

New Trends and Techniques in Nuclear Structure Studies with High-Resolution In-Beam γ -Spectroscopy

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Counts

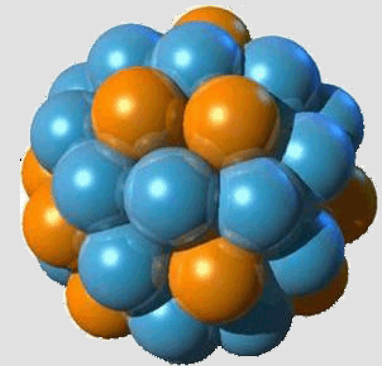
1. High Resolution Spectroscopy techniques

- Introduction
- γ -tracking arrays
- Complementary instrumentation

2. Nuclear Structure

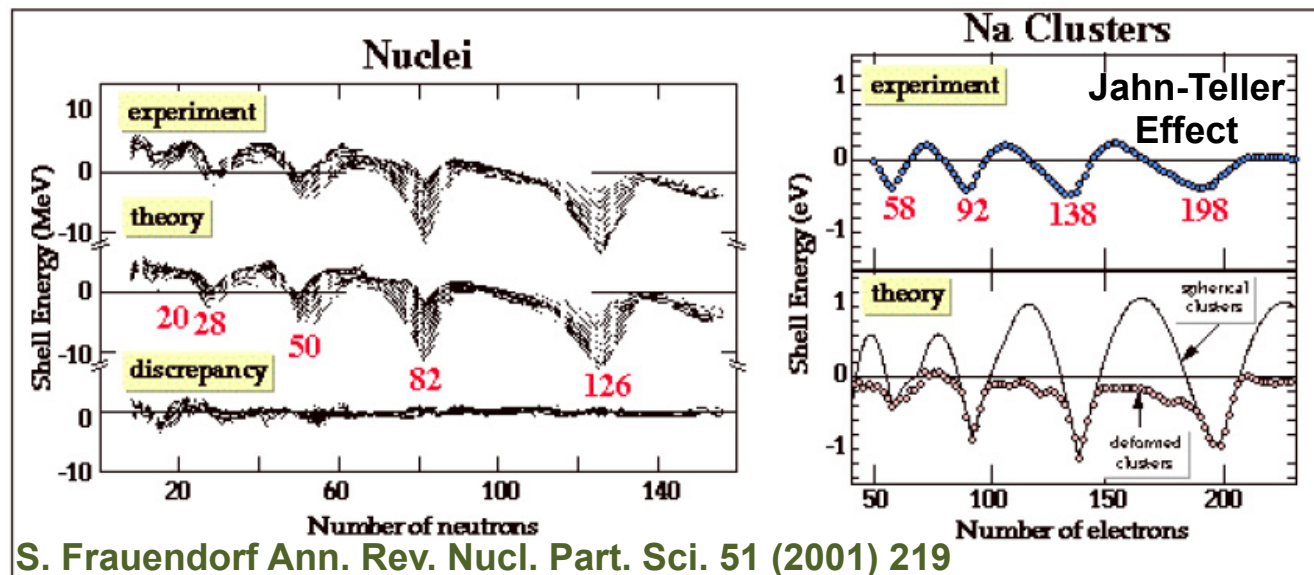
- Proton-Rich & N=Z Nuclei
- Neutron-rich $\rightarrow$ Large Isospin Values
- Collective & Transitional Phenomena

Energy [keV]

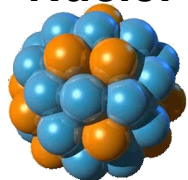


Structure of the atomic nucleus

- 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.



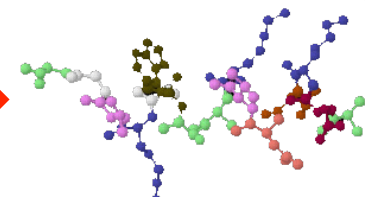
Nuclei



Many-body systems: phase transitions
piloted by few quantal states

R.A.Brogia JoP Conf. Ser. 41 (2006) 1

Protein Folding



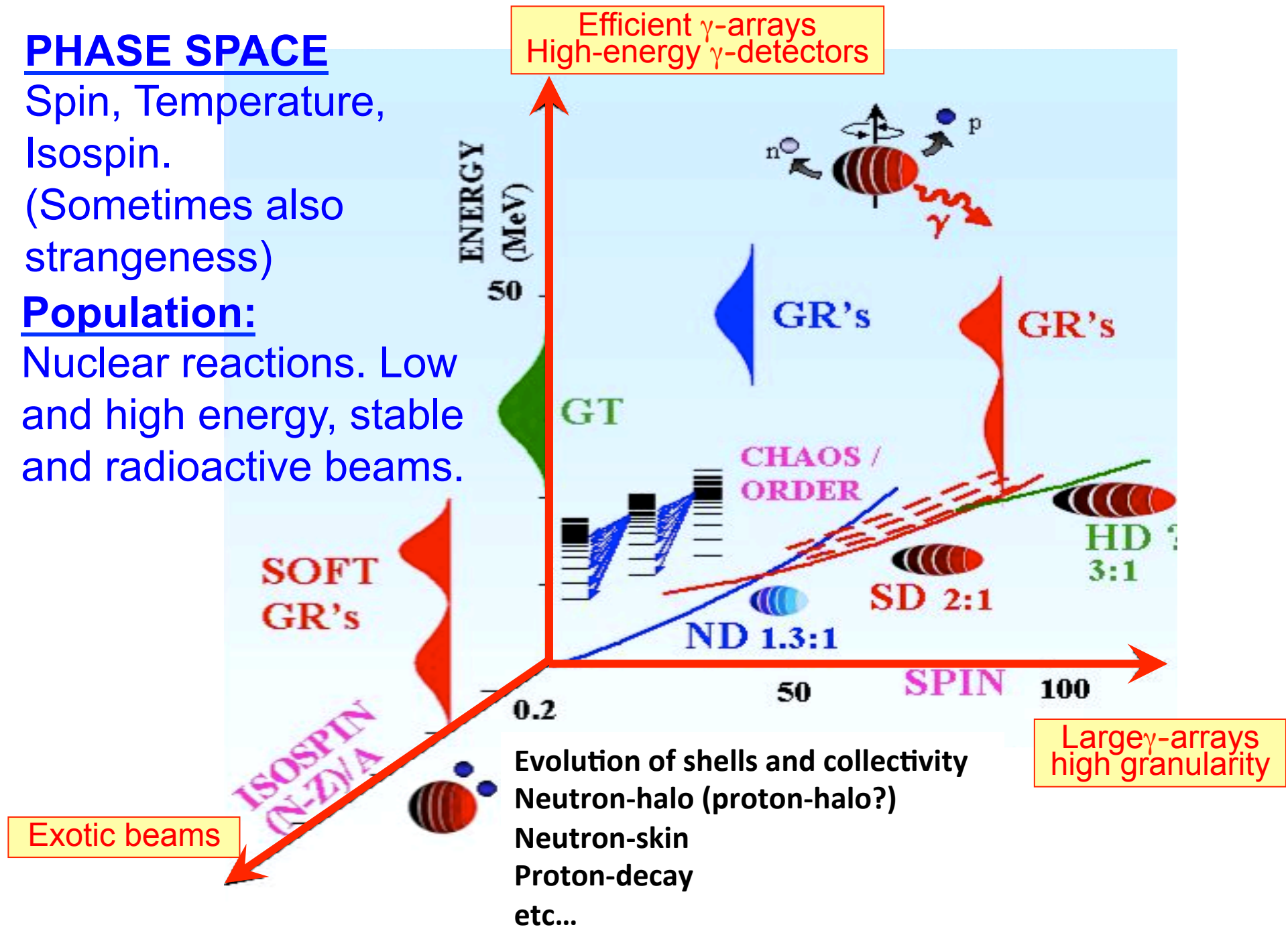
PHASE SPACE

Spin, Temperature,
Isospin.

(Sometimes also
strangeness)

Population:

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

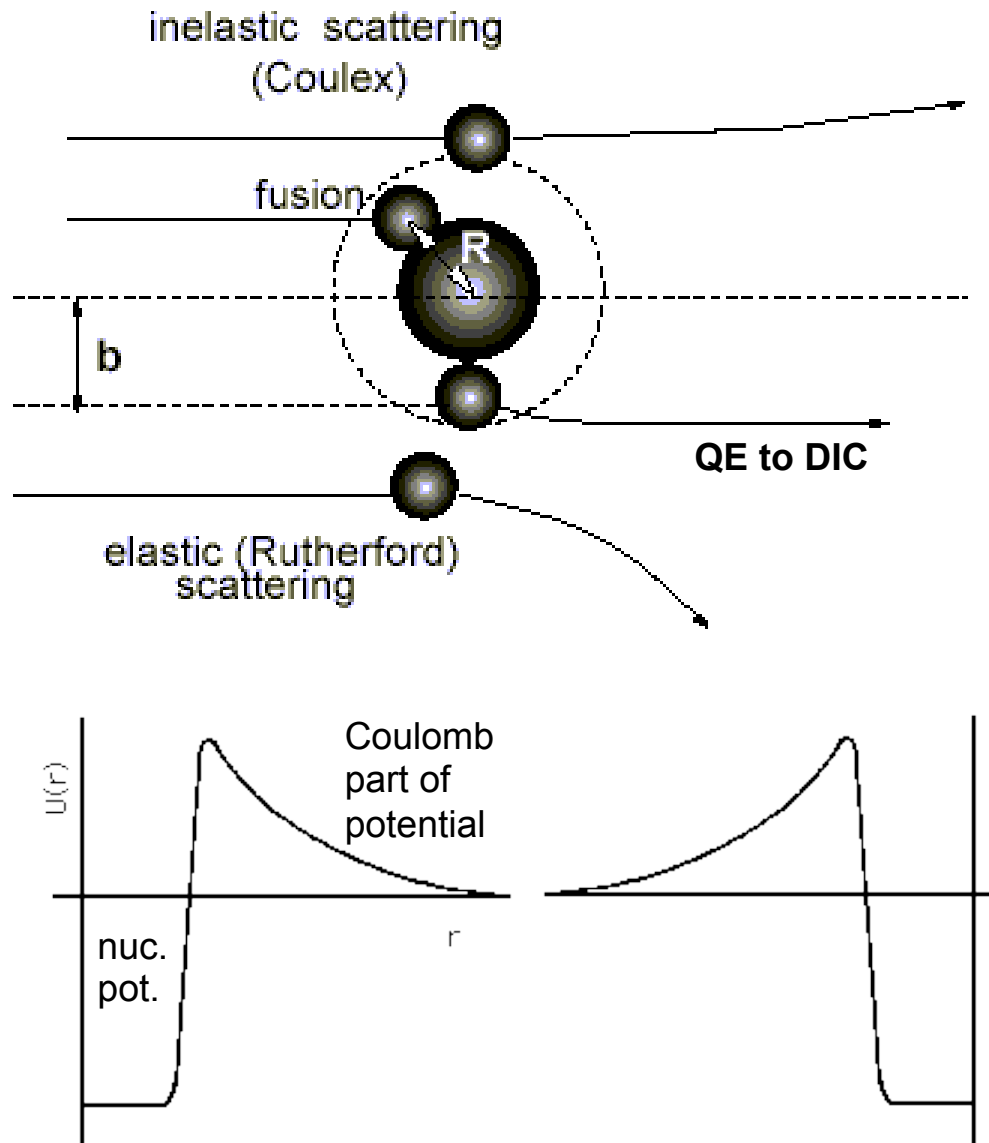


In-Beam Spectroscopy

Key-Issues

- **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 and Selectivity.**
- **Reaction rates could by limited by the detector counting rates**

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



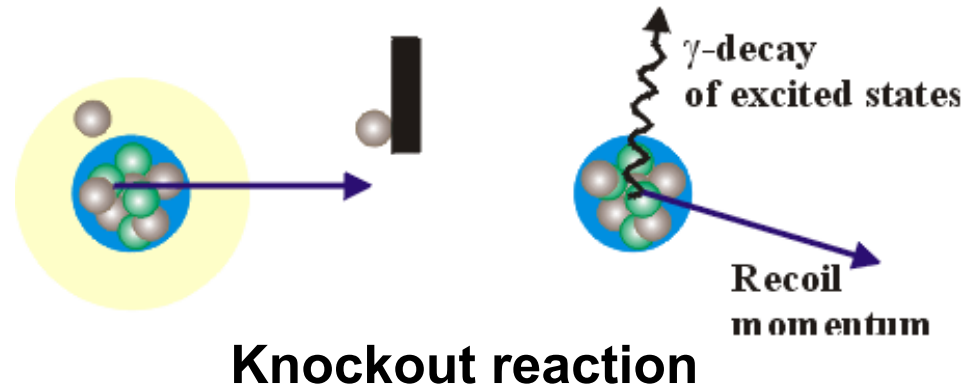
Smaller impact parameter "b"

- 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

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

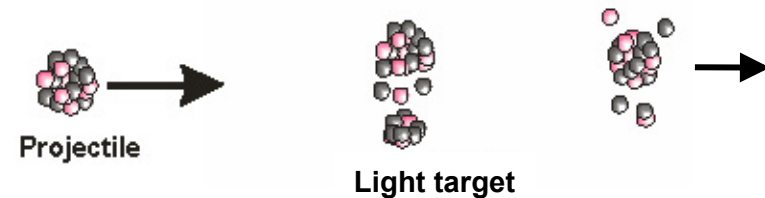
Generally used with exotic ion beams produced by fragmentation or fission at relativistic energies

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

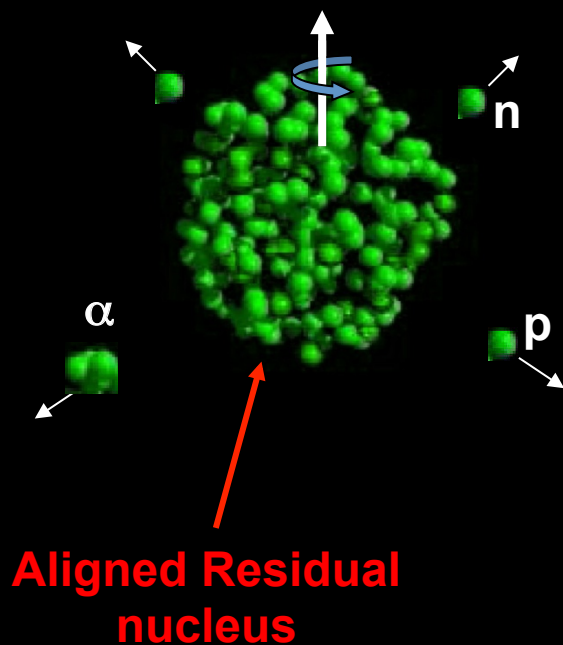


Cross sections :

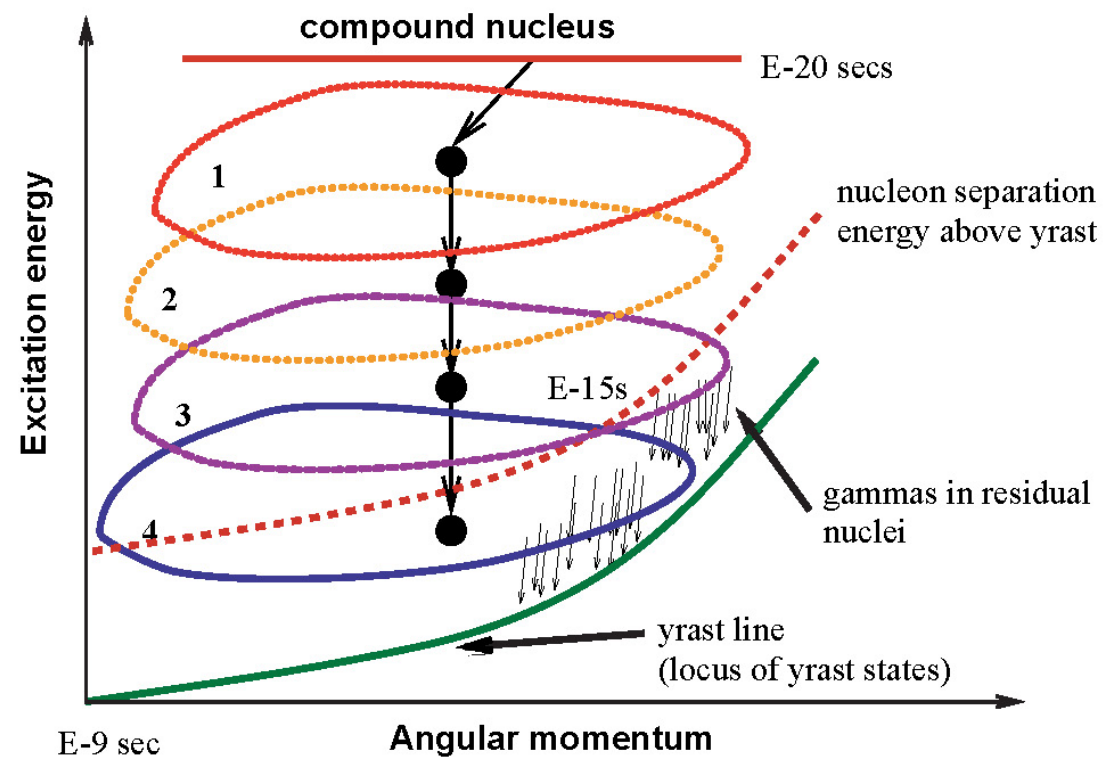
- up to 1 barn for Coulex (large Z nuclei)
- tens of mbarn for proton scattering and 1 nucleon knockout,
- down to few mb for 2 nucleons knockout.
- smaller cross sections for fragmentation



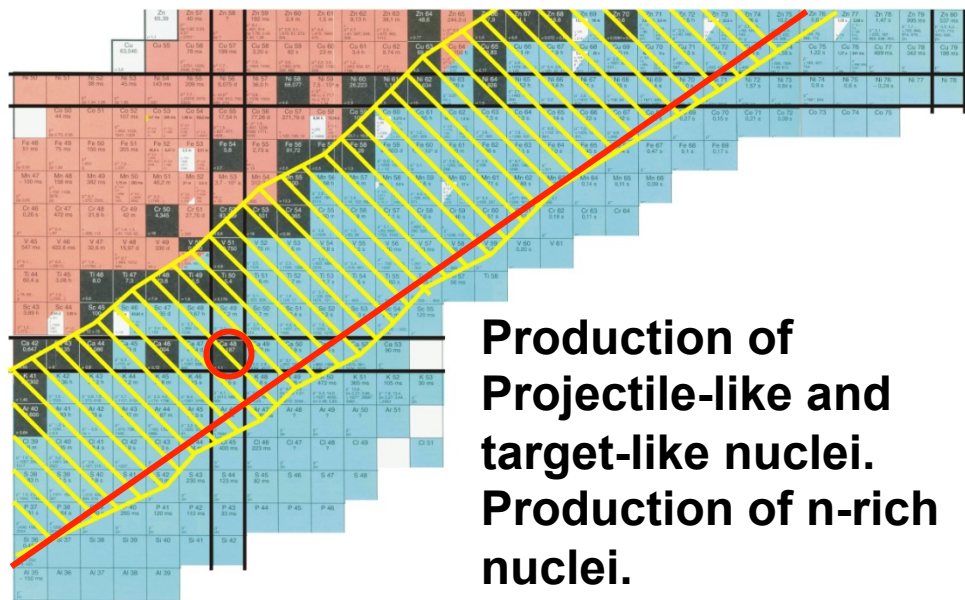
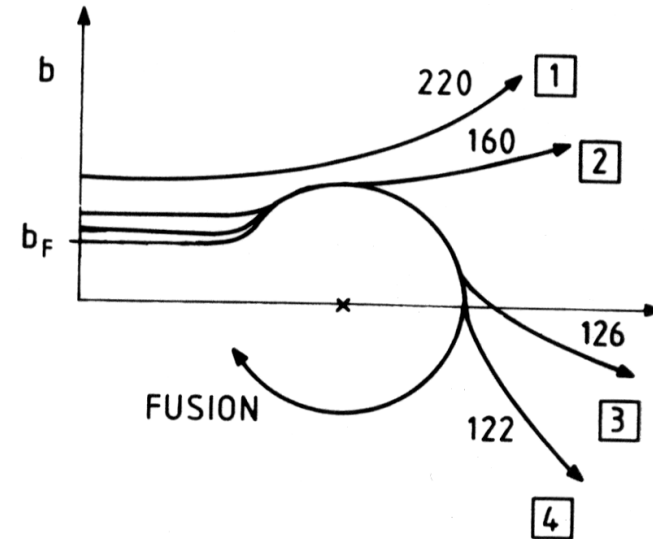
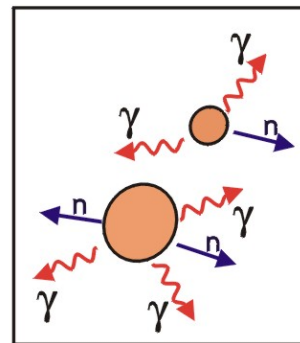
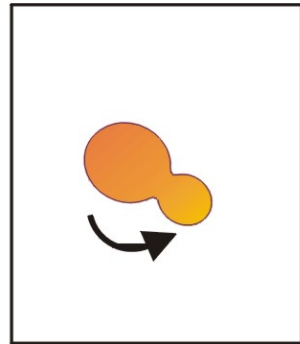
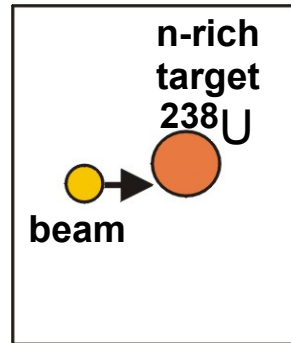
Example: FUSION-EVAPORATION REACTIONS



Hauser-Feshbach Theory

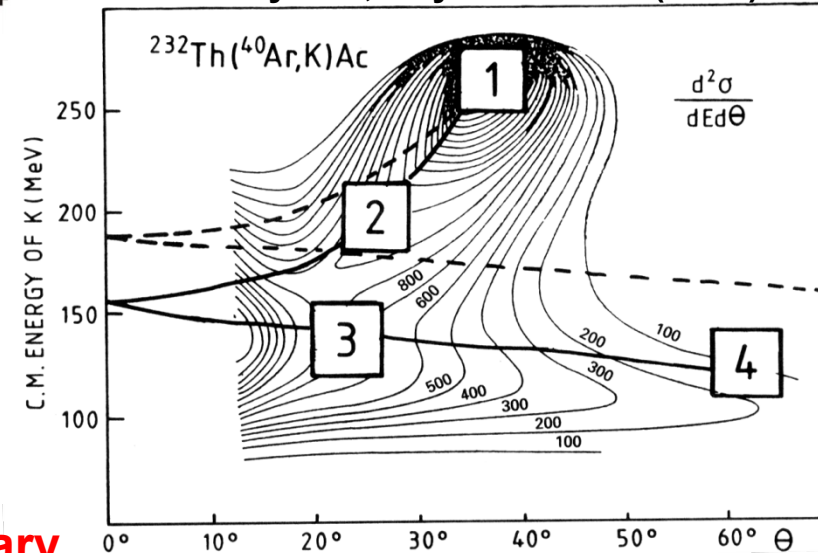


Example: GRAZING REACTIONS

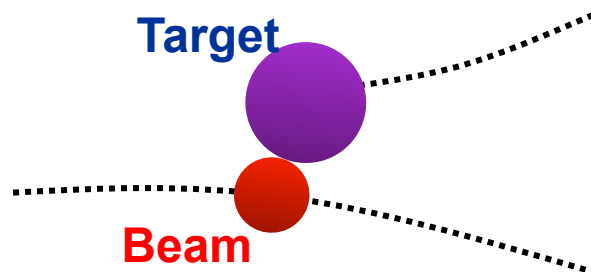


Production of
Projectile-like and
target-like nuclei.
Production of n-rich
nuclei.

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



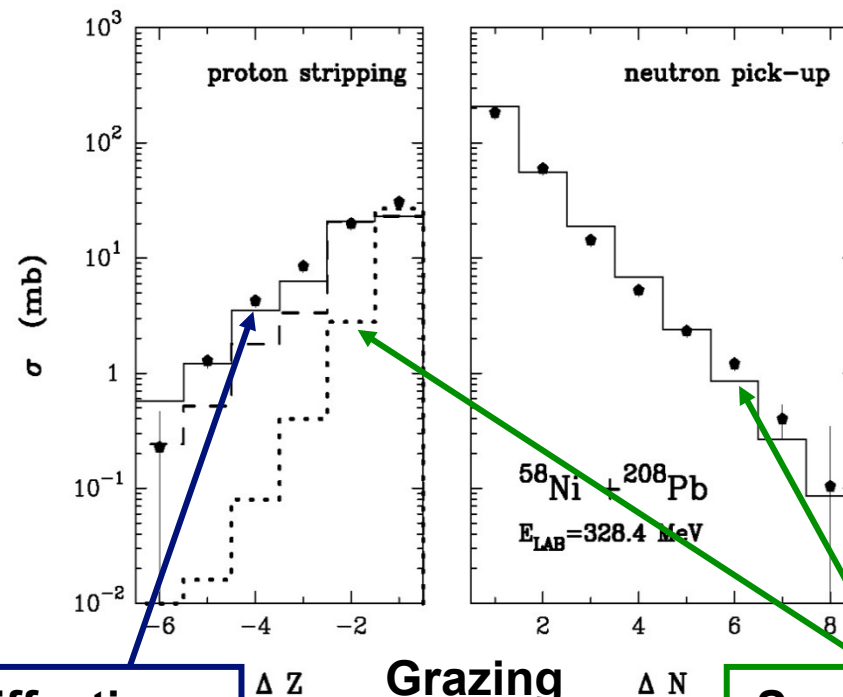
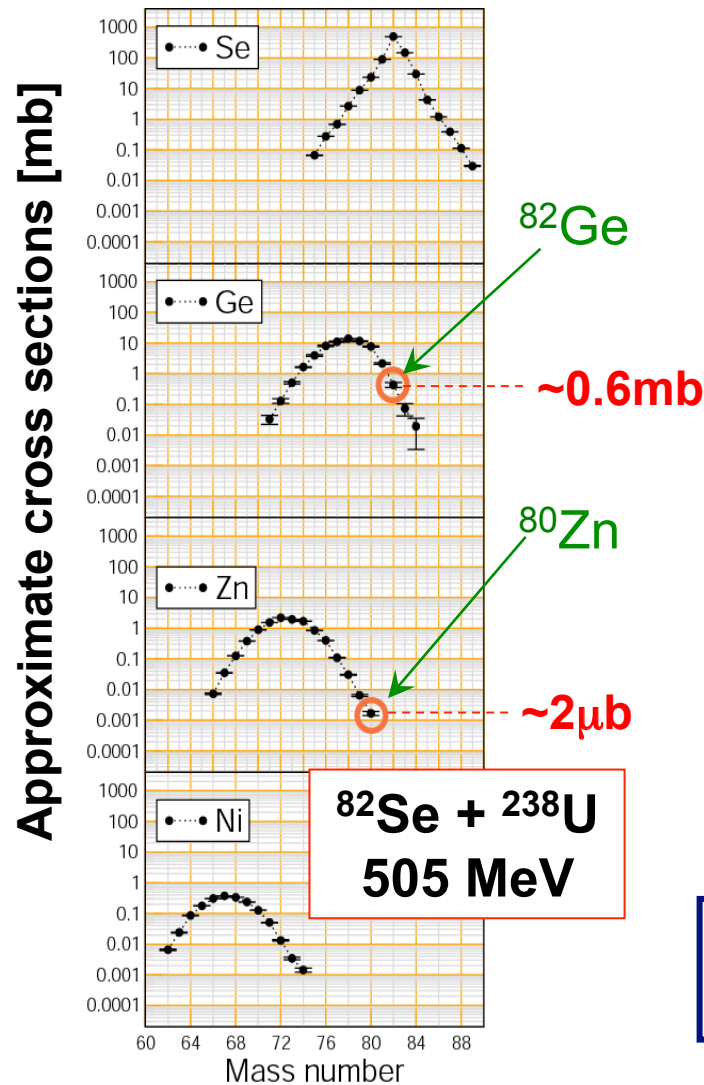
Identification of products with complementary detectors or by γ -spectroscopy of the partner s is required



Grazing reactions transferring several nucleons, a tool to study neutron-rich nuclei

Deep-inelastic reactions used since thick target pioneering work of R.Broda et al. (PLB 251 (90) 245)

Use of Multinucleon-transfer at the grazing angle triggered by the LNL reaction mechanism group.



