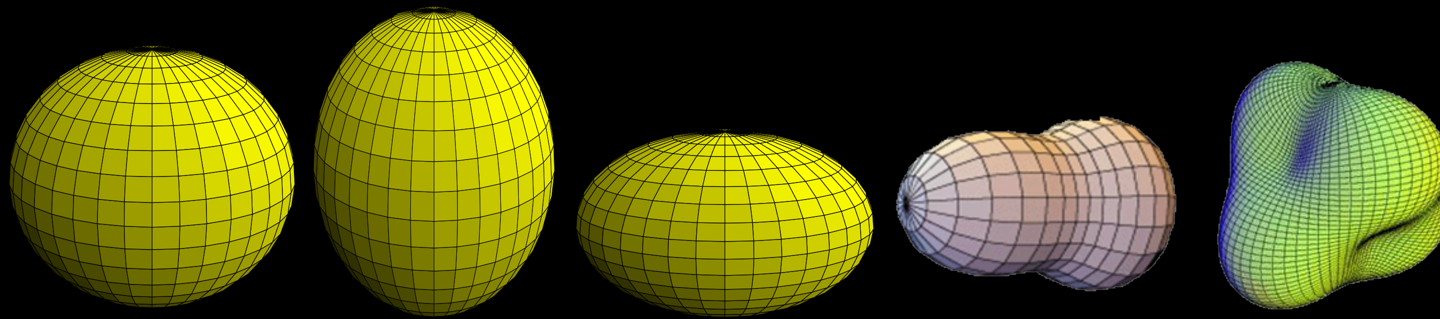
- **The atomic nucleus is a complex fermionic system, based on two different particles, interacting via an effective force strongly influenced by in-medium effects.**

- **Nuclei are small enough that the quantum nature of its constituents determines its properties but large enough that macroscopic features begin to evolve.**

- **Nuclei have been the traditional objects for studying mesoscopic (many body) phenomena, as well as Open Quantum Systems in the limits of stability.**

Nuclear Collectivity

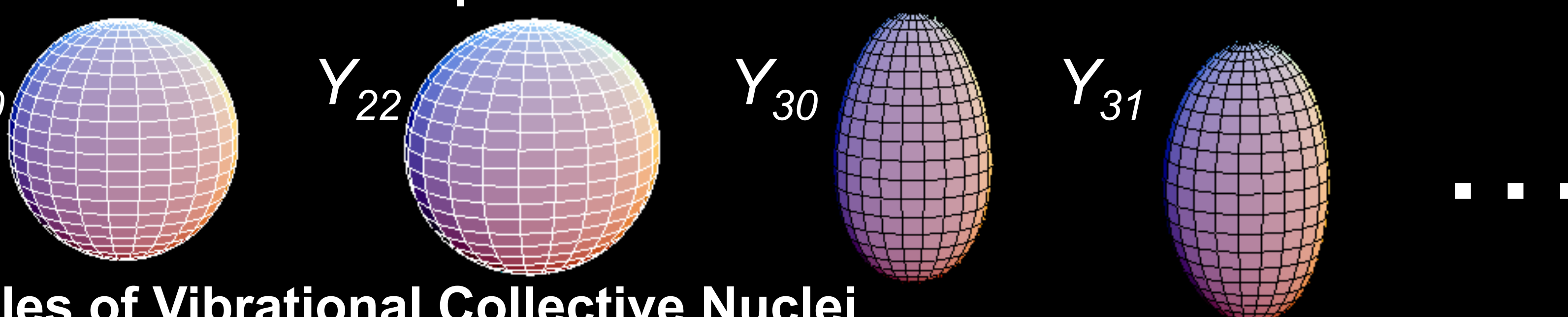
Examples of Nuclear Shapes



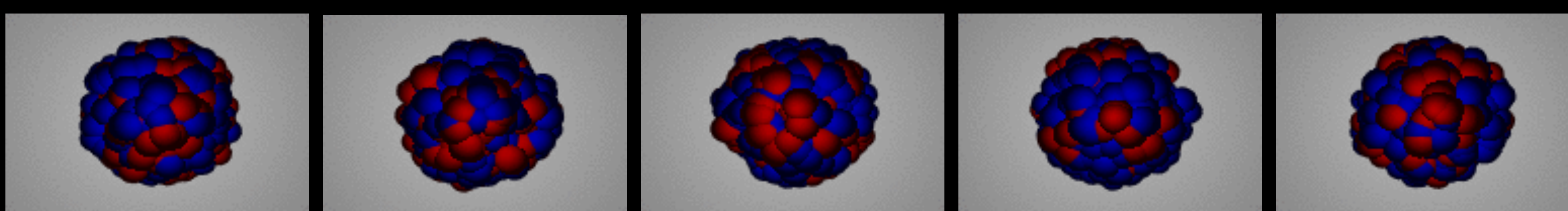
Spherical Prolate Oblate Octupole Tetrahedric

Examples of Nuclear Shape Vibrations

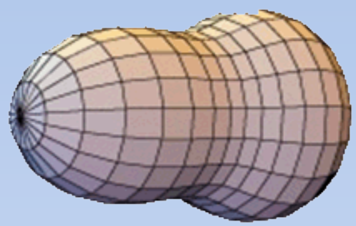
Y_{20} Y_{22} Y_{30} Y_{31}

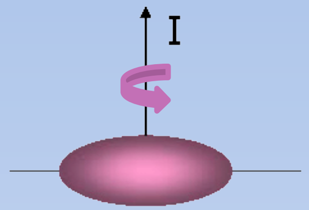


Examples of Vibrational Collective Nuclei

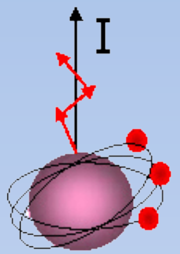


GMR (Isoscalar) GMR (isovector) GDR (isovector) GQR (isoscalar) GQR (isovector)

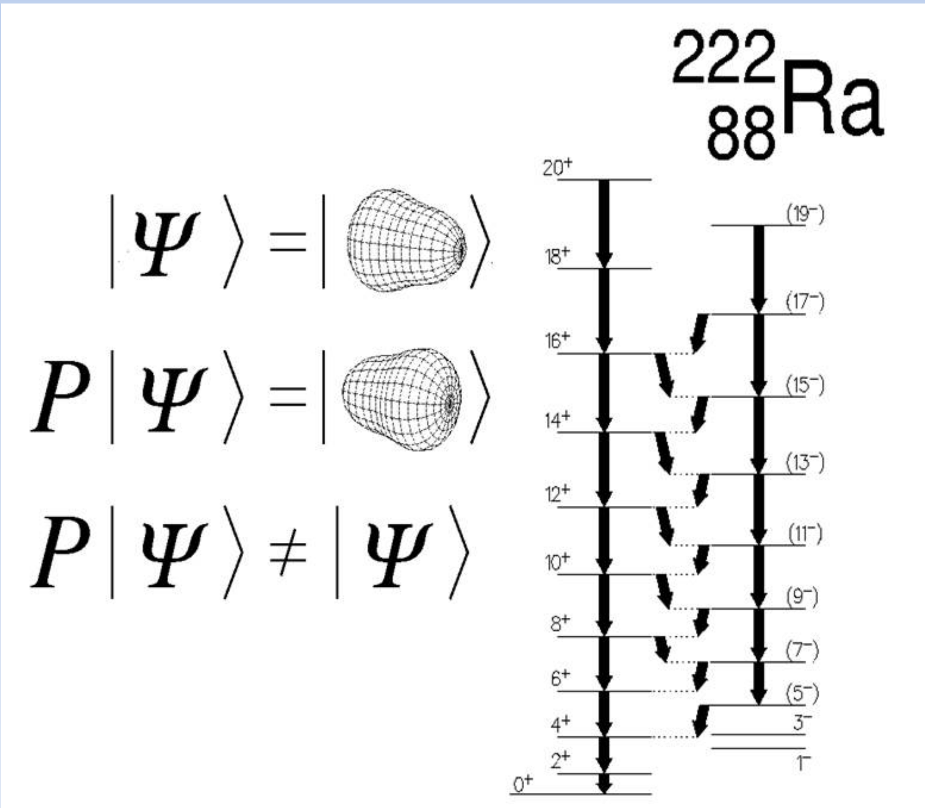


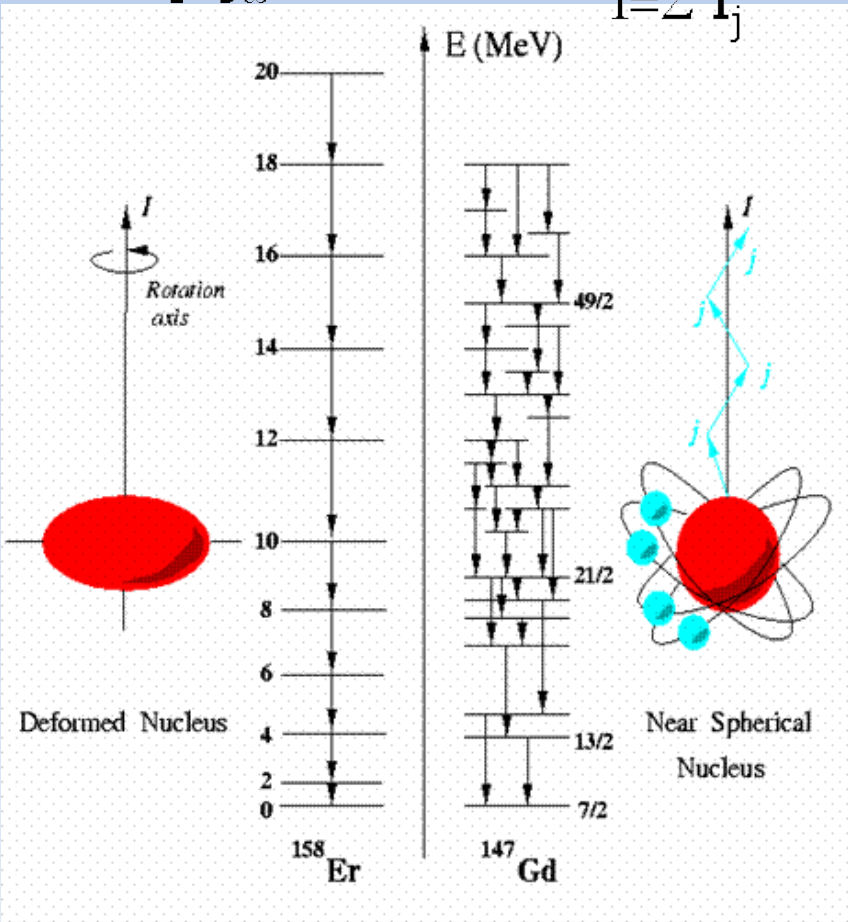


$I = J\omega$



$I = \Sigma I_j$



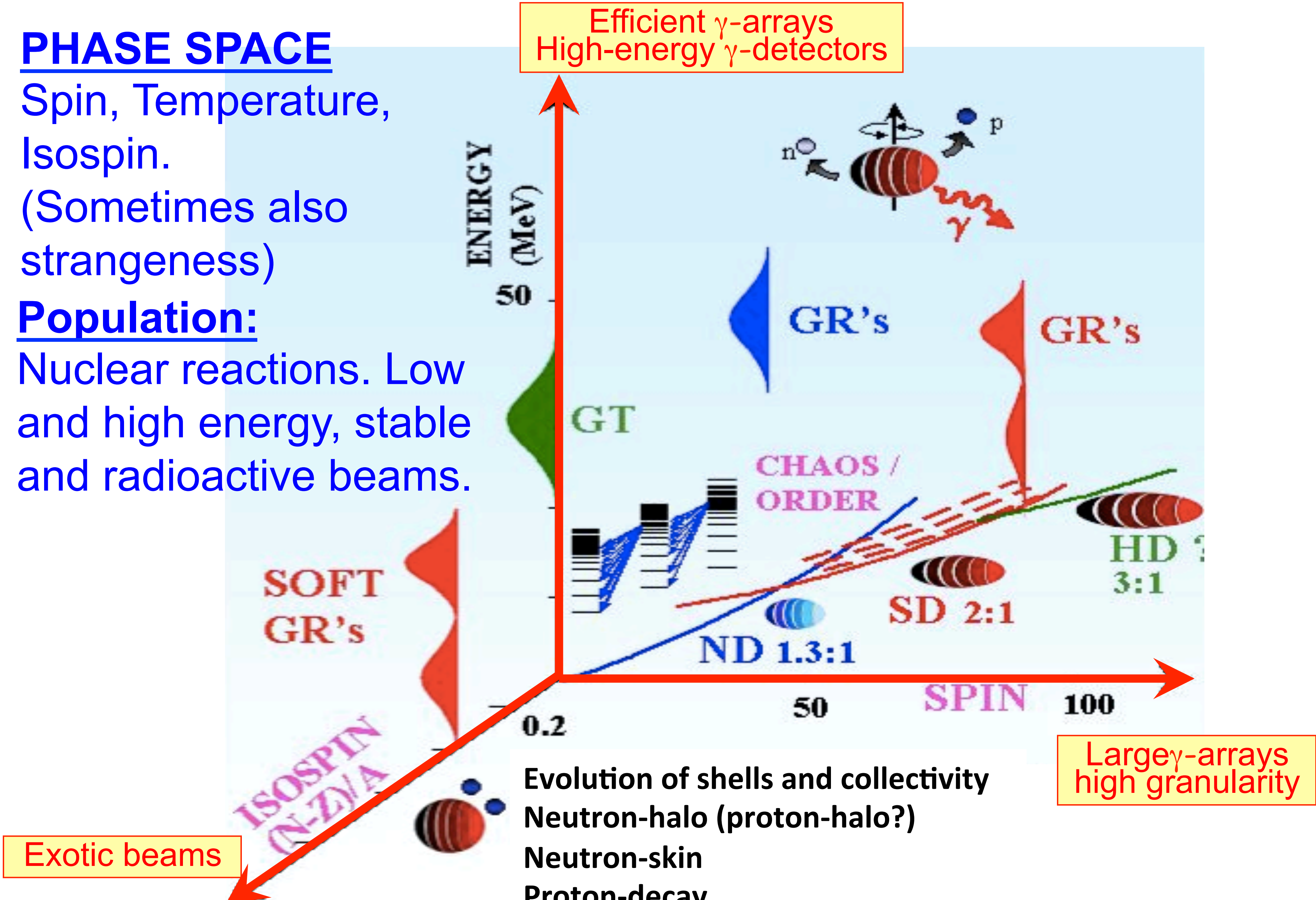


PHASE SPACE

Spin, Temperature, Isospin. (Sometimes also strangeness)

Population:

Nuclear reactions. Low and high energy, stable and radioactive beams.

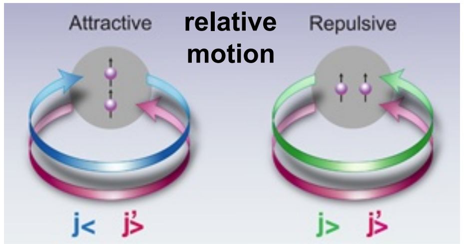


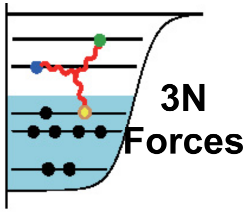
Evolution of shells and collectivity
Neutron-halo (proton-halo?)
Neutron-skin
Proton-decay
etc…

Some Scientific Topics

Organization of Nuclear Matter and Emerging Phenomena. In-media Fundamental Interactions, Origin and Evolution of Nuclear Matter

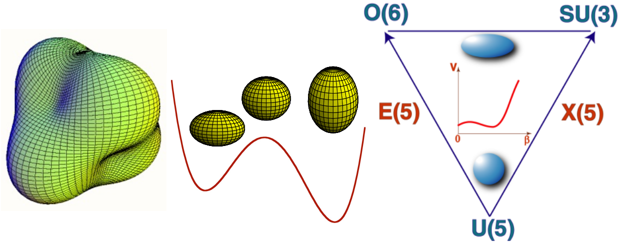
- **Shell Structure Far From Stability:** large nucleon asymmetry lead to shell modifications driven by the spin-isospin nucleon-nucleon interaction and close to the drip-line by the weakening of the spin-orbit interaction

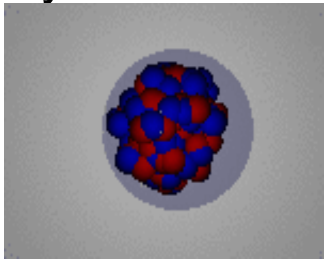




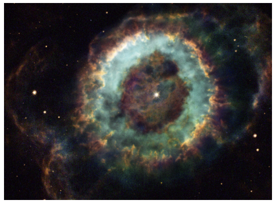
- **Three Body Forces:** testing the role of three nucleon (3N) forces in the microscopic description of the atomic nucleus. Indications of important role in the vicinity of proton as well as neutron drip-lines.

- **Nuclear Shapes:** coexistence of different nuclear shapes, Large deformation, high-rank symmetries, phase transition, dynamic and critical point symmetries.





- **Spin-isospin Response Of Nuclei:** out-of-phase density oscillations of the neutron and proton fluids provided information on macroscopic nuclear properties associated with isovector fields.



- **Nuclear Matter Appearance and Evolution:** nuclear astrophysics, explosive scenarios and the rp-process, the origin of the elements heavier than Iron and the r-process

- **and Clustering in Nuclei, New forms of nuclear pairing, In-Media isospin breaking interactions, Study of Open Quantum Systems, etc …**

In-Beam Spectroscopy Key Aspects

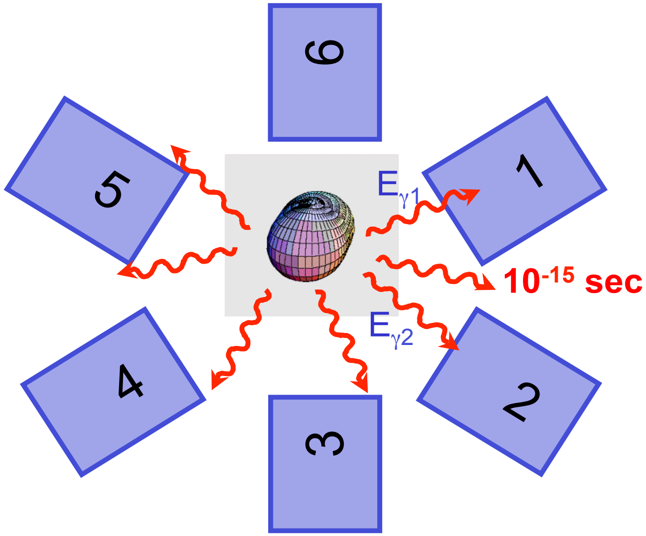
- Direct detection of the "prompt" de-excitation γ-rays emitted by the nucleus of interest

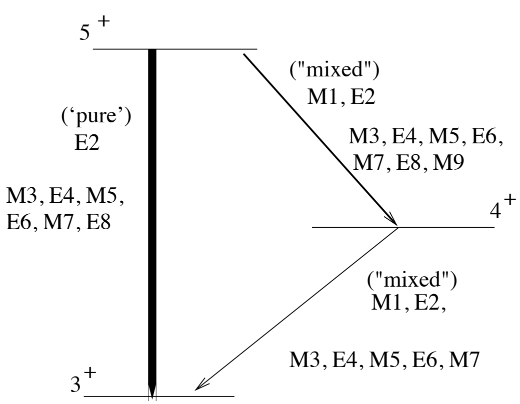
- The nucleus to be studied "must" be in a excited state:
  - The nucleus can be created in a excited state or
  - The nucleus must be excited during the reaction process

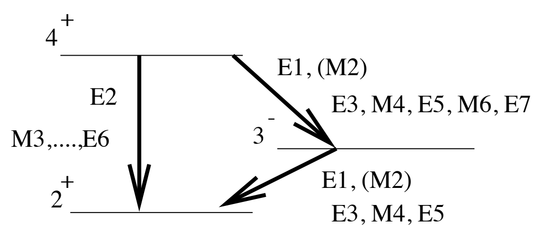
- The detection system are installed around the reaction point
  - Key factors are Efficiency, Peak-to-Total, i.e. signal-to-noise and Selectivity.
  - Reaction rates could by limited by the detector counting rates limit.

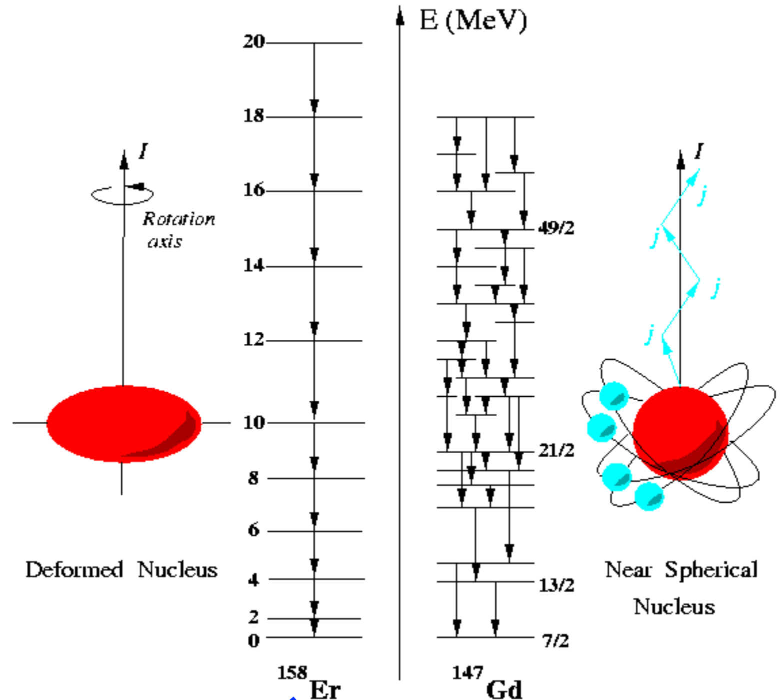
- In addition to the γ-ray detector, frequently, complementary detectors and devices are necessary to improve selectivity or to perform a particular measurement.

In-beam Experiments and Nuclear Structure









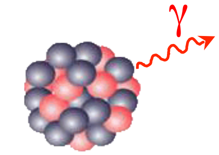
Collective rotation leads to **regular** band structures

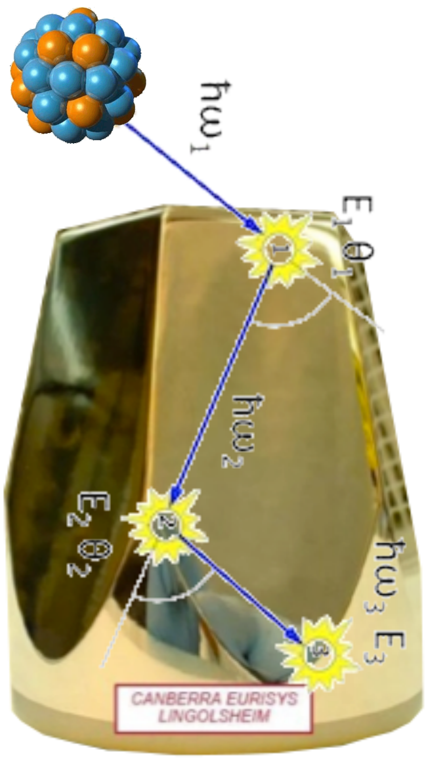
Single-particle generation of spin leads to an **irregular** level structure

B(E/Mλ) The decay probability is governed by the matrix element of the multipole operator

$$m_{fi}(\sigma L) = \int \Psi_f^* m(\sigma L) \Psi_i dv$$

High Resolution γ-ray Spectroscopy

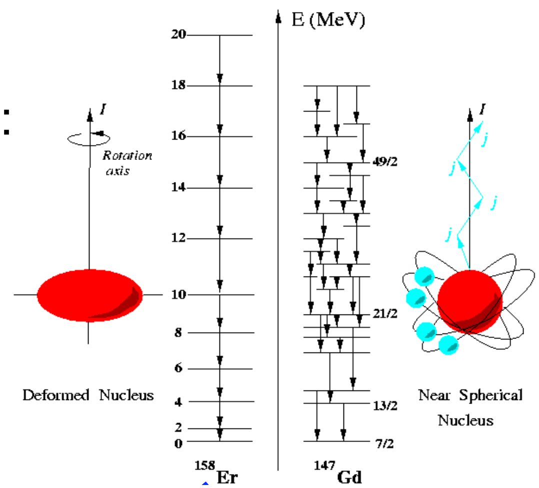


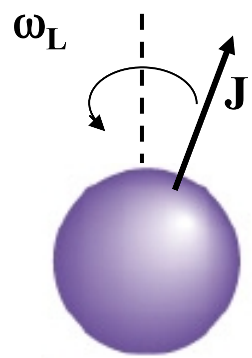


Transition probabilities by Doppler or indirect methods

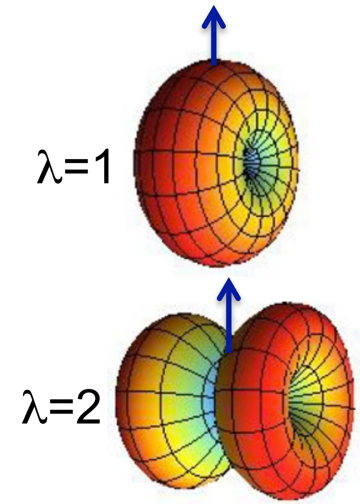
B(E/Mλ)

Sequence of Excited States: γ-ray Energy, intensity and coincidence analysis



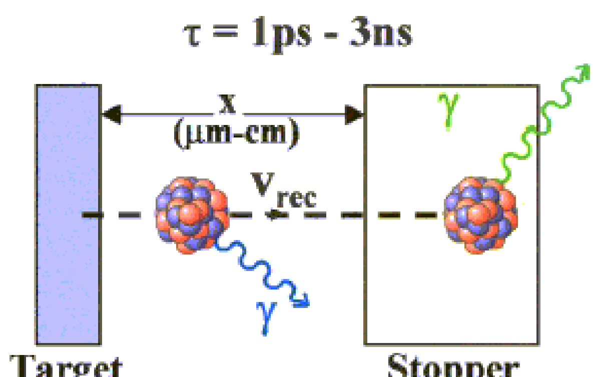


Nuclear Moments (e.g.: g-factors magnetic field)