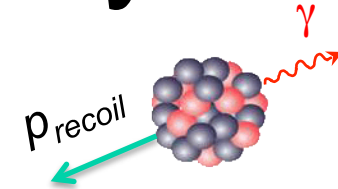
Effective
Pairing Term

Grazing
calculations

Sequential
Transfer

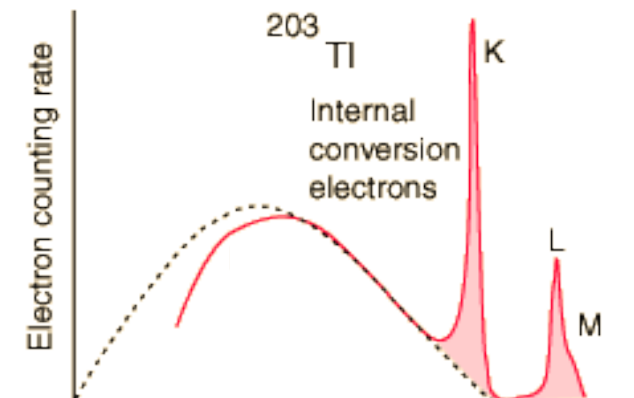
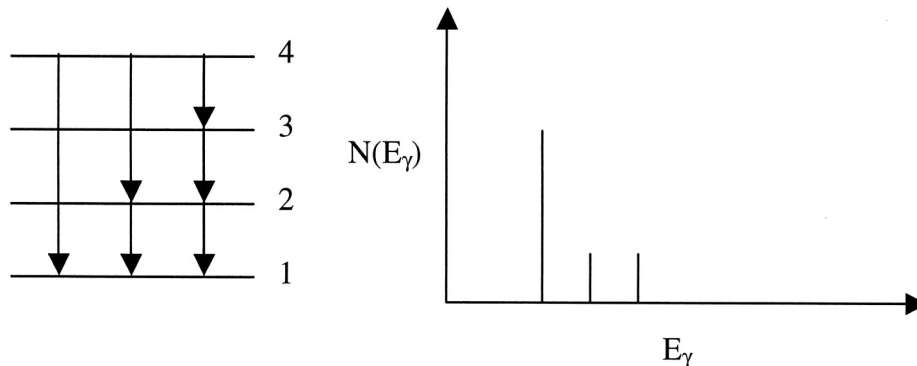
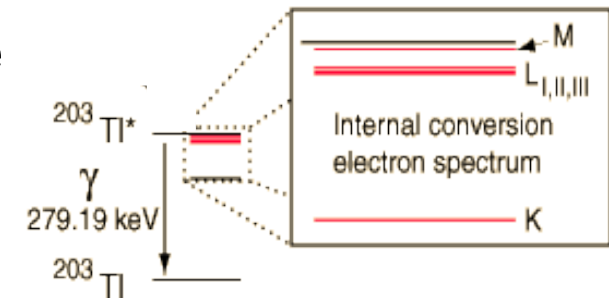
Electromagnetic decay

- There are three types of electromagnetic decay, γ -ray emission, internal conversion (IC) and pair production ($E > 1.02 \text{ MeV}$).
- In electromagnetic decays $\Delta N = \Delta Z = \Delta A = 0$, 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.



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

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



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.

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

A photon with ℓ units of angular momentum

is called a 2^ℓ -pole photon.

$\ell = 1 \Rightarrow$ dipole

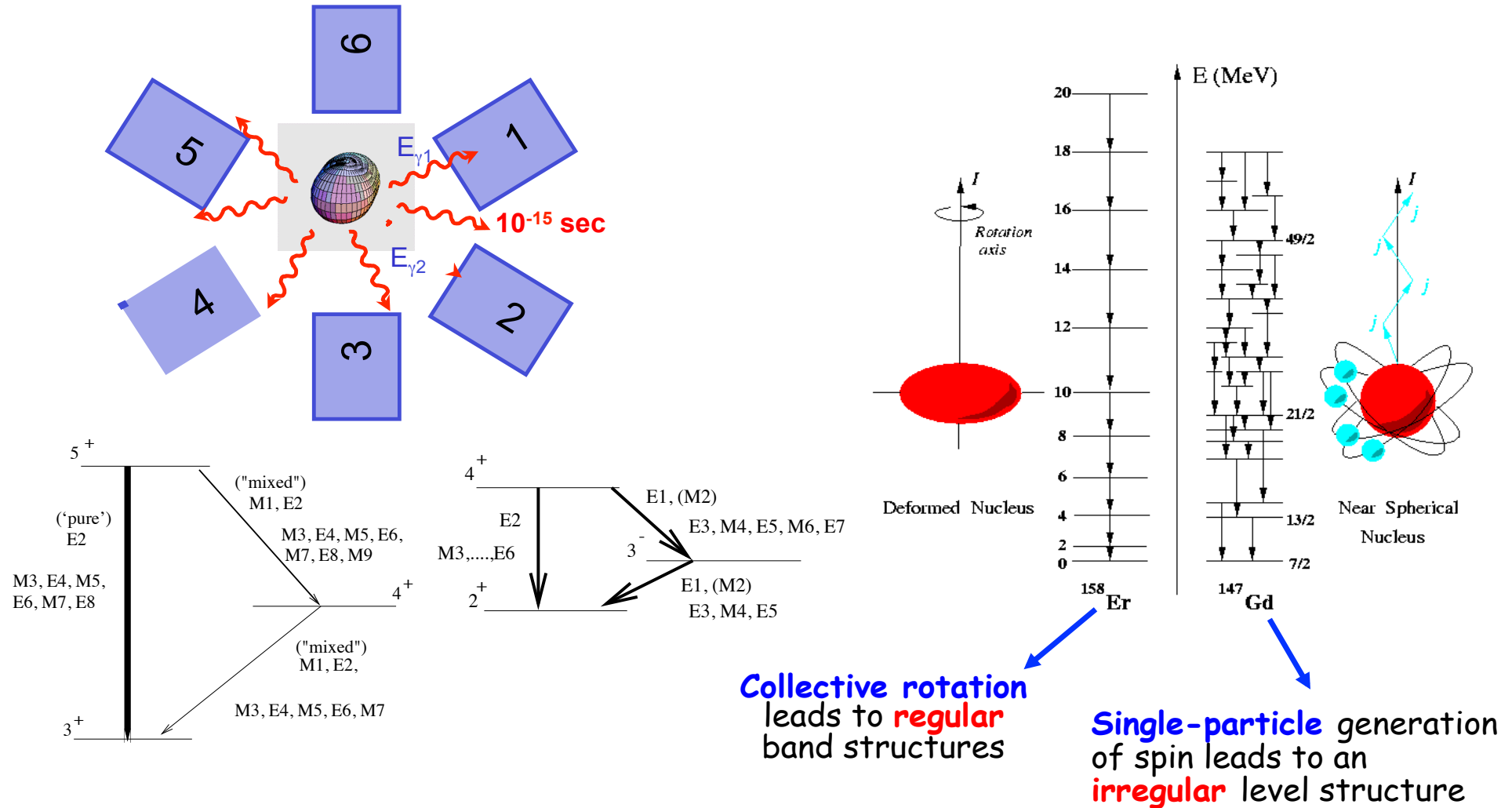
$\ell = 2 \Rightarrow$ quadrupole

$\ell = 3 \Rightarrow$ 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

In-beam Experiments and Nuclear Structure

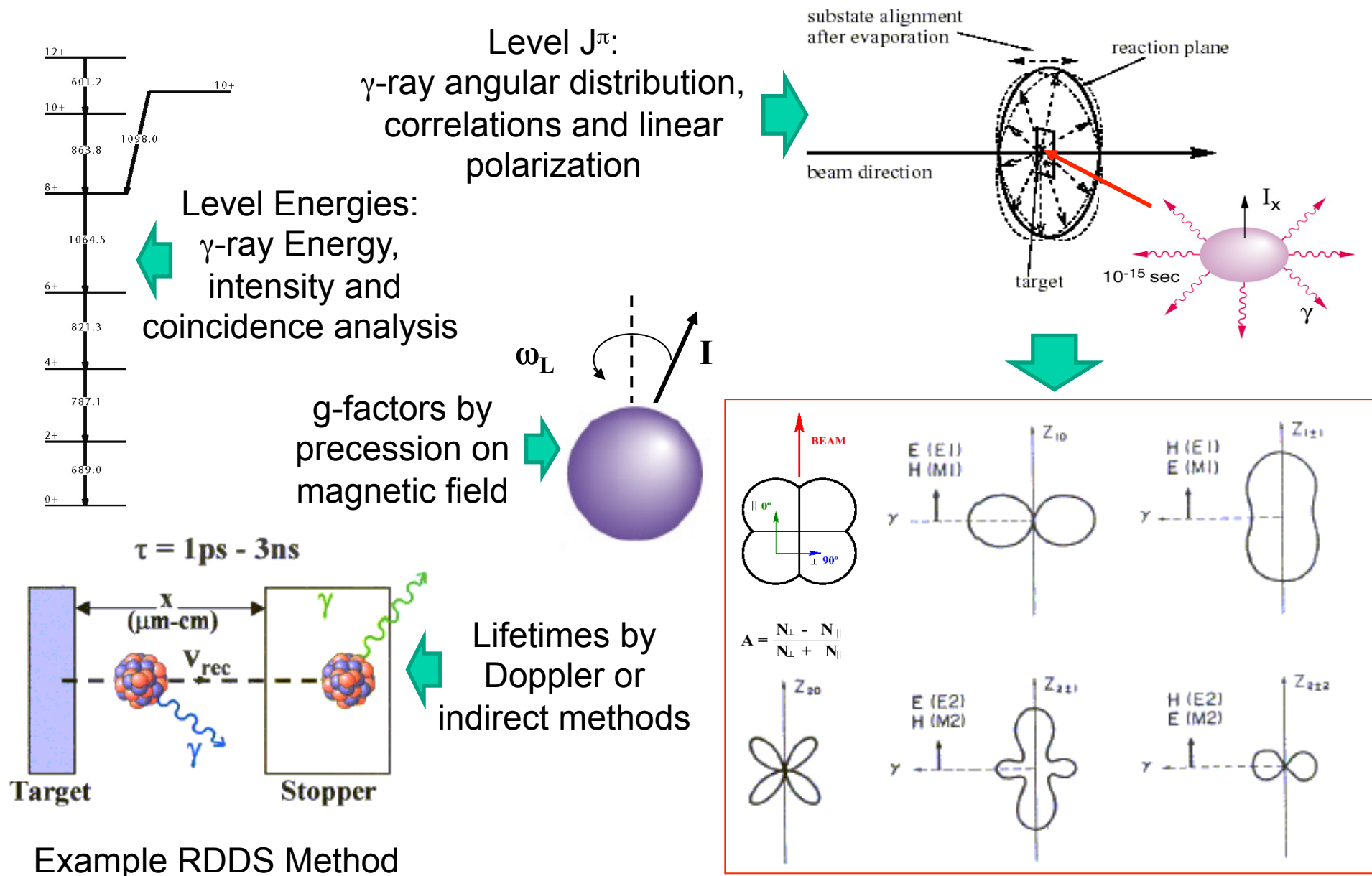


$B(E/M\lambda)$

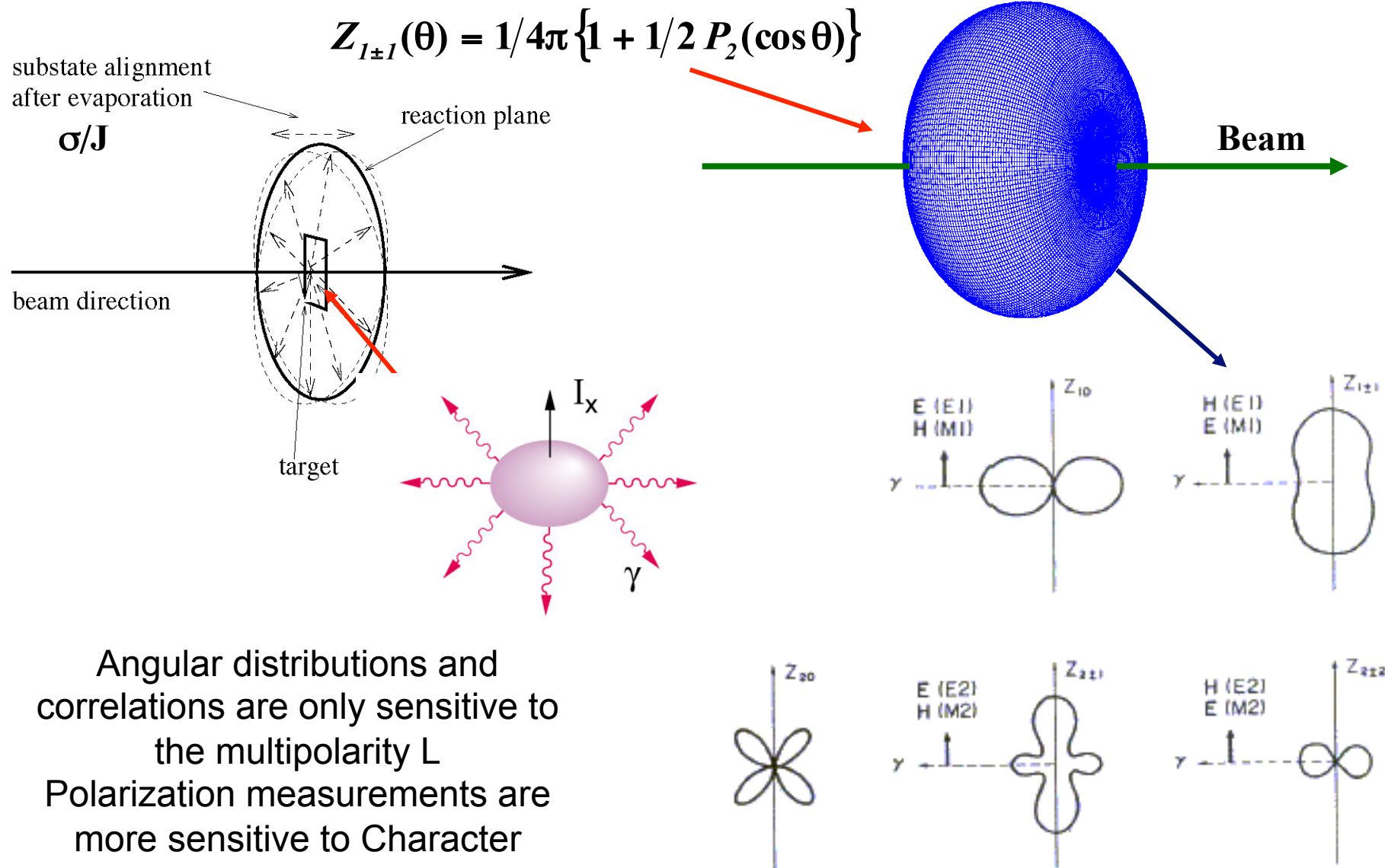
The decay probability is governed by the matrix element of the multipole operator

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

Measurements with HR γ -ray spectroscopy



Electromagnetic emission from Oriented Nuclei: Angular distributions

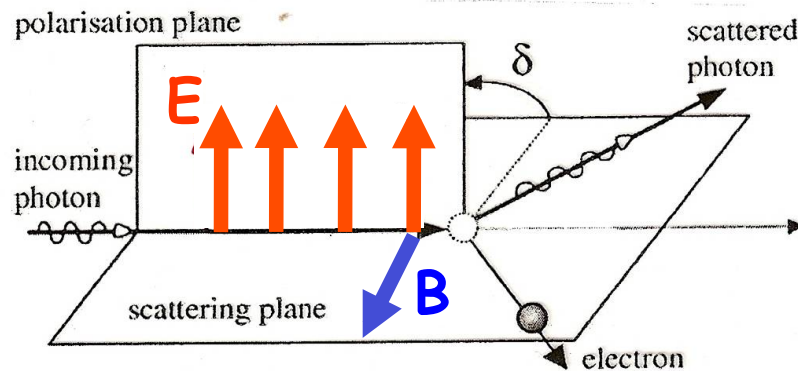


Measurement of the linear polarization

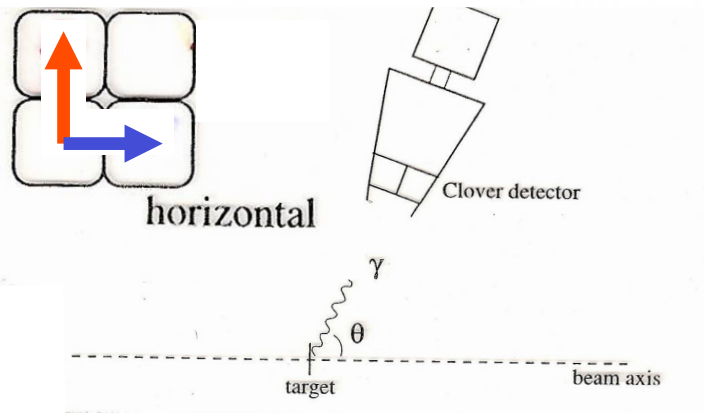
- γ -rays emitted by oriented nuclei are partially polarized. The polarization vector is different for E and M transitions (character)
- Compton scattering can be used to measure the degree of polarization through the dependency with the polarization vector

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

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



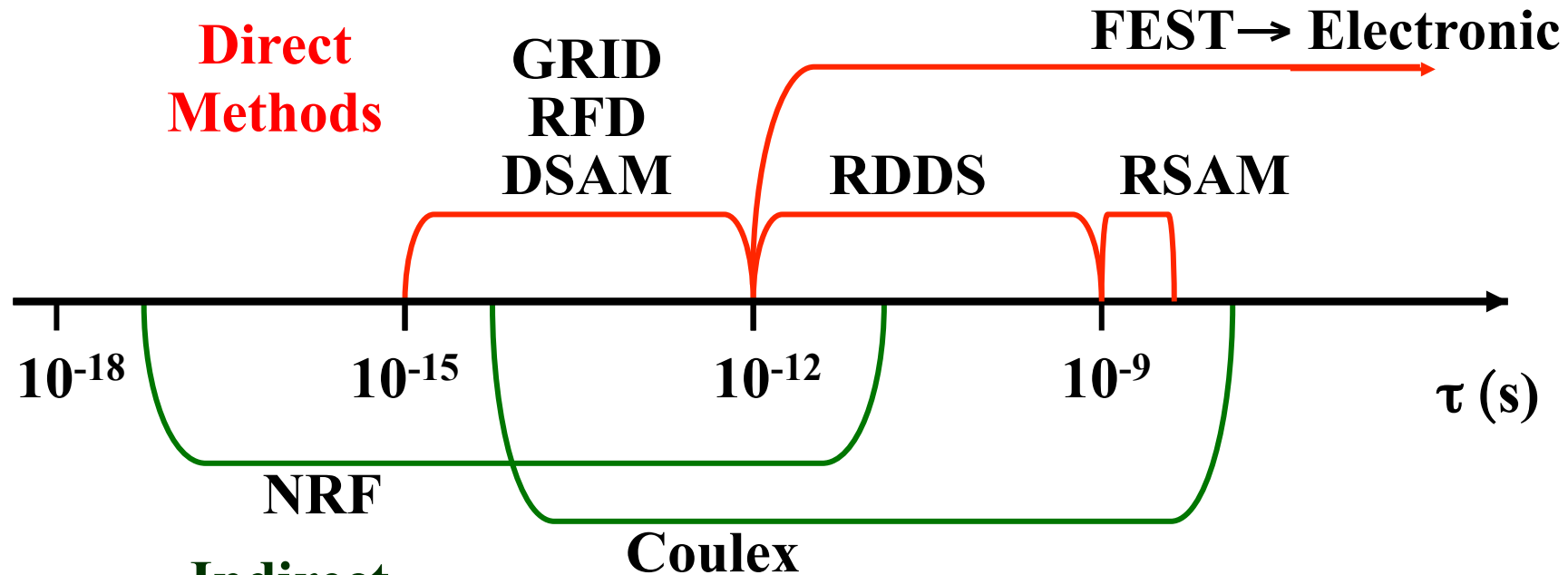
Stretched $E\lambda$ transitions will have positive asymmetry
Stretched $M\lambda$ transitions will have negative asymmetry



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

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

Techniques for lifetime measurements



**Indirect
Methods**

GRID: Gamma ray induced Doppler broadening

DSAM: Doppler shift attenuation method

RFD: Recoil straggling method

RDDS: Recoil distance Doppler shift method

RSAM: Recoil shadow anisotropy method

FEST: Fast electronic scintillation method

NRF: Nuclear resonance fluorescence

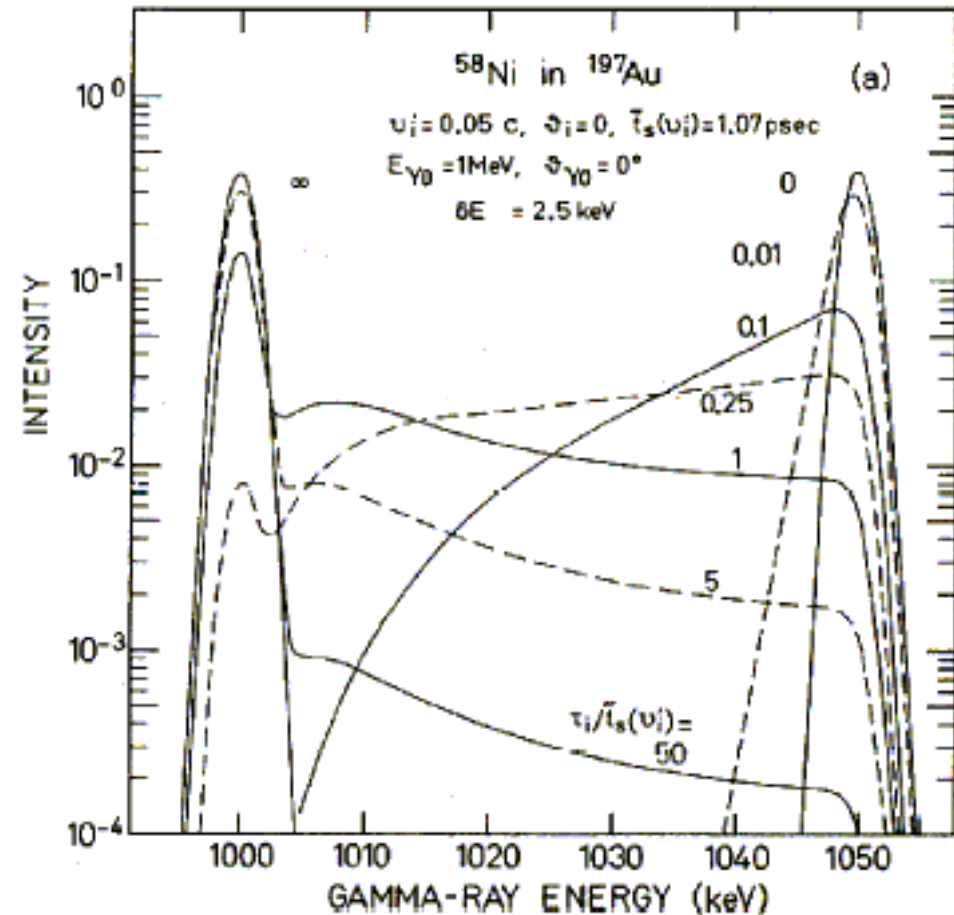
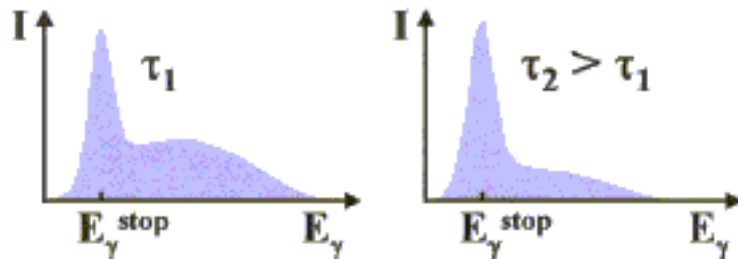
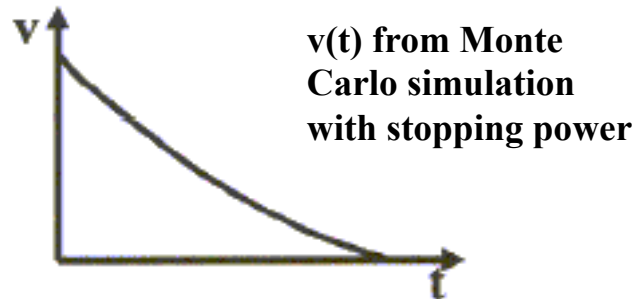
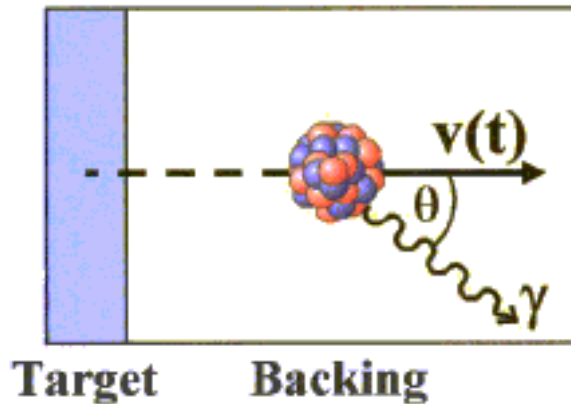
Coulex: Coulomb excitation cross section