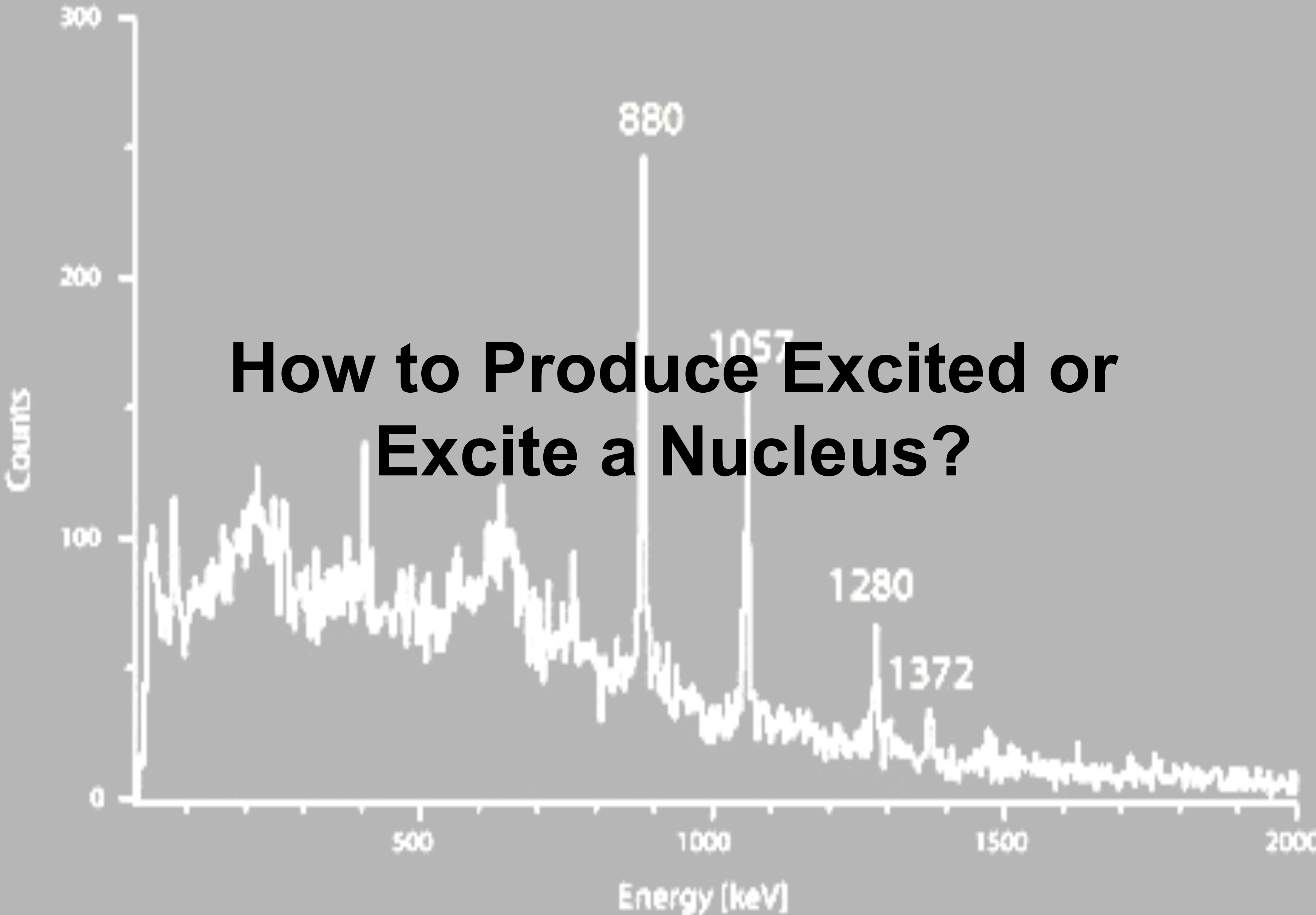


State Quantum numbers J^{π}

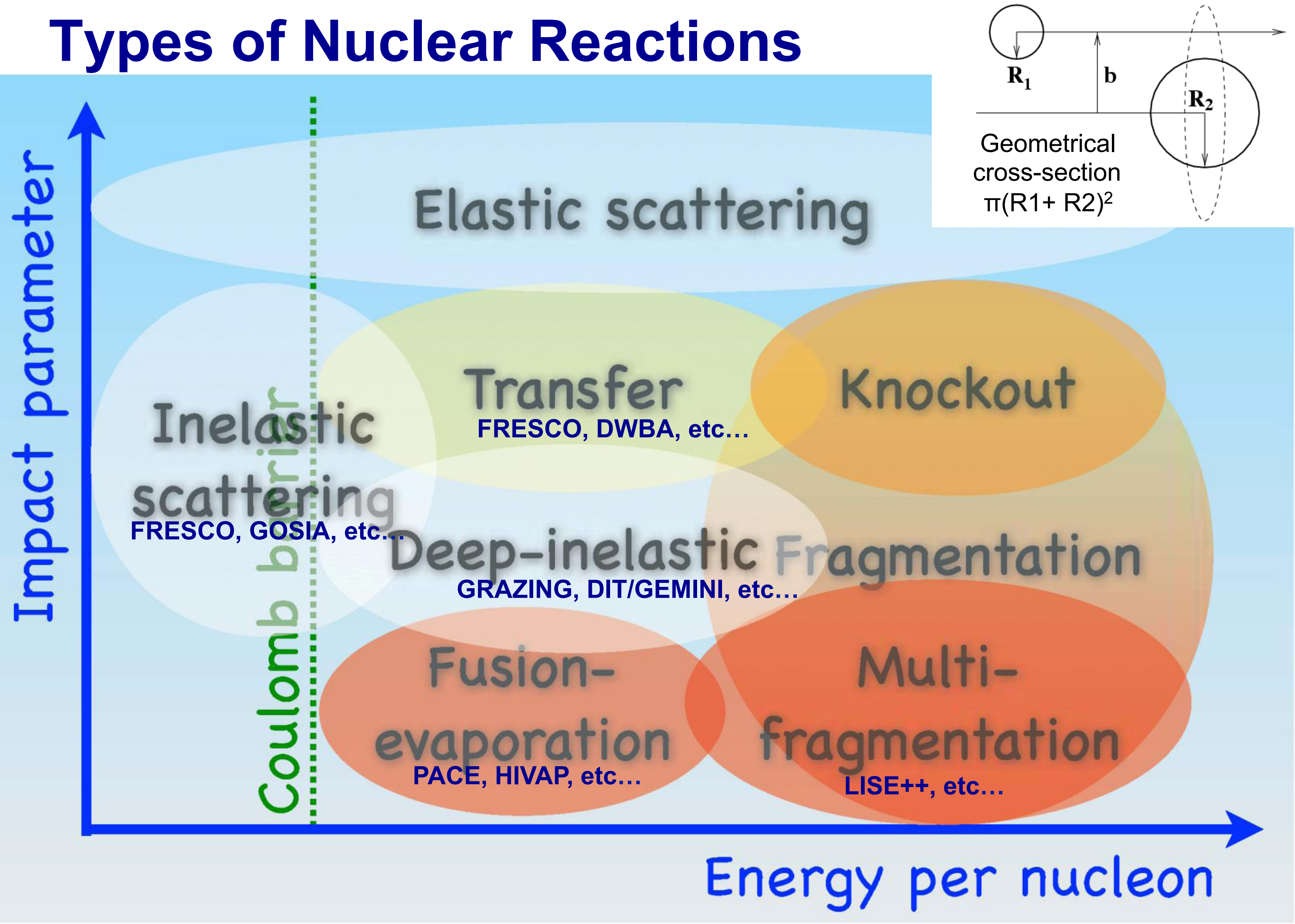
γ-ray angular distribution, correlations and linear polarization



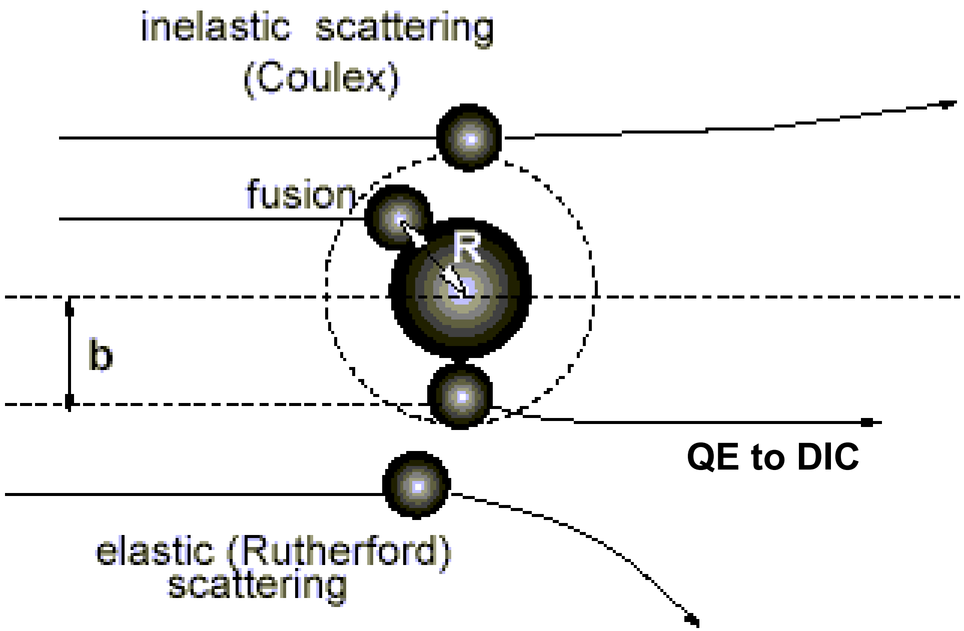
How to Produce Excited or Excite a Nucleus?

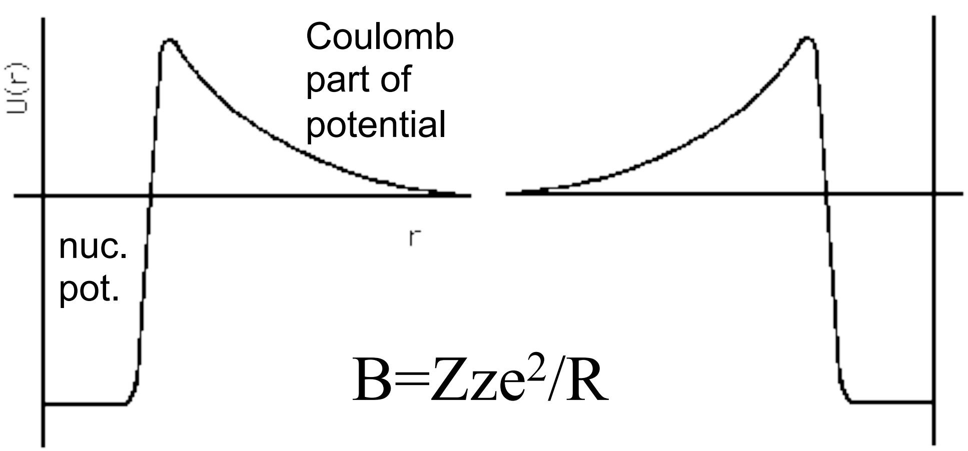


Types of Nuclear Reactions



Low Energy reaction mechanisms used for γ-Spectroscopy (up to ~10 MeV.A)



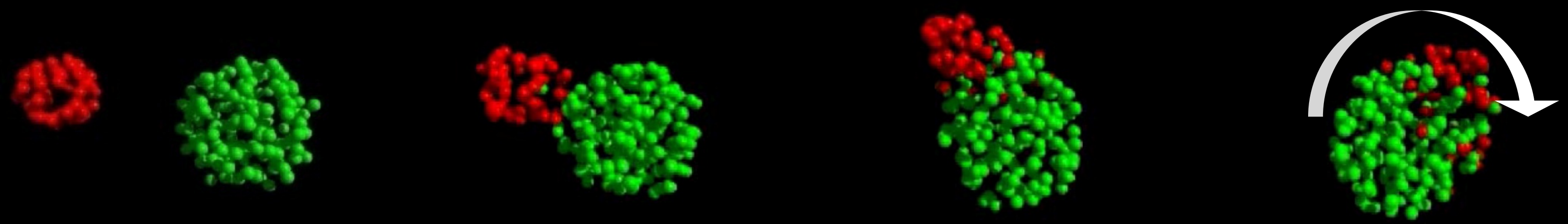


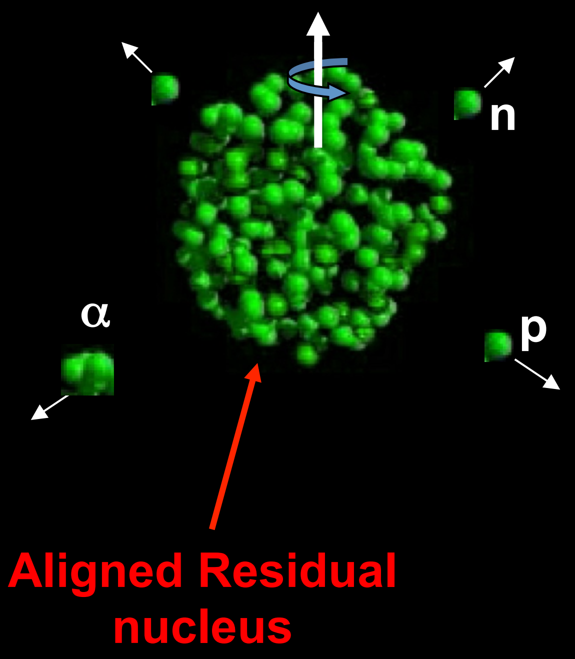
Smaller impact parameter “b”

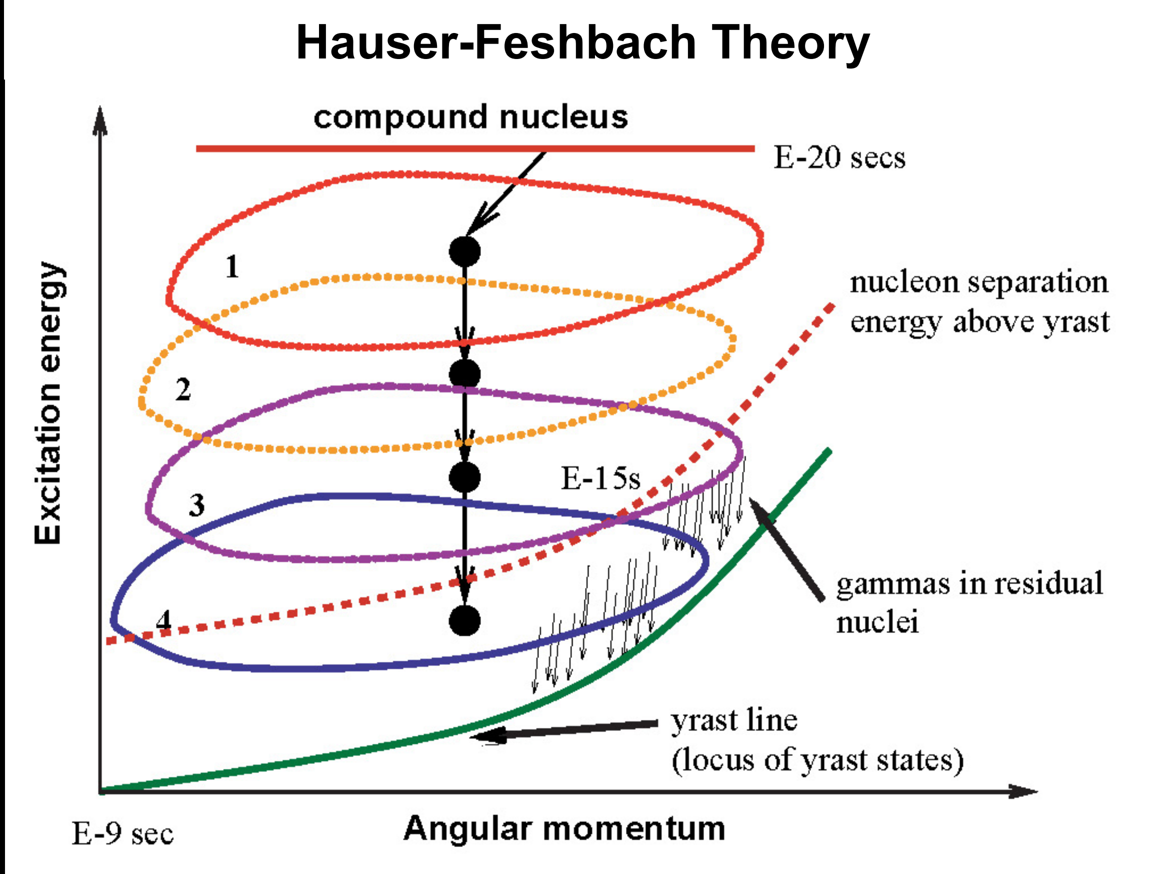
- Coulomb excitation and Inelastic scattering.
- Transfer and quasi-elastic processes (p,n capture...).
- Multi-nucleon transfer.
- Deep Inelastic Collisions.
- Quasi-fusion reactions.
- Fusion with light particles evaporation .
- Fusion with evaporation of Massive Fragments (IMF)
- Fusion-fission

Cross sections up to few barns typically from tens of mb to μb

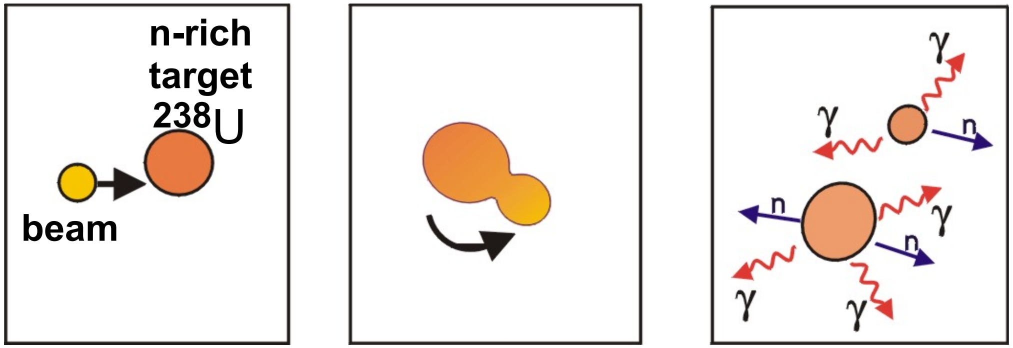
Example: FUSION-EVAPORATION REACTIONS

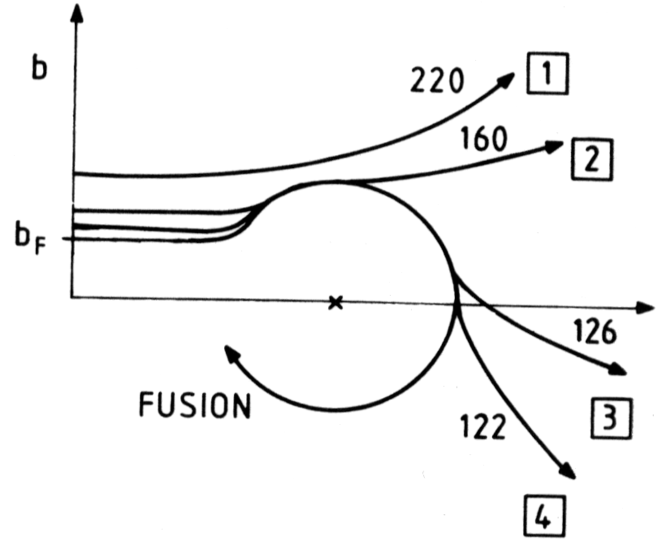




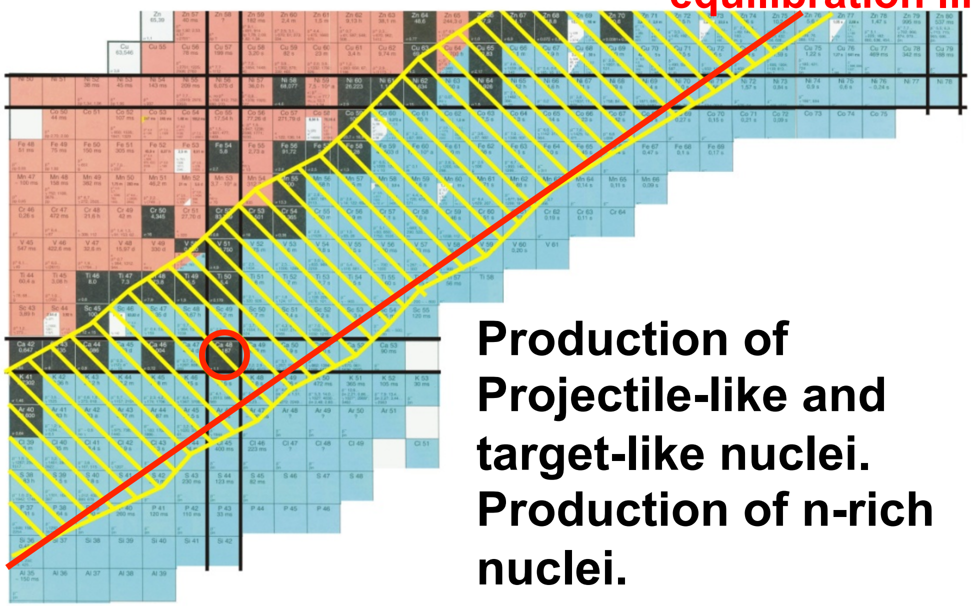


Example: GRAZING REACTIONS



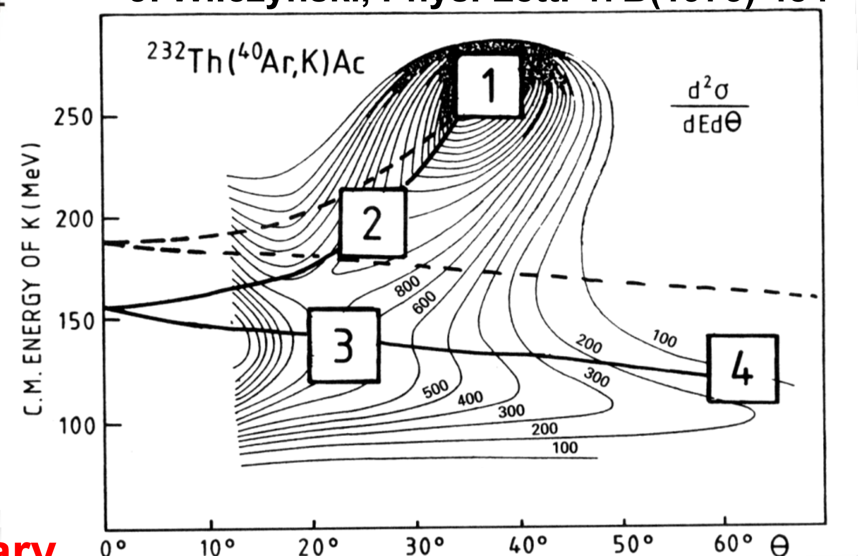


N/Z
equilibration line



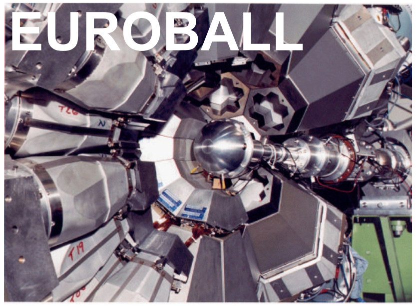
Production of Projectile-like and target-like nuclei. Production of n-rich nuclei.

J. Wilczynski, Phys. Lett. 47B(1973) 484



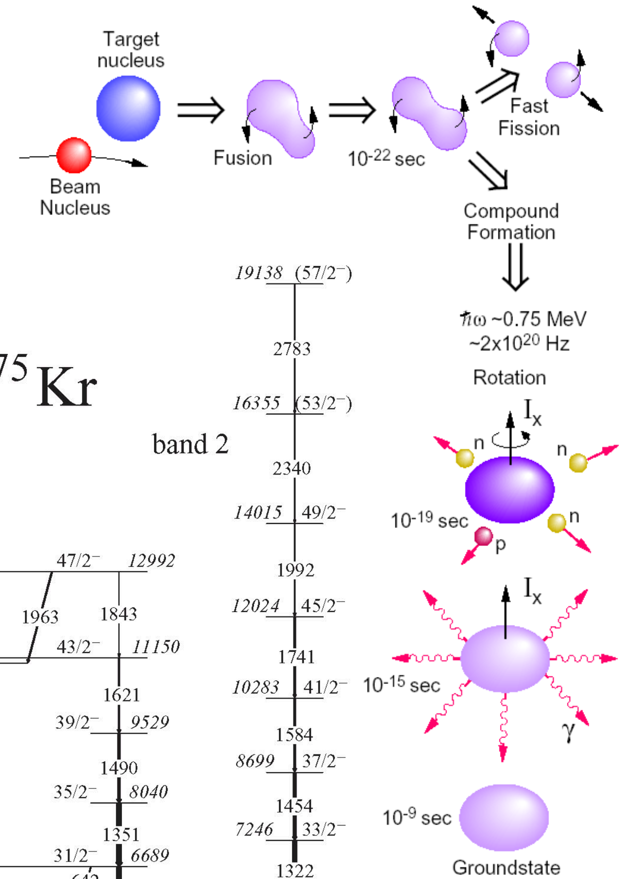
Identification of products with complementary detectors or by γ-spectroscopy of the partners is required

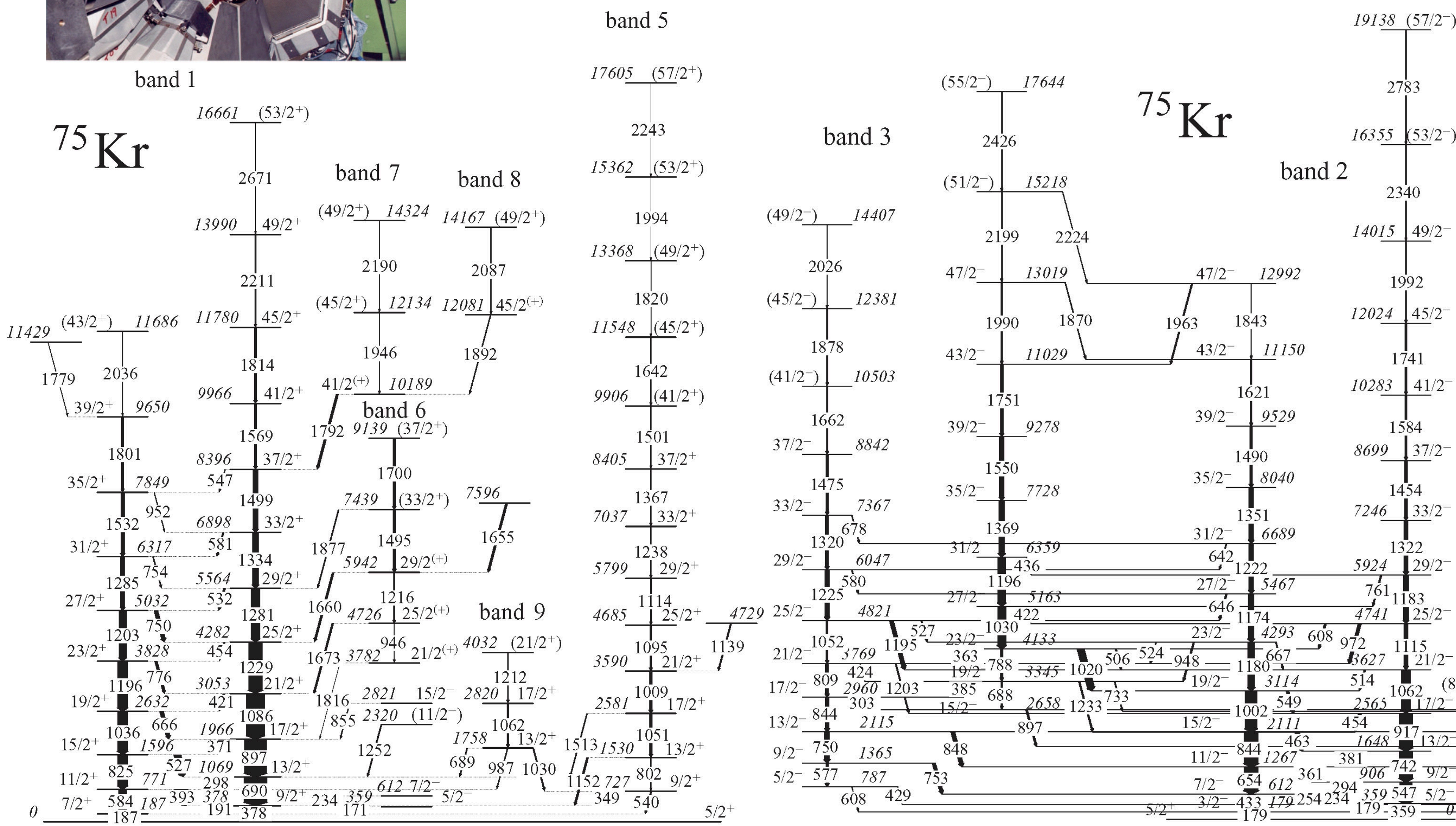
Example: Spectroscopy with Fusion-Evaporation Reactions



$^{40}Ca(^{40}Ca,4pn)^{75}Kr^*$

States identified up to J=57/2 and 19 MeV excitation energy

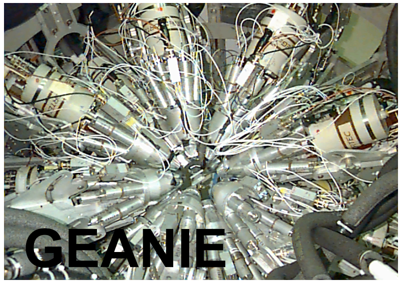




Th. Steinhardt, et al., Phys. Rev. C **86**, 064310 (2012)

Example: Spectroscopy with neutron Inelastic Scattering

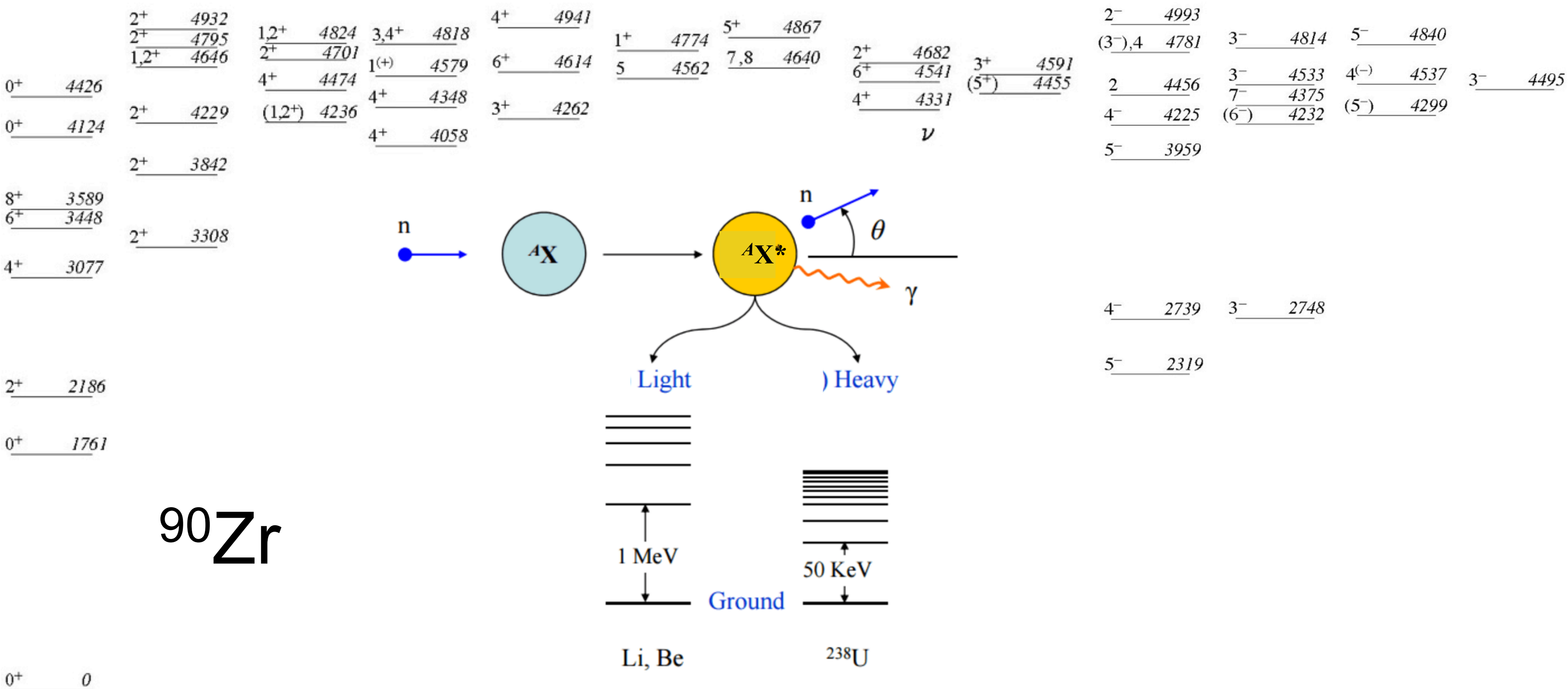
LANSCE/WNR facility



$^{90}Zr(n, n')^{90}Zr^*$

Neutron energy:
2 to 12 MeV

States identified up to J~6
and ~6 MeV excitation energy



P.E. Garrett, et al., Phys. Rev. C **68**, 024312 (2003)