NFR:

Coulex:

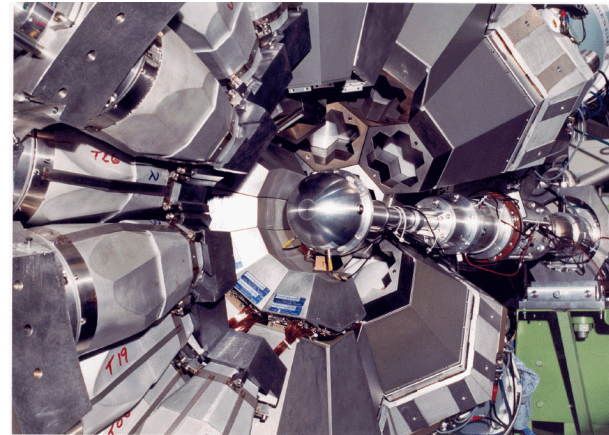
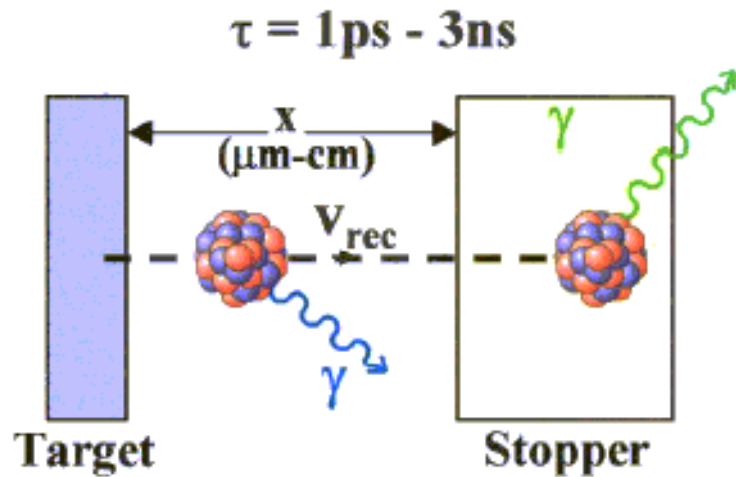
Doppler Shift Attenuation Method

$$\tau = 0.1 - 1.5 \text{ ps}$$

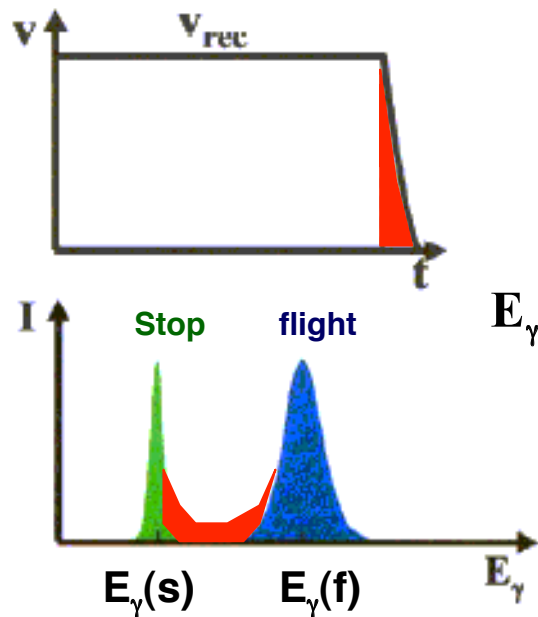


Line shapes for ^{58}Ni stopped in ^{197}Au with a beam velocity of $v/c=0.05$ and measured at $\theta=0^\circ$

Recoil Distance Doppler Shift Method



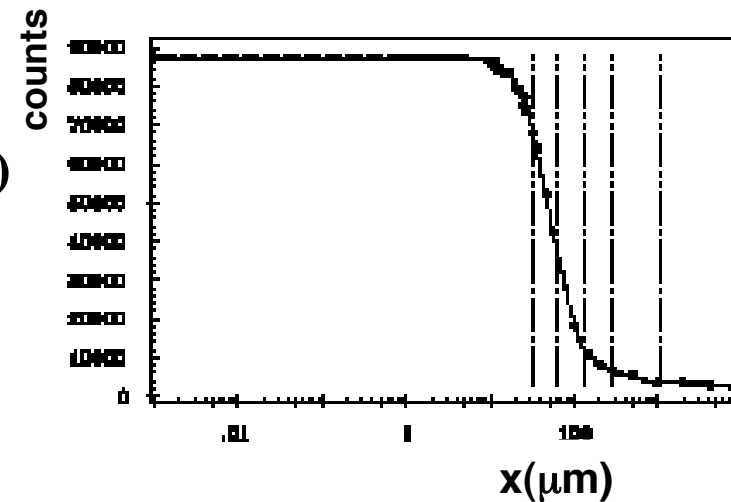
Koeln University plunger



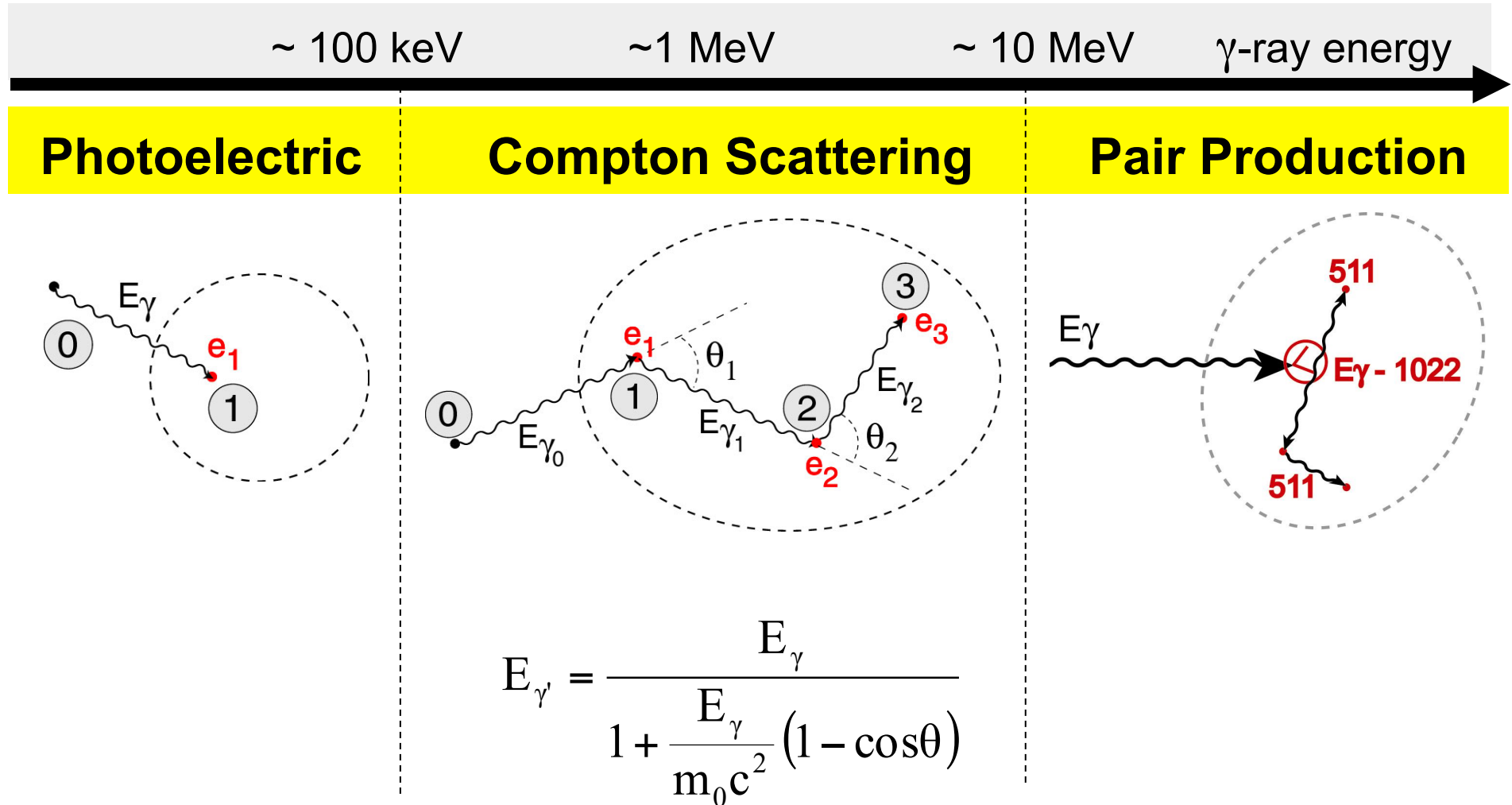
$$E_{\gamma}(f) \approx E_{\gamma}(s) \left(1 + \frac{V_{\text{rec}}}{c} \cos \theta \right)$$

$$I(f) = N_0 (1 - e^{-(x/V_{\text{rec}}\tau)})$$

Decay Curve



Interaction of the γ -rays with matter

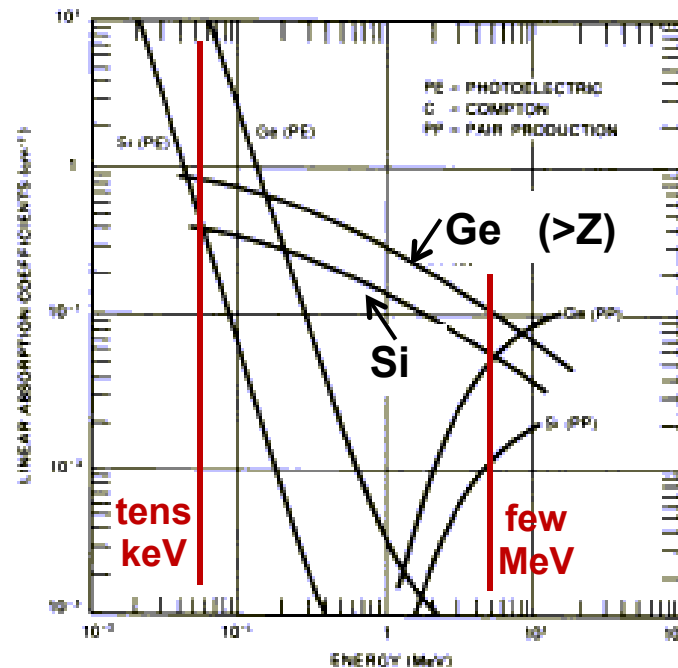
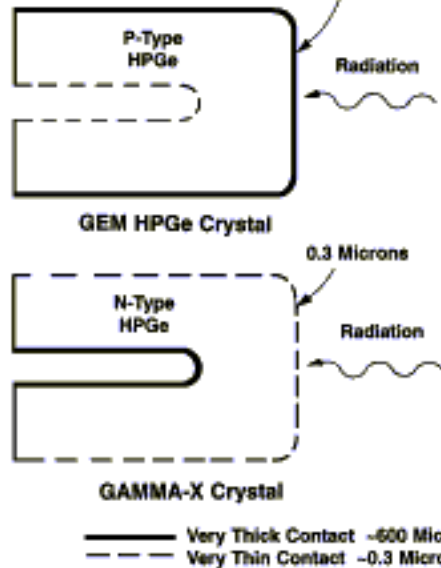


Instrumentation for HR γ -ray spectroscopy

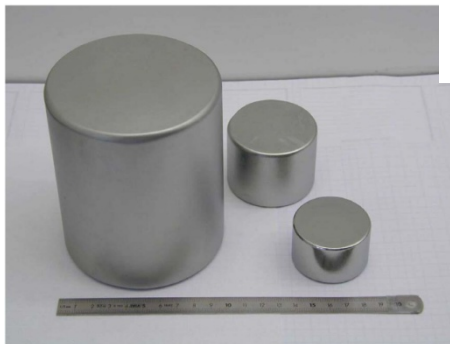
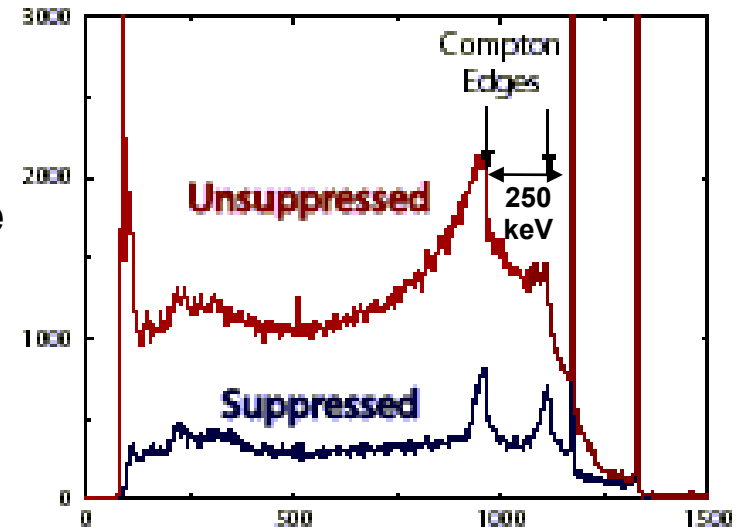
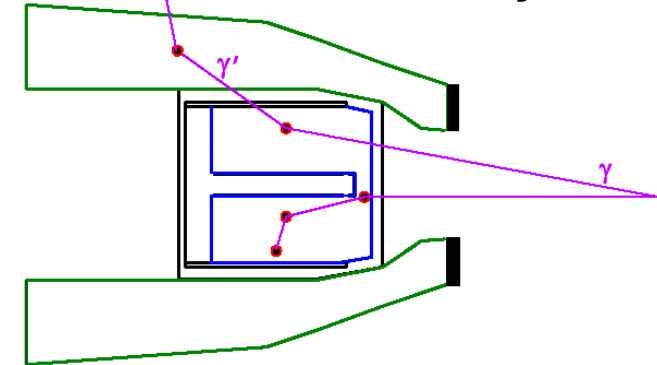
High resolution γ -ray spectroscopy $\rightarrow$ large volume semiconductor detectors
in particular detectors based on HP-Ge (impurities $\sim 10^{-12}$)

Present Ge

>2 kg/crystal ~600 Microns



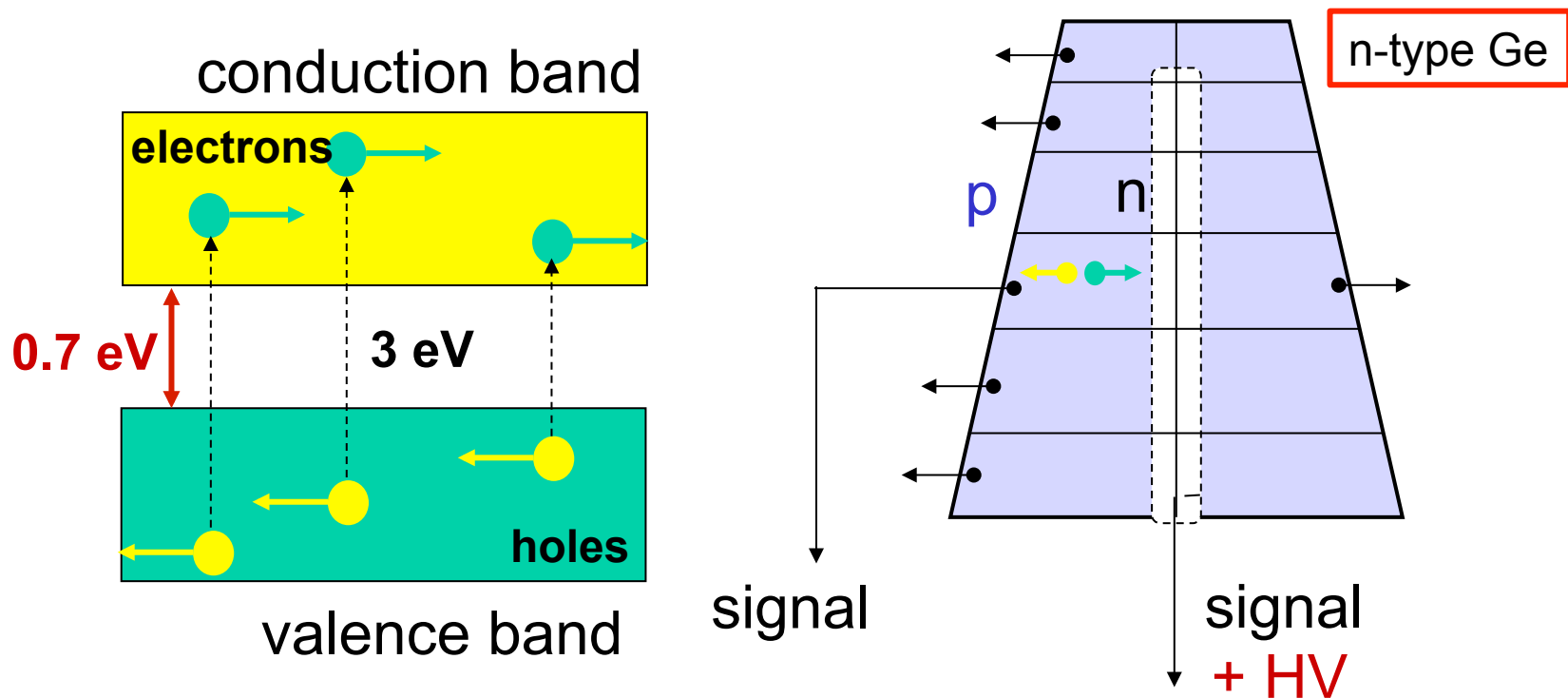
Compton suppressed Ge-detectors $\rightarrow$ arrays



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)**

$$\sqrt{N}/N = 0.0018 \rightarrow 1.8 \text{ keV } (E_\gamma = 1 \text{ MeV})$$

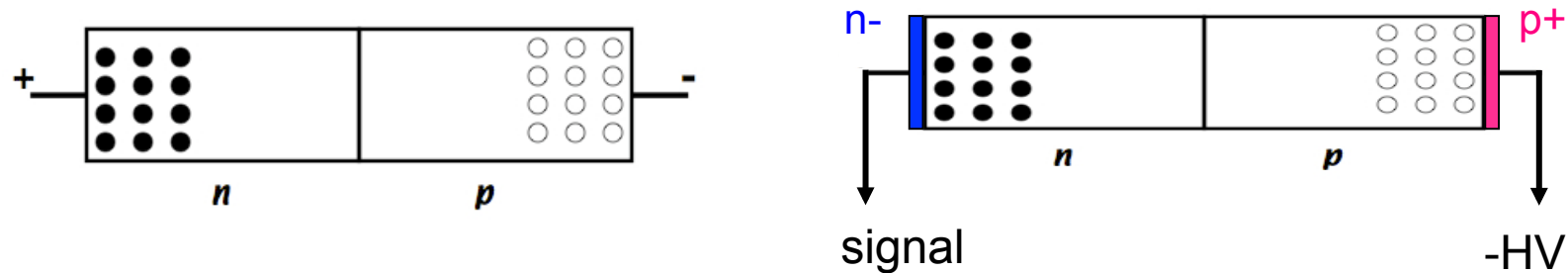
Thermally activated charge carriers in the conduction band density at room temperature $\sim 2.5 \cdot 10^{13} \text{ cm}^{-3}$ for Ge ($\sim 1.5 \cdot 10^{10} \text{ cm}^{-3}$ for Si)

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



$$\text{FWHM}^2 = W_D^2 + W_X^2 + W_E^2 + W_{\text{Doppler}}^2$$

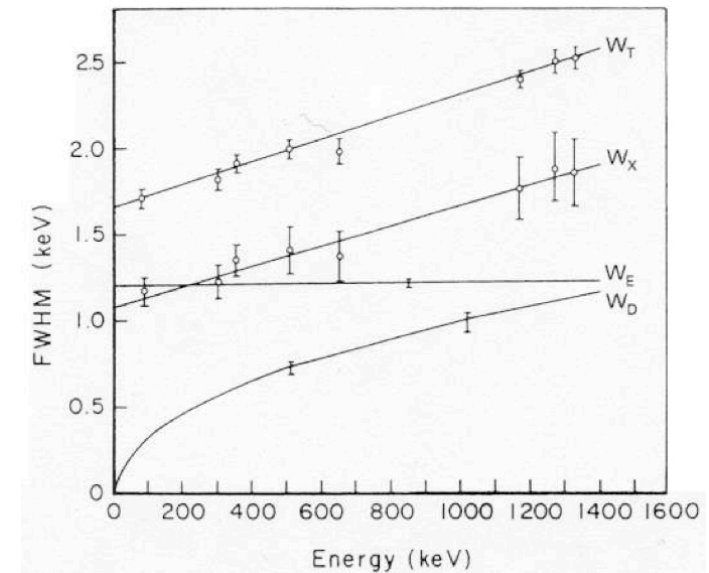
$$W_D = 2.35 \sqrt{F \epsilon E_\gamma} \text{ Statistical fluctuations of carriers}$$

$\epsilon = 2.96 \text{ eV @ } 77 \text{ K}$ Fano factor $F \sim 0.1$
(not all the deposited energy goes to create e-h pairs)

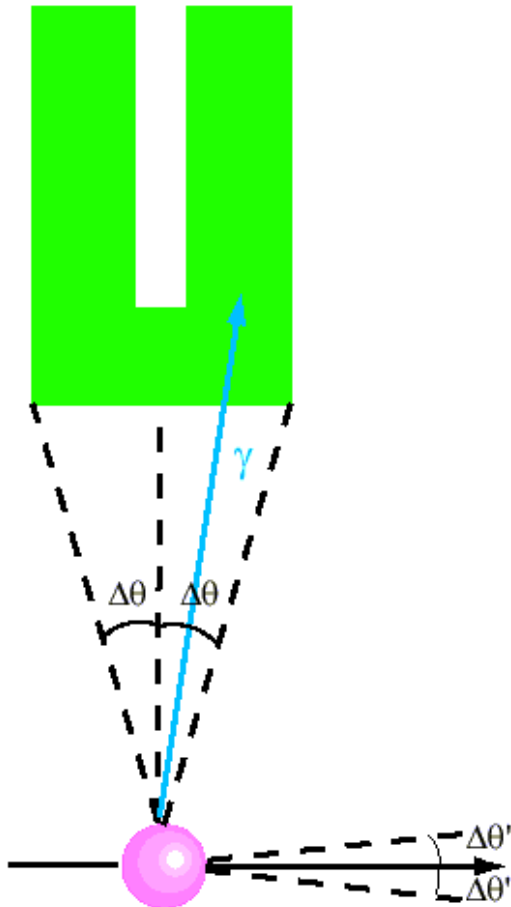
W_X incomplete charge collection

W_E electronic noise

W_{doppler} Doppler broadening

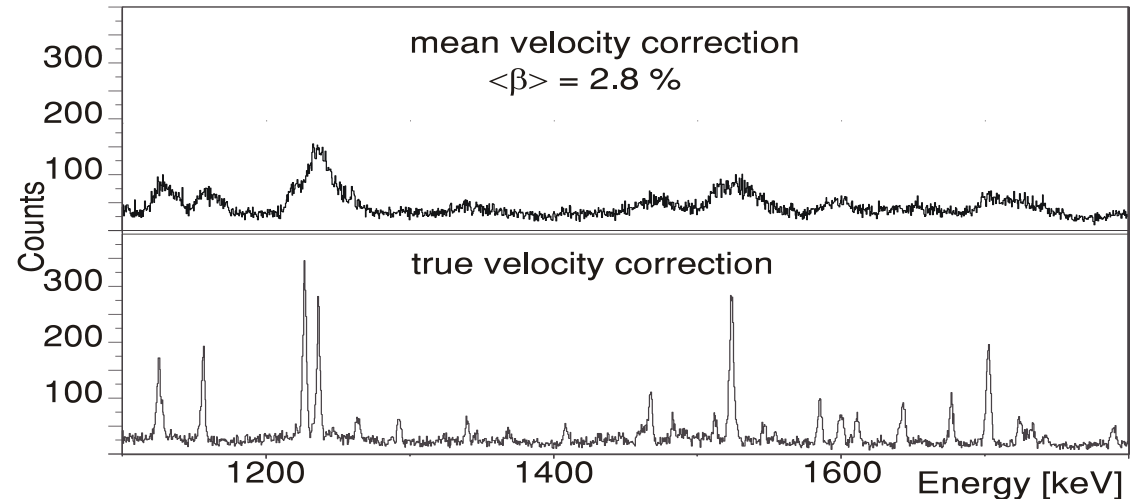


Doppler Broadening

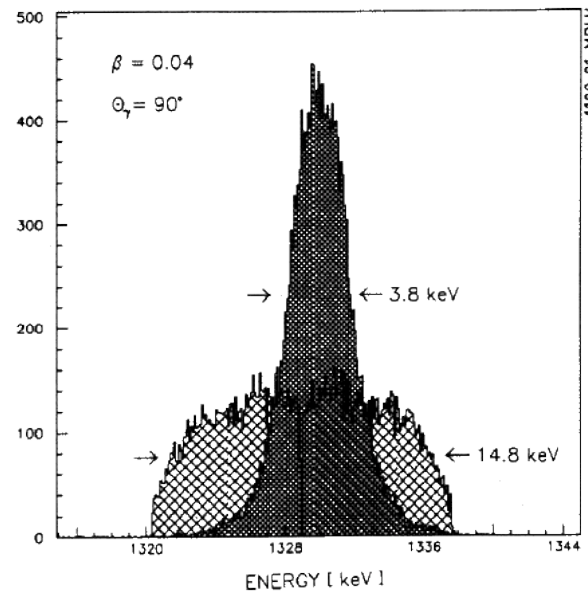


$$E_s = E_0 \left(1 + v/c \cos \theta \right)$$

$$\Delta E_s = E_0 v/c \sin \theta \Delta \theta$$



Dedicated ancillary detectors for the determination of the recoil trajectory

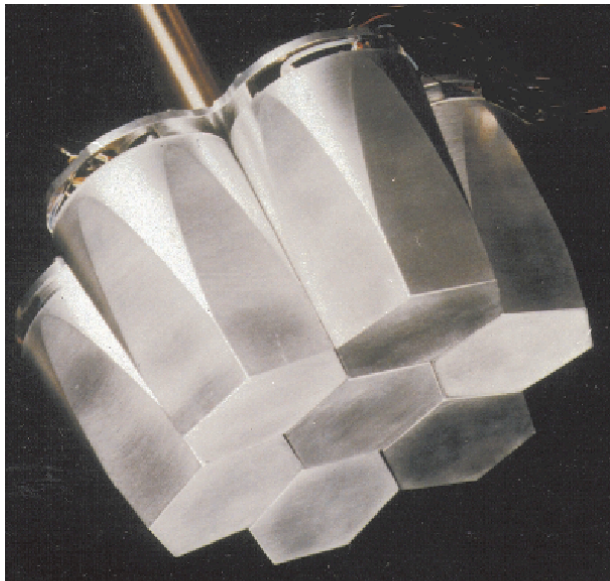
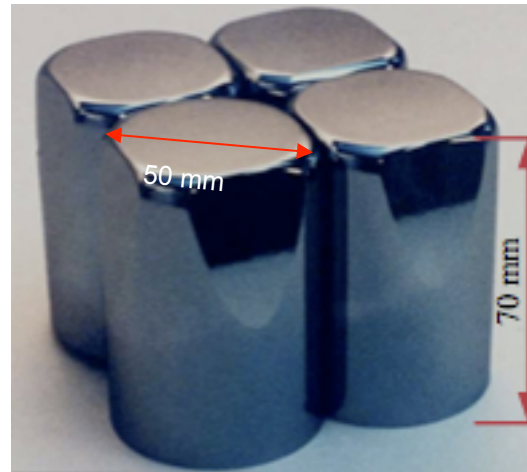