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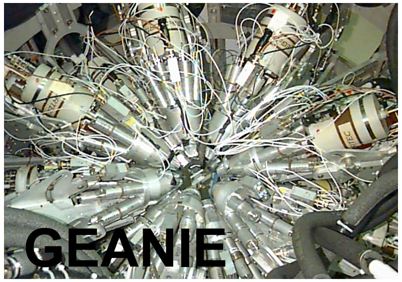

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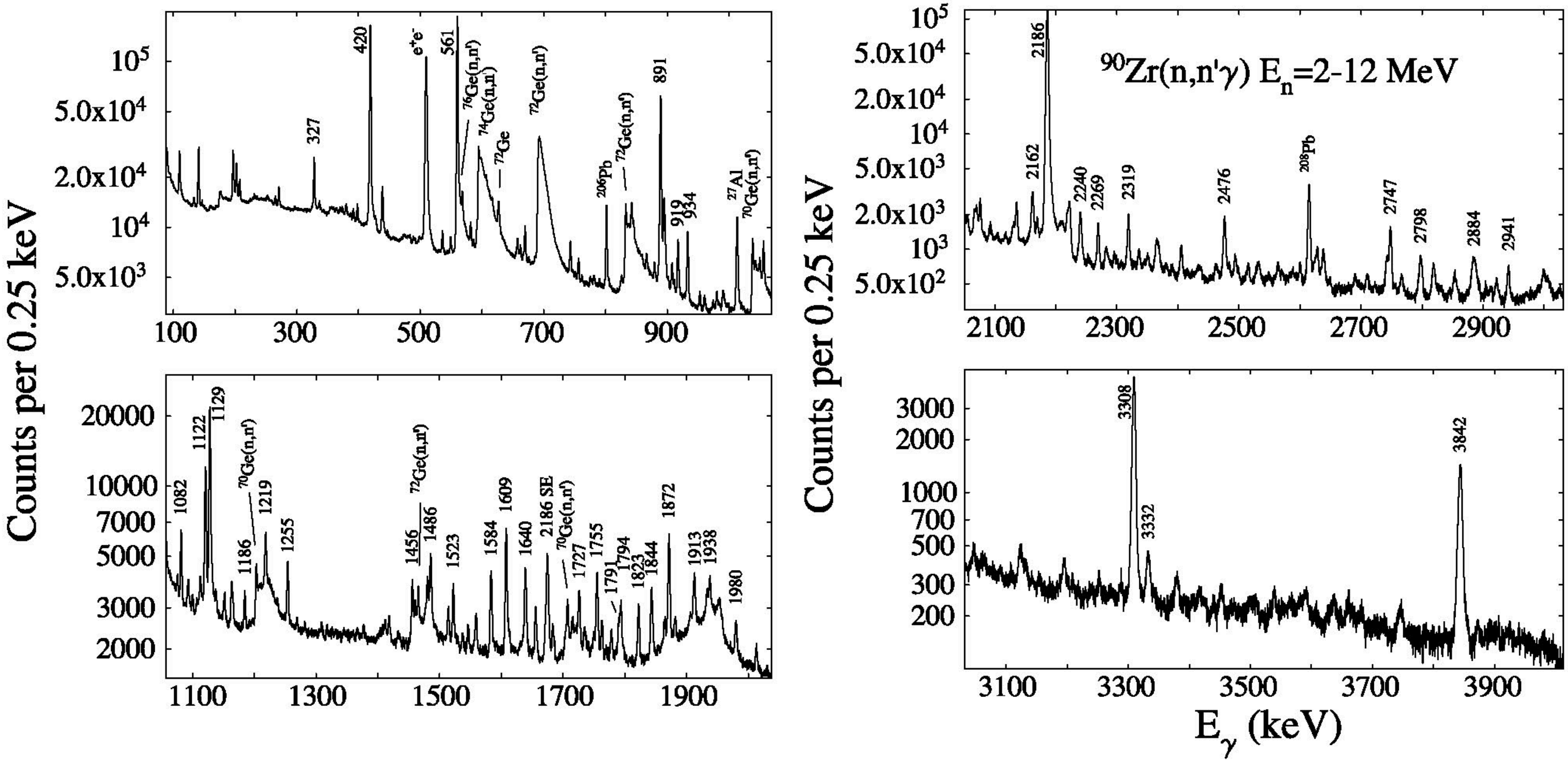
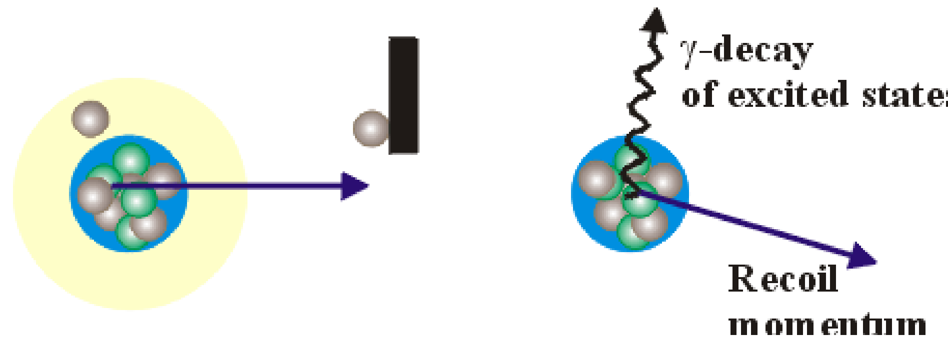


P.E. Garrett, et al., Phys. Rev. C **68**, 024312 (2003)

High energy reaction mechanisms used for γ-Spectroscopy (above ~40 MeV.A)

Generally used with exotic ion beams produced by fragmentation or fission at relativistic energies

- Relativistic (single step) Coulomb excitation
- Inverse proton scattering
- Knockout reactions
- Fragmentation reactions



Knockout reaction

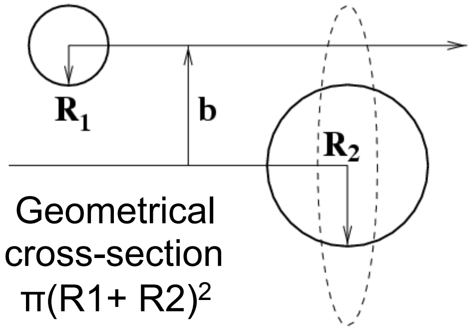
Cross sections :

- up to1 barn for Coulex (large Z nuclei)
- tens of mbarn for proton scattering and 1 nucleon knockout,
- down to few mb for 2 nucleons knockout.
- smaller cross sections for fragmentation

Fragmentation reaction

Yields from Cross-Section Estimates

- The Cross-Section estimate σ is given in barn i.e. 10^{-28} m^2 = 100fm



Geometrical cross-section $\pi(R1+R2)^2$

- The yield of a reaction is proportional to the Cross-section, the number of atoms in the target and the atoms per second in the beam:
  - Cross-section are given in barn's ($10^{-24}cm^2$)
  - Target thicknesses are usually given in mg/cm^2
  - The beam intensity is given in particles per second (pps) or in particle nA (pnA).

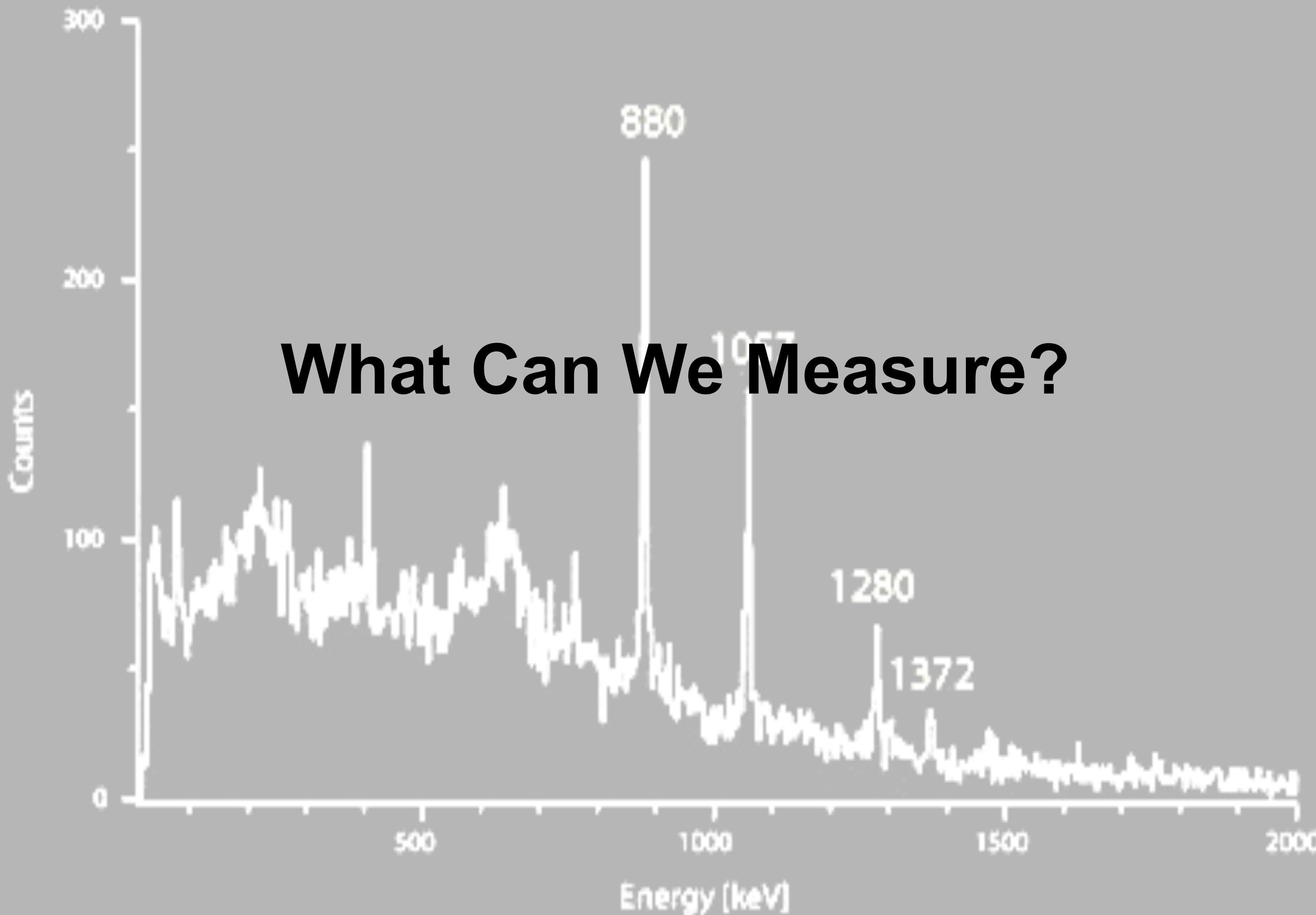
$$yield = \sigma\,(barn) \cdot 10^{-24}\left(\frac{cm^2}{barn}\right) \cdot \frac{Target\ \left(\frac{g}{cm^2}\right)}{Mol\ weight\ (g)} \cdot N_A \cdot Beam\left(\frac{Atoms}{s}\right)$$

The production cross-section does not imply that a transition or particular phenomena will be observed with such intensity, e.g. superdeformed bands 1/100 yield

Further Information on Reactions Cross-Section Determination:

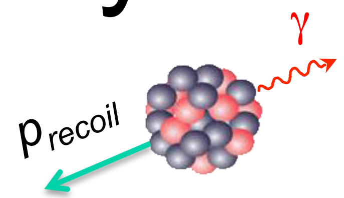
- Inelastic, Transfer Reactions, Grazing etc…
  - http://nrv.jinr.ru/nrv/
- GOSIA (Coulomb excitation
  - http://www.pas.rochester.edu/~cline/Gosia/
- Fusion-Evaporation Reactions
  - PACE in LISE++: http://lise.nscl.msu.edu/lise.html
  - HIVAP: W. Reisdorf, Z. Phys. A **300**, 227 (1981)
- Relativistic Coulomb Excitation
  - DWEIKO: C.Bertulani et al. Comput. Phys. Commun. 152 (2003) 317.
- Fragmentation, Knock-out etc..
  - LISE++: http://lise.nscl.msu.edu/lise.html

What Can We Measure?



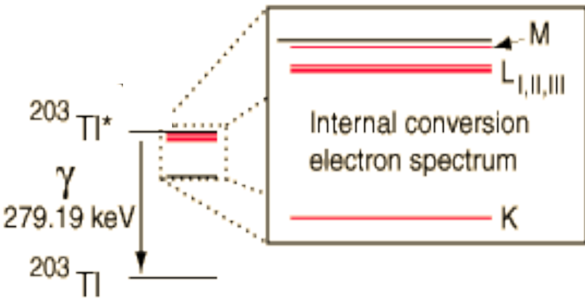
Electromagnetic decay

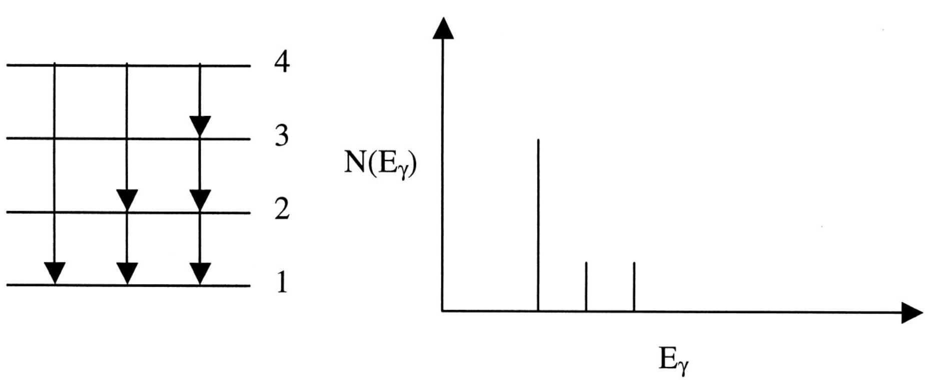
- There are three types of electromagnetic decay, γ-ray emission, internal conversion (IC) and pair production (E>1.02MeV).
- In electromagnetic decays ΔN=ΔZ=ΔA=0, with just a lowering of the excitation energy of the nucleus.
- In γ-ray emission, the emitted photons are mono-energetic and have an energy corresponding to almost all of the energy difference between the final and initial state of the system.

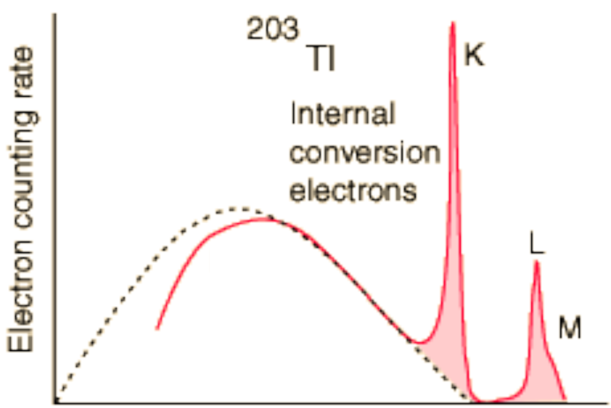


$$p_\gamma = p_{recoil}$$

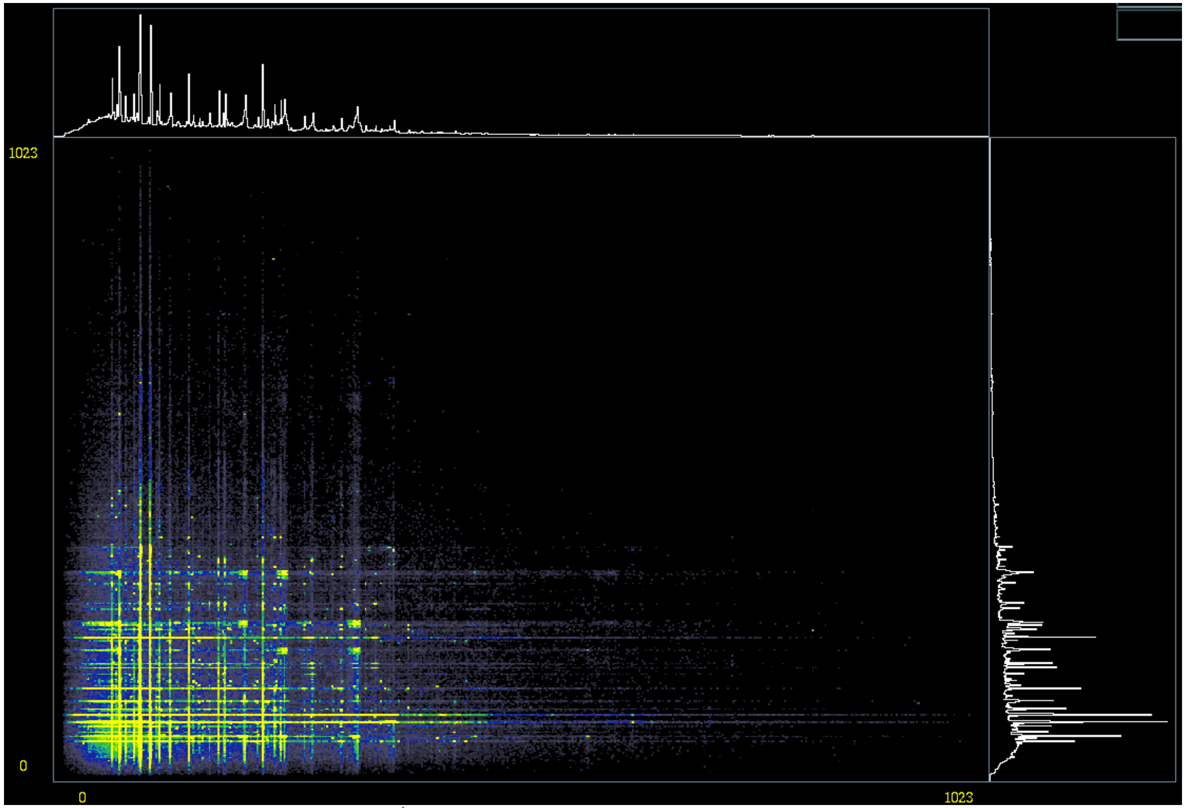
$$T_{recoil} = \frac{p_{recoil}^2}{2m_{recoil}} = \frac{p_\gamma^2}{2m_{recoil}} = \frac{E_\gamma^2}{2m_{recoil}c^2}$$



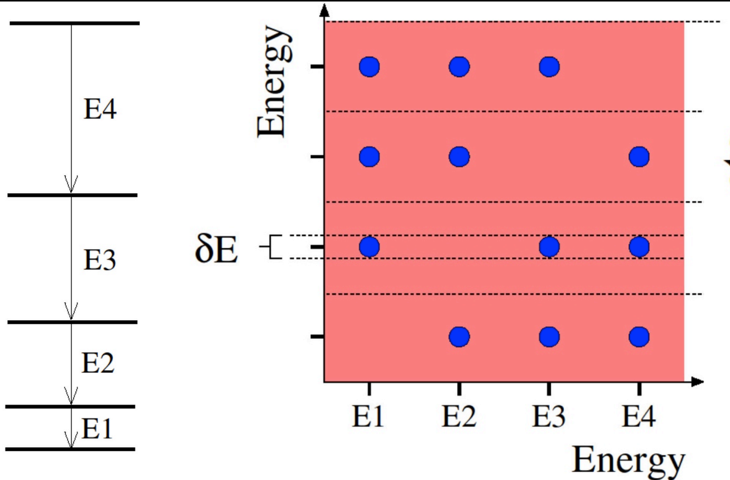


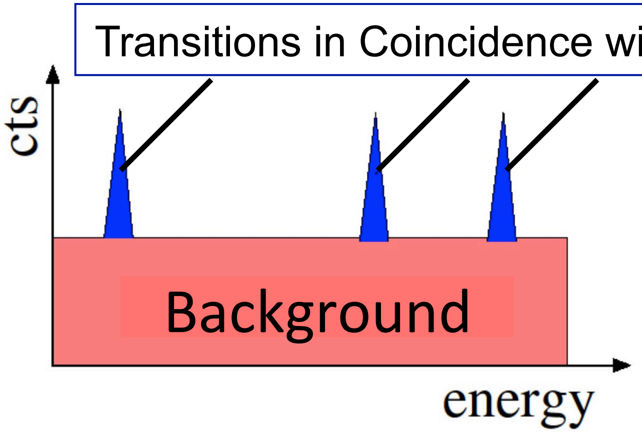


γ-ray Coincidence Analysis



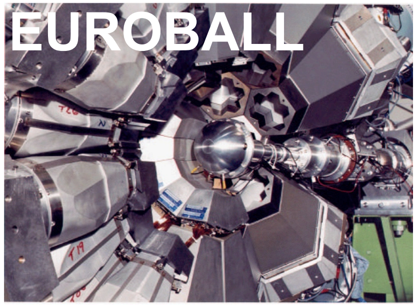
- With two or more detectors it is possible to create two or higher dimension histograms.
- The 1D projection with a condition in one of the axis provides the spectrum of γ-rays "in coincidence".
- The "coincidence" relationships allow to create the energy level scheme of the nucleus for a particular reaction.



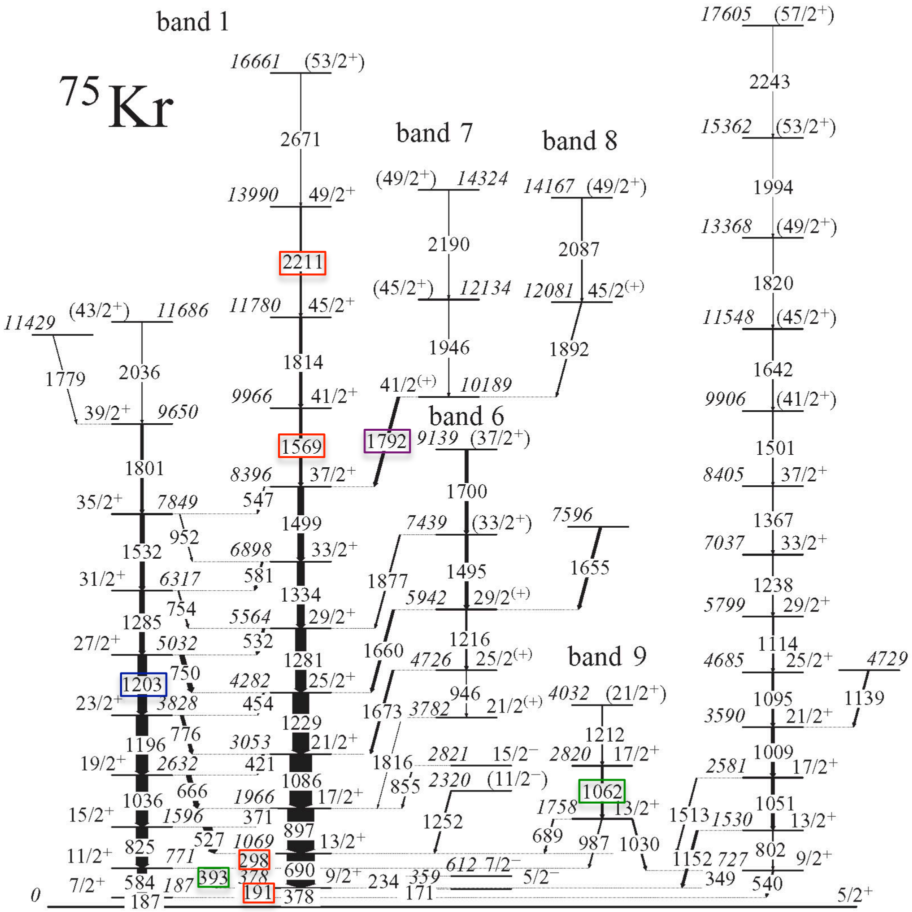


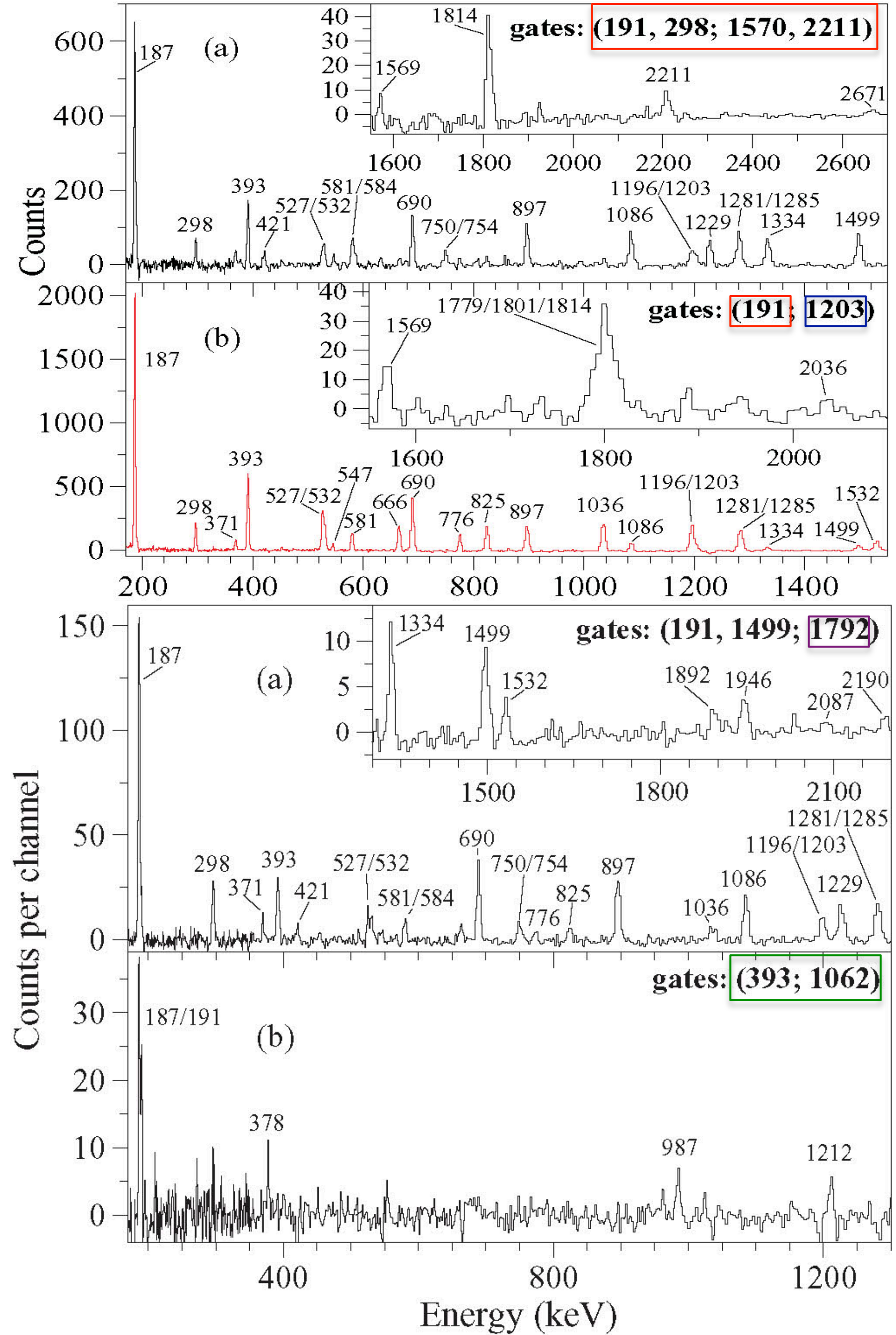
The Compton background is as well in coincidence with the transition

Example: Coincidence Analysis in Fusion-Evaporation Reactions



$^{40}Ca(^{40}Ca,4pn)^{75}Kr^{*}$





Th. Steinhardt, et al., Phys. Rev. C **86**, 064310 (2012)

Electromagnetic Decay

- The initial and final states have a definite angular momentum and parity. The photon carries away a definite amount of angular momentum. Angular momentum and parity must be conserved.
- Multipolarity is a measure of the angular momentum carried away by the photon.
- Transitions are classified as electric or magnetic based on whether the radiation is due to a shift in the charge distribution or a shift in the current distribution.
- Based upon the type of operator involved in the transition, there are restrictions on the parity change in the transition.

$$\left|\left(I_i - I_f\right)\right| \leq \ell \leq \left(I_i + I_f\right)\hbar$$

A photon with ℓ units of angular momentum is called a 2^ℓ − pole photon.