Development of segmented Ge detectors and Pulse Shape Analysis techniques for position determination

Composite detectors

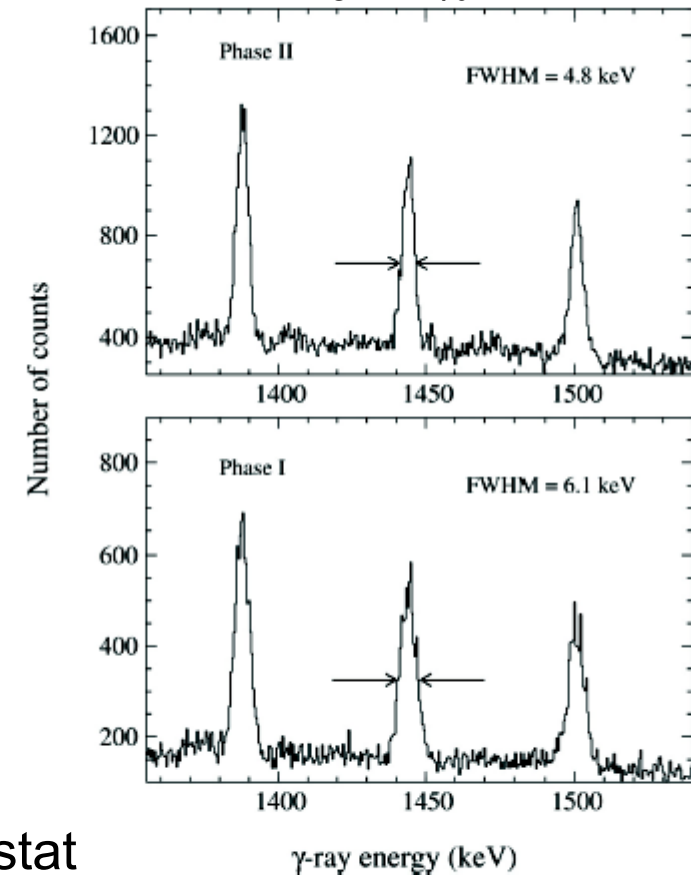
=> Reduction of $\Delta\theta_D$

- Eurogam II
- Clovers:
 - 4 crystals in 1 cryostat



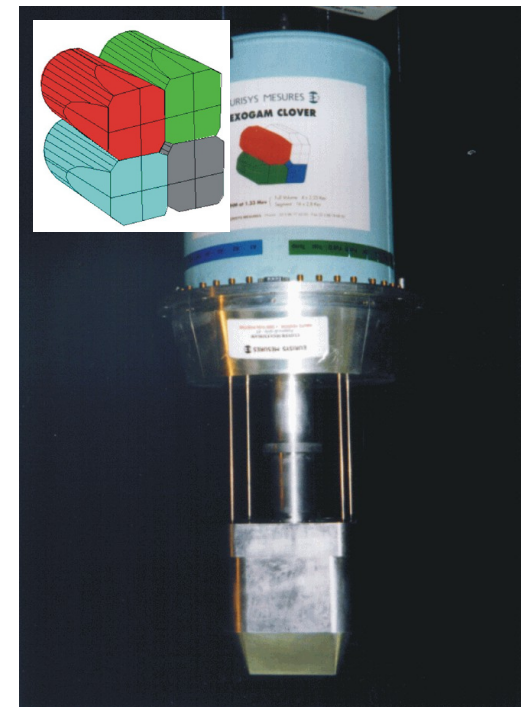
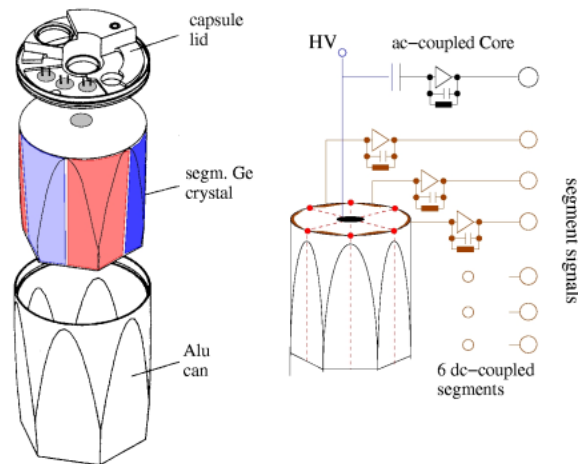
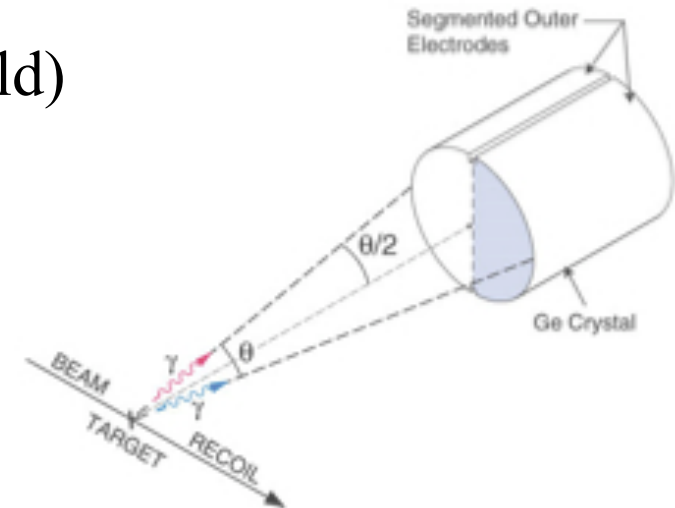
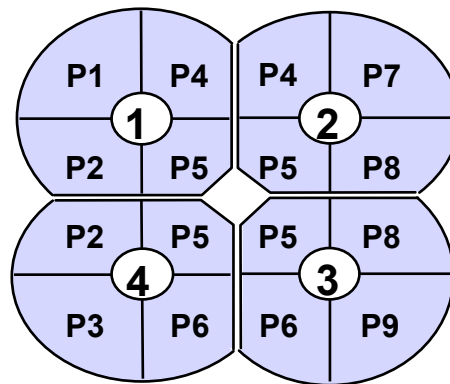
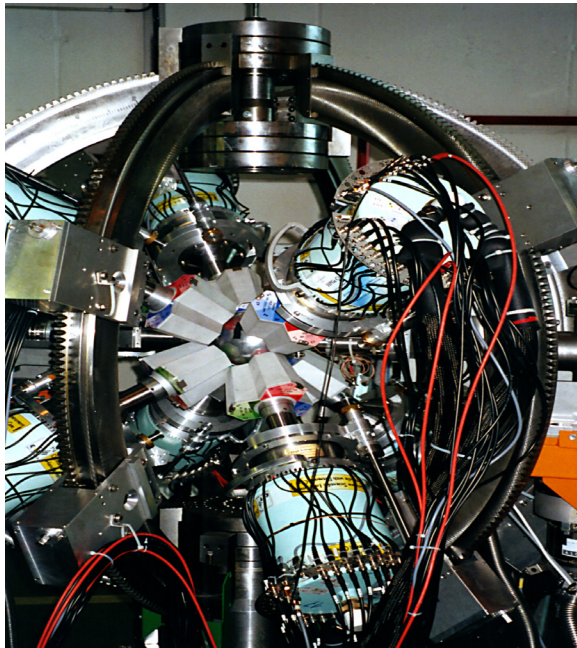
- Euroball
- Clusters:
 - 7 crystals in 1 cryostat

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

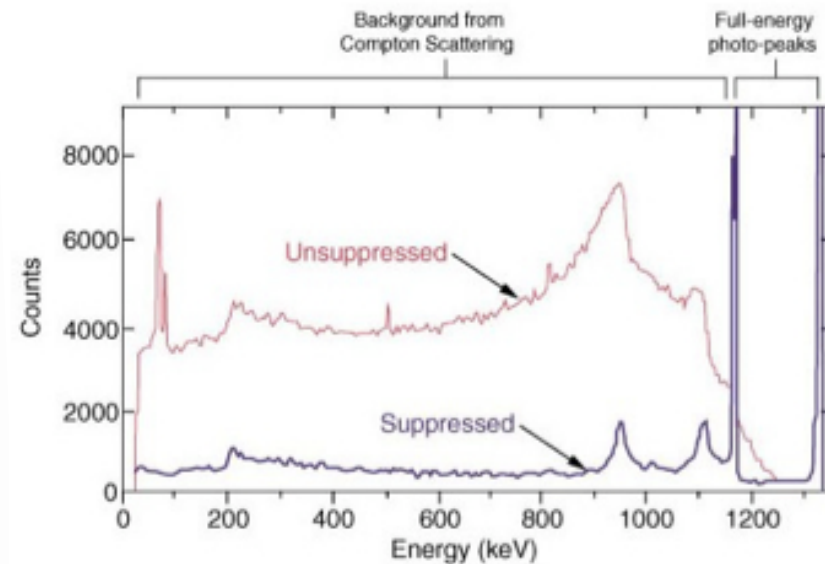
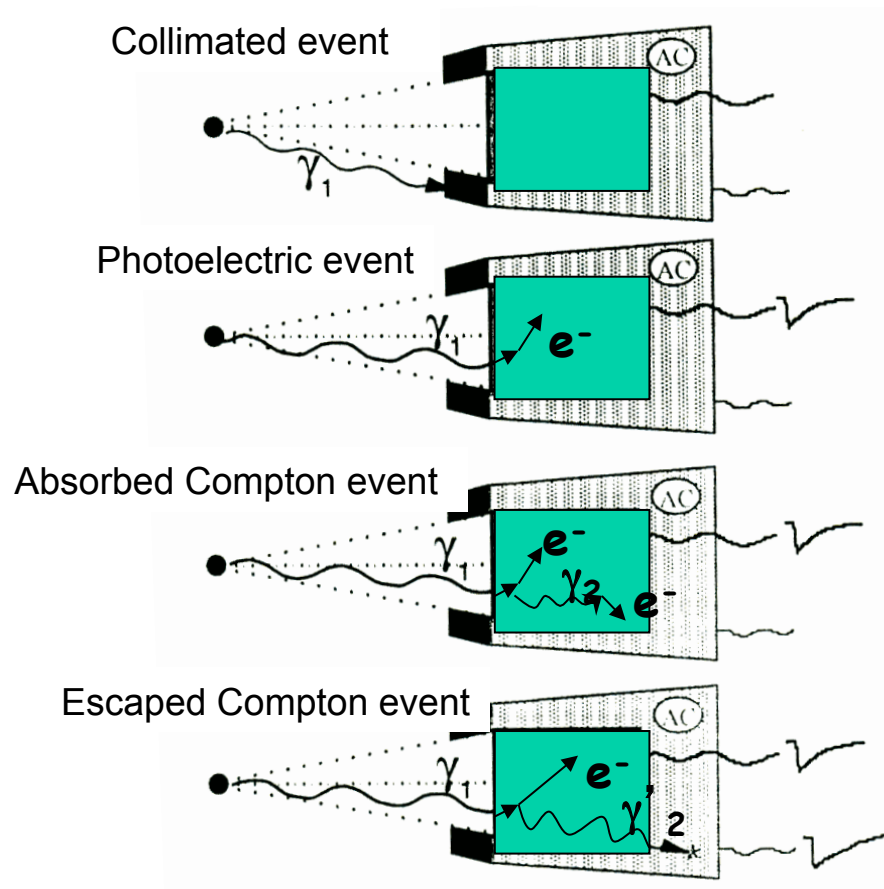


Electrical Segmentation of detectors

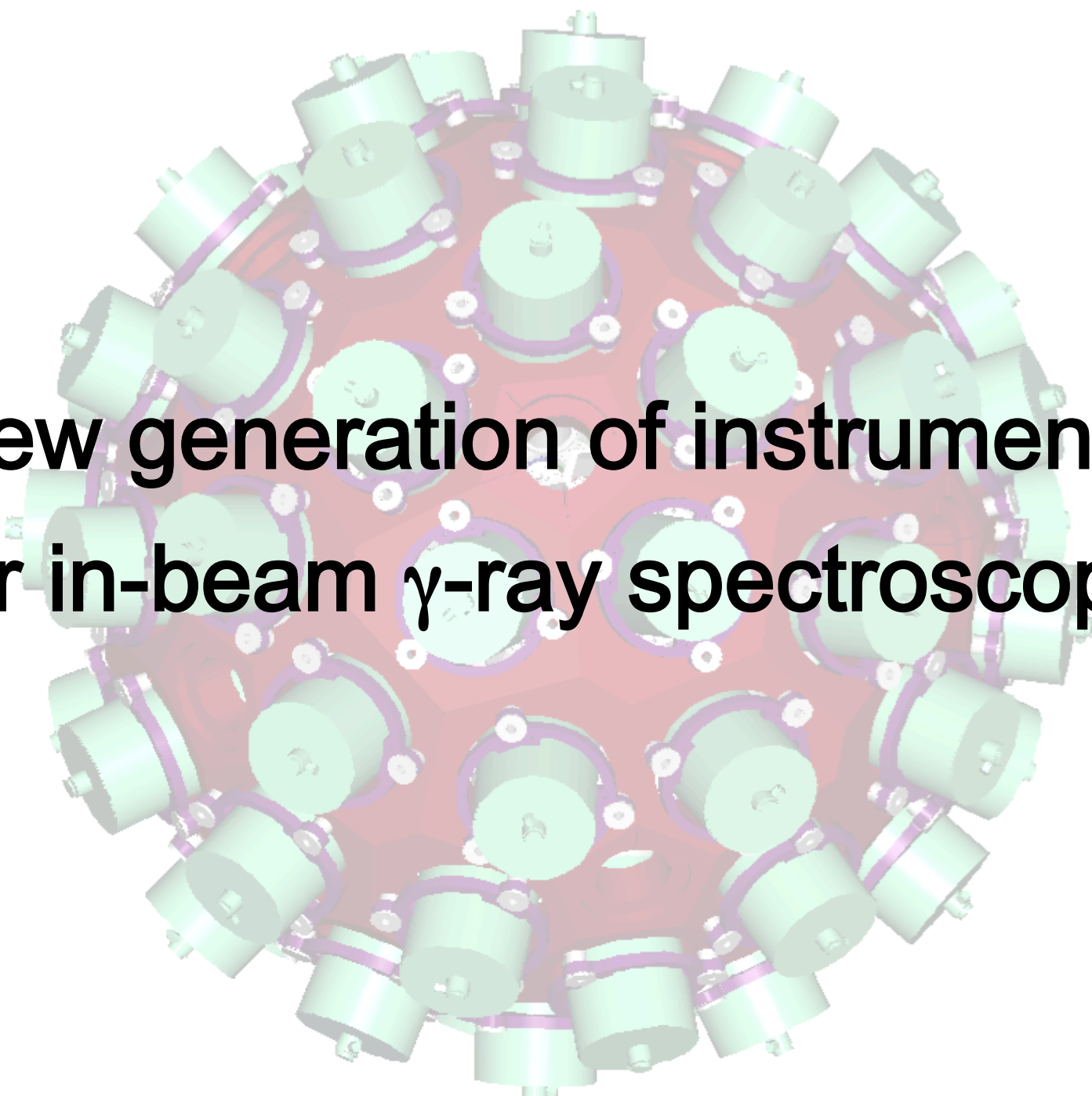
- Gammasphere segmented detector (2 Fold)
- Exogam at Ganil (Segmented Clover)
- Miniball at Isolde (Segmented



Signal-to-noise ratio and Compton suppression



$$P/T \sim 0.2-0.3 \Rightarrow 0.5-0.6$$

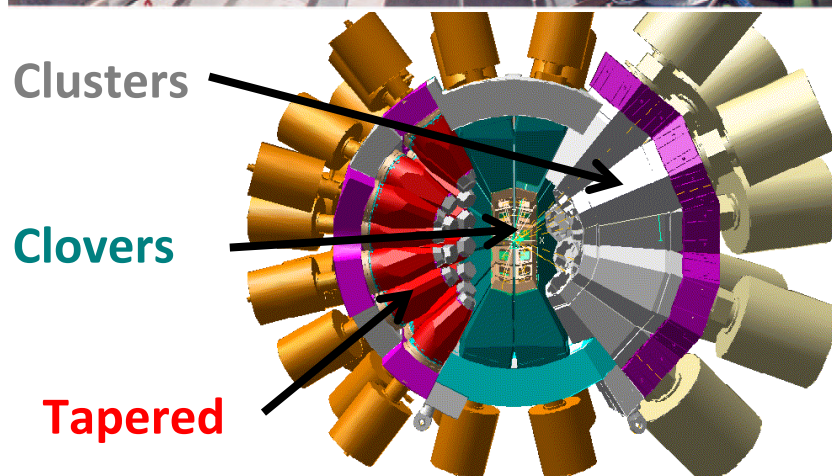
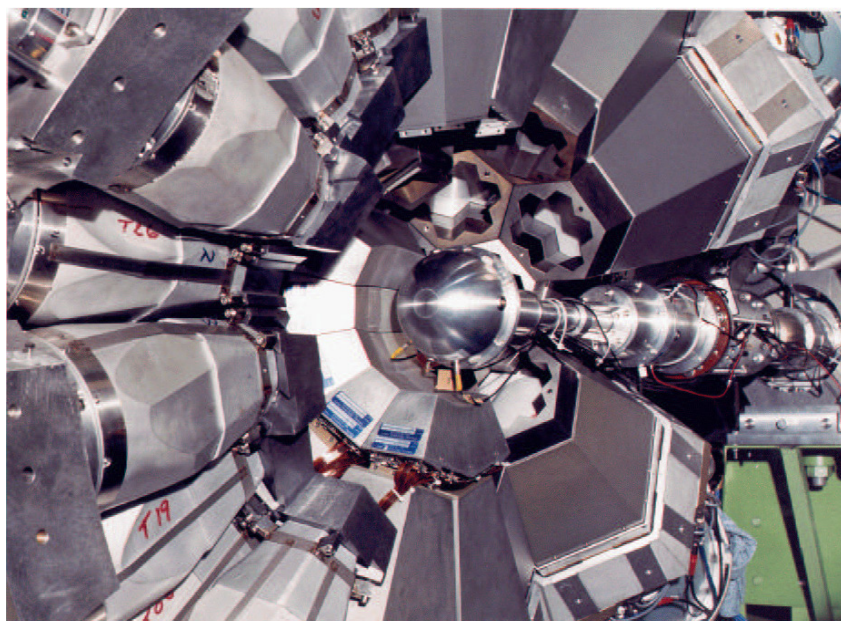
A 3D CAD model of a spherical detector array. The array consists of numerous cylindrical detector modules, colored light blue, arranged in a spherical geometry. These modules are interconnected by a network of purple rings and smaller components, forming a complex, symmetrical structure. The entire assembly is centered around a common point, with the modules pointing outwards in various directions.

**New generation of instruments
for in-beam γ -ray spectroscopy**



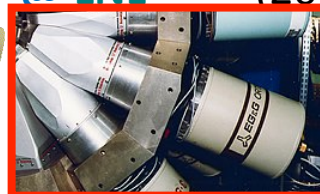
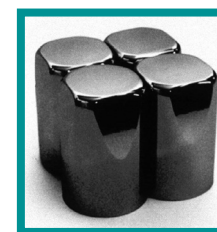
EUROBALL: First Large Ge-Array build by a broad European collaboration

- EUROBALL collaboration started in early 90's. First campaigns at LNL in 1996-1998 and IReS 1999-2003.
- More than 150 publications in refereed journals. More than 60 from the sub-array campaigns
- Technological developments on composite and latter on encapsulated detectors



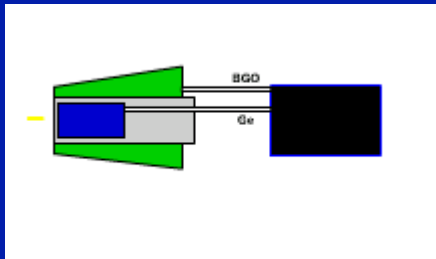
Cluster Composite Detectors 105 Ge
(~60%) 15 Cluster → **RISING Campaigns**
@FRS-GSI

Clover Composite Detectors: 104 Ge
(~20%) (26 Clover) → **CLARA Campaign**
@ LNL (2008 → JUROGAM II)



Tapered Detectors: ~30 Ge (70%)
→ **JUROGAM I Campaign @JYFL**
(2008 → ORGAM)

Large γ -Arrays based on Compton Suppressed Spectrometers



$\epsilon \sim 10 - 5 \%$
($M_\gamma=1 - M_\gamma=30$)

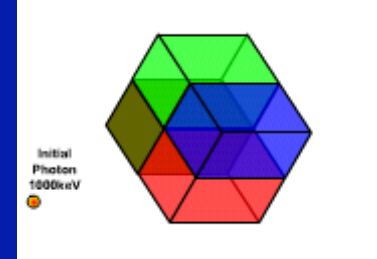


Compact γ -Arrays optimized
Doppler correction, low M_γ

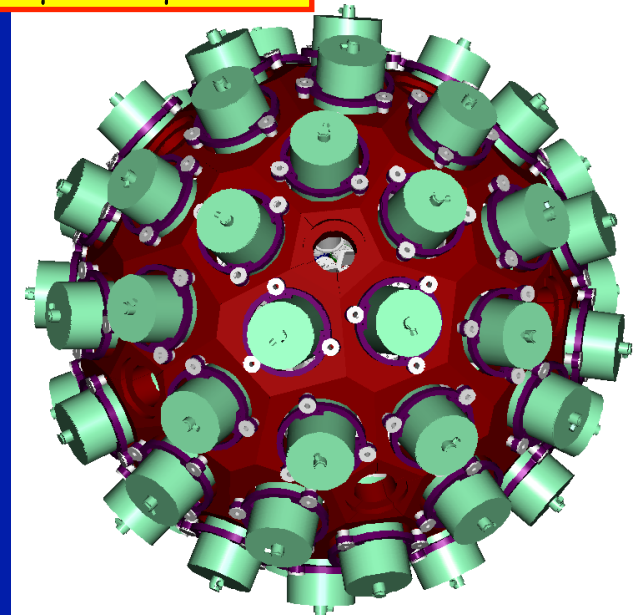
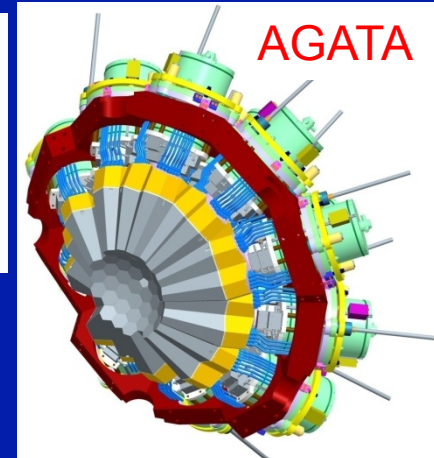


$\epsilon \sim 20 \%$ $M_\gamma=1$

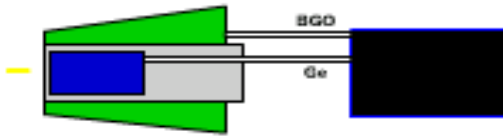
Tracking Arrays based on Position Sensitive Ge Detectors



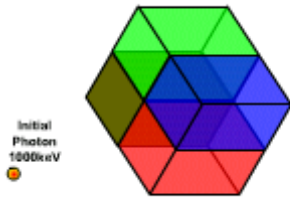
$\epsilon \sim 40 - 20 \%$
($M_\gamma=1 - M_\gamma=30$)