$\ell = 1 \Rightarrow$ *dipole*

$\ell = 2 \Rightarrow$ *quadrupole*

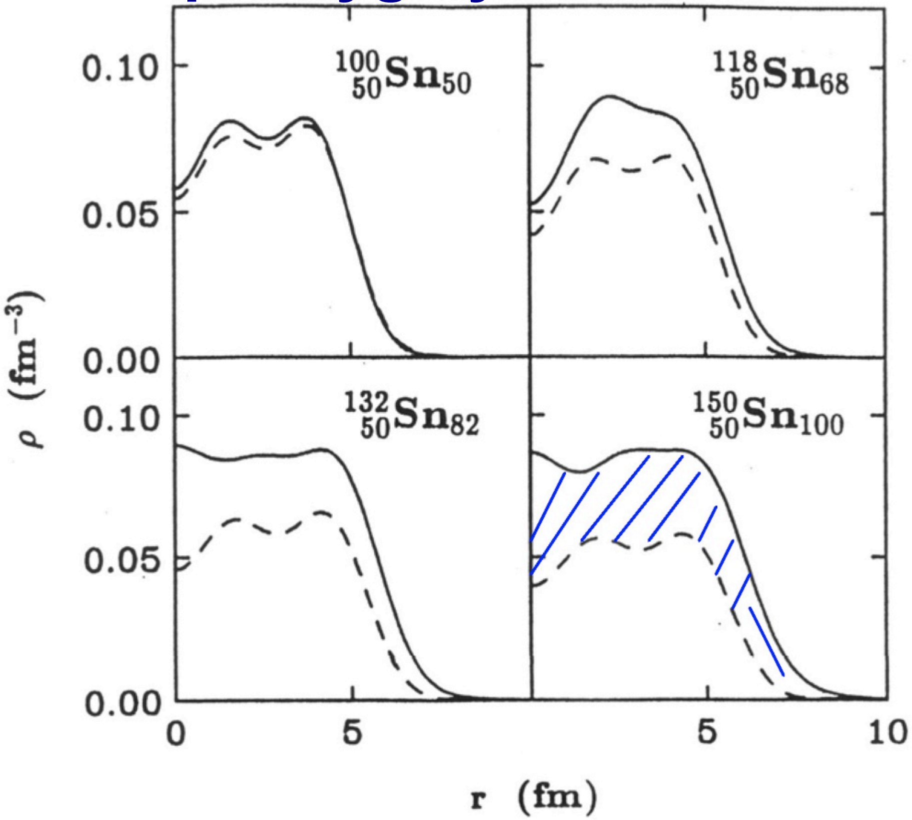
$\ell = 3 \Rightarrow$ *octupole*

TABLE 9.1 γ-Ray Selection Rules and Multipolarities

Radiation Type	Name	$l = \Delta I$	$\Delta\pi$
E1	Electric dipole	1	Yes
M1	Magnetic dipole	1	No
E2	Electric quadrupole	2	No
M2	Magnetic quadrupole	2	Yes
E3	Electric octupole	3	Yes
M3	Magnetic octupole	3	No
E4	Electric hexadecapole	4	No
M4	Magnetic hexadecapole	4	Yes

Example Pygmy Resonances

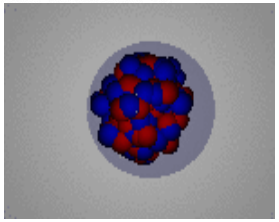
Dobaczewski, Hamamoto, Nazarewicz and Sheikh, Acta.Phys.Pol. **B25** (1994) 541



Calculated one-nucleon densities

—— neutrons

- - - - protons



Static distributions of charges and currents give static electric and magnetic fields.
These fields can be analyzed in terms of the multipole moments of
the charge distribution (dipole moment, quadrupole moment, and so on).
See Krane Section 3.5

e.g. -charge oscillating along one axis: produces an electric dipole radiation field
-variation of the current (circular current loop): a magnetic dipole radiation field

Weisskopf estimates: The transition is due to a single proton that changes from one shell-model state to another: EL/ML electric/Magnetic transition probability.

$$\lambda(EL) \cong \frac{8\pi(L+1)}{L[(2L+1)!!]^2}\frac{e^2}{4\pi\varepsilon_0\hbar c}\left(\frac{E}{\hbar c}\right)^{2L+1}\left[\frac{3}{L+3}\right]^2 cR^{2L}$$

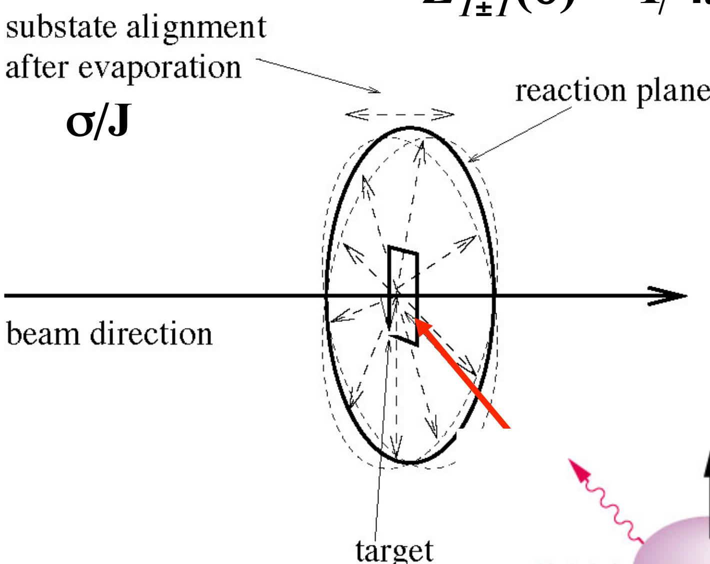
$$\lambda(ML) \cong \frac{8\pi(L+1)}{L[(2L+1)!!]^2}\left(\mu_p - \frac{1}{L+1}\right)^2\left(\frac{\hbar}{m_p c}\right)\left(\frac{e^2}{4\pi\varepsilon_0\hbar c}\right)\left(\frac{E}{\hbar c}\right)^{2L+1}\left[\frac{3}{L+2}\right]^2 cR^{2L-2}$$

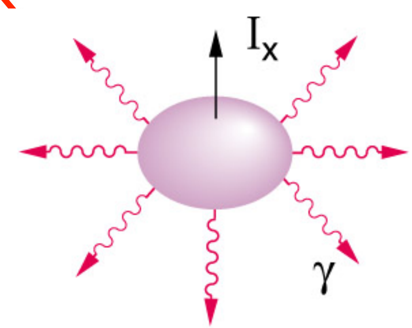
$$\lambda(E1) = 1.0\times10^{14} A^{2/3}E^3$$
$$\lambda(E2) = 7.3\times10^{7} A^{4/3}E^5$$
$$\lambda(E3) = 34 A^{2}E^7$$
$$\lambda(E4) = 1.1\times10^{-5} A^{8/3}E^9$$

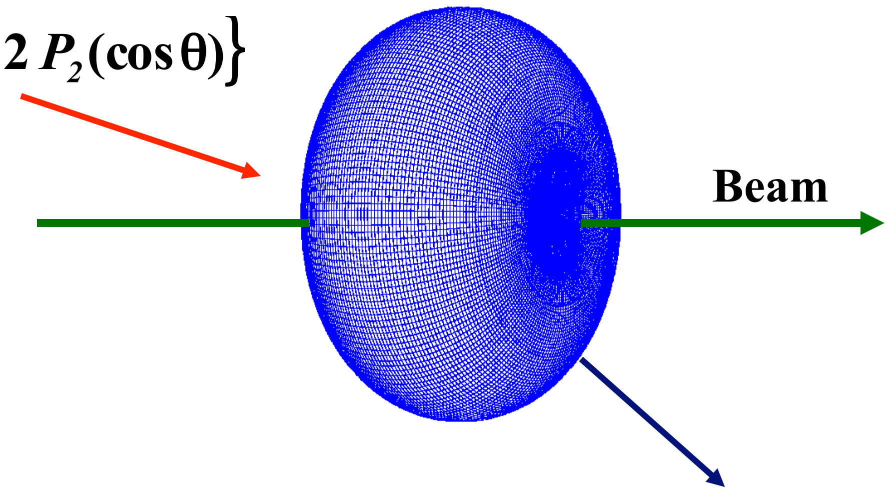
$$\lambda(M1) = 5.6\times10^{13} E^3$$
$$\lambda(M2) = 3.5\times10^{7} A^{2/3}E^5$$
$$\lambda(M3) = 16 A^{4/3}E^7$$
$$\lambda(M4) = 4.5\times10^{-6} A^{2}E^9$$

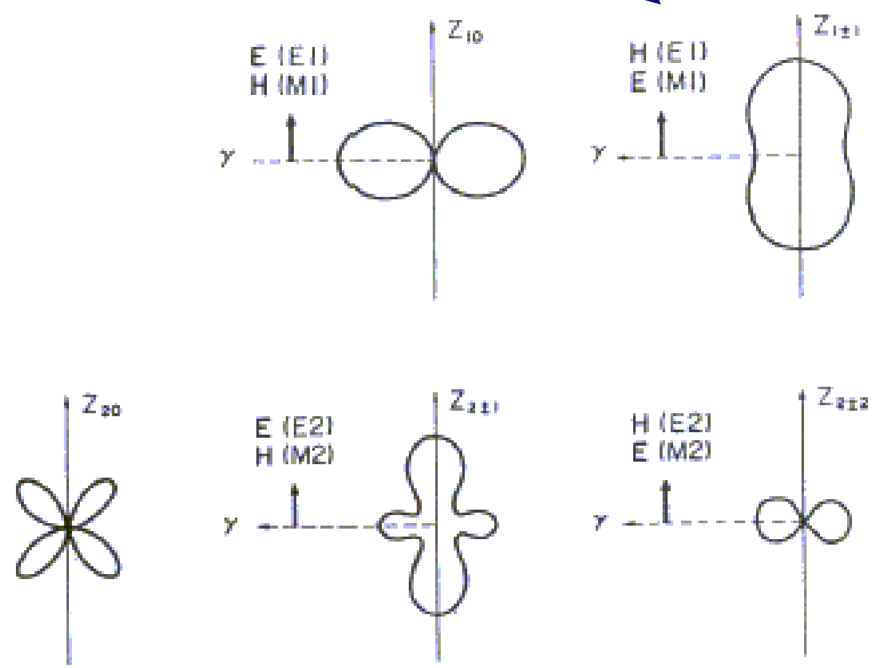
Electromagnetic emission from Oriented Nuclei: Angular distributions

$$Z_{1\pm1}(\theta) = 1/4\pi\left\{1 + 1/2\, P_2(\cos\theta)\right\}$$









Angular distributions and correlations are only sensitive to the multipolarity L
Polarization measurements are more sensitive to Character

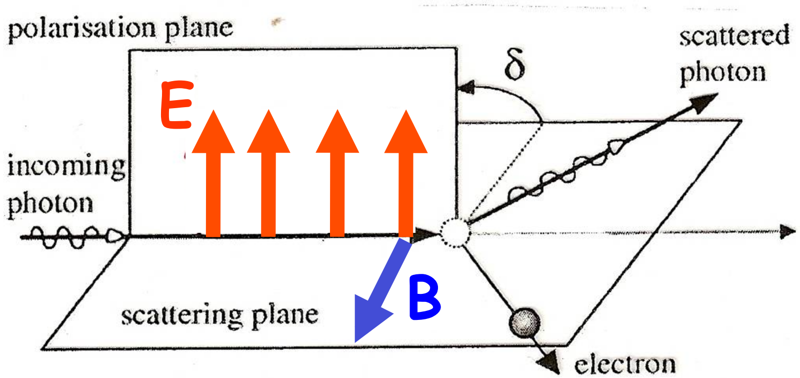
Measurement of the linear polarization

• γ-rays emitted by oriented nuclei are partially polarized. The polarization vector is different for E and M transitions (character)

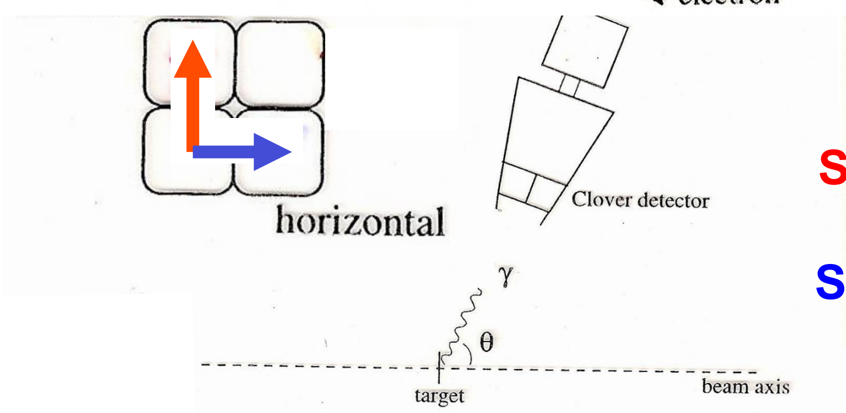
•Compton scattering can be used to measure the degree of polarization through the dependency with the polarization vector

$$\frac{d\sigma_{KN}}{d\Omega} = \frac{r_0^2}{4}\left(\frac{E'}{E}\right)^2\left[\frac{E'}{E} + \frac{E}{E'} - 2\sin^2\theta\cos^2\varphi\right]$$

φ :angle between the scattering plane and the initial polarization plane



$$P_E(\theta) = \frac{1}{Q}\cdot\frac{N_\perp - N_{||}}{N_\perp + N_{||}}$$



Experiments measure the asymmetry.
Q is the sensibility of the polarimeter

Stretched Eλ transitions will have positive asymmetry

Stretched Mλ transitions will have negative asymmetry

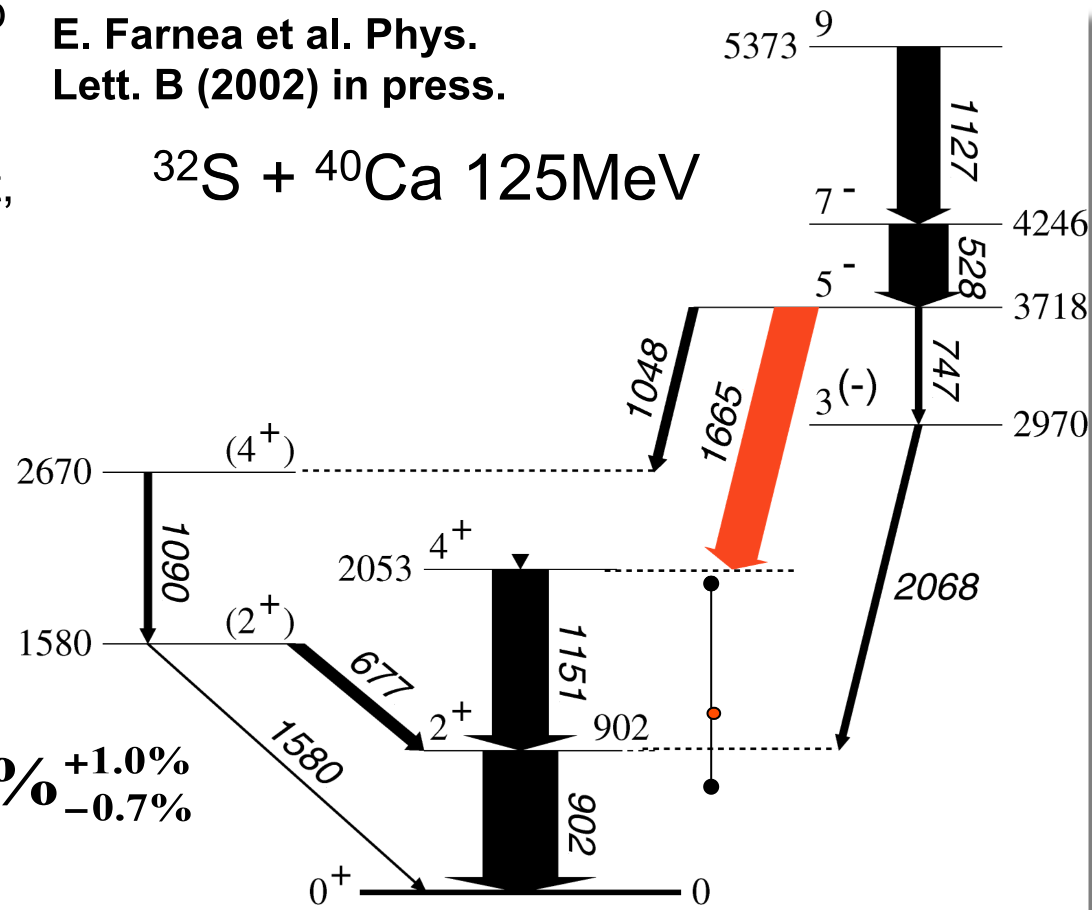
L.M. Garcia-Raffi et al., NIM A 391 (1997) 461

Forbidden E1 transitions in ^{64}Ge between states with T=0

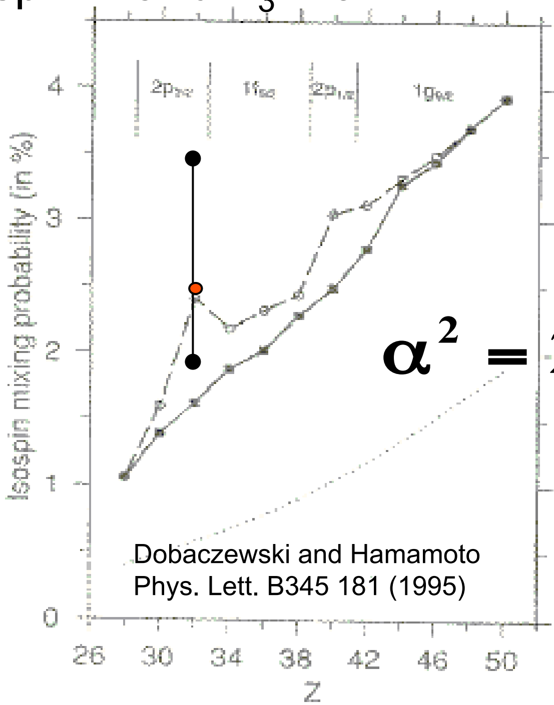
Studying the violation of isospin symmetry induced by the Coulomb interaction is the observation of E1 transitions in even–even $N = Z$ nuclei. In the long-wavelength limit, the matrix elements of the nuclear E1 operator vanish when both the initial and final states have equal isospin T and $T_3 = 0$

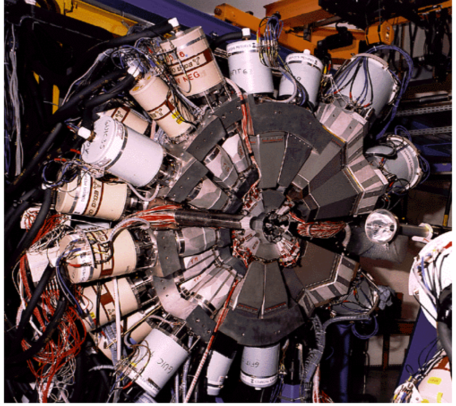
E. Farnea et al. Phys. Lett. B (2002) in press.

^{32}S + ^{40}Ca 125MeV

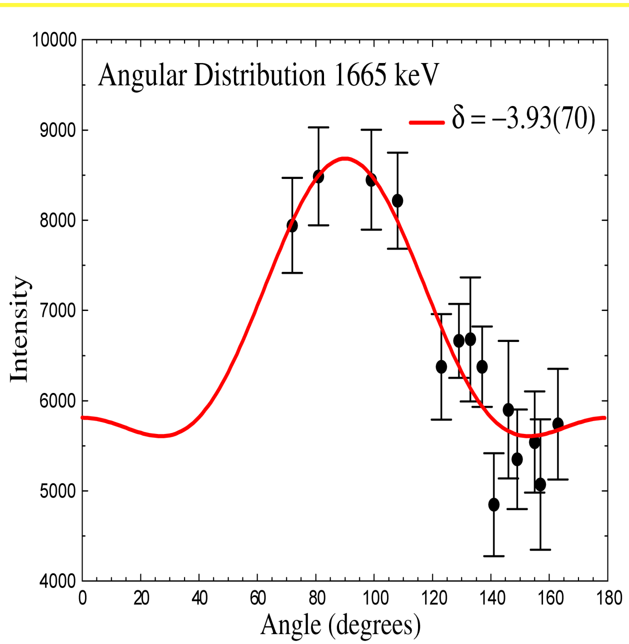


$$\alpha^2 = 2.5\%^{+1.0\%}_{-0.7\%}$$

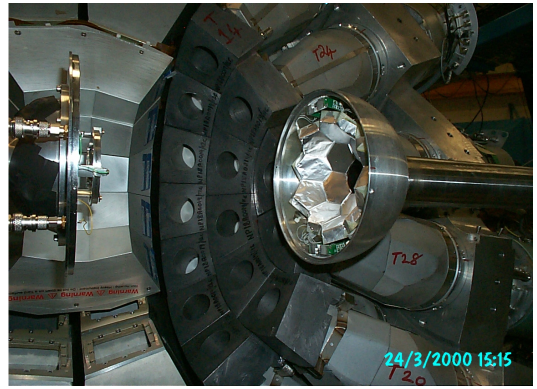




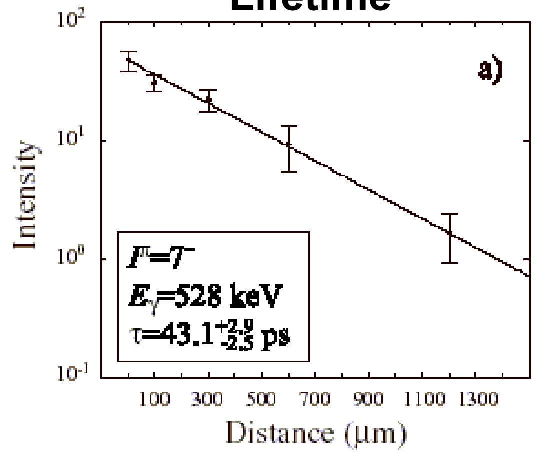
Angular distribution

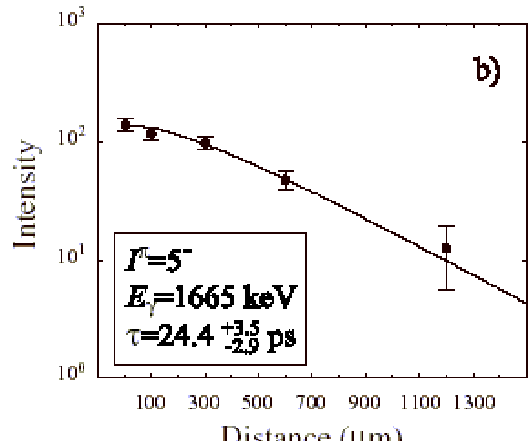


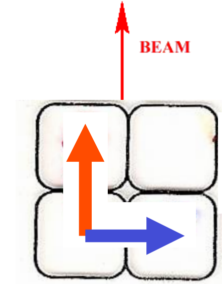
δ = - 3.93 (70)
B(M2) = 6.1(1.6) W.u.
B(E1) = 2.3 (1.3) 10^{-7} W.u.



Lifetime

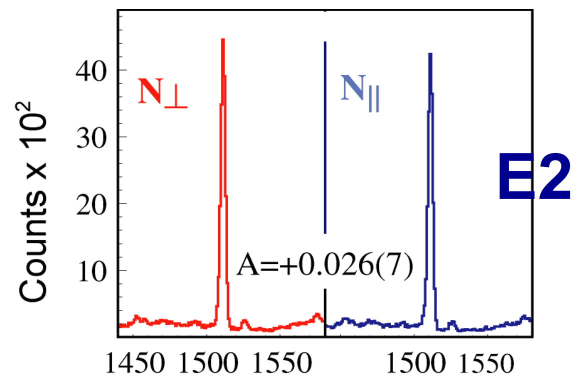


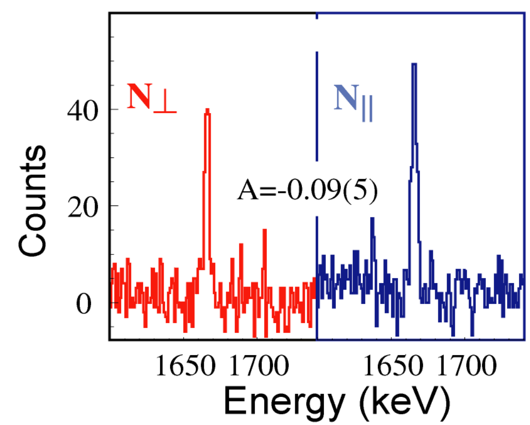




$$A = \frac{N_\perp - N_\parallel}{N_\perp + N_\parallel}$$

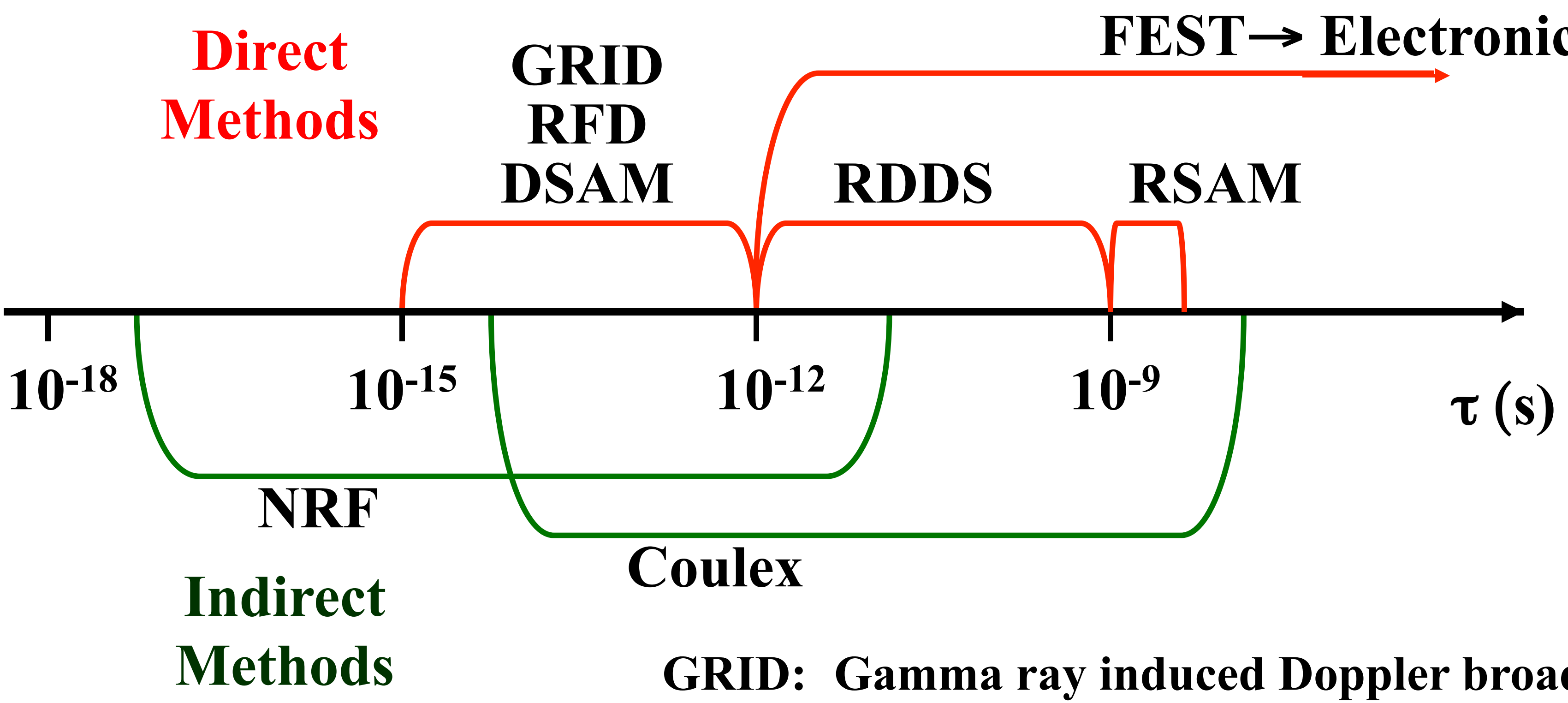
Asymmetry and polarization
$A = N_\perp - N_\parallel/(N_\perp + N_\parallel)$





The 1665 keV transition mixed E1/M2 character ~93% quadrupole contents

Techniques for lifetime measurements



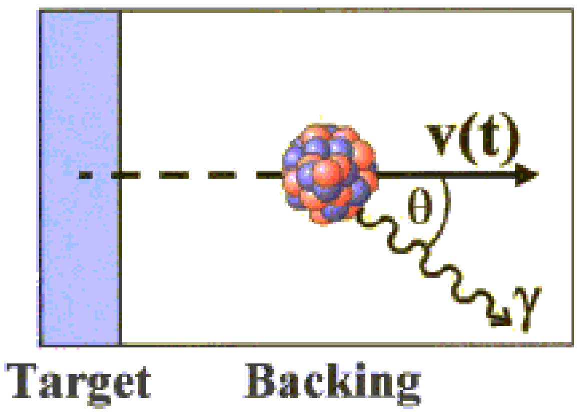
Doppler Techniques

$E^{cm}_{\gamma} = E_{\gamma}(1-\beta\cos\Theta)/(1-\beta^2)^{-1/2}$

GRID: Gamma ray induced Doppler broadening
RFD: Recoil straggling method
DSAM: Doppler shift attenuation method
RDDS: Recoil distance Doppler shift method
RSAM: Recoil shadow anisotropy method
FEST: Fast electronic scintillation method
NFR: Nuclear resonance fluorescence
Coulex: Coulomb excitation cross section

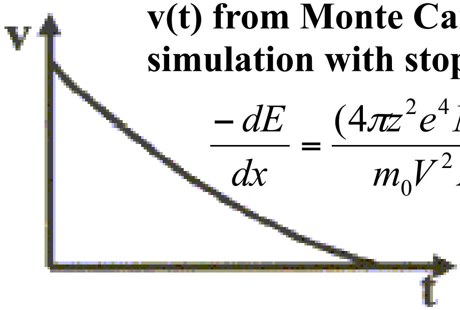
Doppler Shift Attenuation Method

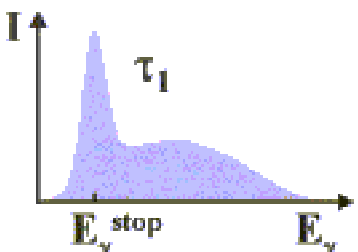
$\tau = 0.1 - 1.5$ ps

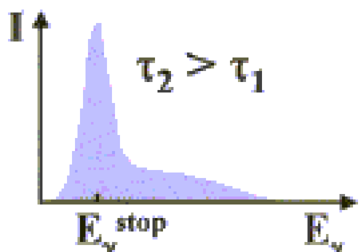


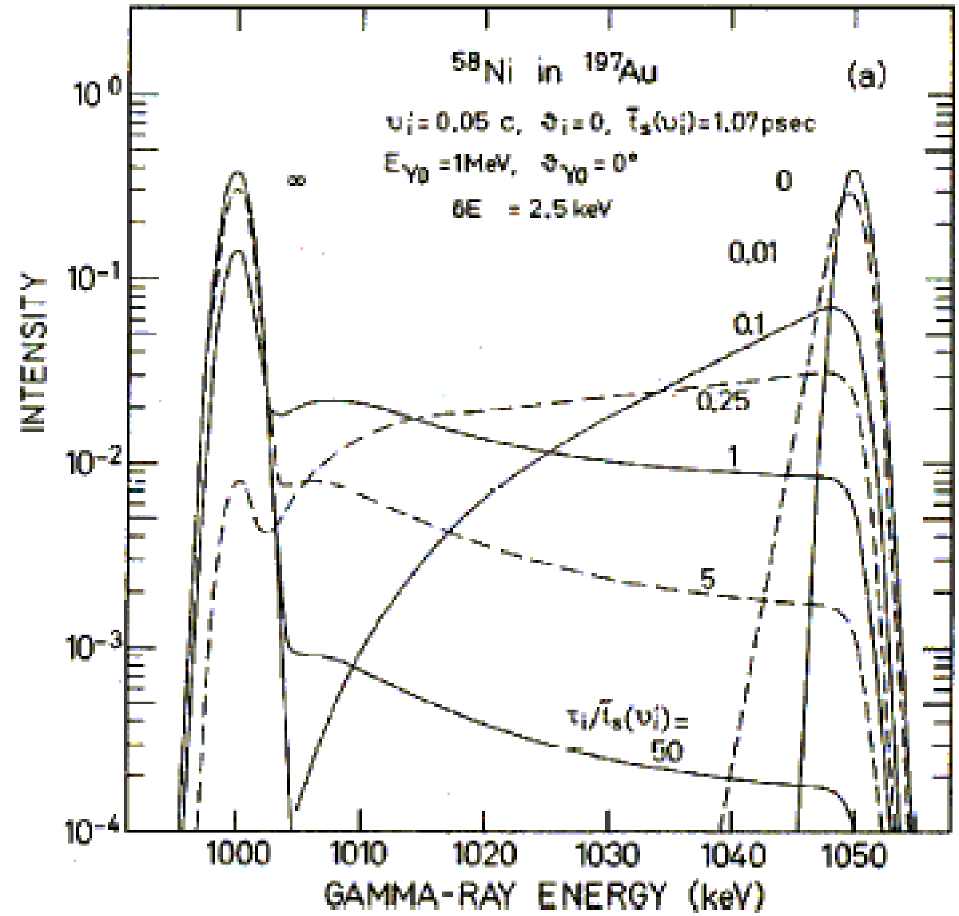
v(t) from Monte Carlo simulation with stopping power

$$\frac{-dE}{dx} = \frac{(4\pi z^2 e^4 NZ)}{m_0 V^2 A} \ln\left(\frac{2m_0 V^2}{I}\right)$$



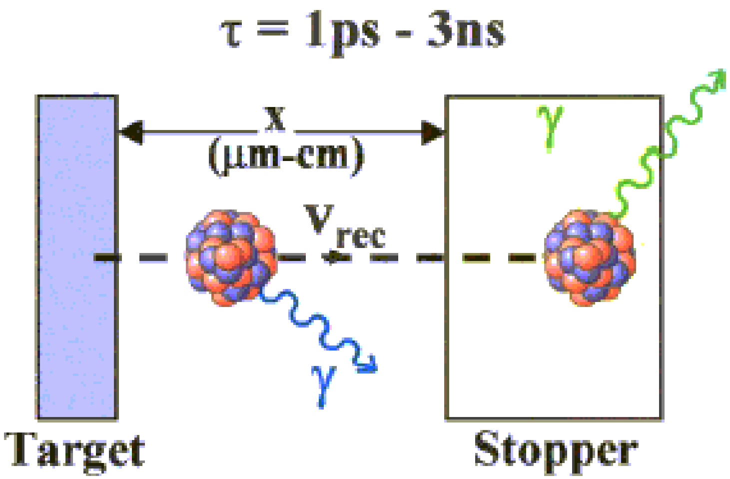


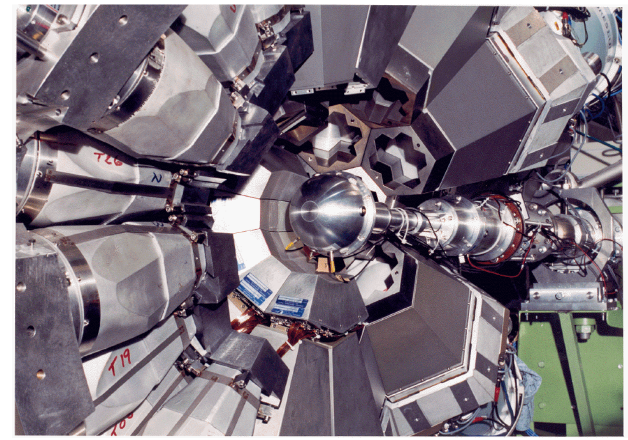




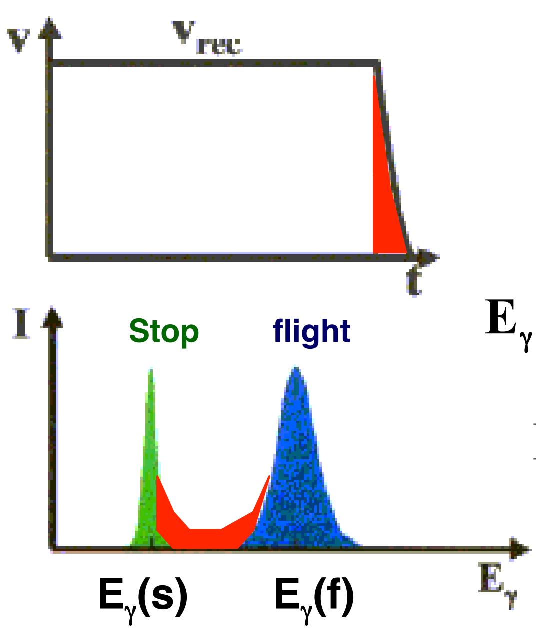
Line shapes for ^{58}Ni stopped in ^{197}Au with a beam velocity of v/c=0.05 and measured at θ=0°

Recoil Distance Doppler Shift Method



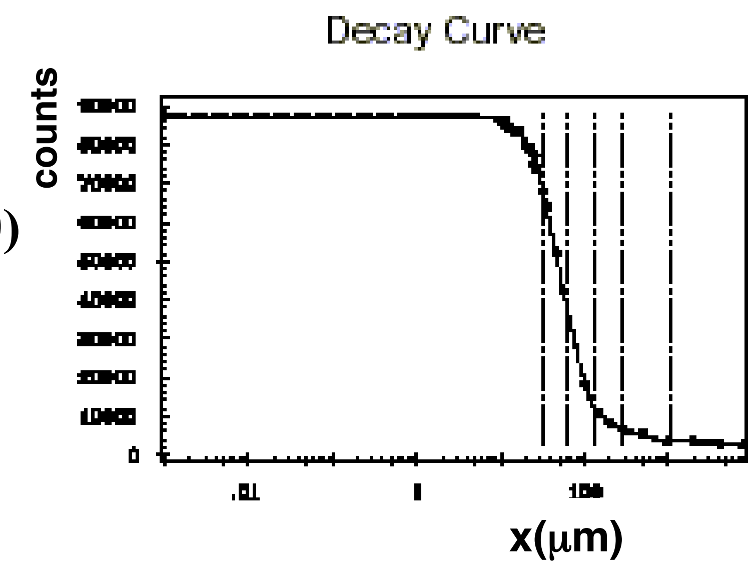


Koeln University plunger

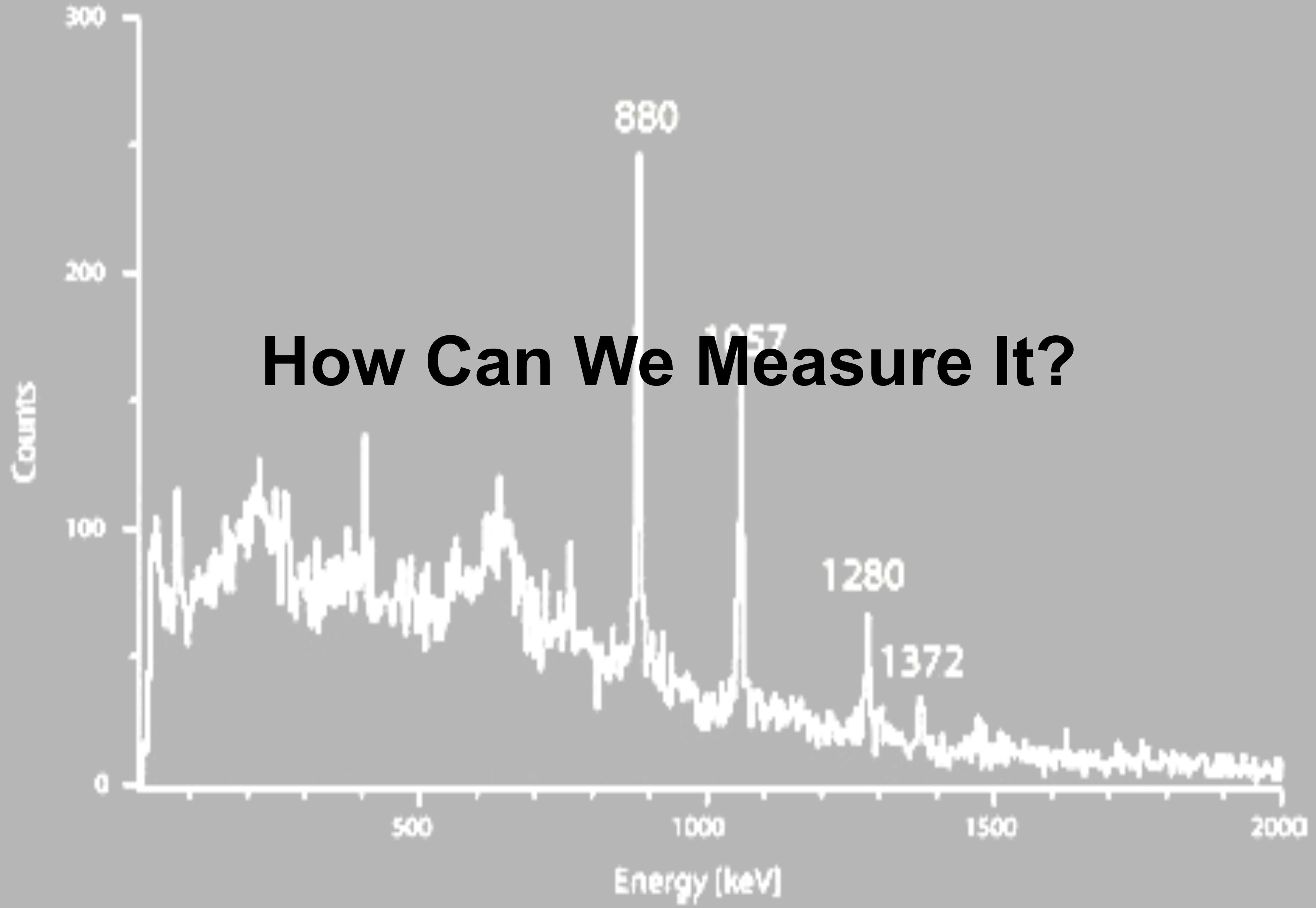


$$E_{\gamma}(f) \approx E_{\gamma}(s)(1 + \frac{v_{rec}}{c}\cos\theta)$$

$$I(f) = N_0(1 - e^{-(x/v_{res}\tau)})$$



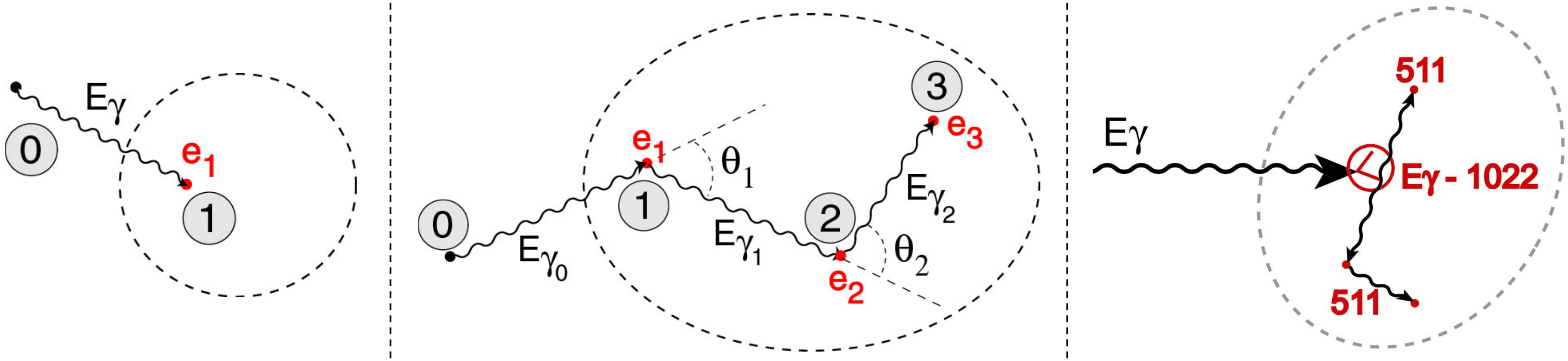
How Can We Measure It?



Interaction of the γ-rays with matter

~ 100 keV | ~1 MeV | ~ 10 MeV | γ-ray energy

Photoelectric | **Compton Scattering** | **Pair Production**

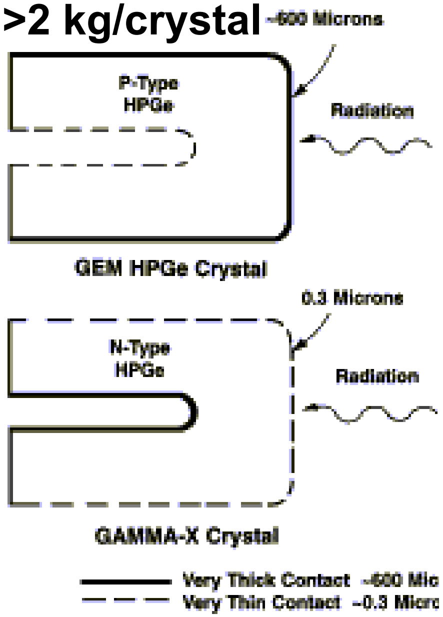


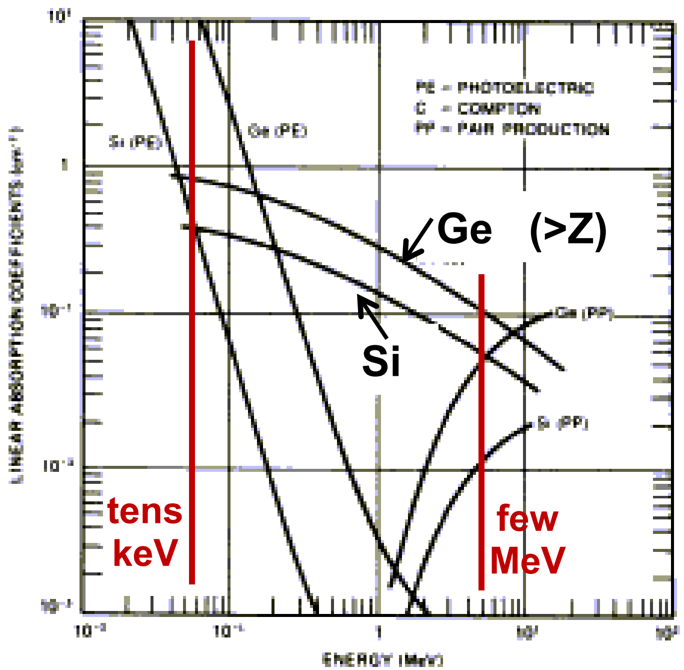
$$E_{\gamma'} = \frac{E_{\gamma}}{1 + \frac{E_{\gamma}}{m_0 c^2}\left(1 - \cos\theta\right)}$$

Instrumentation for HR γ-ray spectroscopy

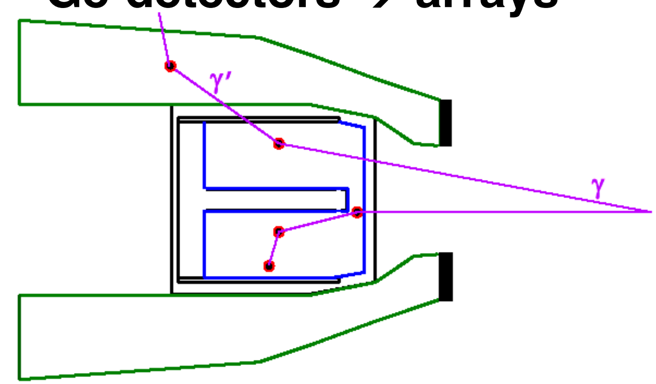
High resolution γ-ray spectroscopy → large volume semiconductor detectors
in particular detectors based on HP-Ge (impurities ~10^{-12})

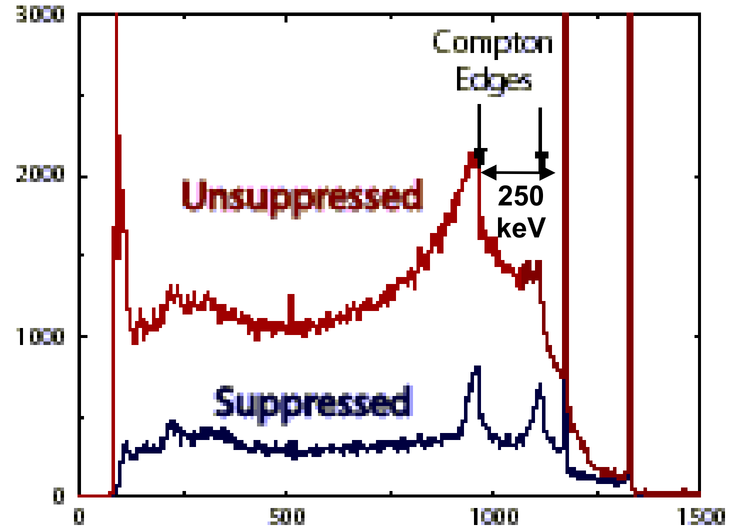
Present Ge
>2 kg/crystal

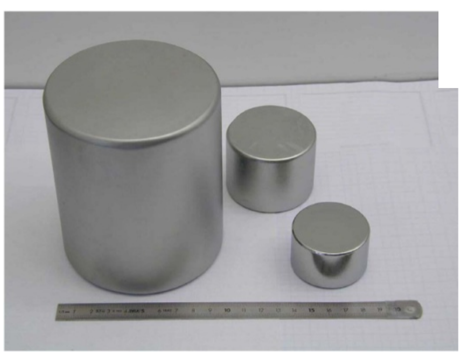




Compton suppressed Ge-detectors → arrays





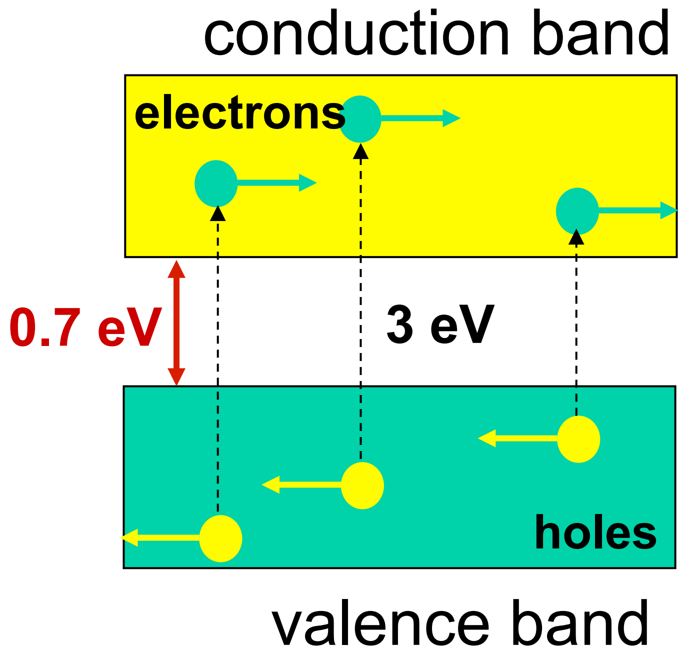


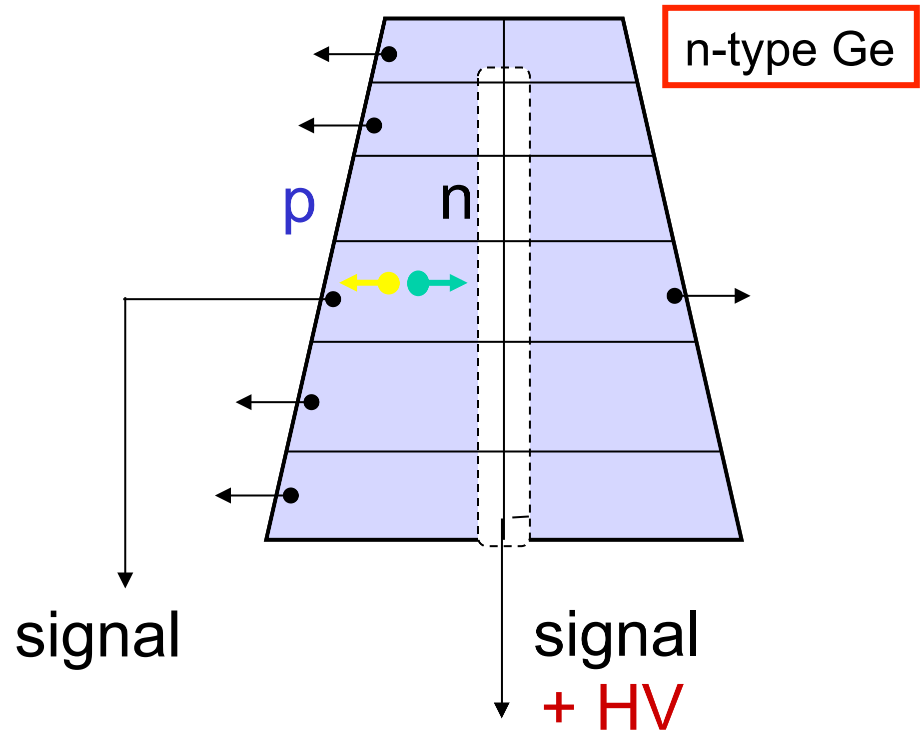
Composite detectors

Bibliography: G.F.Knoll, Radiation Detection and Measurement (Wiley)

Germanium detector

Sensitivity factors: Energy Resolution, Peak to Total Ratio





Number of e-h pairs for 1 MeV, $N = 10^6 / 3 = 3 \times 10^5$

Energy resolution (Fano Factor) $\sqrt{N}/N = 0.0018 \rightarrow 1.8\,\text{keV}\,(E_\gamma = 1MeV)$

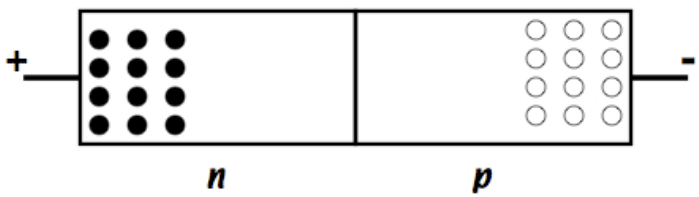
Thermally activated charge carriers in the conduction band density at room temperature ~ 2.5 10^{13} cm^{-3} for Ge (~ 1.5 10^{10} cm^{-3} for Si)

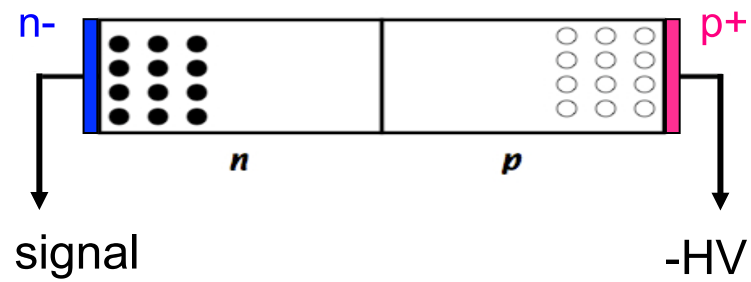
To reduce the number of free charge carriers :

=> deplete material: np junction

=> increase depletion by applying a reverse bias

=> for Ge, cool detector with LN_2 - 77K





$$FWHM^2 = W^2_D + W^2_X + W^2_E + W^2_{Doppler}$$

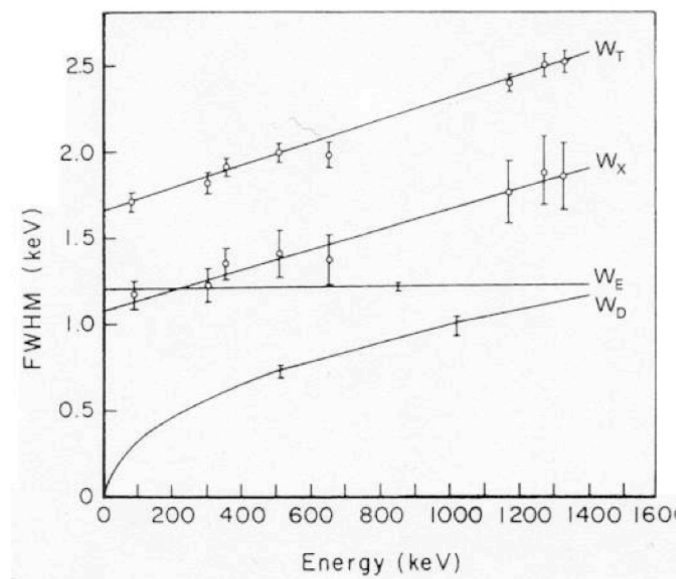
$W_D = 2.35\sqrt{F\varepsilon E_\gamma}$ Statistical fluctuations of carriers

ε = 2.96 eV @ 77 K Fano factor F ~ 0.1
(not all the deposited energy goes to create e-h pairs)