Advantages of γ -ray tracking



Compton Suppression



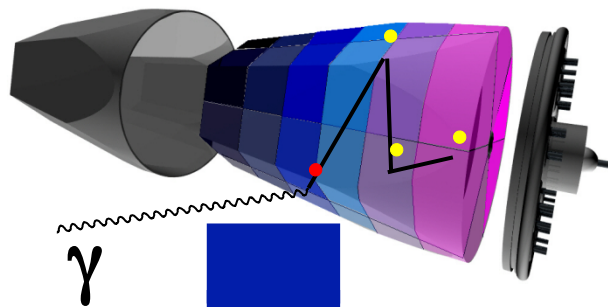
Gamma Tracking

- Efficiency – Proper reconstruction of scattered gamma rays, no solid angle used for Anti-Compton shield
- Peak-to-background – Reject Partially absorbed events
- Doppler correction - Position of first interaction determined
- Polarization – Angular distribution of the scattering sequence
- Counting rate – high segmentation and digital pile-up treatment

Concept of γ -Tracking



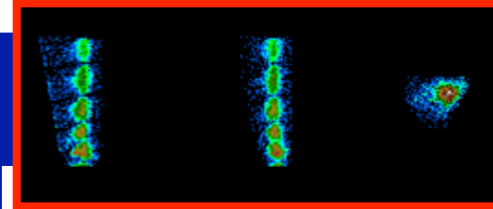
Highly segmented
HPGe detectors
NOVEL PRE-AMPS



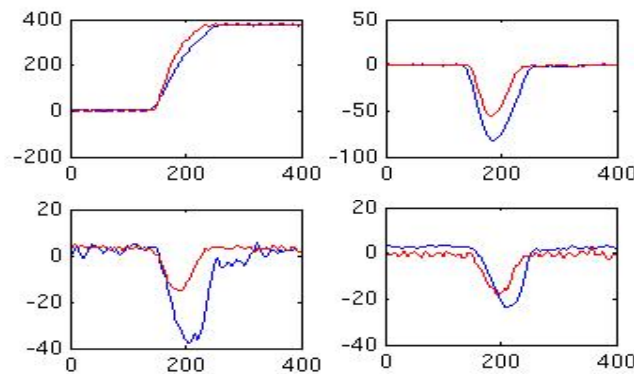
Synchronized digital
electronics
record and process
the segment signals
DIGITIZERS +
PRE-PROCESSING

Identified
interaction points

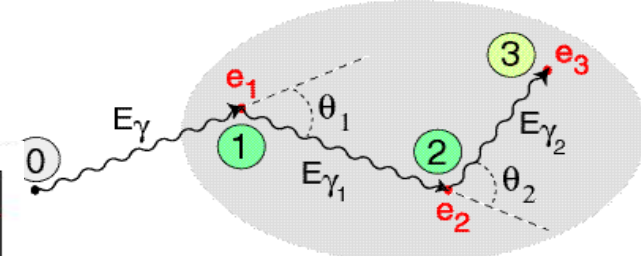
$(x,y,z,E,t)_i$



Pulse Shape Analysis
to de-convolute the
recorded waves
DAQ PSA - FARM



Reconstruction of
interaction tracks
(tracking algorithms
on interaction points)
DAQ TRACKING-FARM

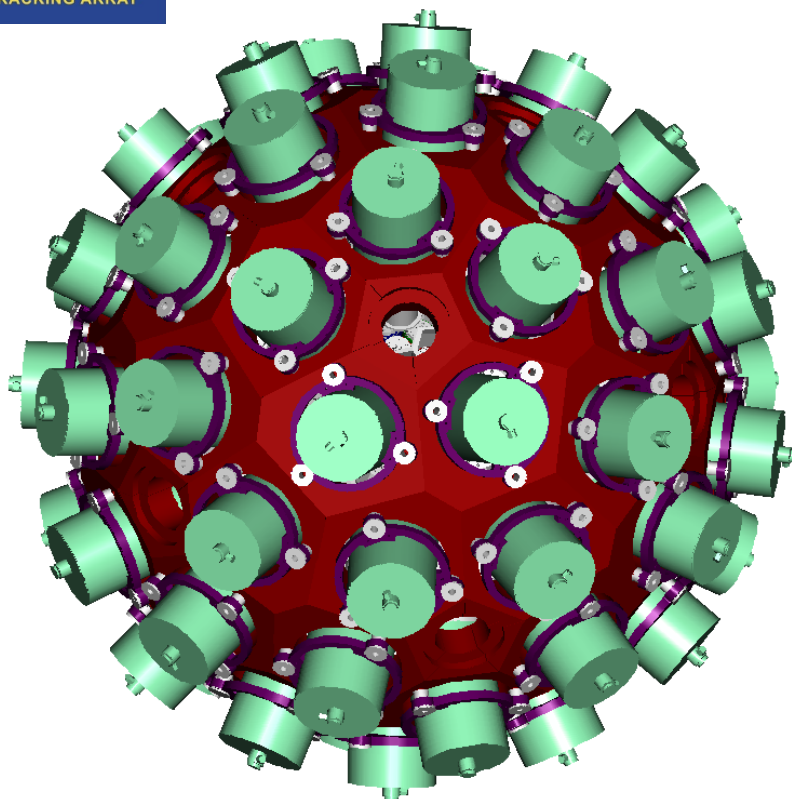


On-line reconstruction
of γ -rays



AGATA

(Advanced **G**amma **T**racking **A**rray)



180 hexagonal crystals	3 shapes
60 triple-clusters	all equal
Inner radius (Ge)	23.5 cm
Amount of germanium	362 kg
Solid angle coverage	82 %
36-fold segmentation	6480 segments
Singles rate	~50 kHz
Efficiency:	43% ($M_\gamma=1$) 28% ($M_\gamma=30$)
Peak/Total:	58% ($M_\gamma=1$) 49% ($M_\gamma=30$)

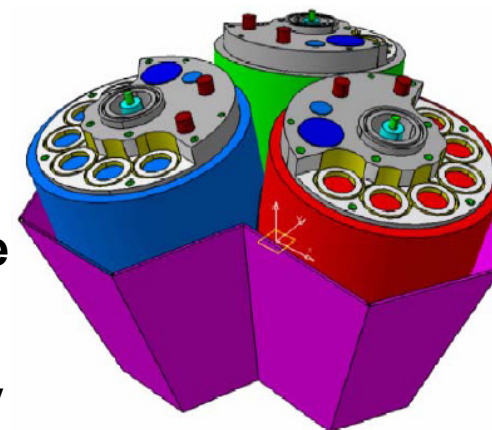
6660 high-resolution digital electronics channels

High throughput DAQ

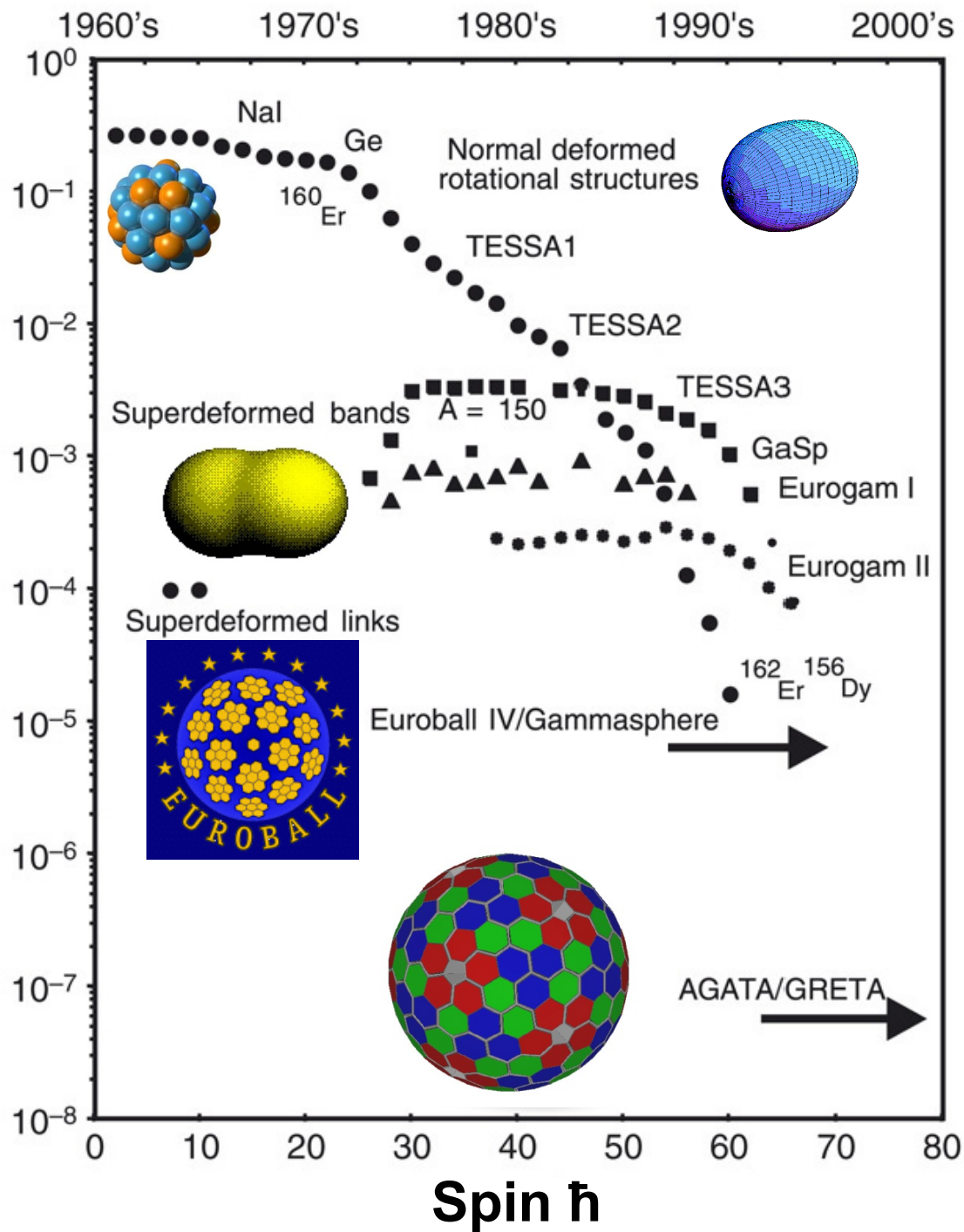
Pulse Shape Analysis → position sensitive operation mode

γ -ray tracking algorithms to achieve maximum efficiency

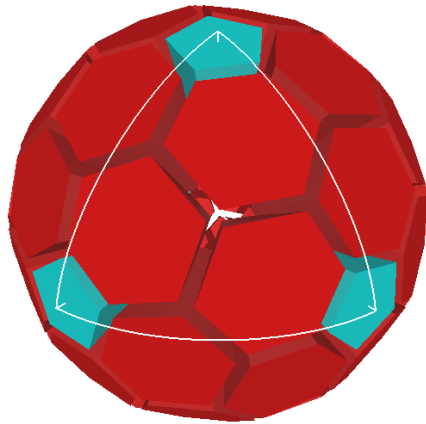
Coupling to complementary detectors for added selectivity



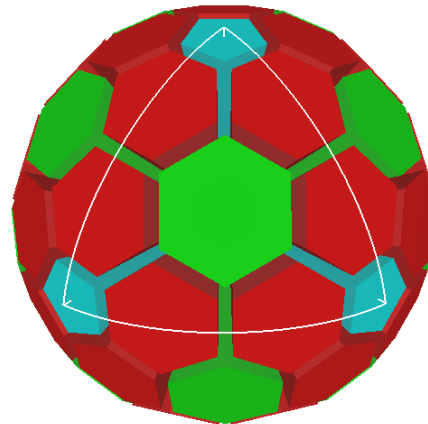
Sensitivity as fraction of reaction channel



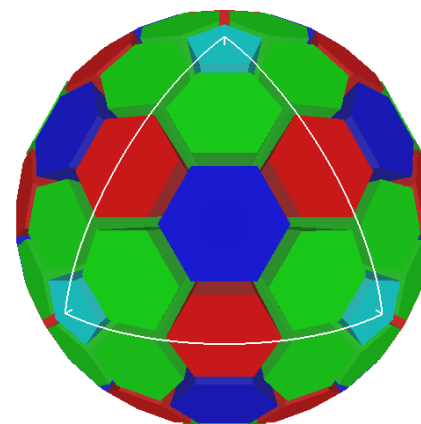
Geodesic Tiling of Sphere using 60–240 hexagons and 12 pentagons



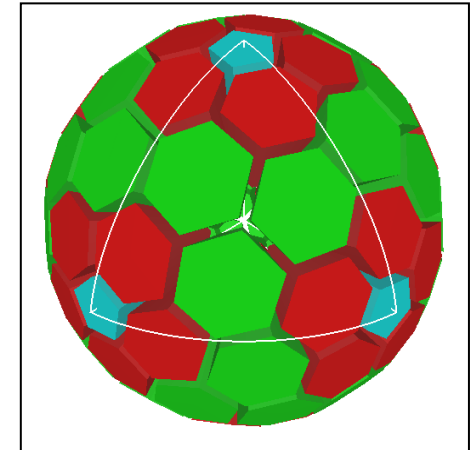
60



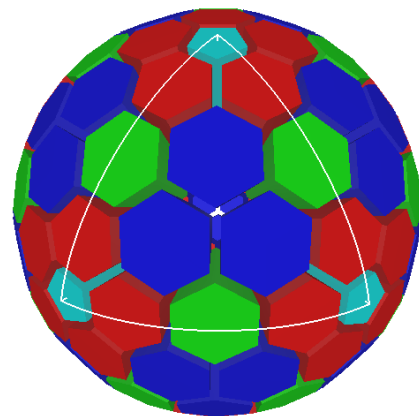
80



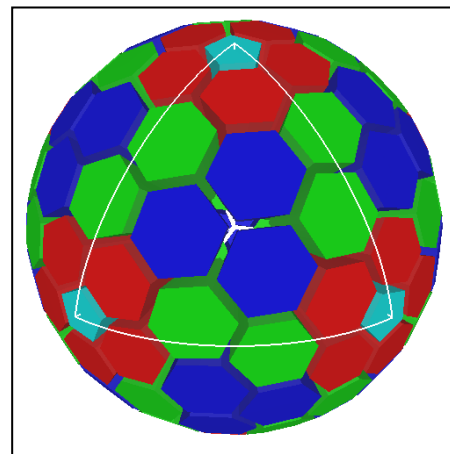
110



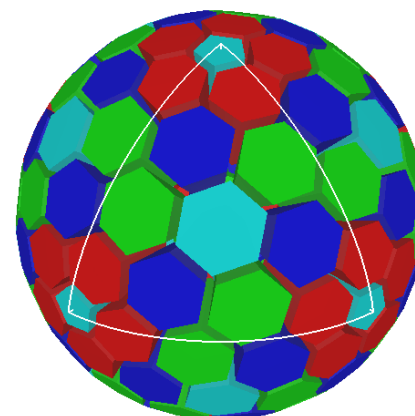
120



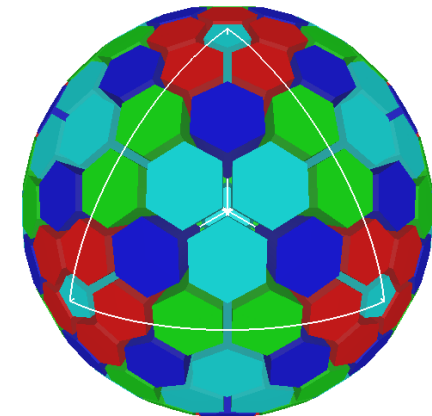
150



180

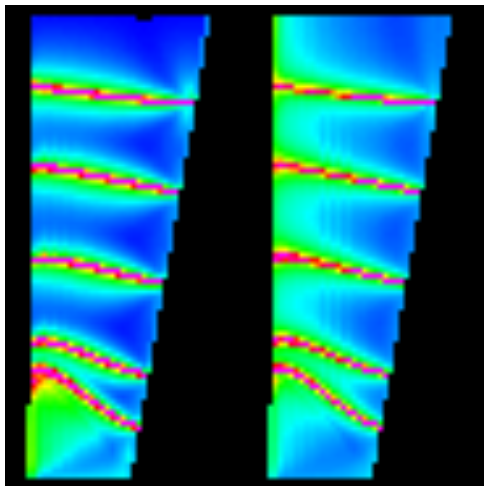
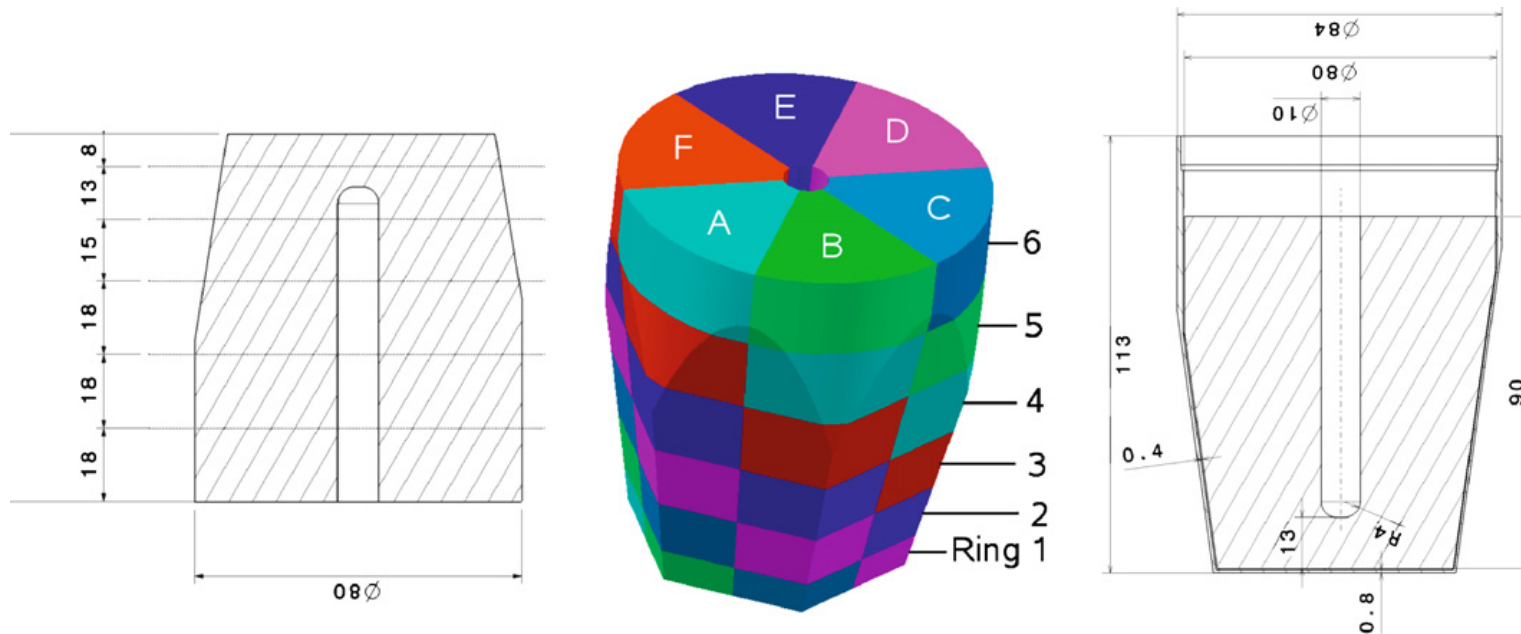


200

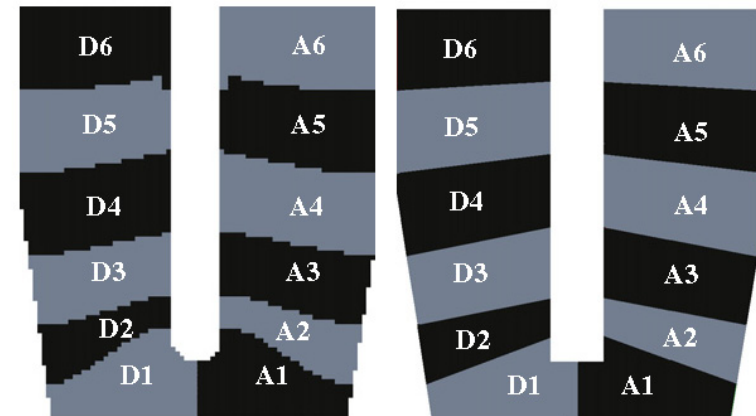


240

Segmentation of the AGATA detector



Pulse Shape Simulations
Th. Kröll, A. Görgen



Implementation in GEANT4

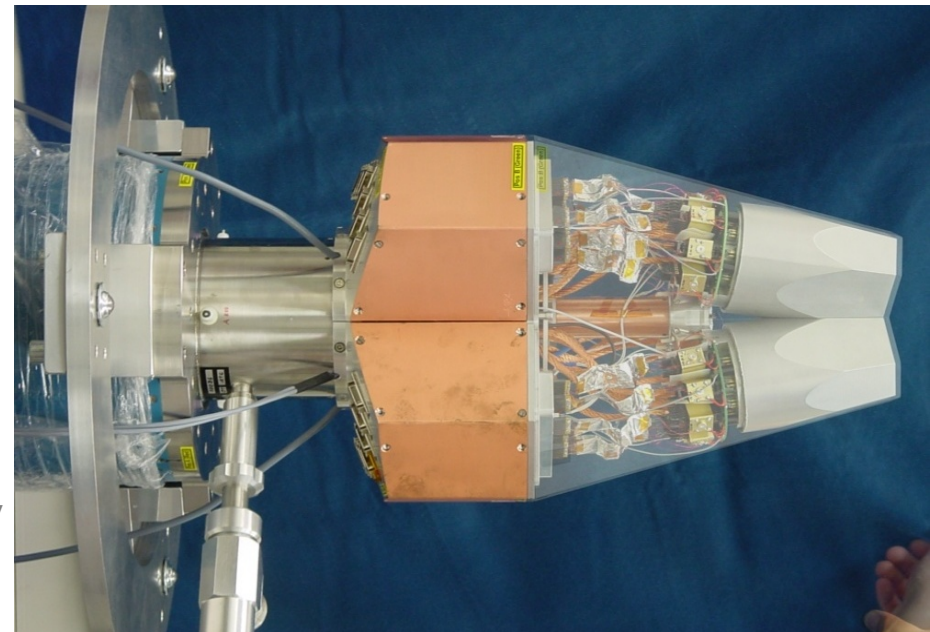
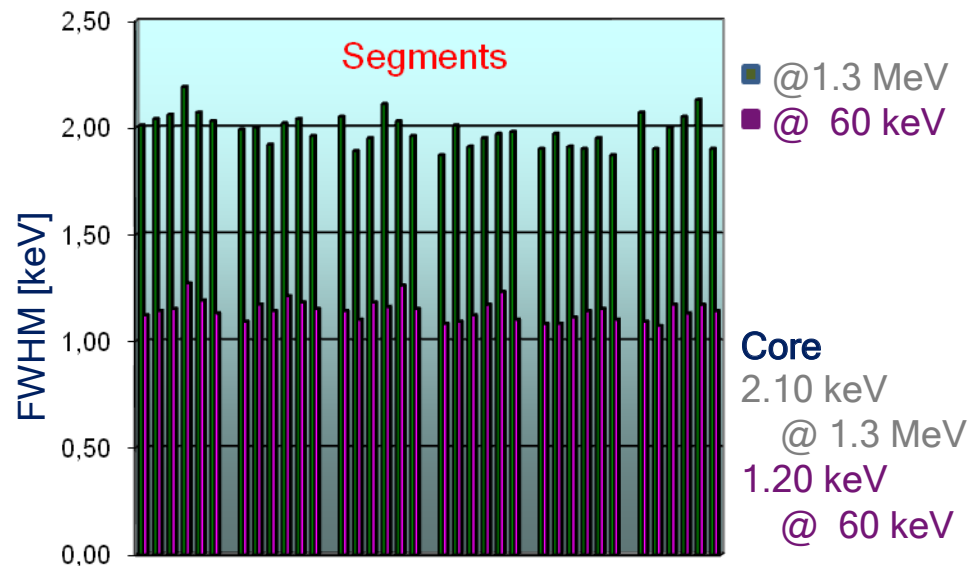
A.Wiens et al. NIMA 618 (2010) 223
E.Farnea et al. NIMA 621 (2010)331

AGATA Triple Cryostat

- integration of 111 high resolution spectroscopy channels
- cold FET technology for all signals

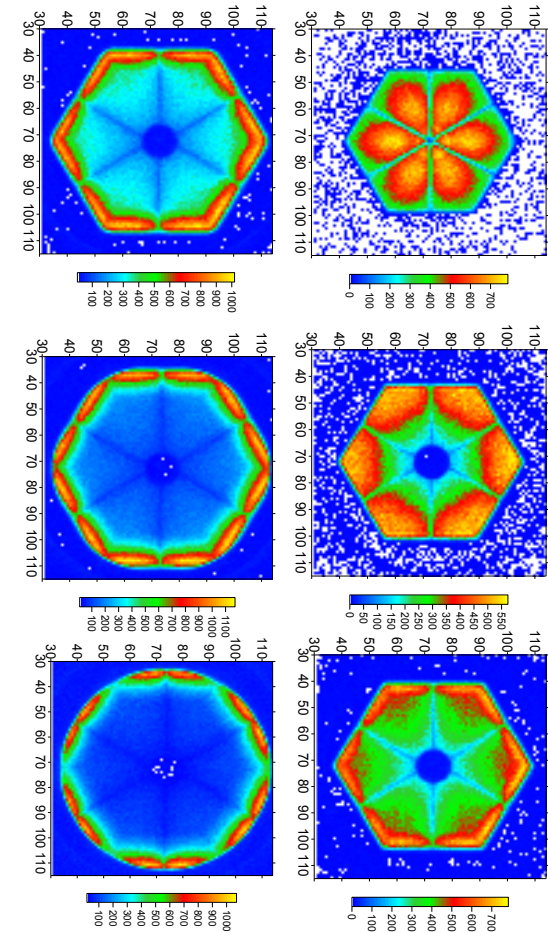
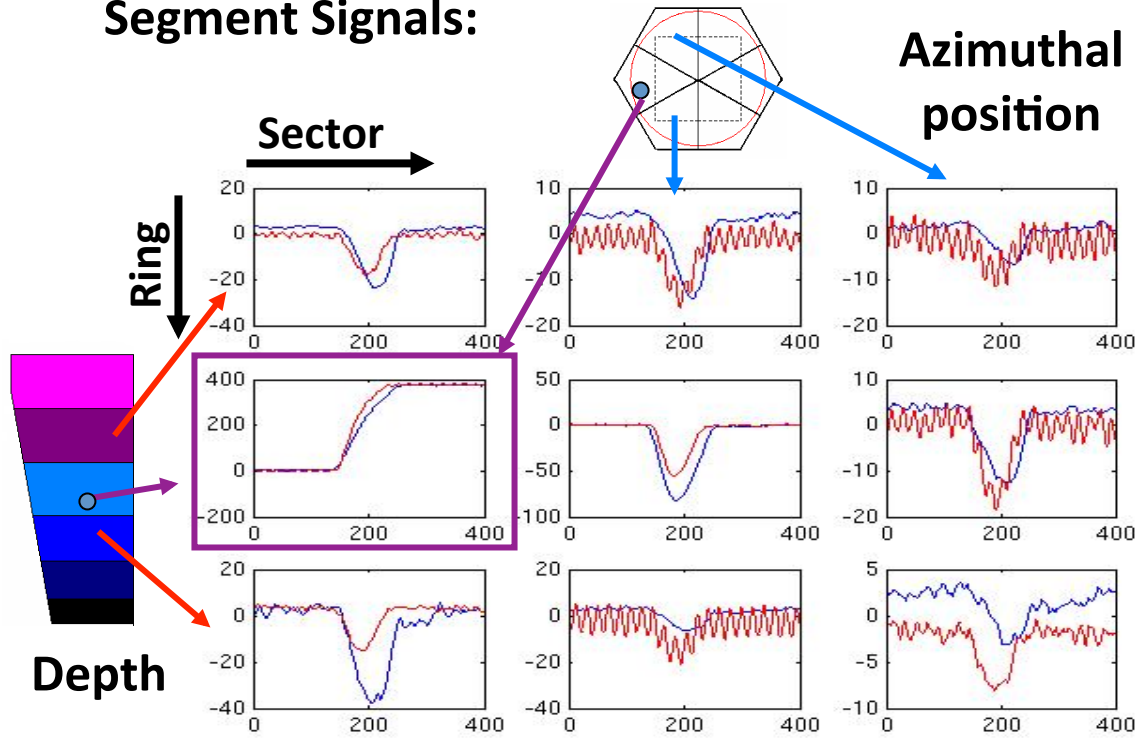
Challenges:

- mechanical precision
- optimal LN2 consumption
- microphonics
- noise, high frequencies

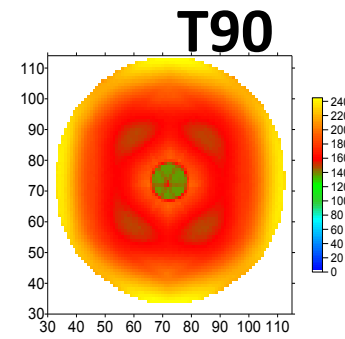
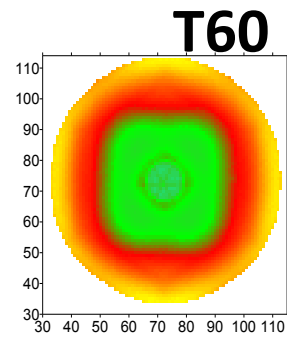
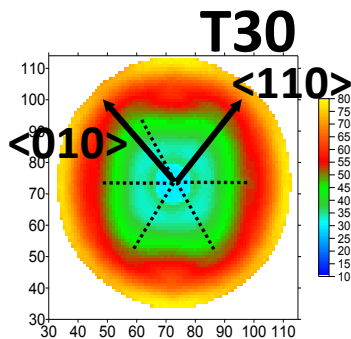
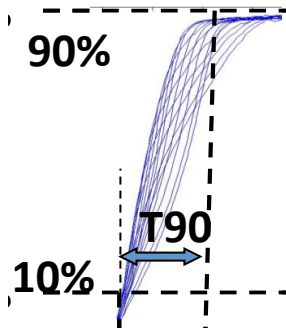


AGATA Detector Characterization

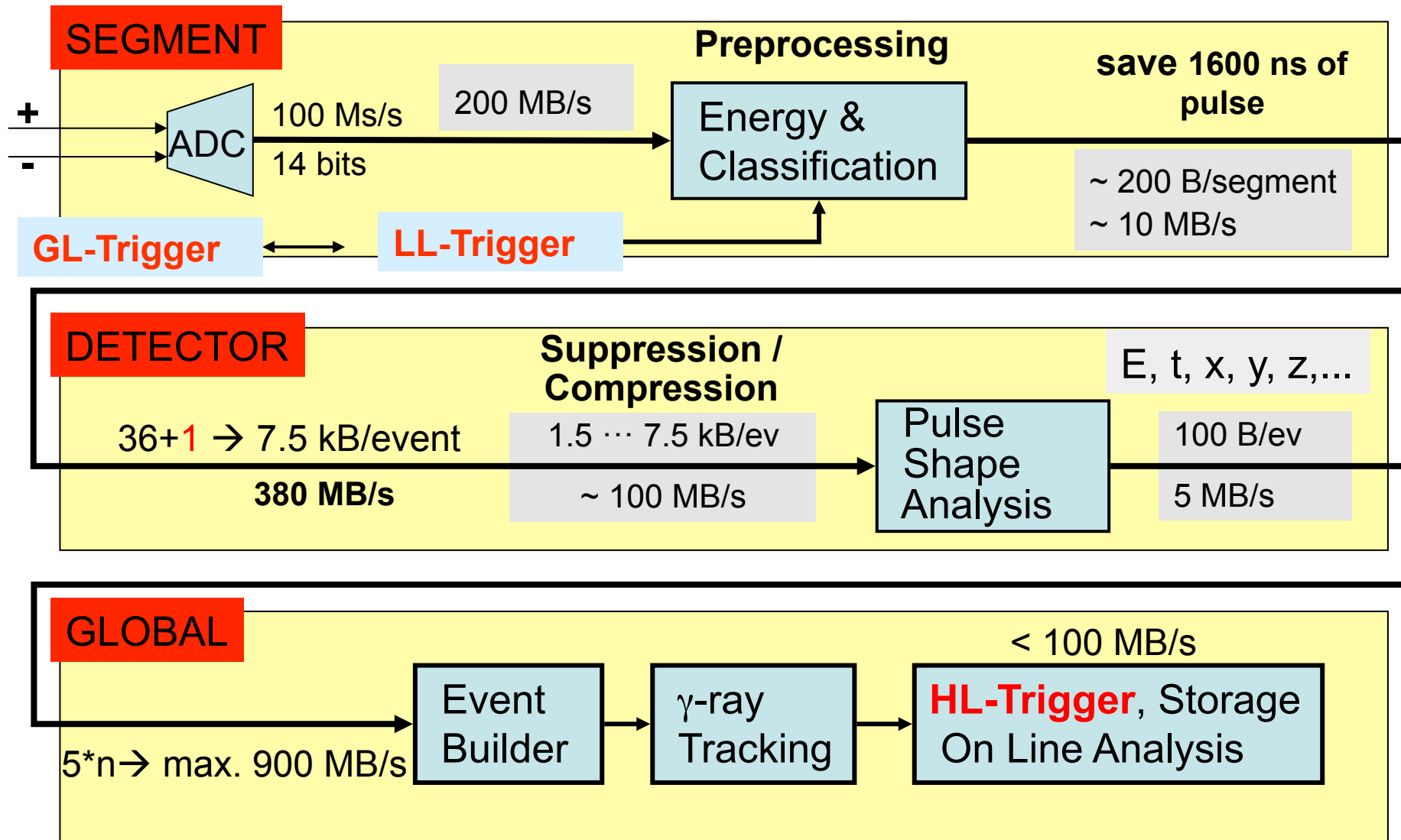
Segment Signals:



Core Signals: Radial position

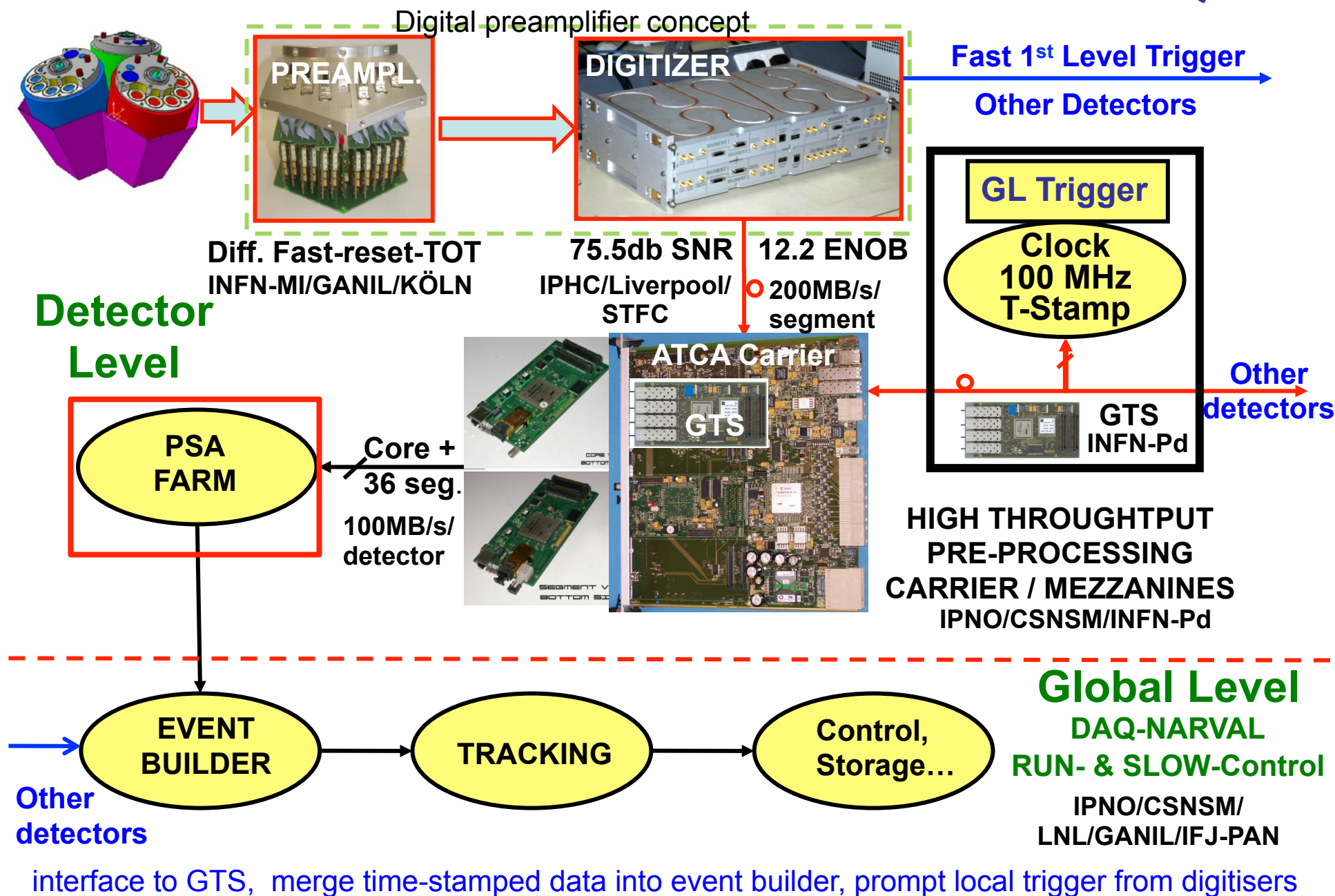


Data Flow in AGATA Rates @ 50 kHz singles

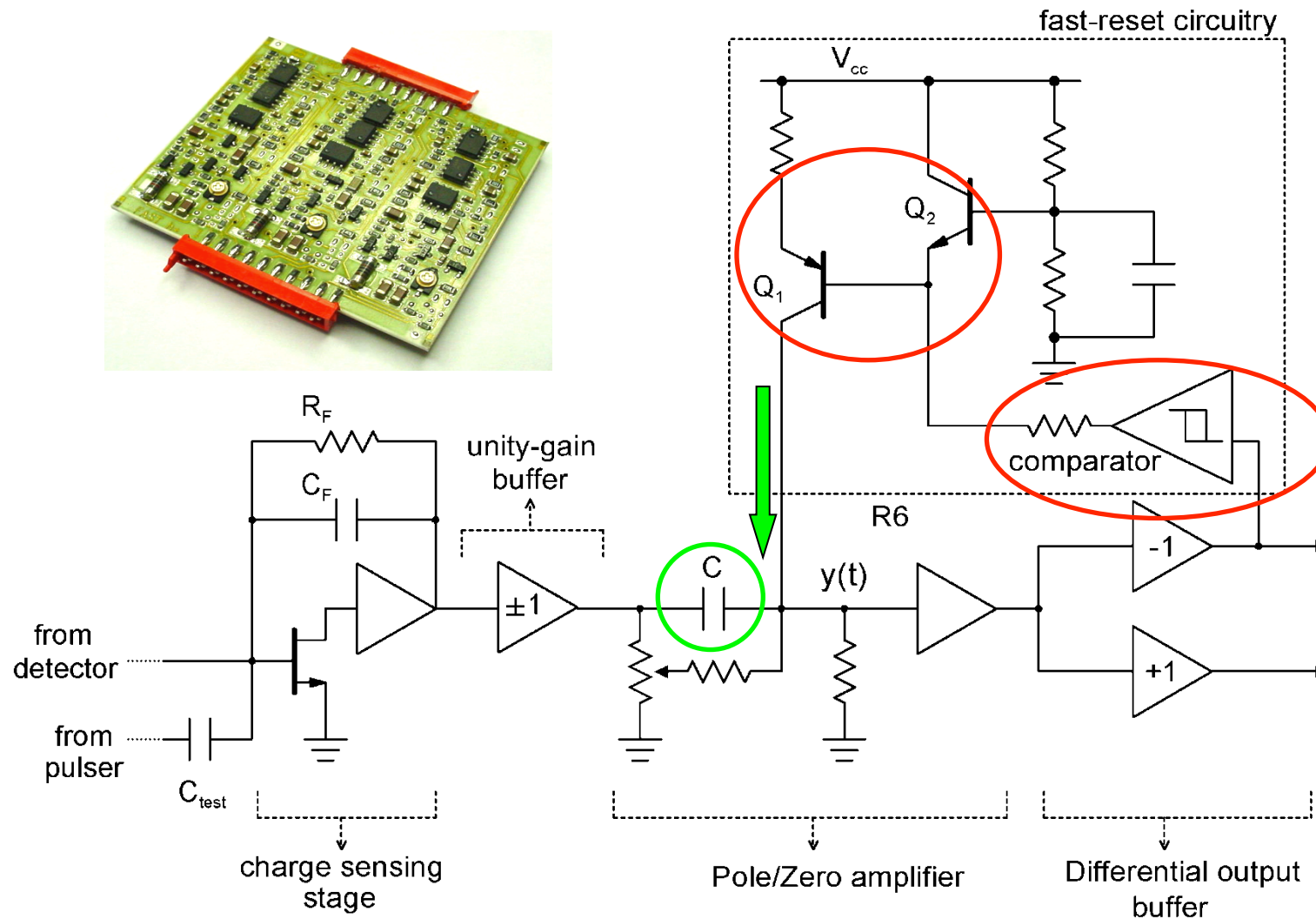


GLobal-Trigger to reduce event rate to what PSA is able to manage

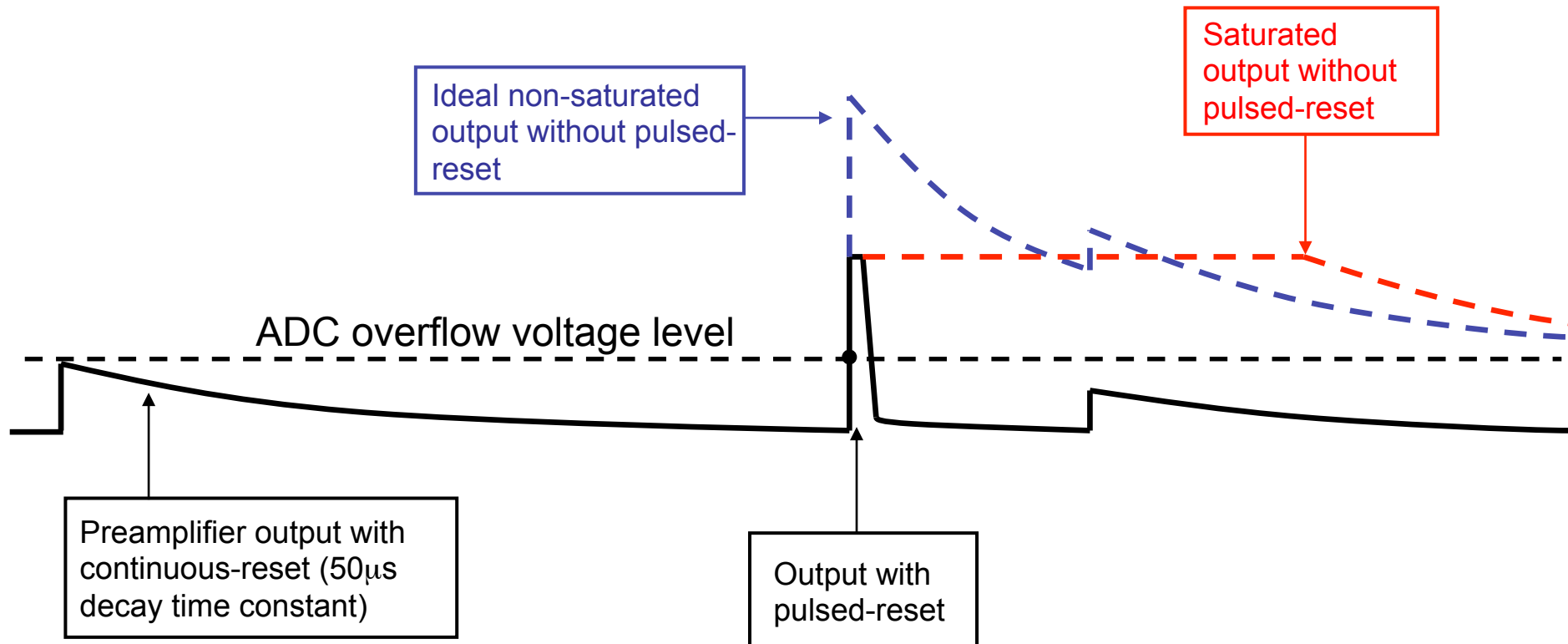
Structure of Electronics and DAQ



AGATA hybrid charge sensitive preamplifiers



Mixed reset technique: continuous + pulsed

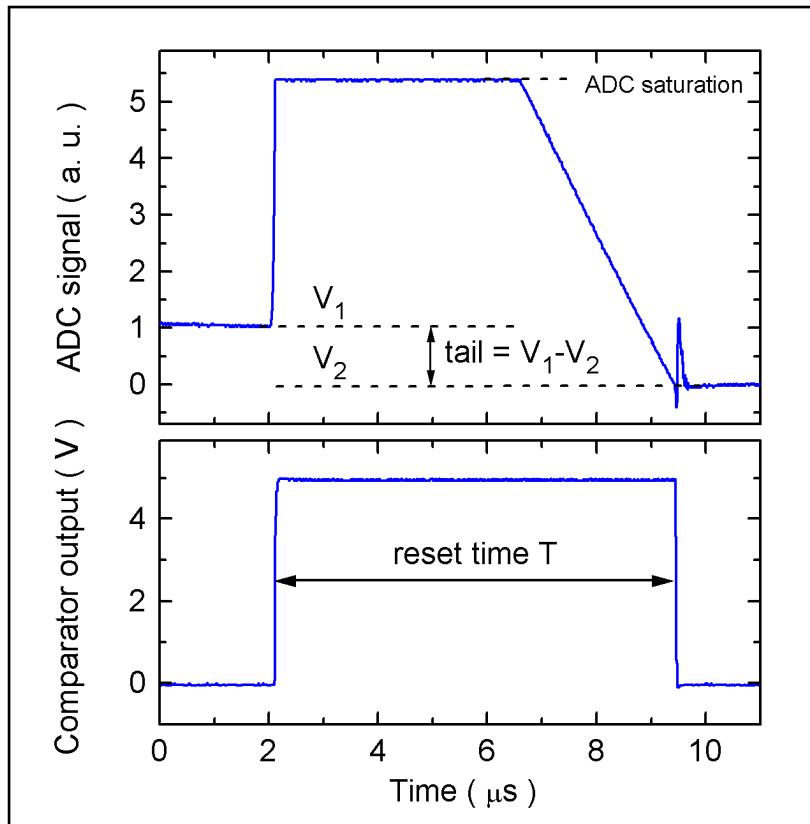


An ADC overflow condition would saturate the system for a long while



A pulsed-reset mechanism allows a **fast recovery of the output quiescent value**, so minimizing the system dead time

Time-Over-Threshold (TOT) technique



second-order time-energy
relation

offset term

$$E = b_1 T + b_2 T^2 - k_1 (V_1 - V_2) + E_0$$

contribution of the tail
due to previous events

E = energy of the large signal

T = reset time

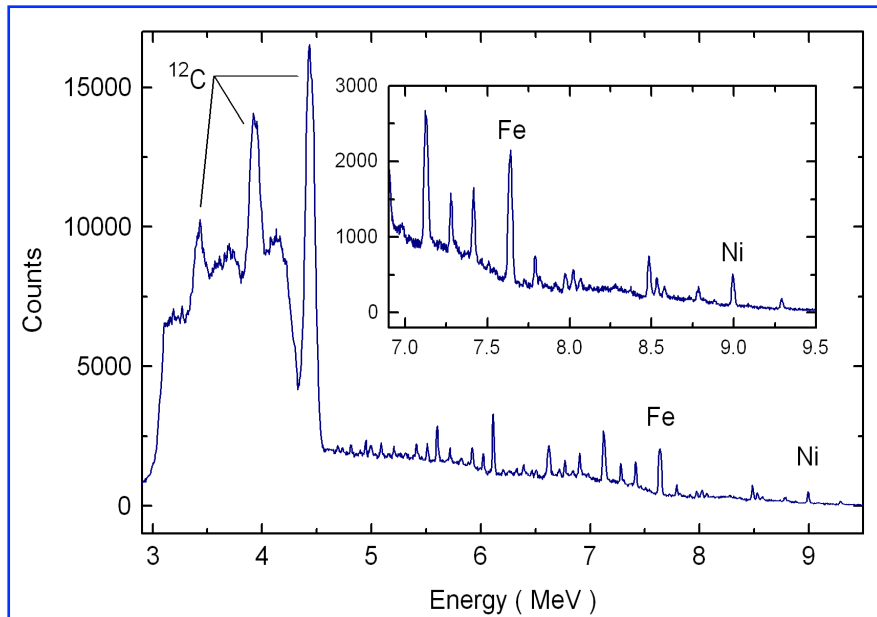
V_1, V_2 = pre-pulse and post-pulse baselines

b_1, b_2, k_1, E_0 = fitting parameters

Within ADC range ➡ standard “pulse-height mode” spectroscopy

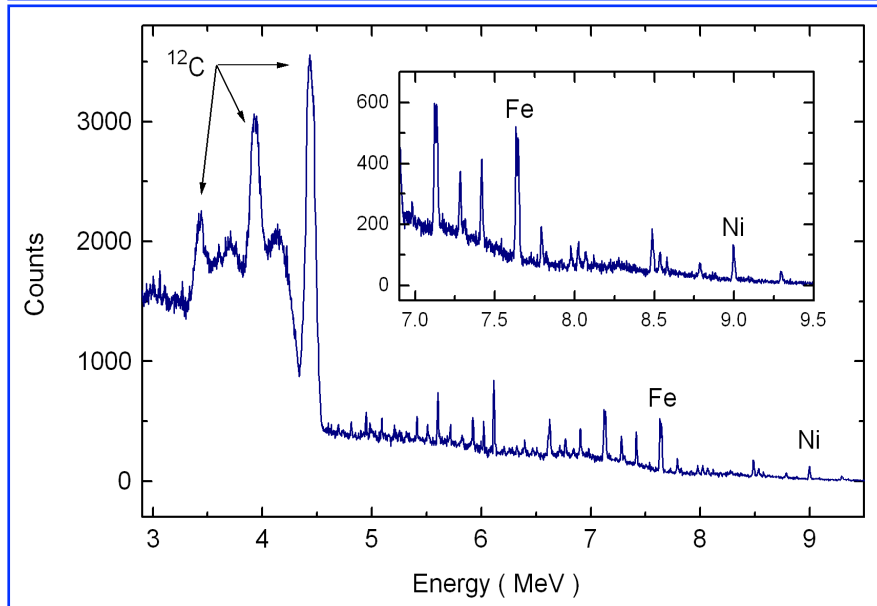
Beyond ADC range ➡ new “reset mode” spectroscopy

Source test $^{241}\text{Am}+\text{Be}$



← “reset” mode

Energy	Resolution (fwhm) in <u>pulse-height</u> mode		Resolution (fwhm) in <u>reset</u> mode	
4.440 MeV (^{12}C)	104 keV	2.34 %	104 keV	2.34 %
~5.6 MeV	10.5 keV	0.14 %	18.8 keV	0.34 %
~6.1 MeV	15.1 keV	0.17 %	17.1 keV	0.28 %
7.6312 MeV (Fe)	11 keV	0.14 %	18.8 keV (29.4 keV for the double-peak)	0.25 % (0.38 % for the double-peak)
7.6456 MeV (Fe)	11 keV	0.14 %		
8.9984 MeV (Ni)	15 keV	0.17 %	18.9 keV	0.21 %



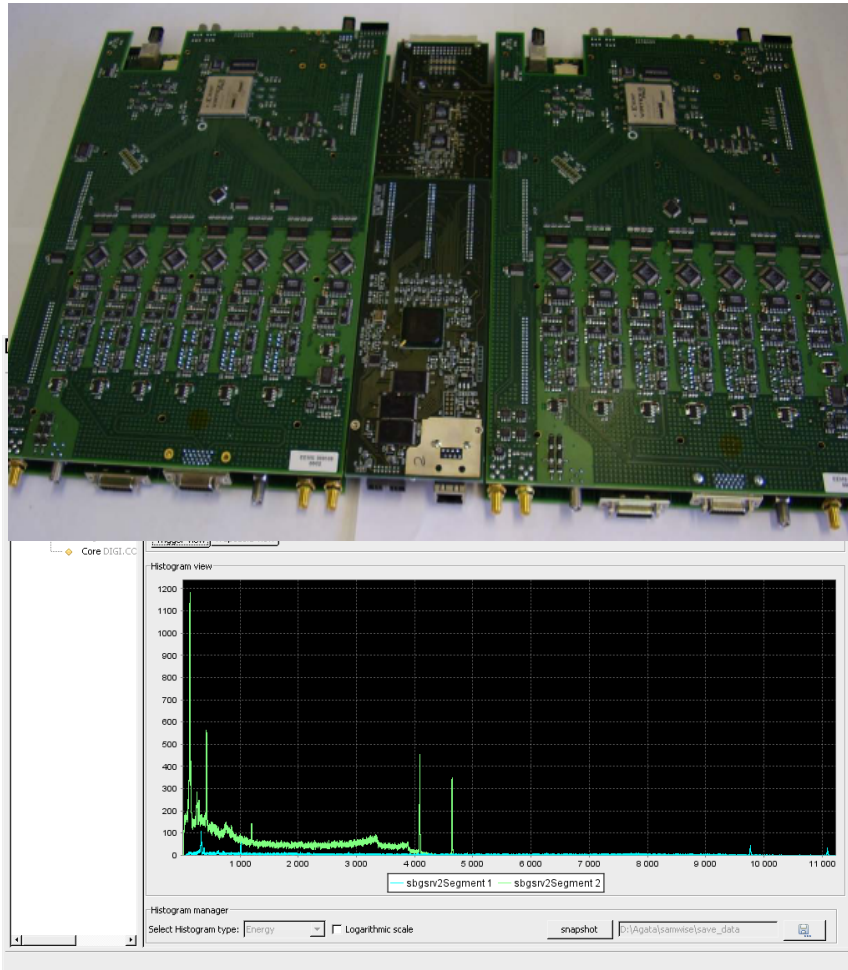
← “pulse-height” mode

The AGATA Digitiser

Excellent Performance:

SNR average value 75.45 dB.