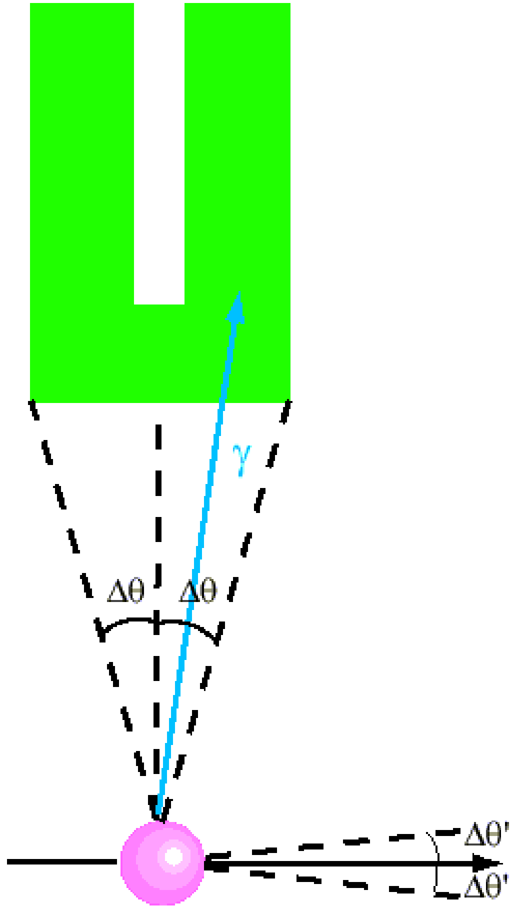
W_X incomplete charge collection

W_E electronic noise

$W_{doppler}$ Doppler broadening

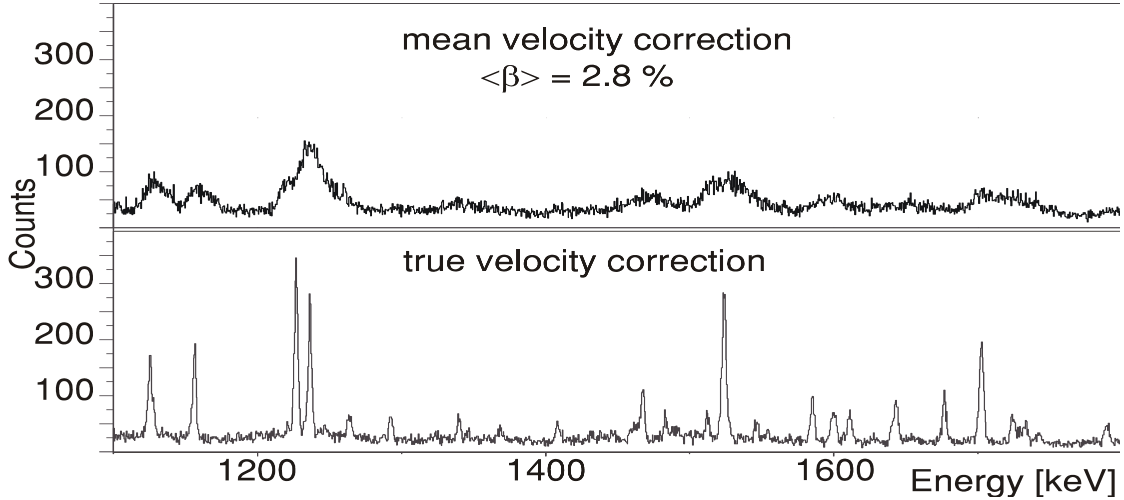


Doppler Broadening

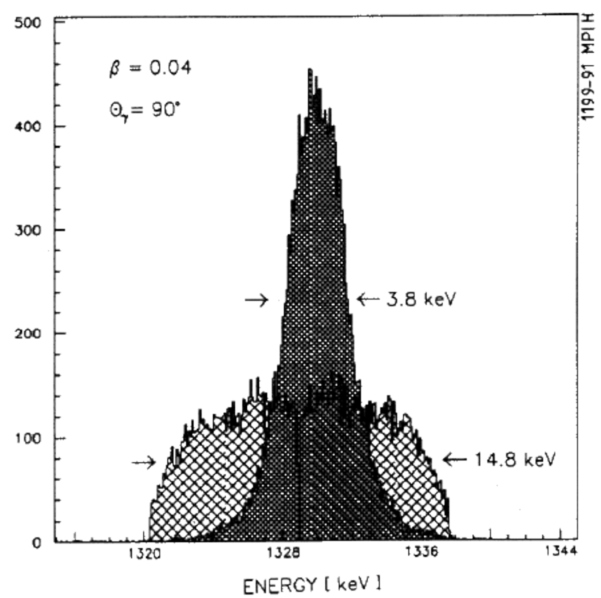


$$E_S = E_0\left(1 + v/c\cos\theta\right)$$

$$\Delta E_S = E_0\, v/c \sin\theta\Delta\theta$$



Dedicated ancillary detectors for the determination of the recoil trajectory



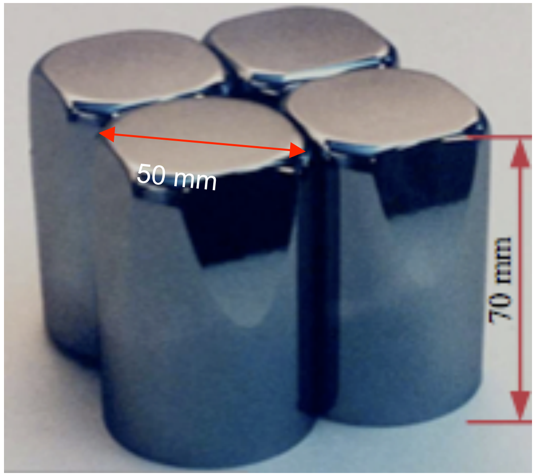
Development of segmented Ge detectors and Pulse Shape Analysis techniques for position determination

Composite detectors

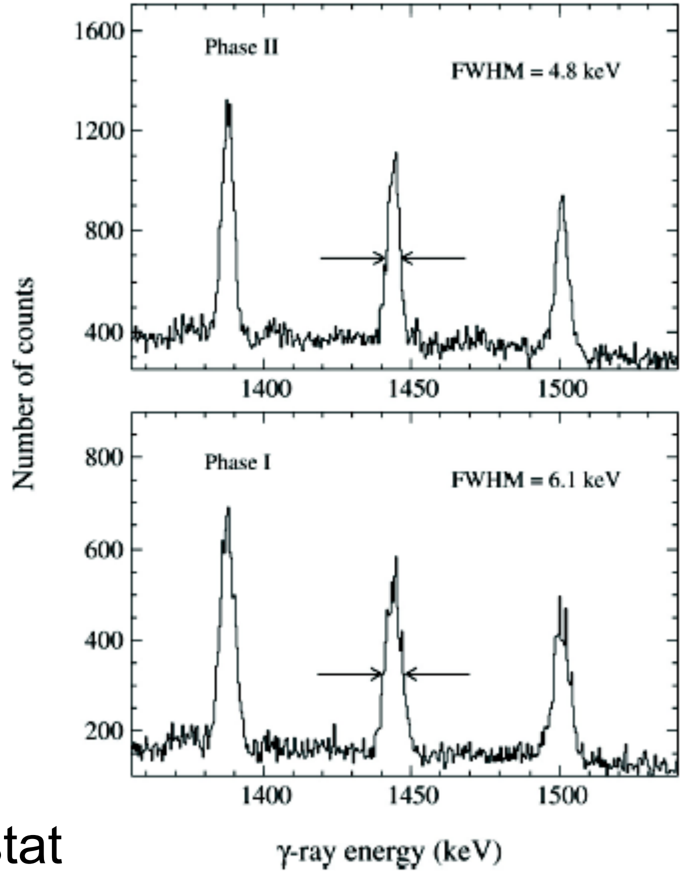
=> Reduction of $\Delta\theta_D$

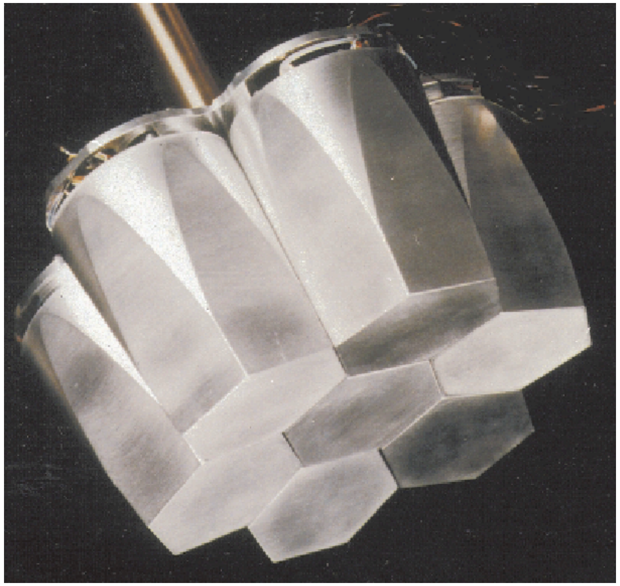
- Eurogam II
- Clovers:

- 4 crystals in 1 cryostat



^{30}Si(158 MeV)+^{124}Sn → ^{149}Gd
v/c=2.1%



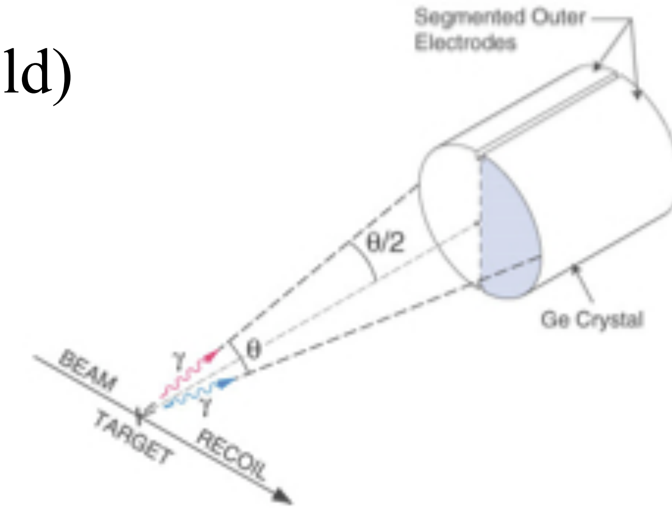


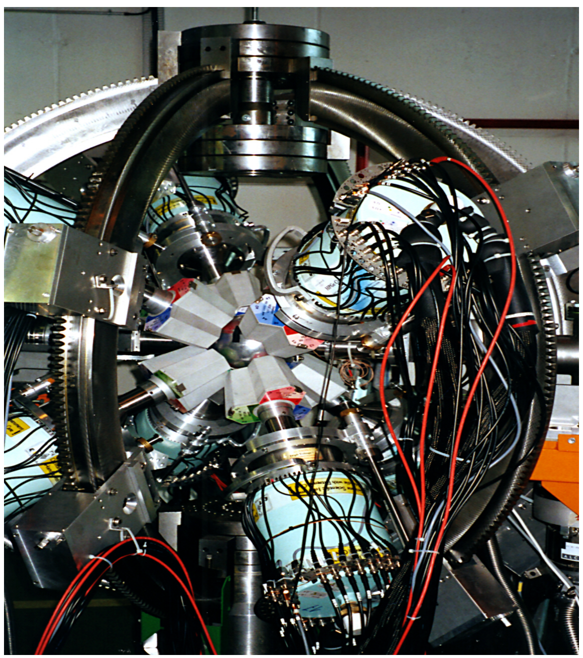
- Euroball
- Clusters:

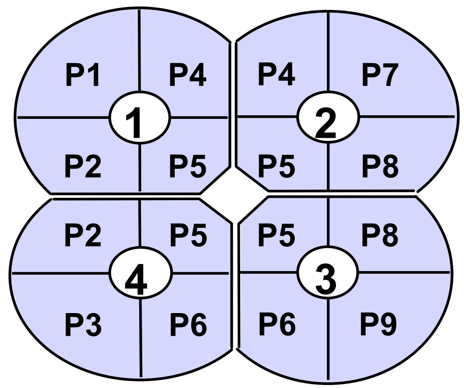
- 7 crystals in 1 cryostat

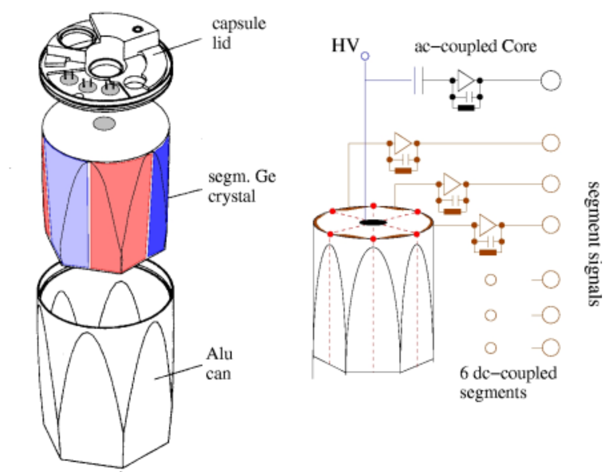
Electrical Segmentation of detectors

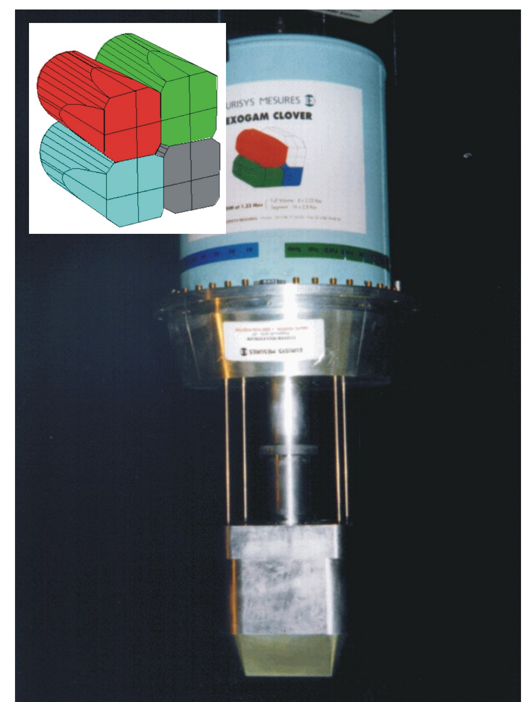
- Gammasphere segmented detector (2 Fold)
- Exogam at Ganil (Segmented Clover)
- Miniball at Isolde (Segmented



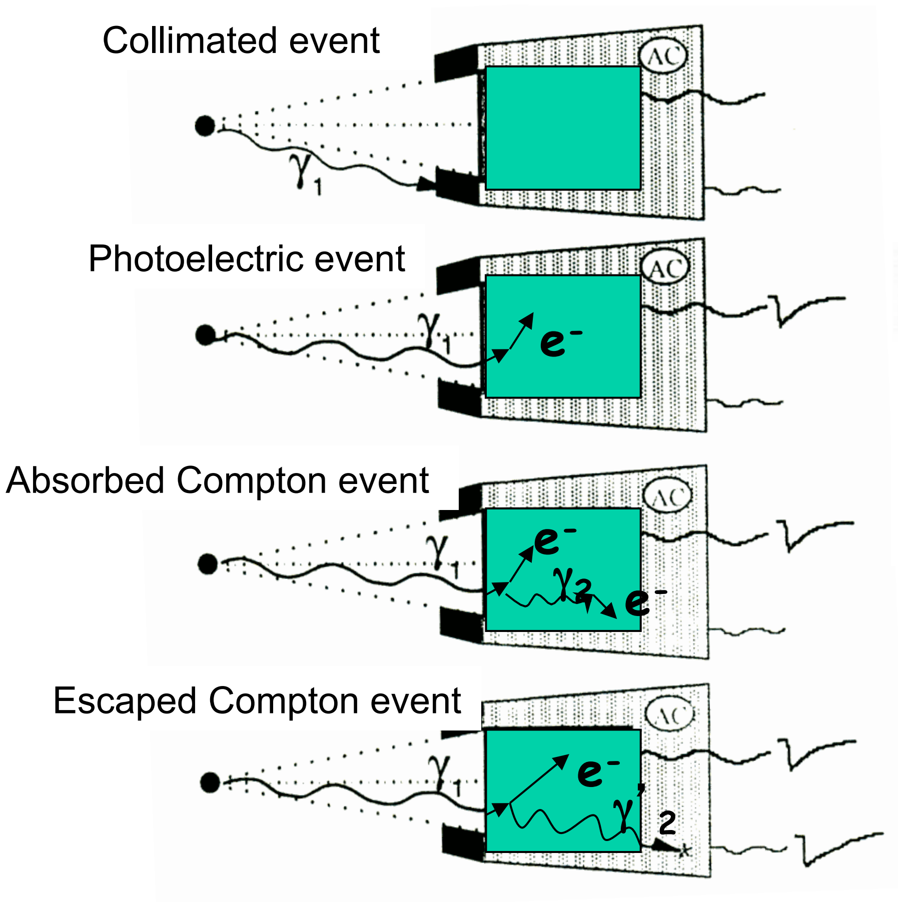


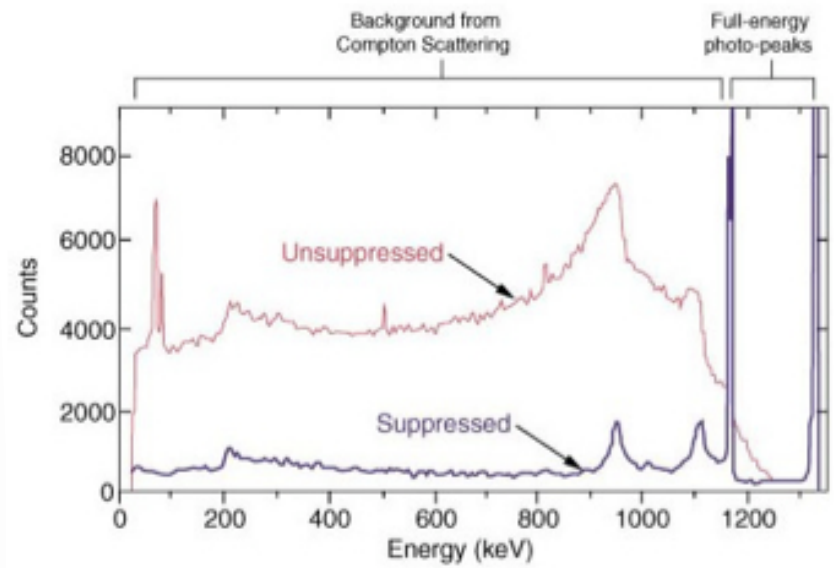






Signal-to-noise ratio and Compton suppression

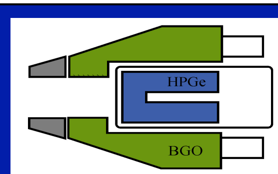




P/T ~ 0.2-0.3 => 0.5-0.6

HR γ-Spectroscopy Instrumentation for Nuclear Structure

Late 90's
Large γ−Arrays

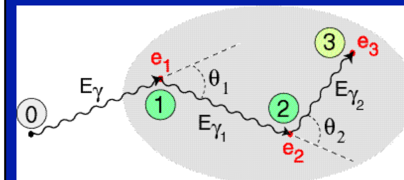


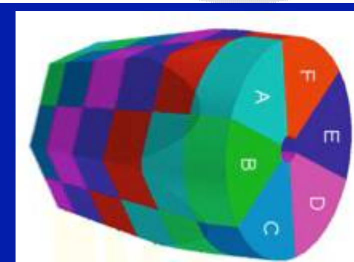
ε ~ 10 — 5 %
(M_γ=1 – M_γ=30)

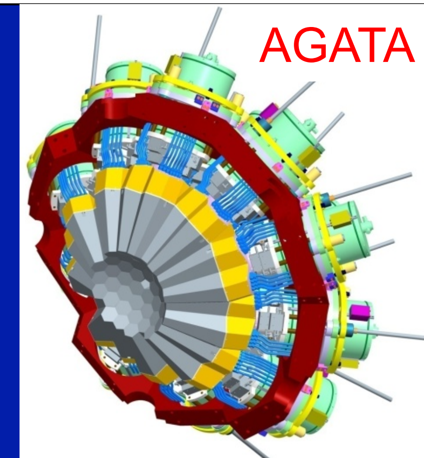
Compact γ−Arrays optimized
Doppler correction, low Mγ

ε ~ 20 % M_γ=1

Tracking Arrays based on
Position Sensitive Ge Detectors

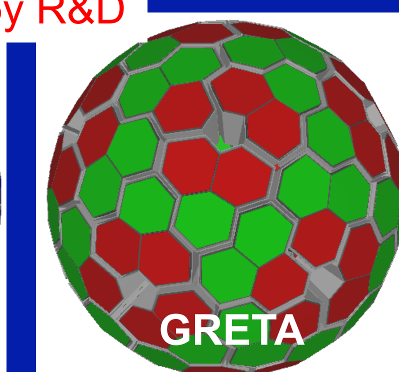






Two Tracking Arrays projects:
GRETA (USA) & AGATA (EU)

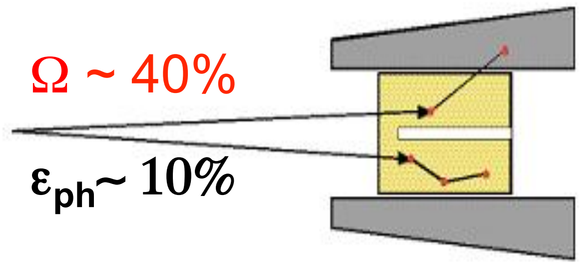
>15y R&D



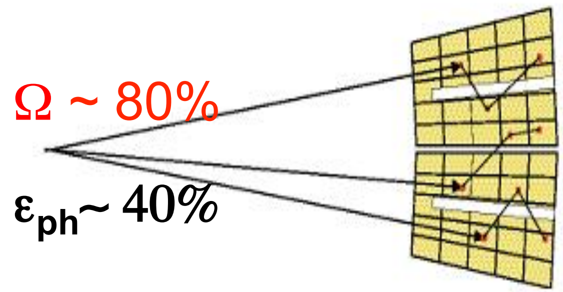
ε ~ 40 — 20 %
(M_γ=1 – M_γ=30)

Tracking Array Benefits

Conditions:
- Low intensity for the nuclei of interest / require high sensitivity
- High background levels
- Large Doppler broadening (specially in in-flight facilities)
- High counting rates (digital FEE)
- High γ-ray multiplicities (Tracking)

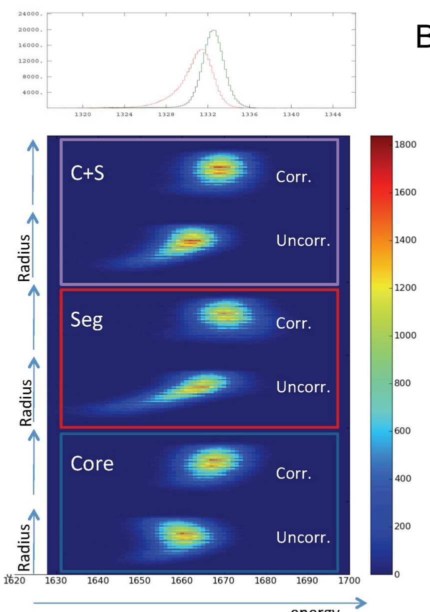


Compton Suppressed
- solid angle taken by the AC shields
- large opening angle ➔ poor energy resolution



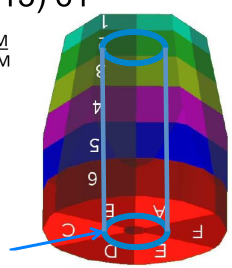
Tracking array
- Large solid angle
- Position sensitive mode using PSA
- Large P/T using tracking for γ-ray reconstruction

Correction of neutron damage



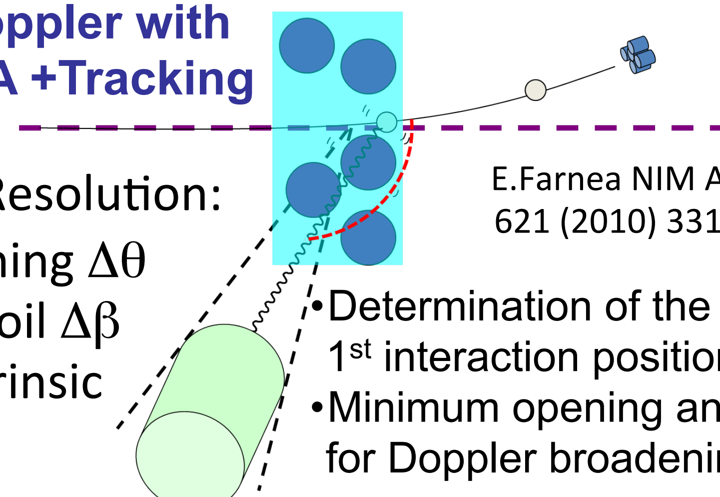
B.Bruyneel EPJ A 49 (2013) 61

FWHM 1.3MeV	FWTM FWHM
2.06	1.91
2.44	1.83
2.51	1.83
2.88	2.34
2.30	1.83
2.34	1.83



- Radial dependency of charge trapping

Doppler with PSA +Tracking

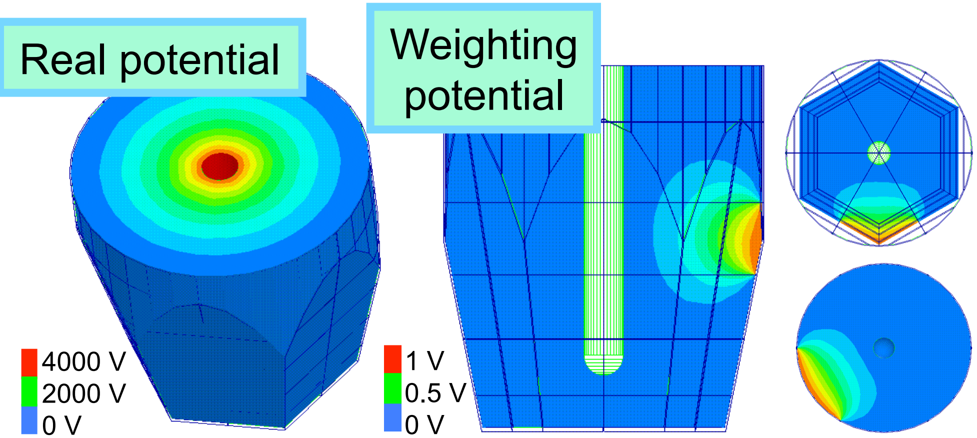


Total Resolution:
Opening Δθ
Recoil Δβ
Intrinsic

E.Farnea NIM A 621 (2010) 331

- Determination of the 1st interaction position
- Minimum opening angle for Doppler broadening

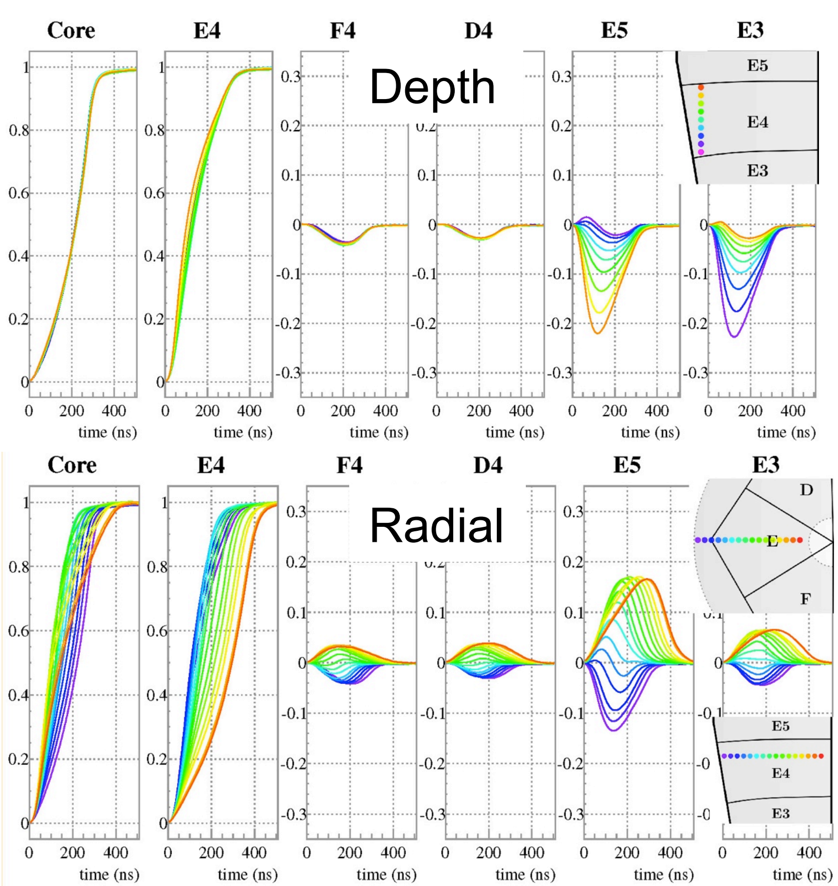
Position Sensitive Detector for γ-rays

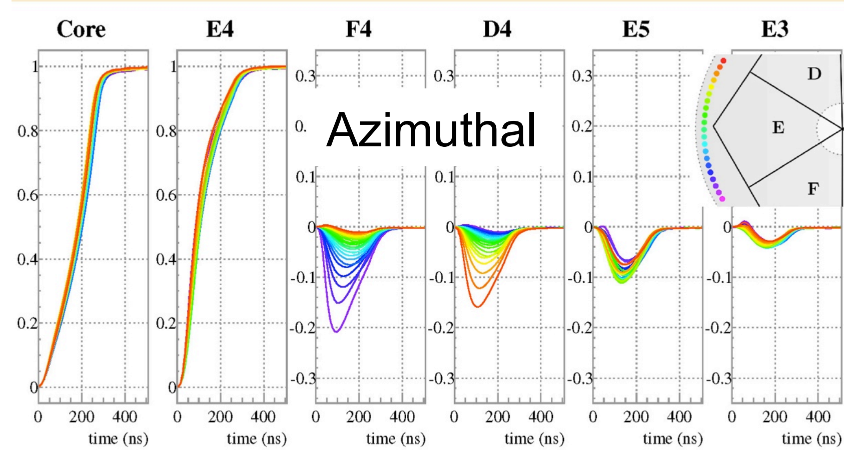


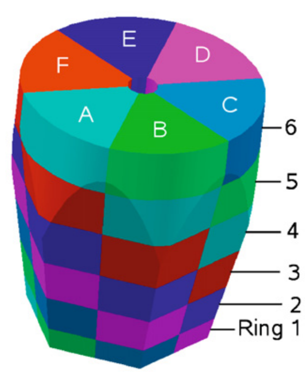
Induced current by the moving charge in the sensing contact → weighting potential Ramo's Theorem.

$$i_k = -q\vec{v}\cdot\vec{\nabla}\phi_k(r_q)$$

E. Gatti, et al. NIM 193 (82) 651





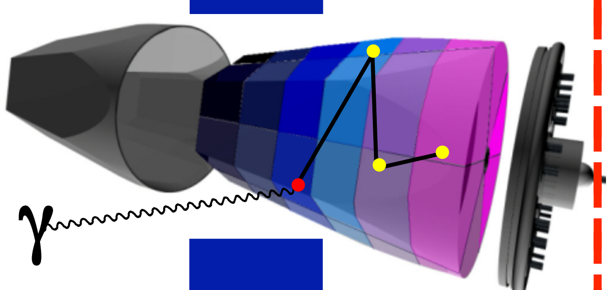


Figures courtesy of M.Ginsz, et al., IPHC Strasbourg

Gamma Tracking Array Concept

AGATA ADVANCED GAMMA TRACKING ARRAY

Highly segmented HPGe detectors



Synchronized digital electronics to digitize (14 bit, 100 MS/s) and process the 37 signals generated by crystals

Readout Raw Data (10 kB/evt/crystal)

HARDWARE

Event building time-stamped data

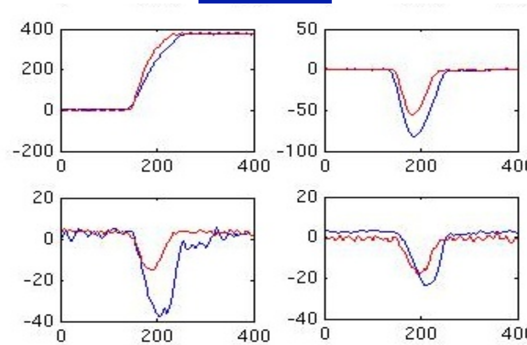
Global level

Local level

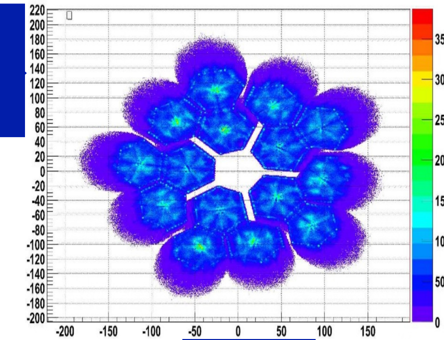
Energies, times, interaction points

$(x,y,z,E,t)_i$

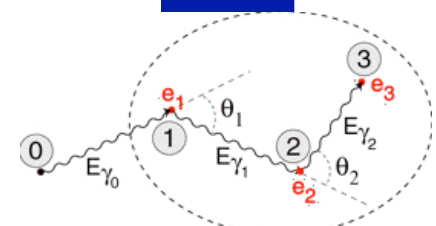
Pulse Shape Analysis of the recorded waves



SOFTWARE

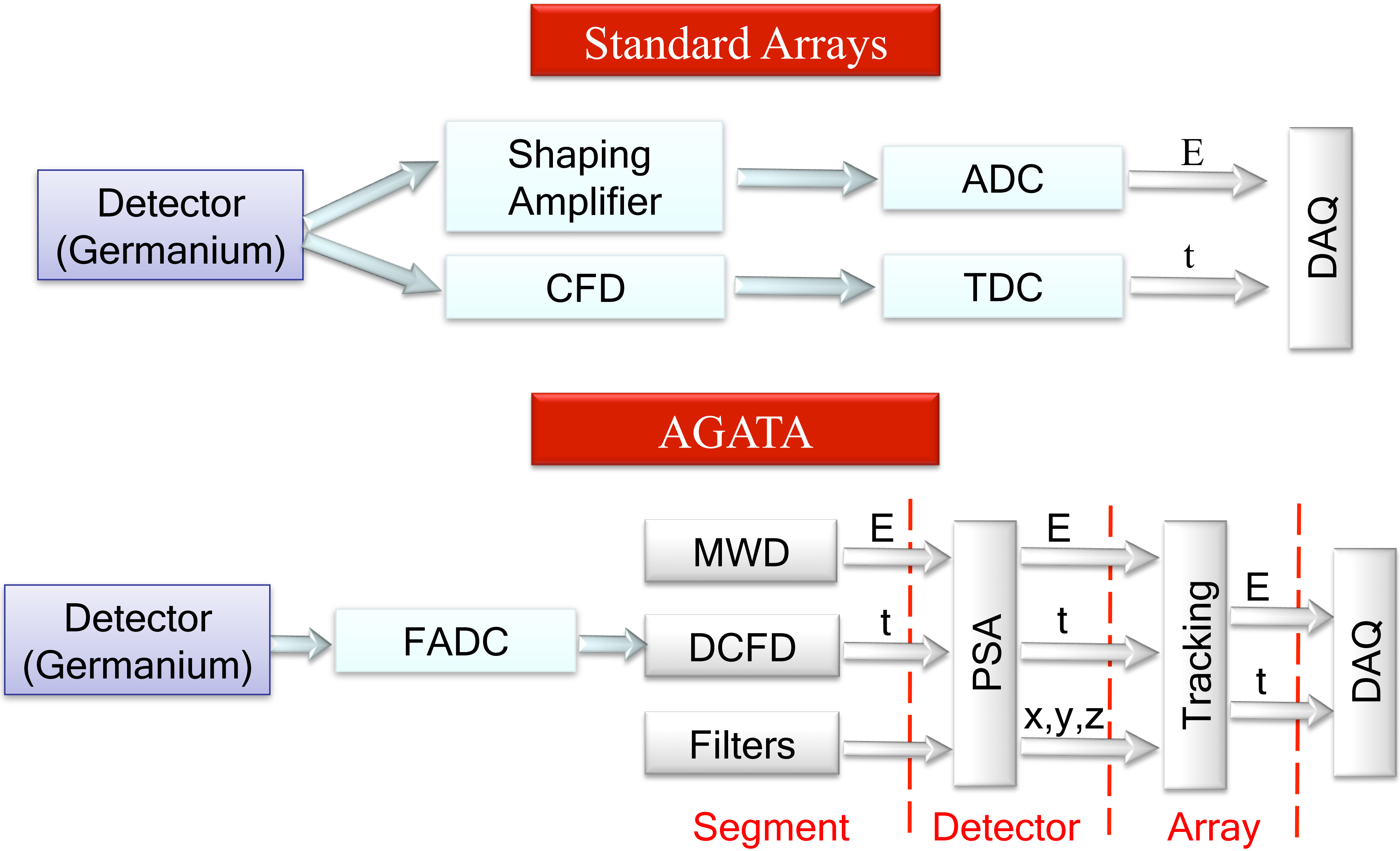


Reconstruction of γ-rays from the hits



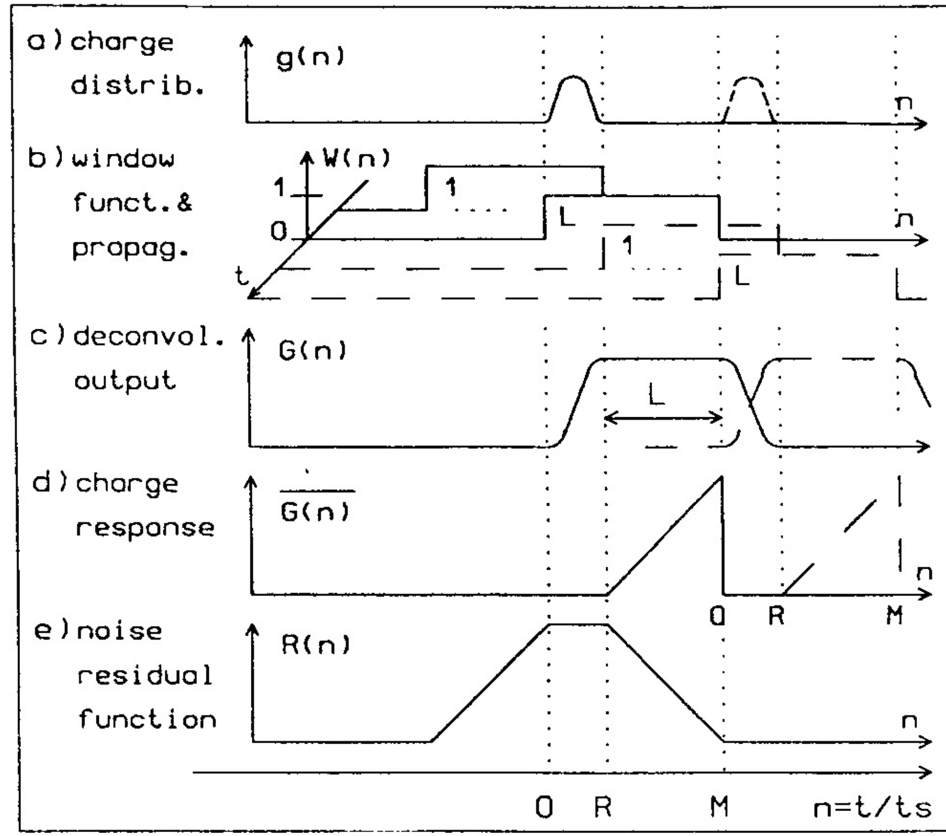
Analysis & correlation with other detectors

Analogue vs Digital Electronics



Energy with Digital signals: Moving Window Deconvolution

- removes shaping-effect of preamplifier
⇒current signal recovered
- calculates real collected charge by integrating current signal integration carried out within a moving window to avoid summation of events
- noise-suppression by averaging charge signal
- recursive algorithm



G[n] = G[n – 1] + FADC[n] – k × FADC[n – 1] – FADC[n – L] + k × FADC[n – L – 1]

K = pre-amplifier response ($e^{-\alpha}$)

A.Georgiev & W.Gast IEEE Nucl. Sci. 40 (1993) 770

Energy with Digital signals: Moving Window Deconvolution

•removes shaping-effect of preamplifier
⇒current signal recovered
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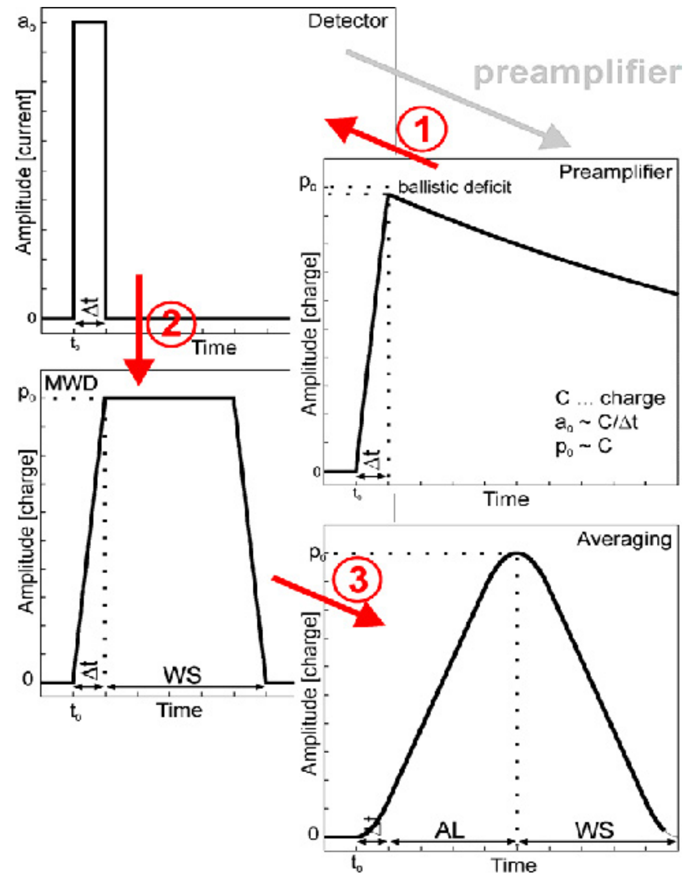


G[n] = G[n – 1] + FADC[n] – k × FADC[n – 1] – FADC[n – L] + k × FADC[n – L – 1]

k = pre-amplifier response ($e^{-\alpha}$)

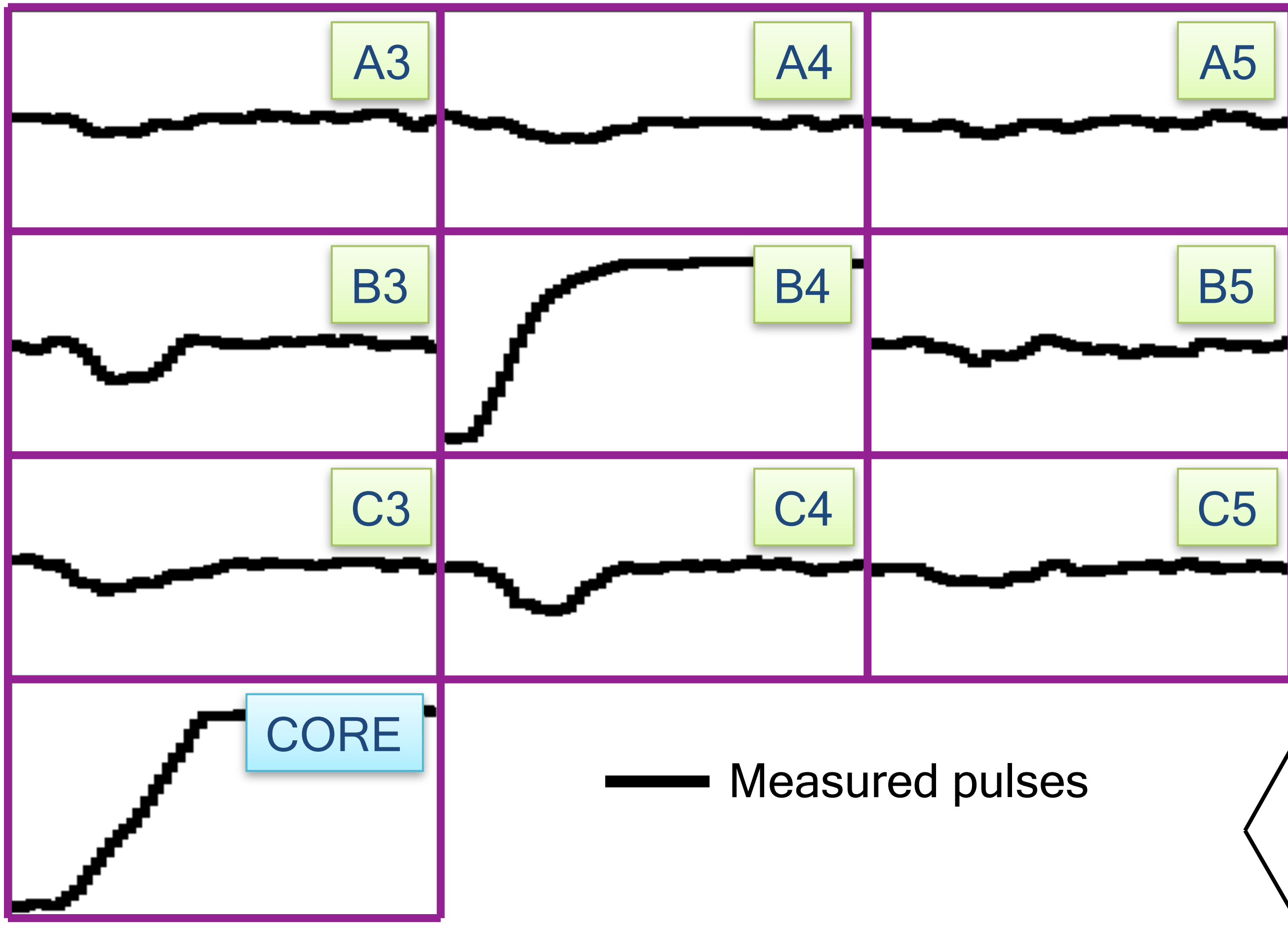
A.Georgiev & W.Gast IEEE Nucl. Sci. 40 (1993) 770

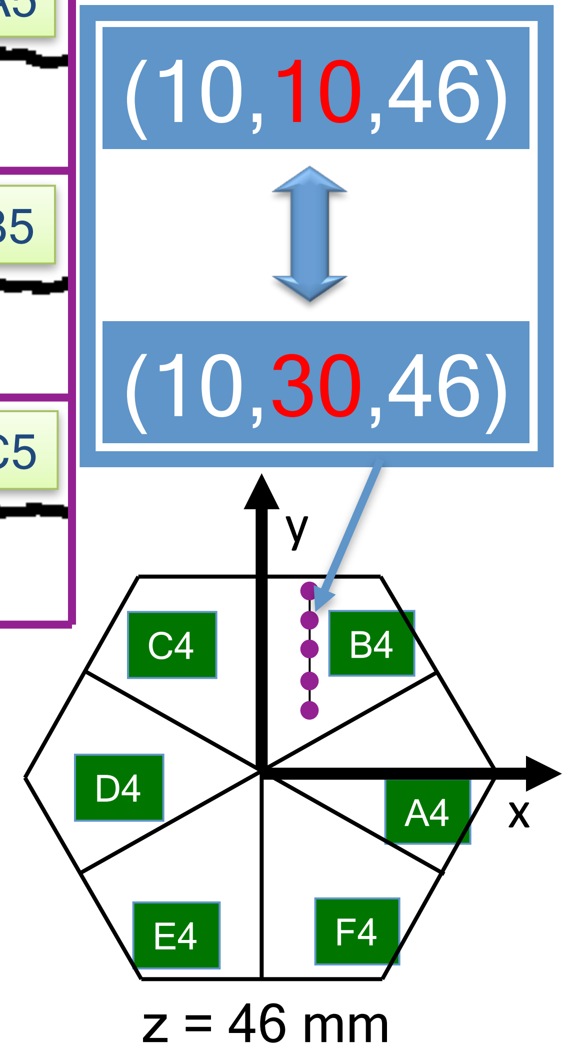
Digital Pulse Processing for typical functions

- *Leading Edge Discrimination:*
- •y[n]=x[n]-x[n-k](*differentiation*)
- •y[n]= (x[n]+x[n-2]) +x[n-1]<<1(*Gaussian filtering*)
- •Threshold comparison →LED time
- *Constant Fraction Discrimination*:
- •y[n]=x[n]-x[n-k](*differentiation*)
- •y[n]= (x[n]+x[n-2]) +x[n-1]<<1(*Gaussian filtering*)
- •y[n]=x[n-k]<<a-x[n](*constant fraction*)
- •*Zero crossing comparison →CFD time*