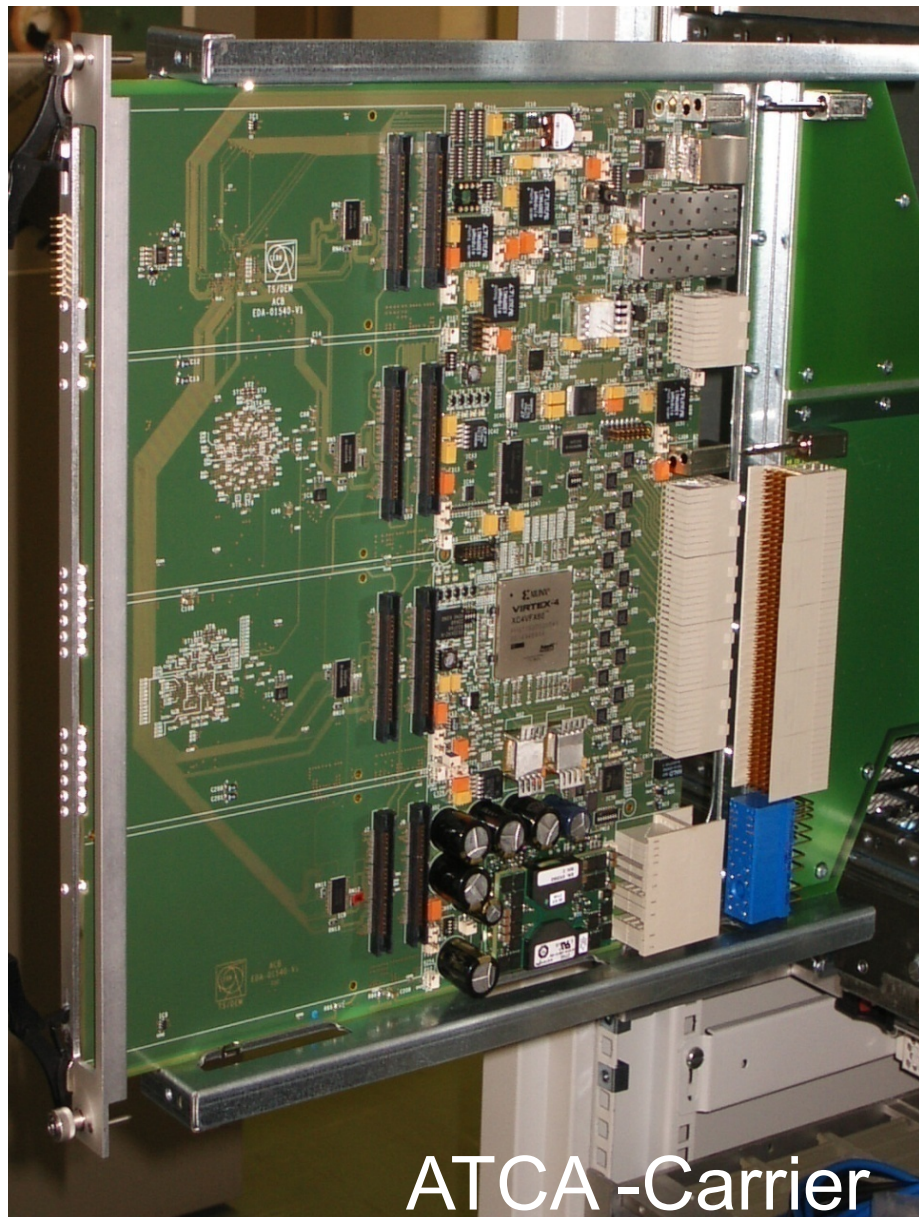
ENOB average value 12.24 bits



- 1 module per AGATA crystal (3 per AGATA triple cluster)
- Analogue and Digital Inspection lines
- Digital CFD decoupled output for General purpose trigger (e.g. Fast trigger complementary detectors conventional electronics)
- Local histogramming capability

IPHC Strasbourg, The University of Liverpool, STFC-Daresbury

ATCA Pre-Processing Electronics

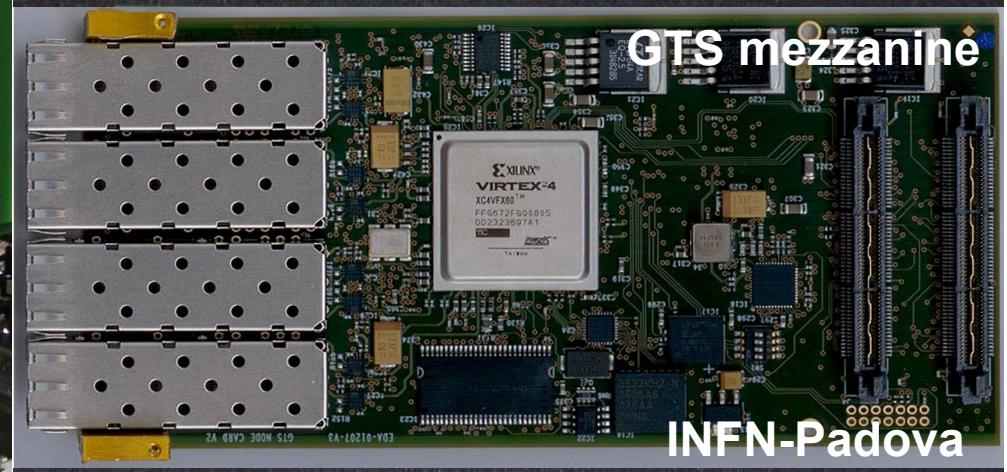


ATCA-Carrier

IPN-Orsav, CSNSM-Orsav, INFN-Padova



SEGMENT mezzanine
(also Core mezzanine)
6 channels



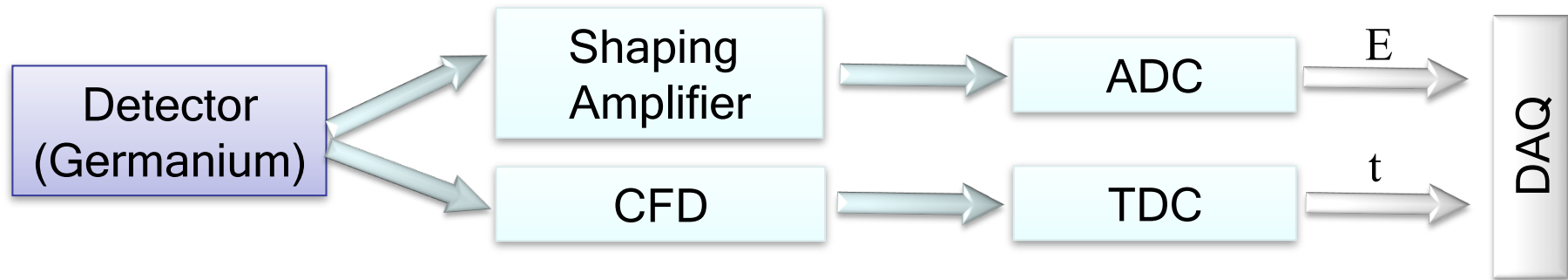
GTS mezzanine

INFN-Padova

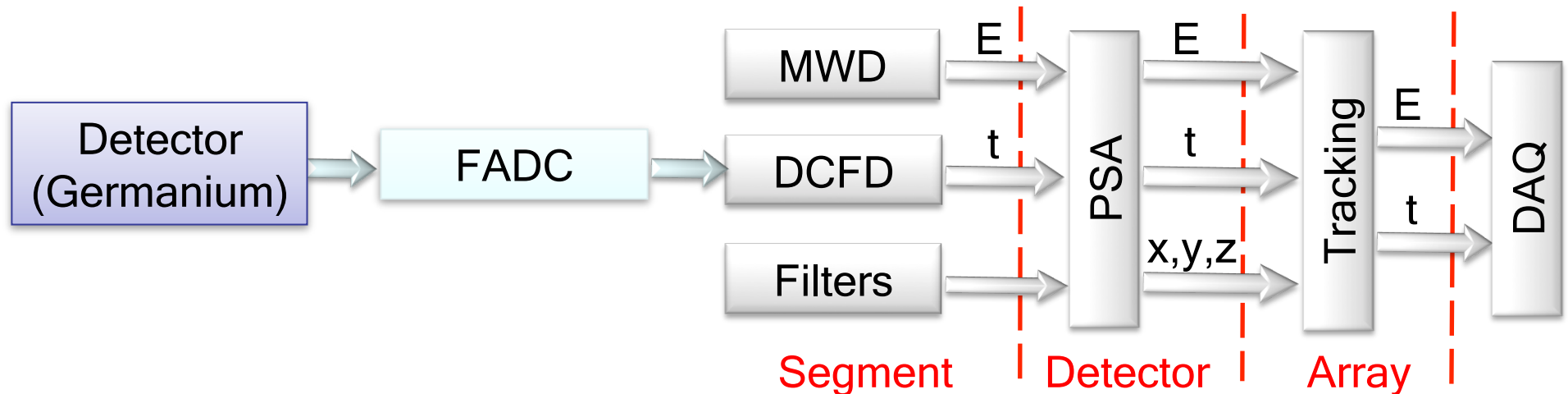
The Pre-Processing is the first level that can interact with the Global Trigger through the GTS mezzannine. It receives, and send to the Digitizer, the Global clock synchronizing the system.

Analogue vs Digital Electronics

Standard Arrays

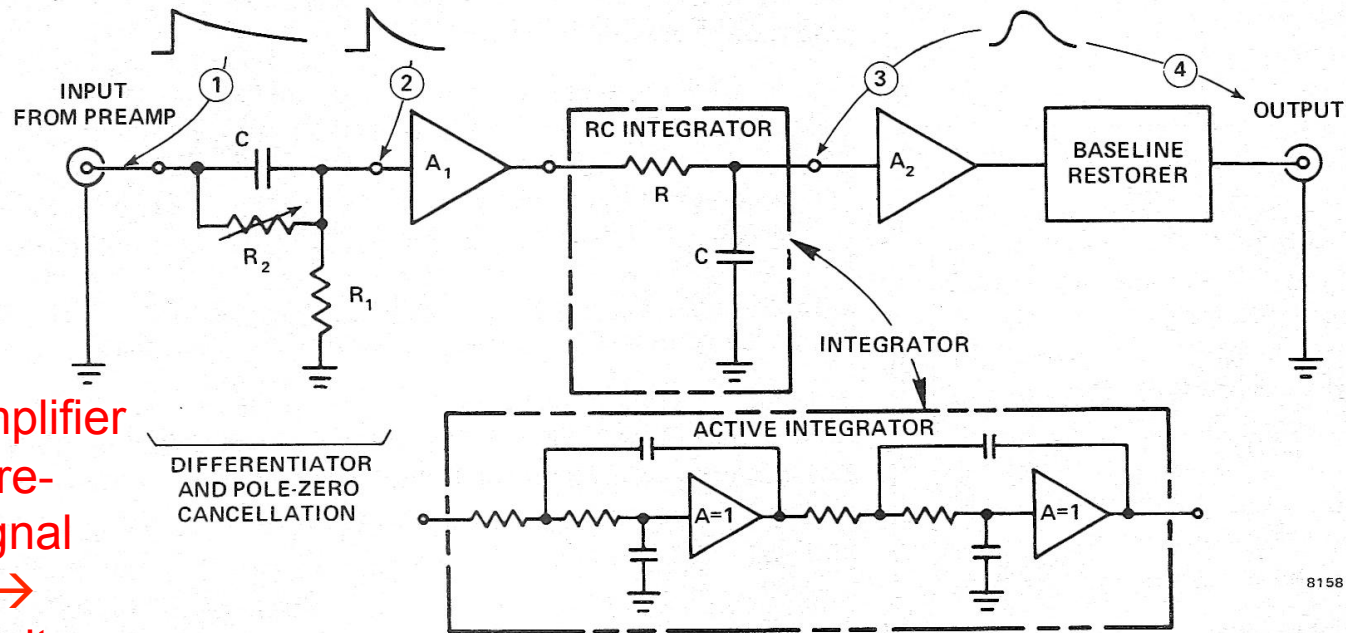


AGATA

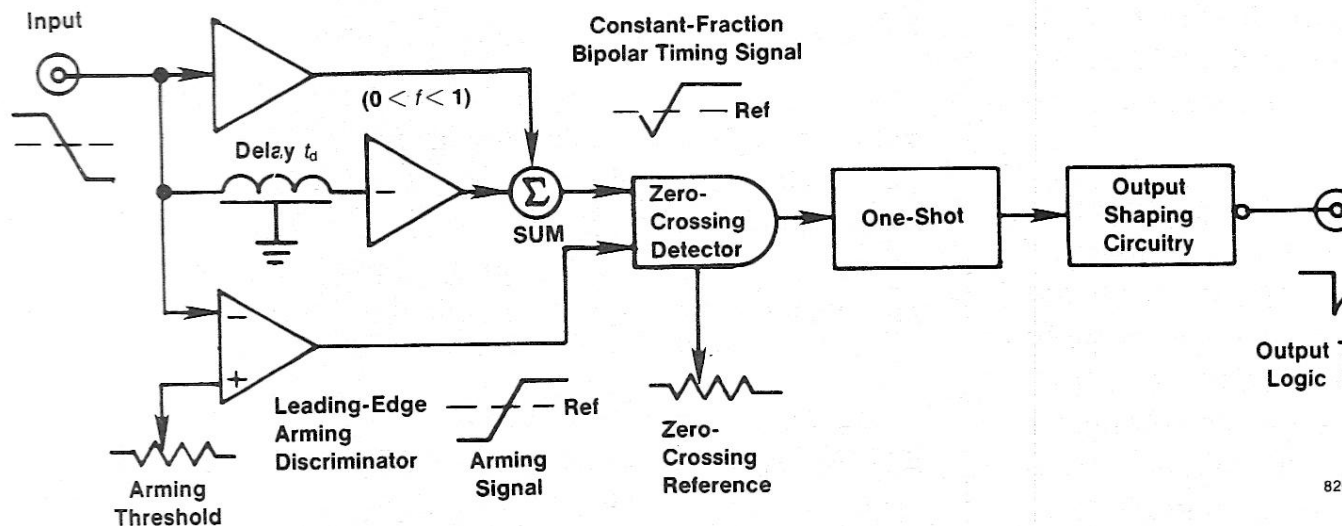


Spectroscopic Amplifier and CFD

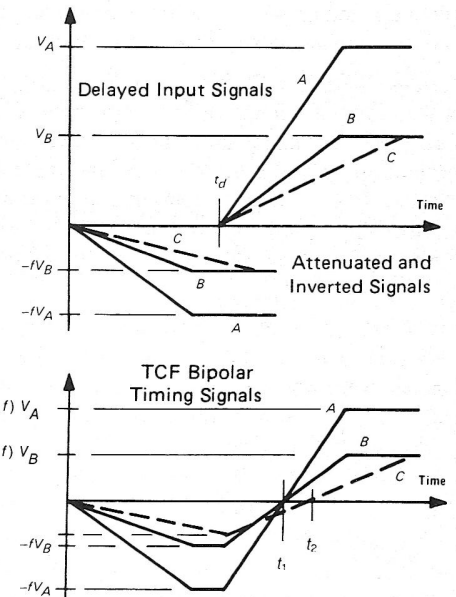
Analogue
Shaping Amplifier
Based on pre-
amplifier signal
integration →
ballistic deficit



8158

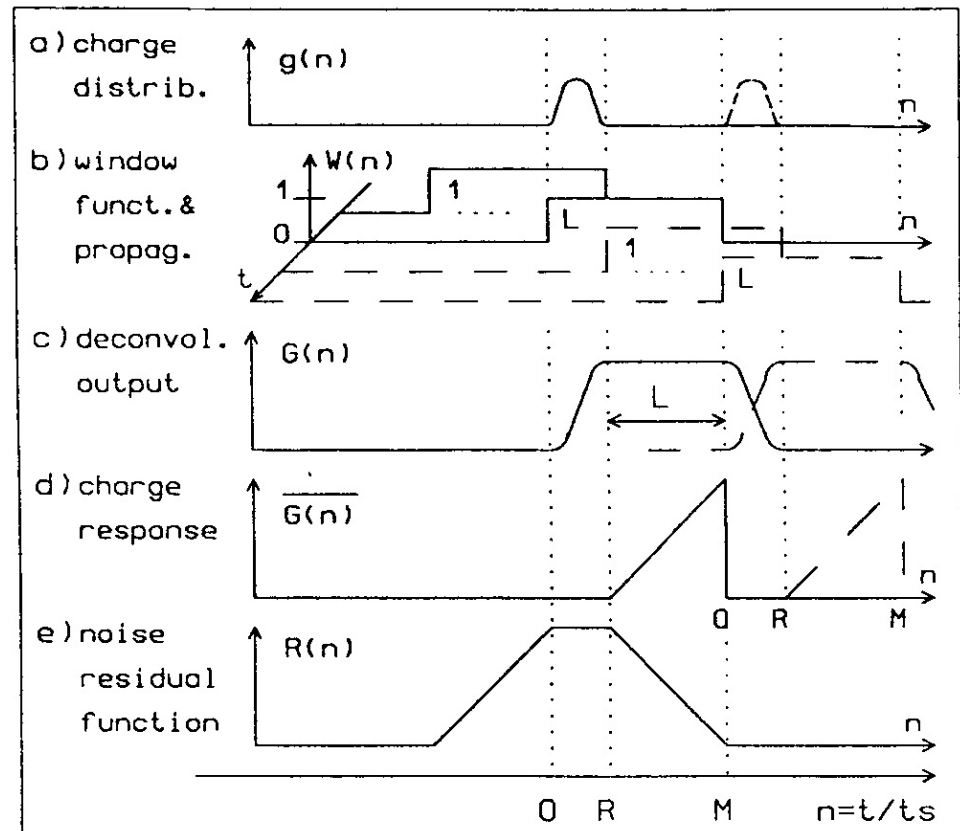


8267



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

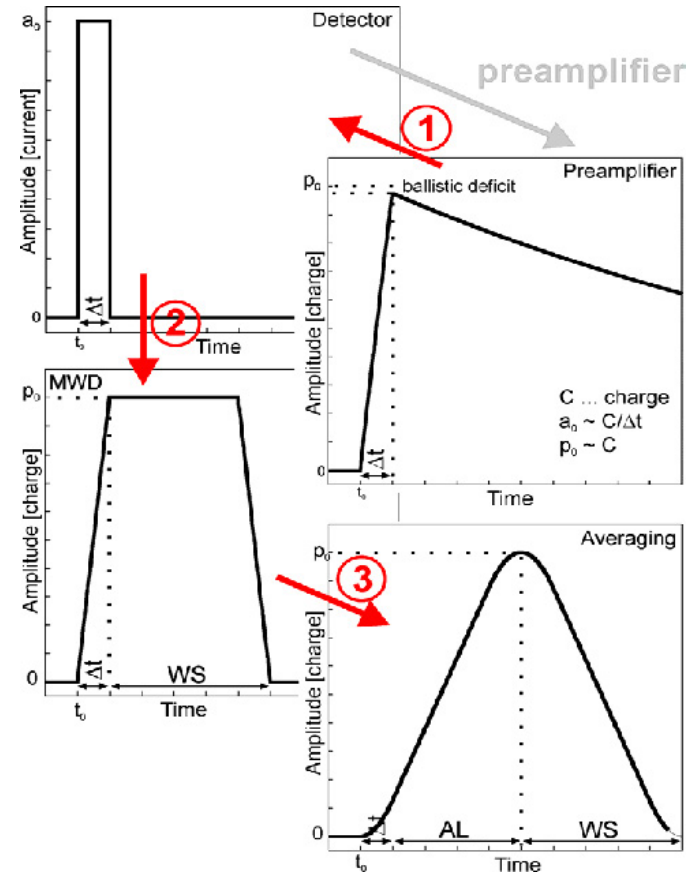


$$G[n] = G[n - 1] + \text{FADC}[n] - k \times \text{FADC}[n - 1] - \text{FADC}[n - L] + k \times \text{FADC}[n - L - 1]$$

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

Energy with Digital signals: Moving Window Deconvolution

- removes shaping-effect of preamplifier
⇒current signal recovered
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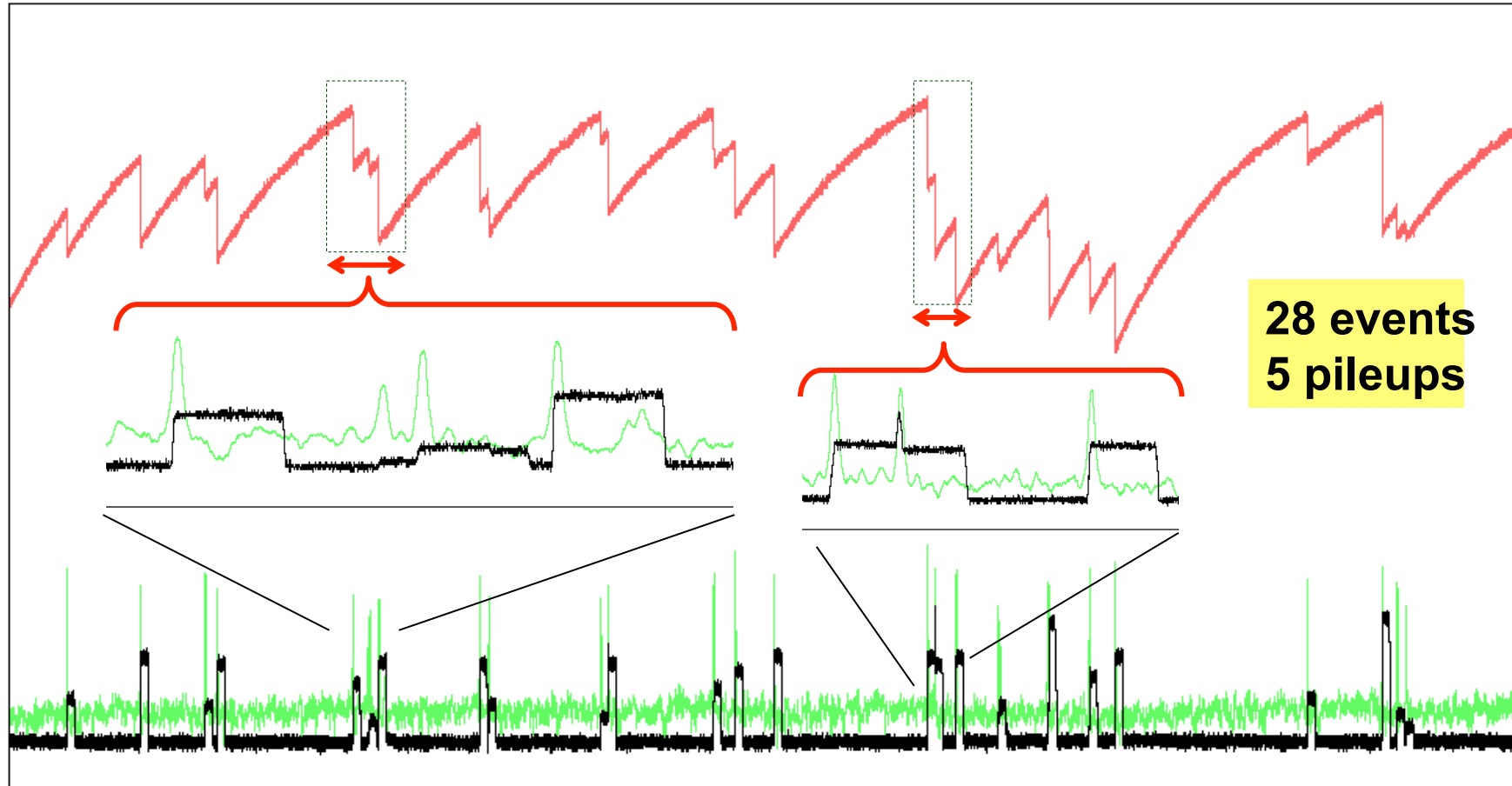
$$G[n] = G[n - 1] + \text{FADC}[n] - k \times \text{FADC}[n - 1] - \text{FADC}[n - L] + k \times \text{FADC}[n - L - 1]$$

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

Digital Pulse Processing for typical functions

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

The Central Contact at 40 kHz



Samples

SCC, MWD (width 5 μ s)