J.T. Anderson IEEE Nucl. Sci. 25 (2007) 1751

Pulse Shape Analysis Concept



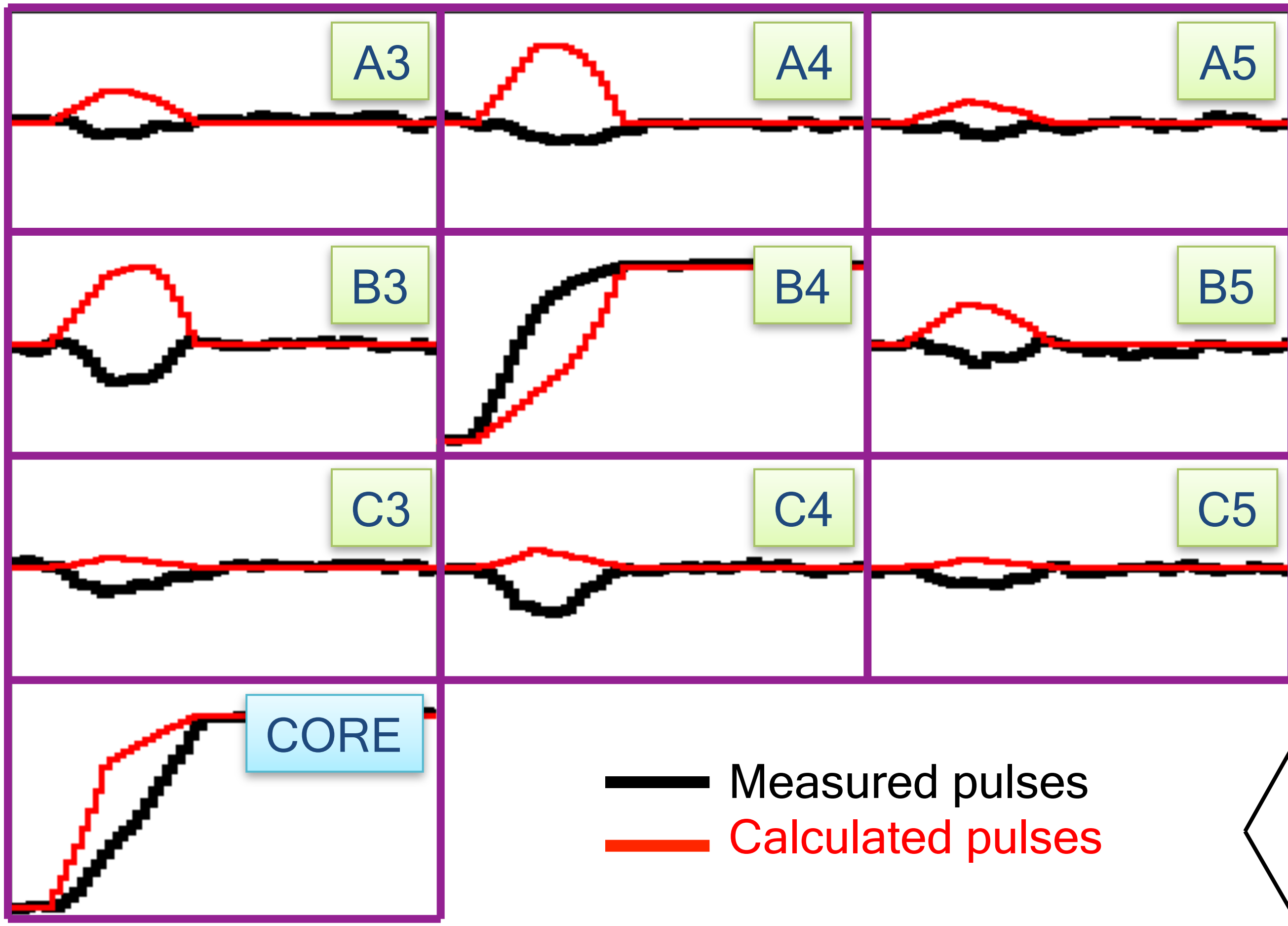


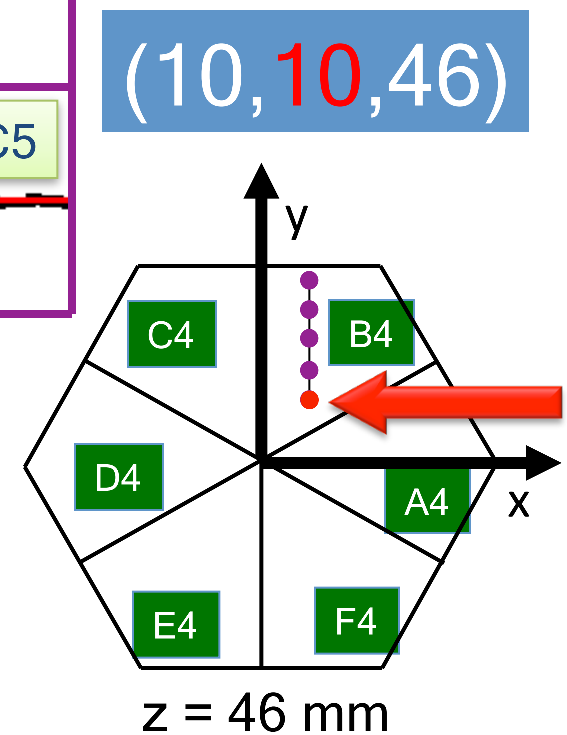
791 keV deposited in segment B4

Very Important: Measured pulses need to be time aligned

R.Venturelli, D.Bazzacco

Pulse Shape Analysis Concept

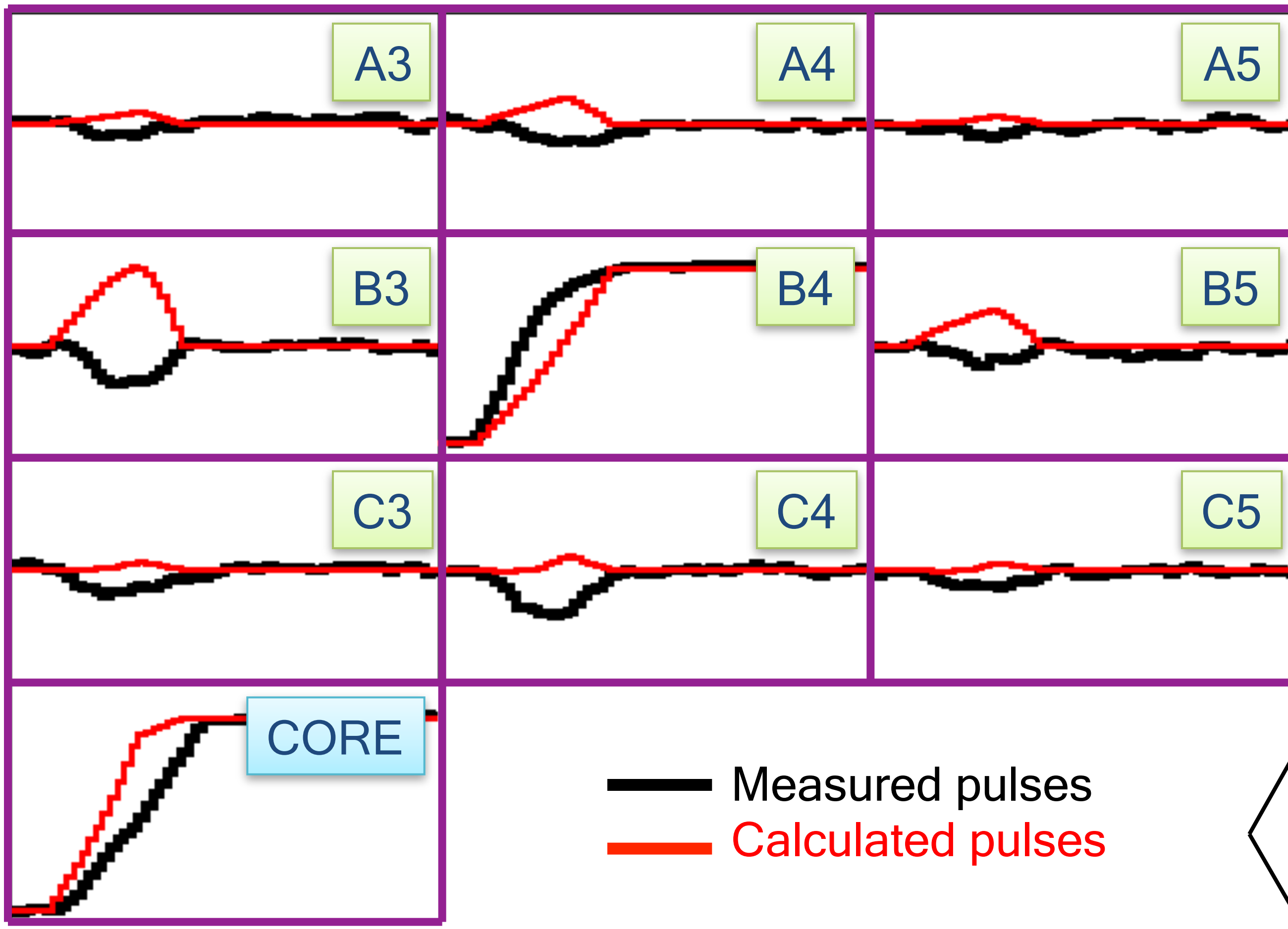




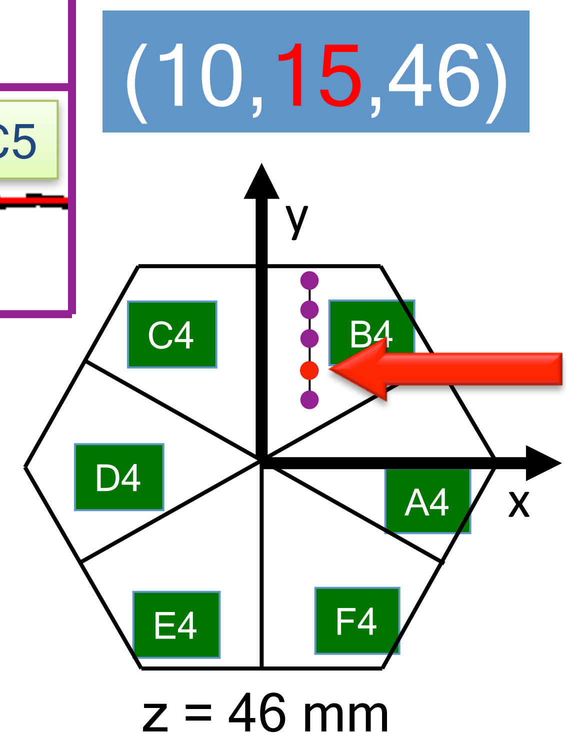
791 keV deposited in segment B4

R.Venturelli, D.Bazzacco

Pulse Shape Analysis Concept

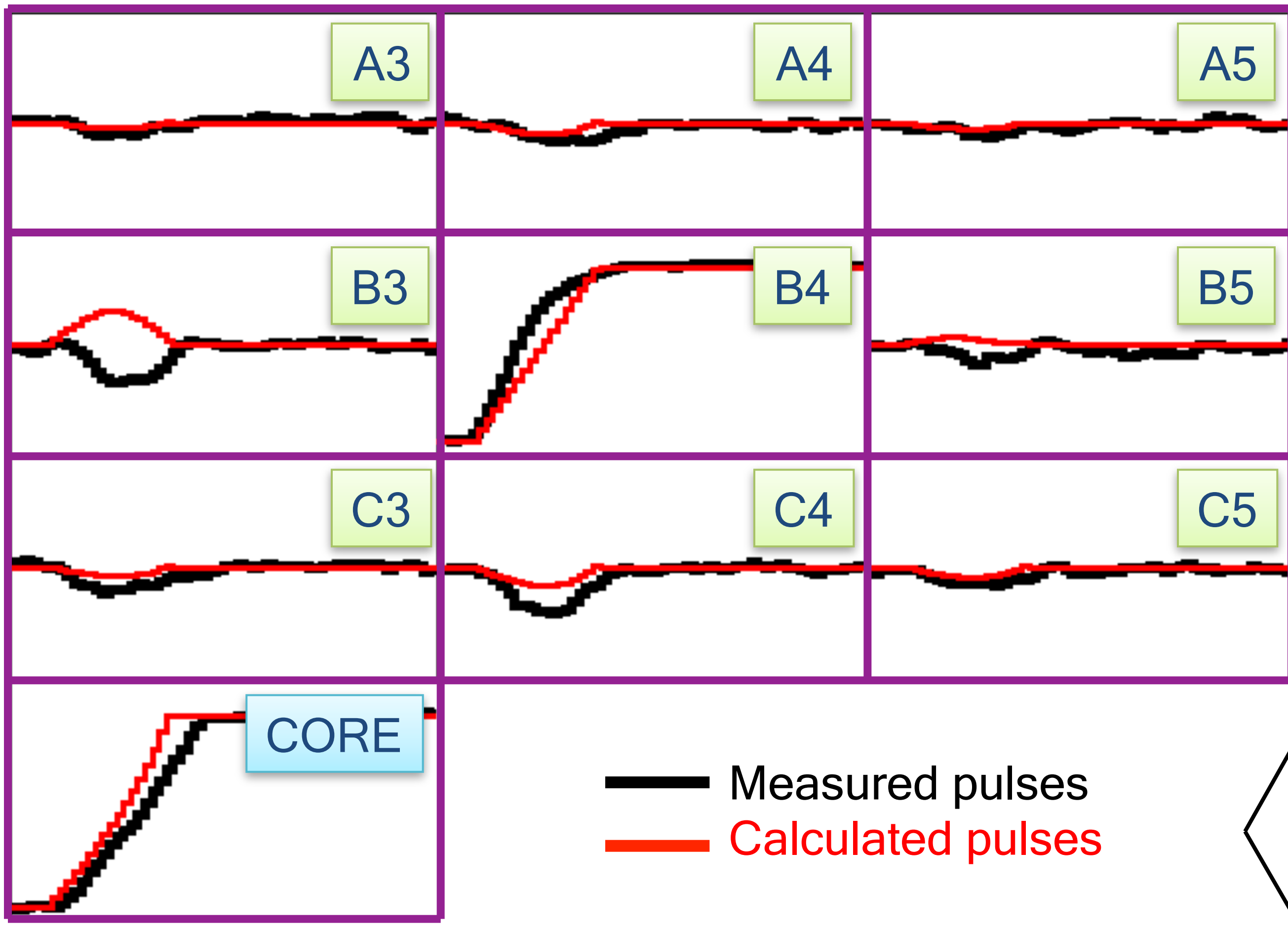


791 keV deposited in segment B4

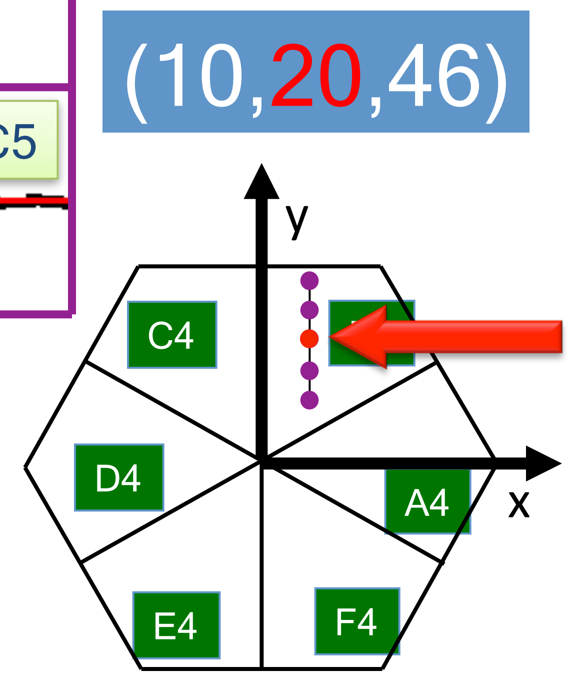


R.Venturelli, D.Bazzacco

Pulse Shape Analysis Concept



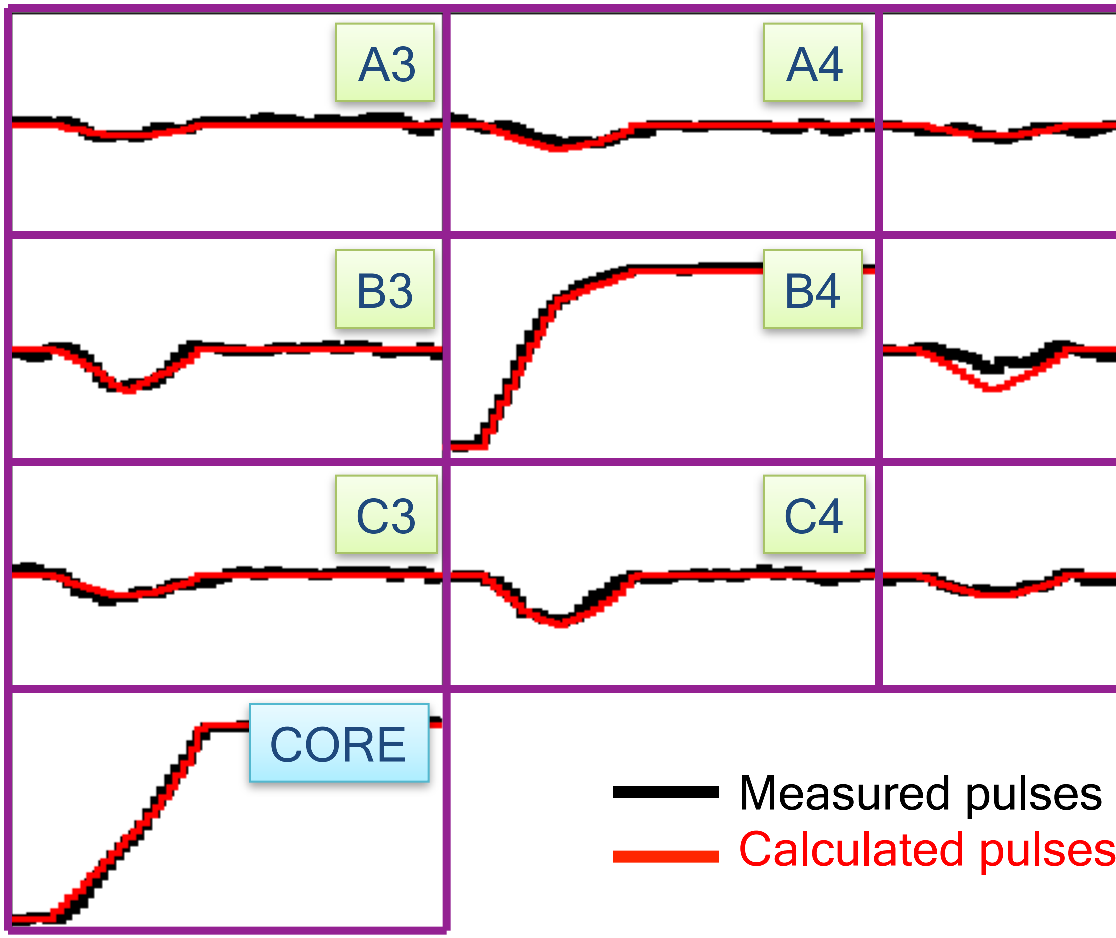
791 keV deposited in segment B4

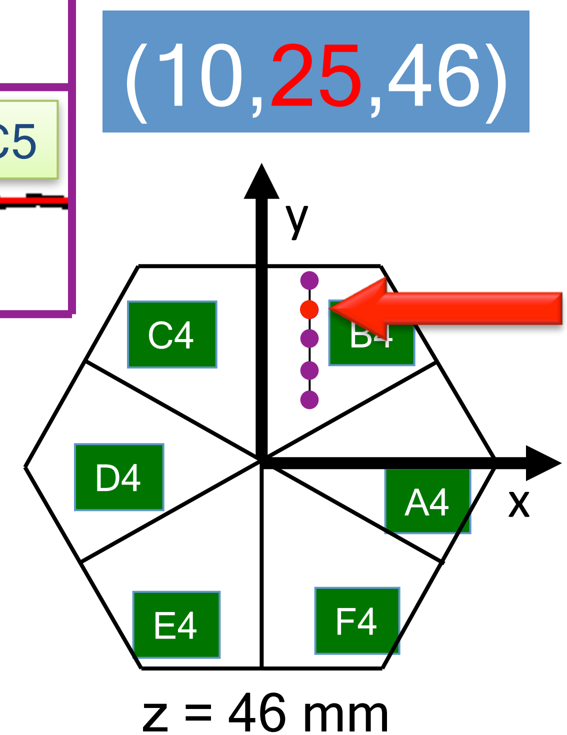


z = 46 mm

R.Venturelli, D.Bazzacco

Pulse Shape Analysis Concept

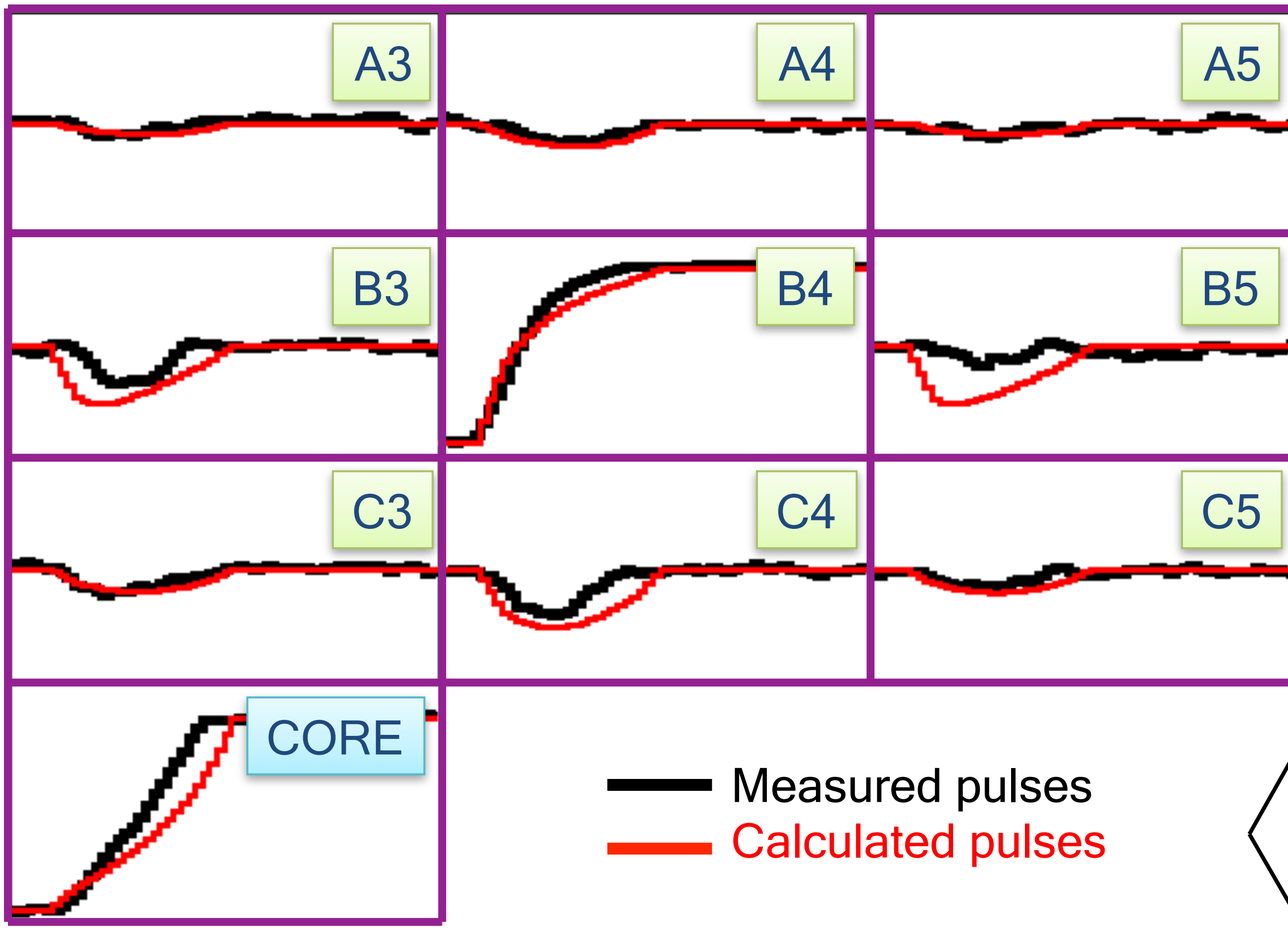




791 keV deposited in segment B4

R.Venturelli, D.Bazzacco

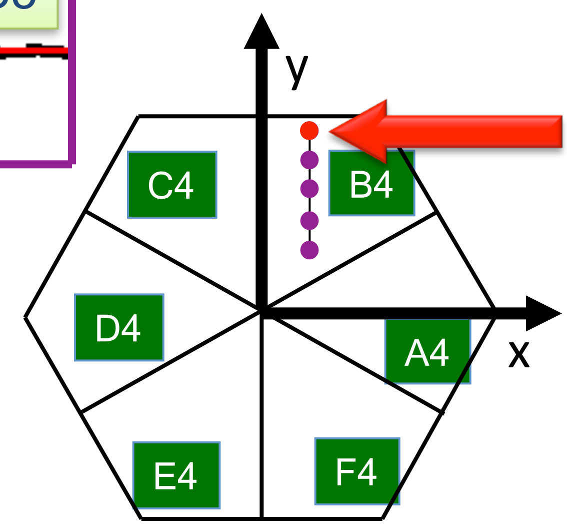
Pulse Shape Analysis Concept



Measured pulses
Calculated pulses

791 keV deposited in segment B4

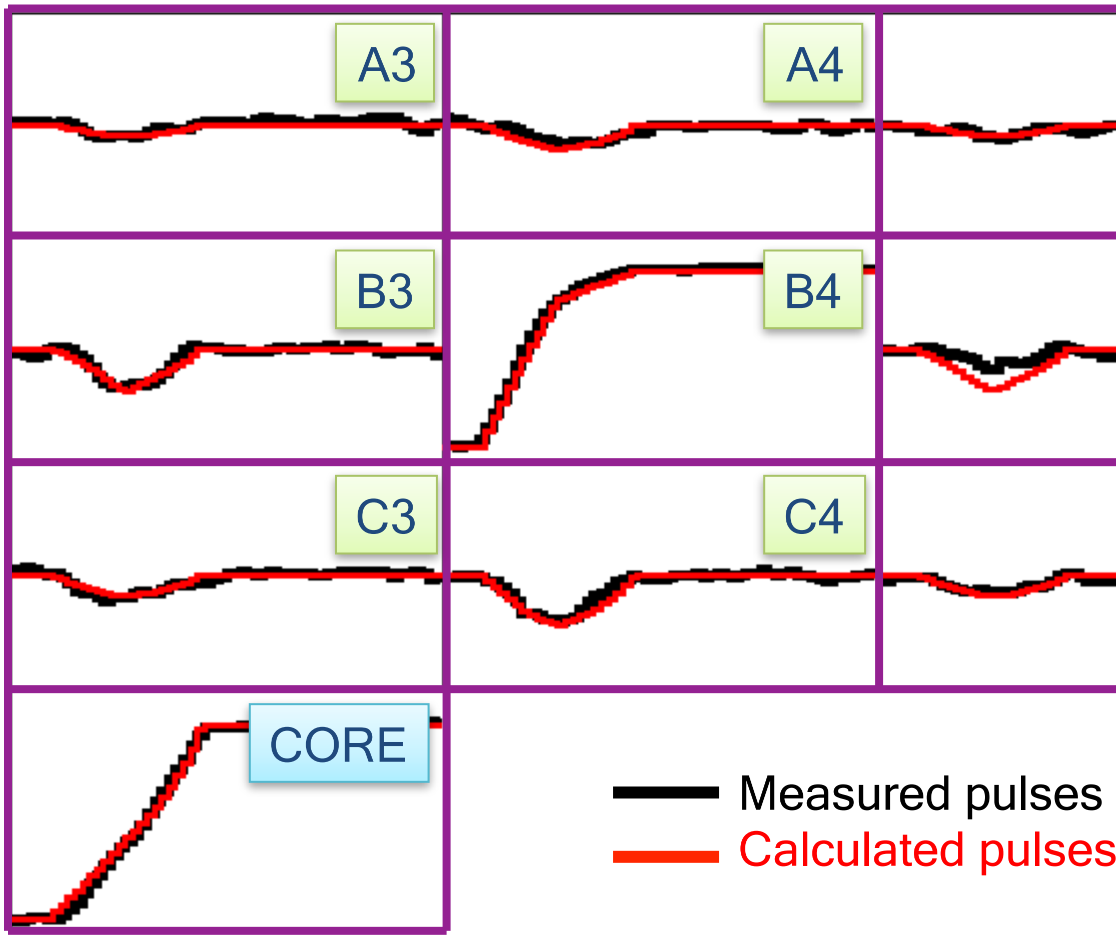
(10,30,46)



z = 46 mm

R.Venturelli, D.Bazzacco

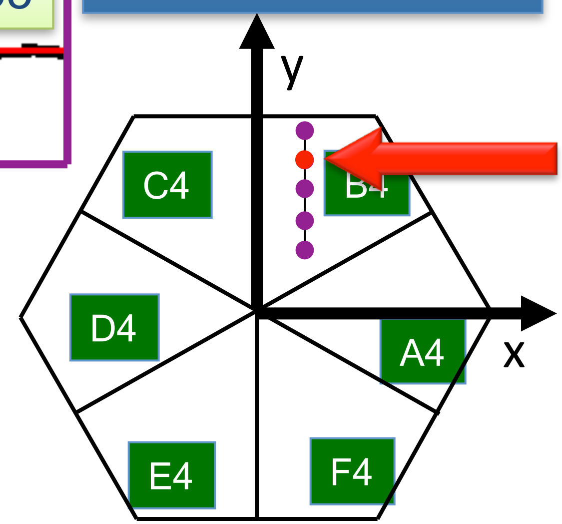
Pulse Shape Analysis Concept



Result of
Grid Search
algorithm

R. Venturelli

(10,25,46)



z = 46 mm

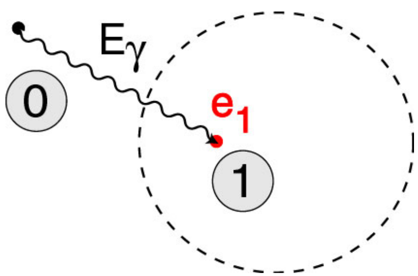
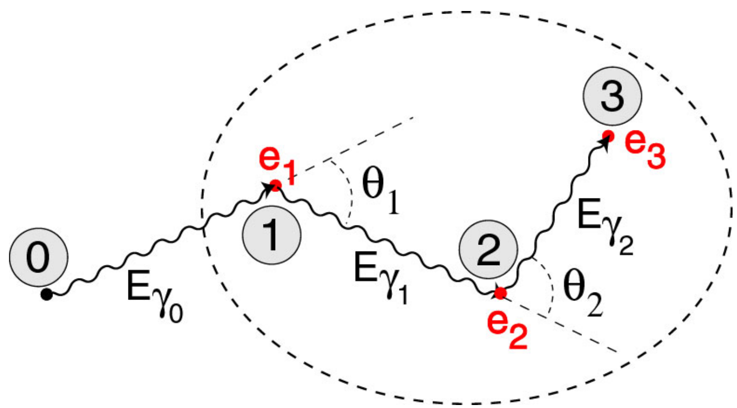
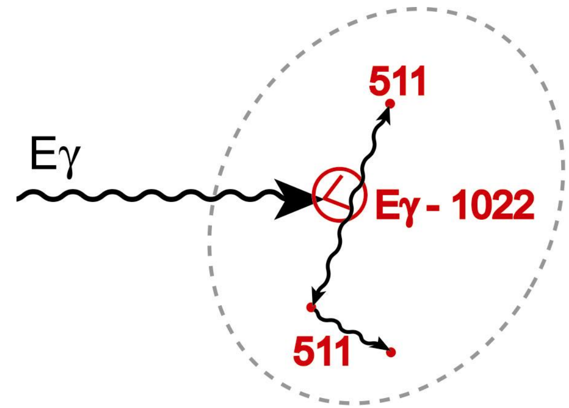
791 keV deposited in segment B4

Set of Energies + Interaction Positions ➡ **Tracking**

R.Venturelli, D.Bazzacco

Interaction - Reconstruction Mechanisms

~ 100 keV ~1 MeV ~ 10 MeV γ-ray energy

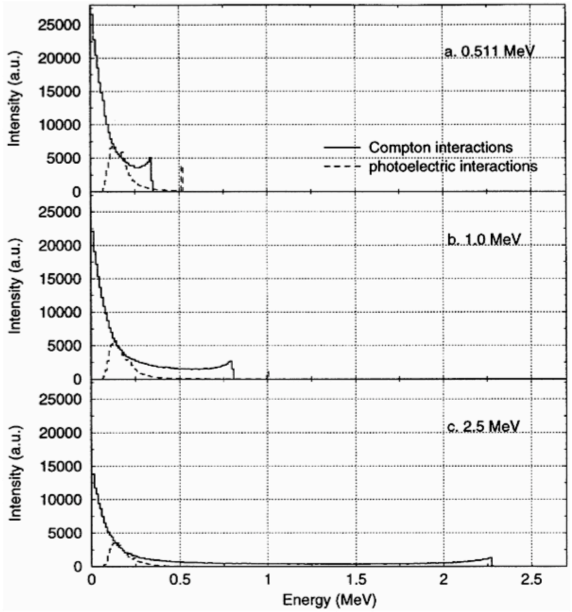
Photoelectric	Compton Scattering	Pair Production
		
Isolated hits	Angle/Energy	Pattern of hits
Probability of interaction depth	$E_{\gamma'} = \dfrac{E_\gamma}{1 + \dfrac{E_\gamma}{m_0 c^2}\left(1 - \cos\theta\right)}$	$E_{1st} = E_\gamma - 2\ mc^2$

Reconstruction efficiencies are limited by :
Position resolution; Short range scattering; Compton profile.

The tracking Algorithms in AGATA

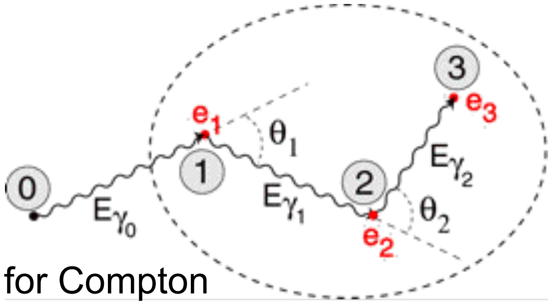
Two main classes:

- algorithms based on back-tracking
  - **J. Van der Marel, B. Cederwall, NIMA 437 (1999) 538.**
  - **J. Van der Marel, B. Cederwall, NIMA 447 (2002) 391.**
  - **L. Milechina, B. Cederwall, NIMA 508 (2003) 394.**
- algorithms based on clusterisation and forward-tracking
  - **G.J. Schmid, et al., NIMA 430 (1999) 69.**
  - **D. Bazzacco, MGT code developed within the TMR program 'Gamma-ray tracking detectors'**
  - **I. Piqueras, et al. NIMA 516 (2004) 122**



$$E_{s,p} = \frac{E_t}{1 + E_t/m_e c^2(1 - \cos\theta_p)}$$

Forward-tracking

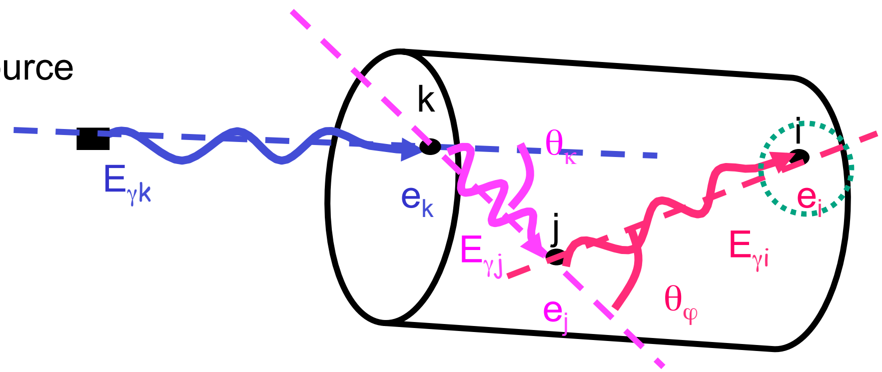


Probability for Compton or photoelectric and for the path in Germanium

$$L = \prod_{n=1}^{N} P_n \exp - \left[\frac{E_{\gamma n} - E_{\gamma n,pos}}{\sigma_E} \right]^2$$

Likelihood

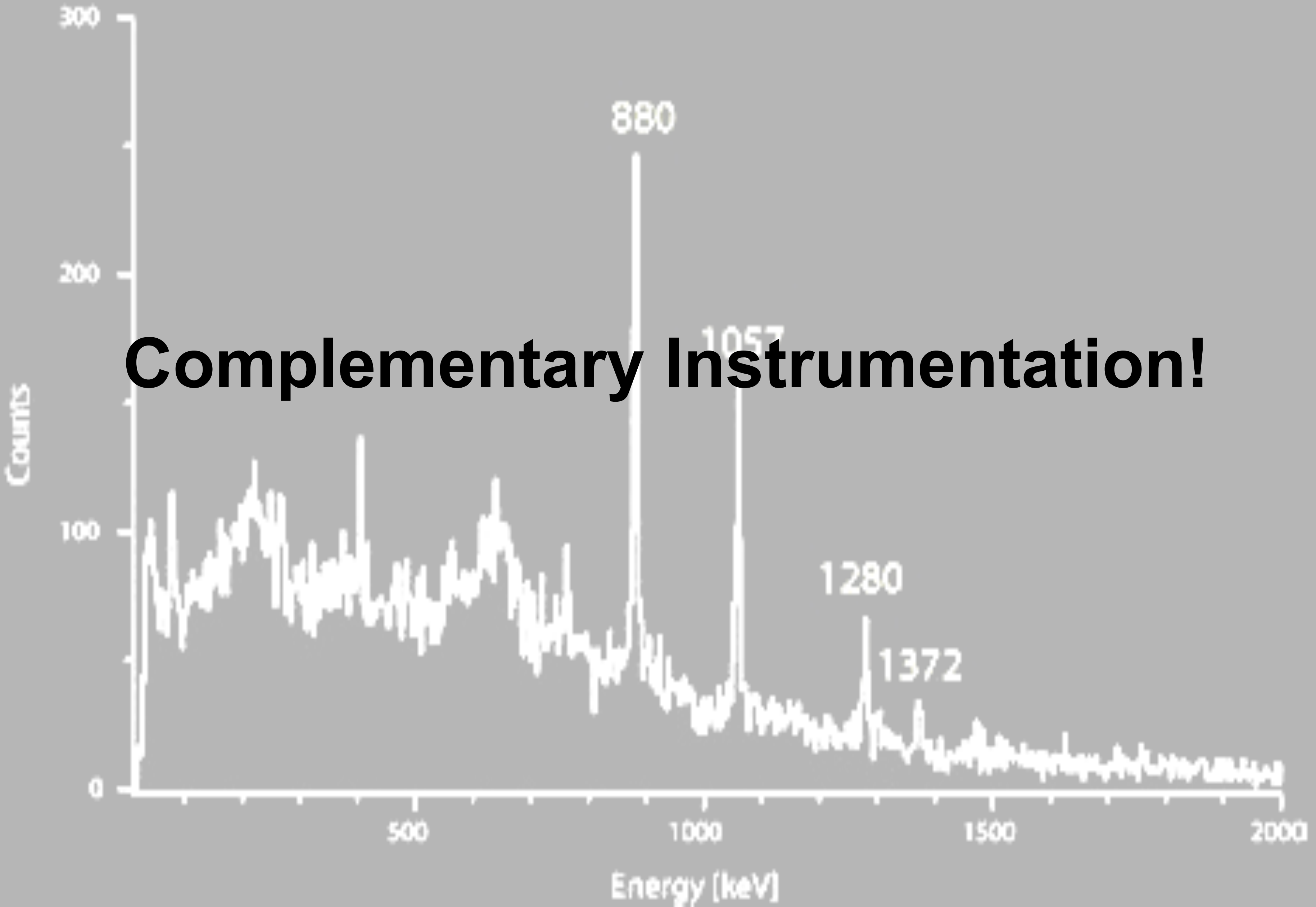
Back-tracking



$$\cos(\theta) = 1 - m_e c^2(1/E_{sc} - 1/E_{inc})$$

A.Lopez-Mertens et al. NIMA 533 (2004) 454

Complementary Instrumentation!



Complementary Instrumentation

- Fundamental to increase the sensitivity of the γ-ray detector. Identifying the reaction channel or reaction products:
  - Particle detectors (Light charged particles or neutrons)
  - Spectrometers (Identification of the reaction products)
  - Beam Trackers (for relativistic experiments)
  - etc…
- Fundamental to perform some measurements
  - Plunger devices for RDDS measurements
  - Fast Scintillators for timing measurements
  - etc…