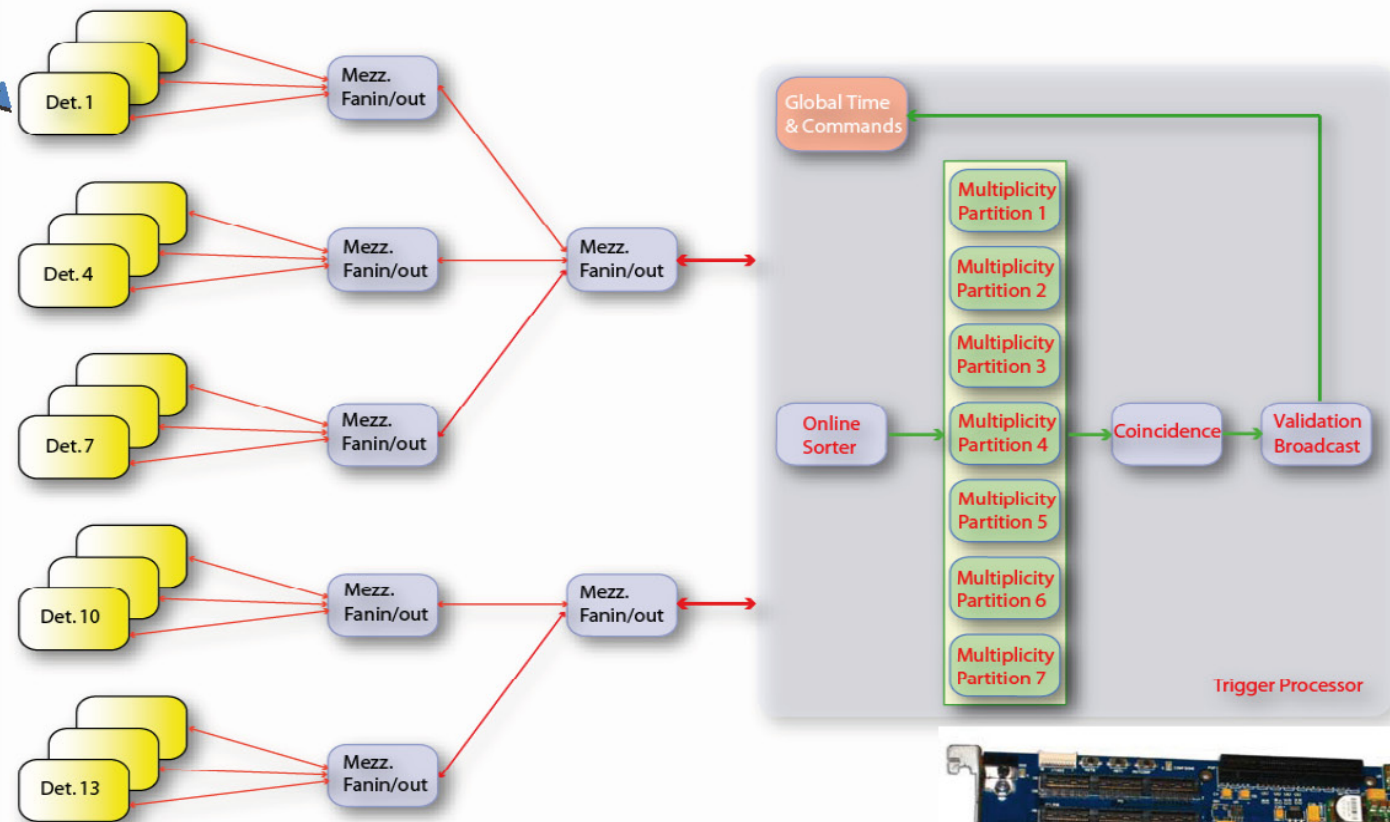
1 ms
sampled at 100 Ms/s

The AGATA Trigger System

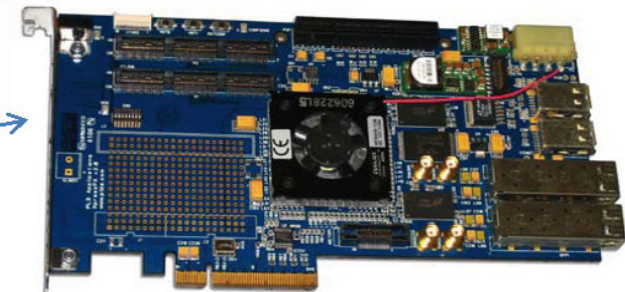
- Tree Structure Based on the GTS Mezzanines
- Trigger Logic Build in the Global Trigger Processor
- Possibility to Define Partitions for Different Detectors or Groups of Detectors
- The logic:
 - Multiplicity conditions within each partition
 - Prompt or Delay Logical Conditions Involving more partitions

Global Trigger Processor

Max 1 MHz trigger requests/channel



48 channels in a Xilinx Virtex-4 Fx100

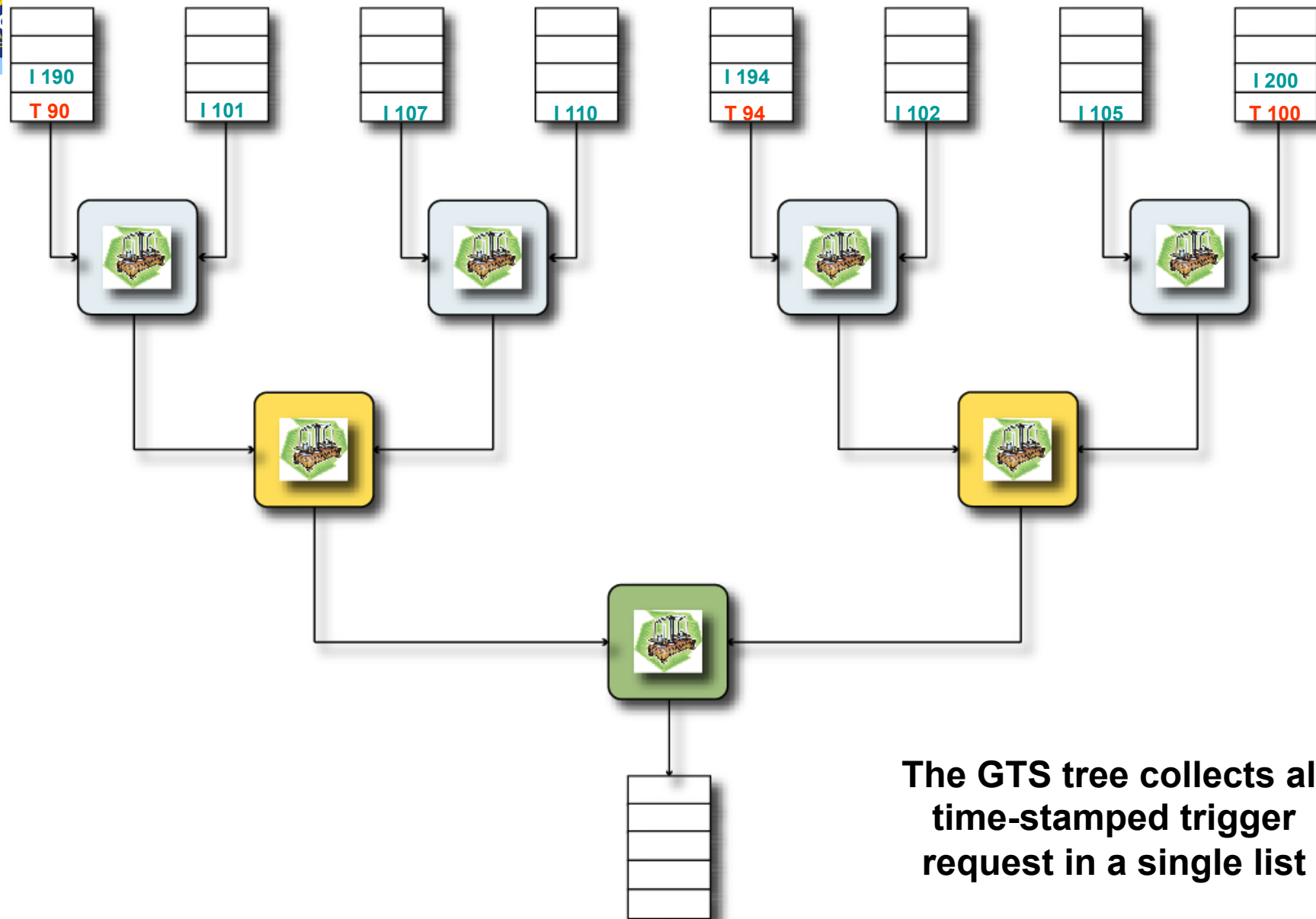


Agata Week - Cologne - March 2009

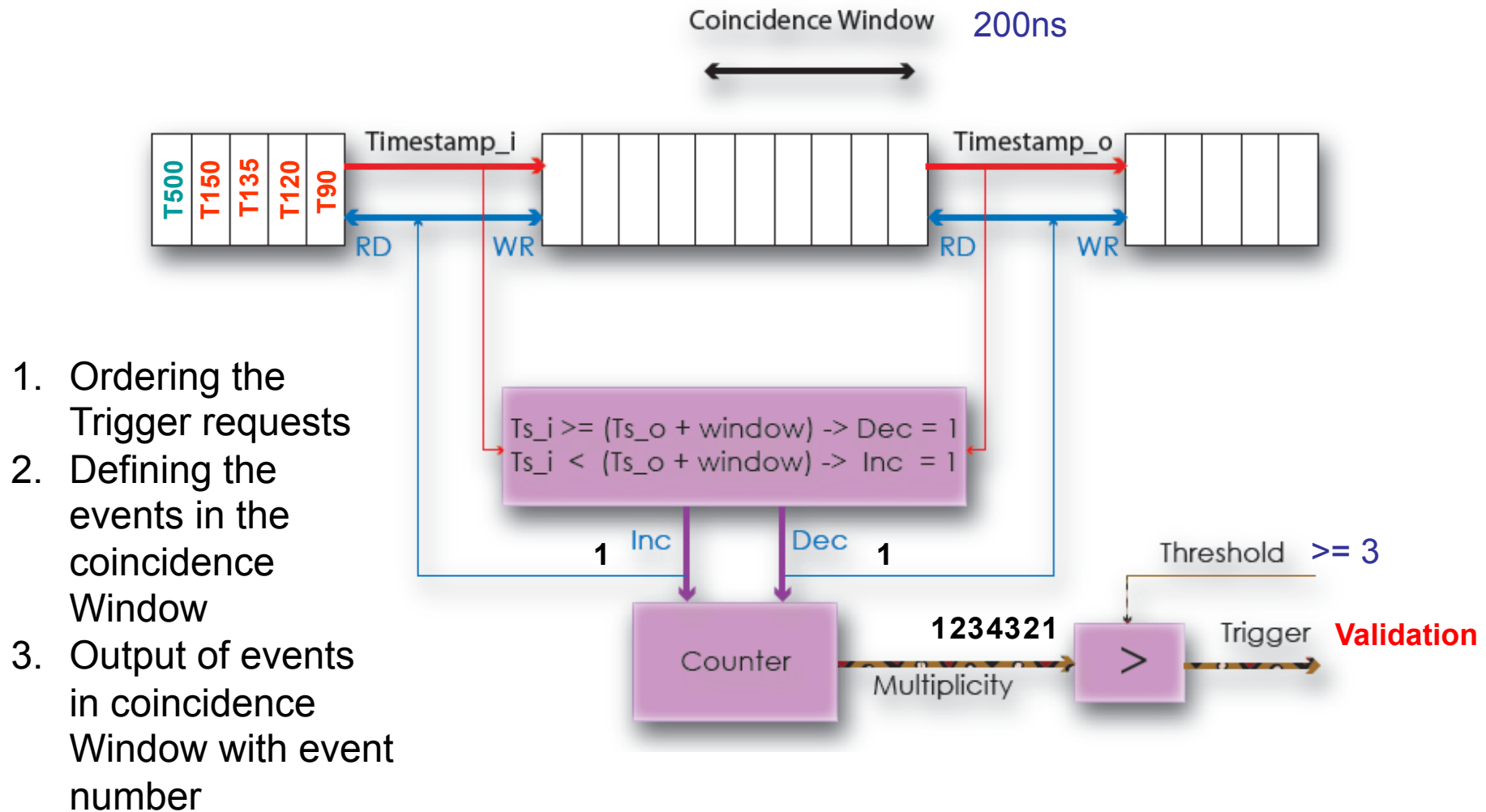
M. Bellato, L. Berti, J. Chavas, INFN-Pd and LNL



Online Sequential Batcher Sort

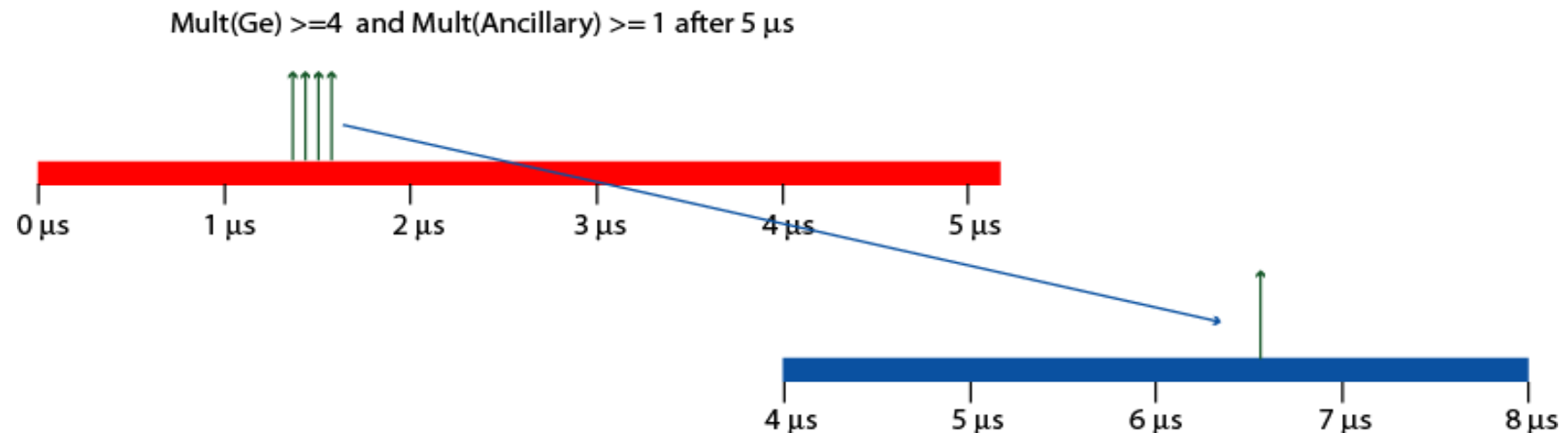


Multiplicity Processor

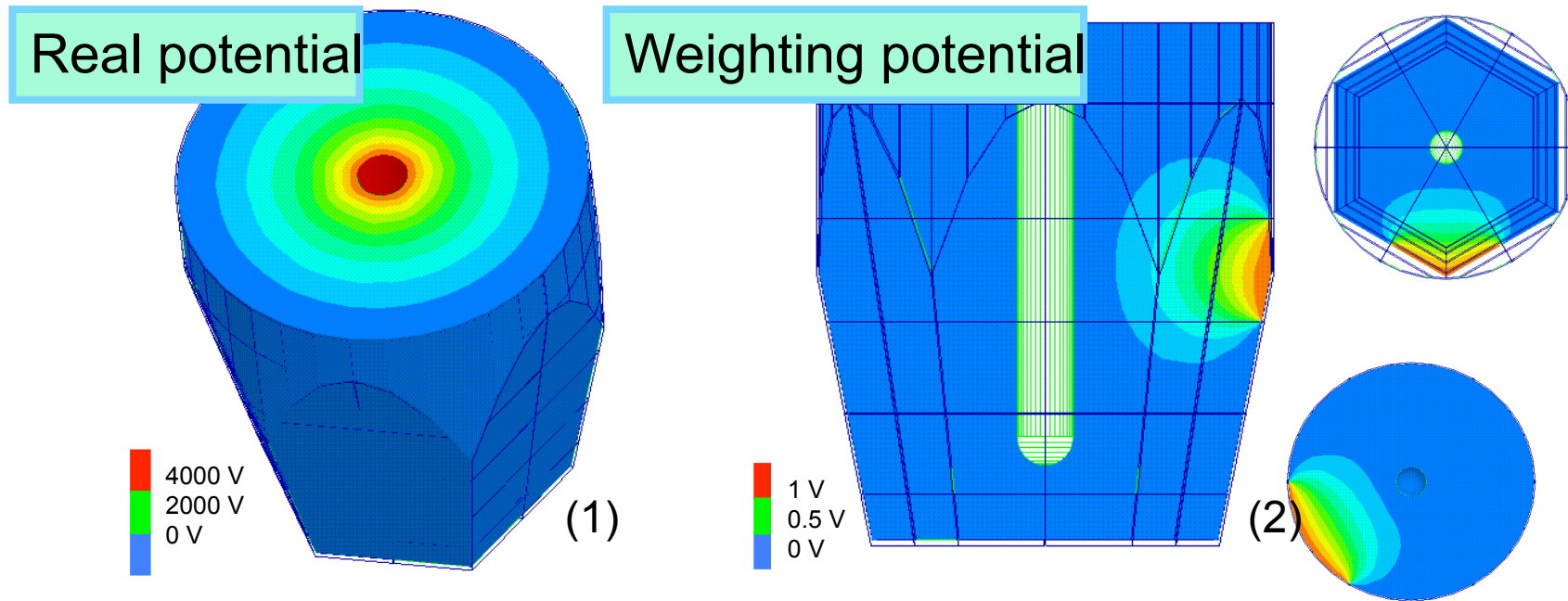


Partitions Coincidence

- Prompt and delayed
- Case study:
 - $M(\text{Ge}) \geq N$ and $M(\text{Other Detector}) \geq K$ before/after ΔT



Calculation of pulse shapes

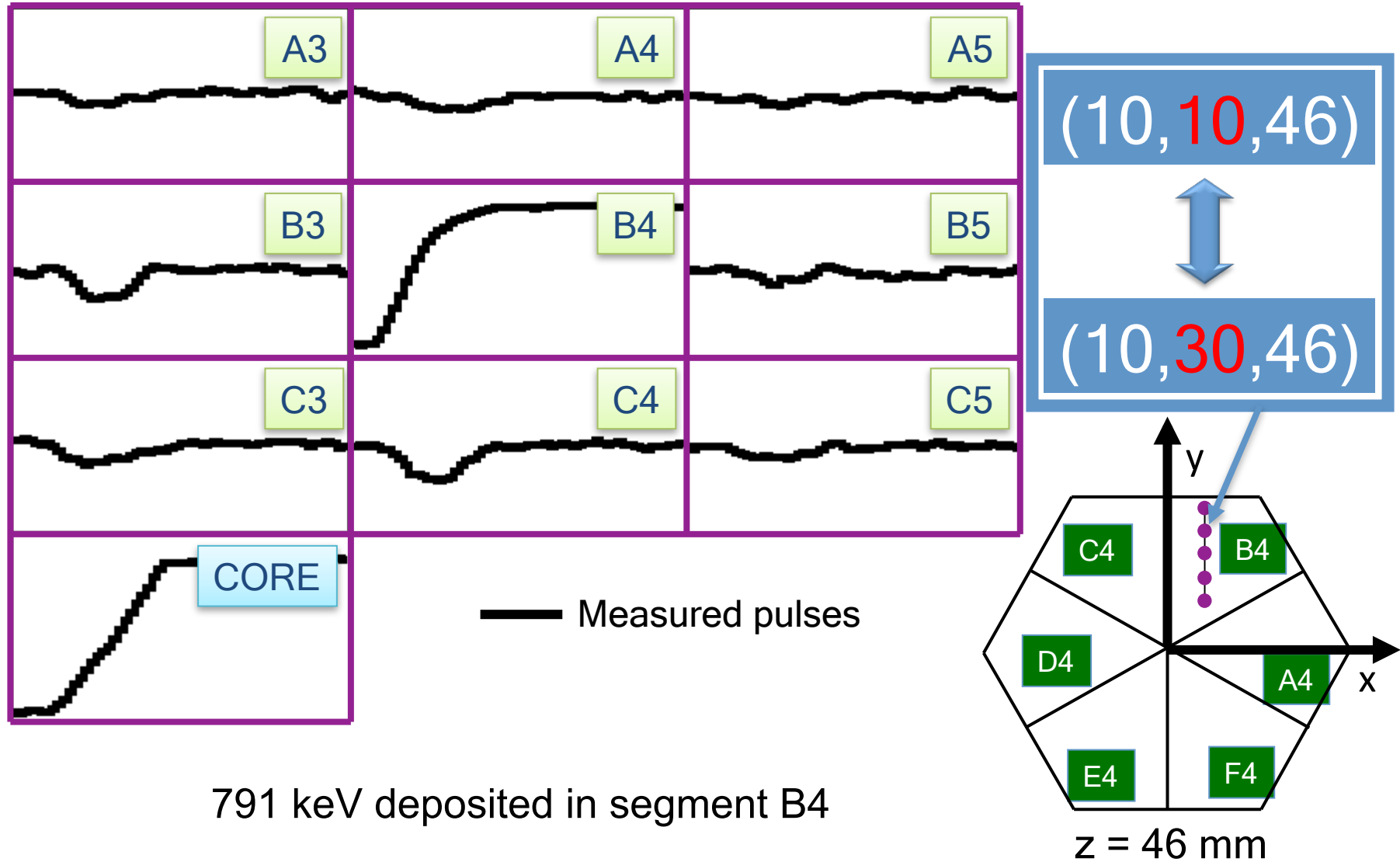


$$i_k = -q\vec{v} \cdot \vec{\nabla} \underbrace{\phi_k(r_q)}_{\text{Weighting potential}}$$

Current of electrode k

- Weighting potential is calculated by applying 1 V on the segment collecting the charge and 0 V to all the others (Ramo's Theorem).
- It measures the electrostatic coupling (induced charge) between the moving charge and the sensing contact.

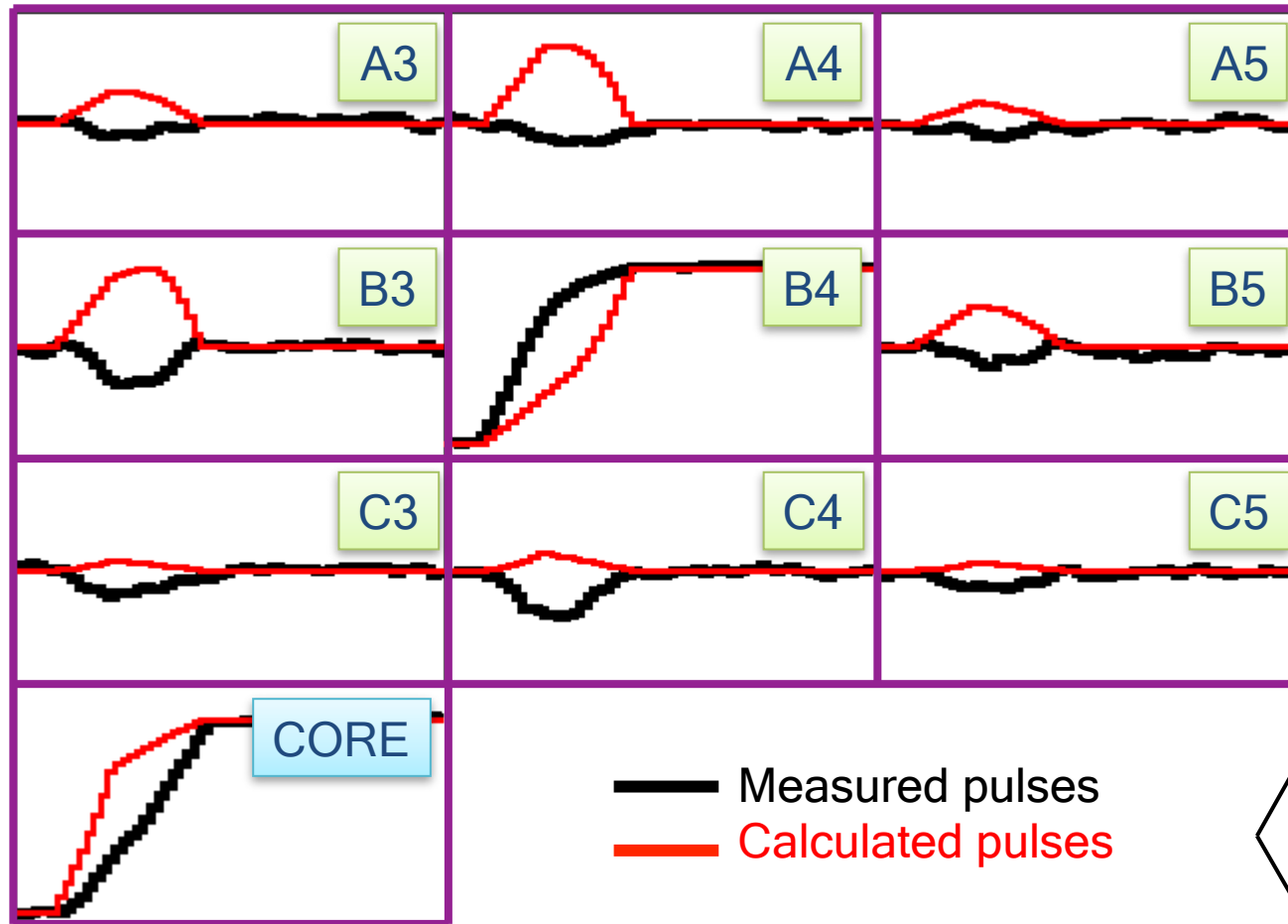
Pulse Shape Analysis Concept



Very Important: Measured pulses need to be time aligned

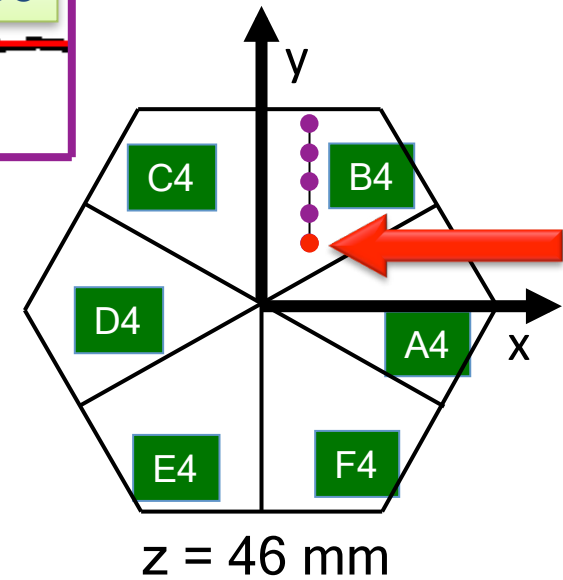
R.Venturelli, D.Bazzacco

Pulse Shape Analysis Concept

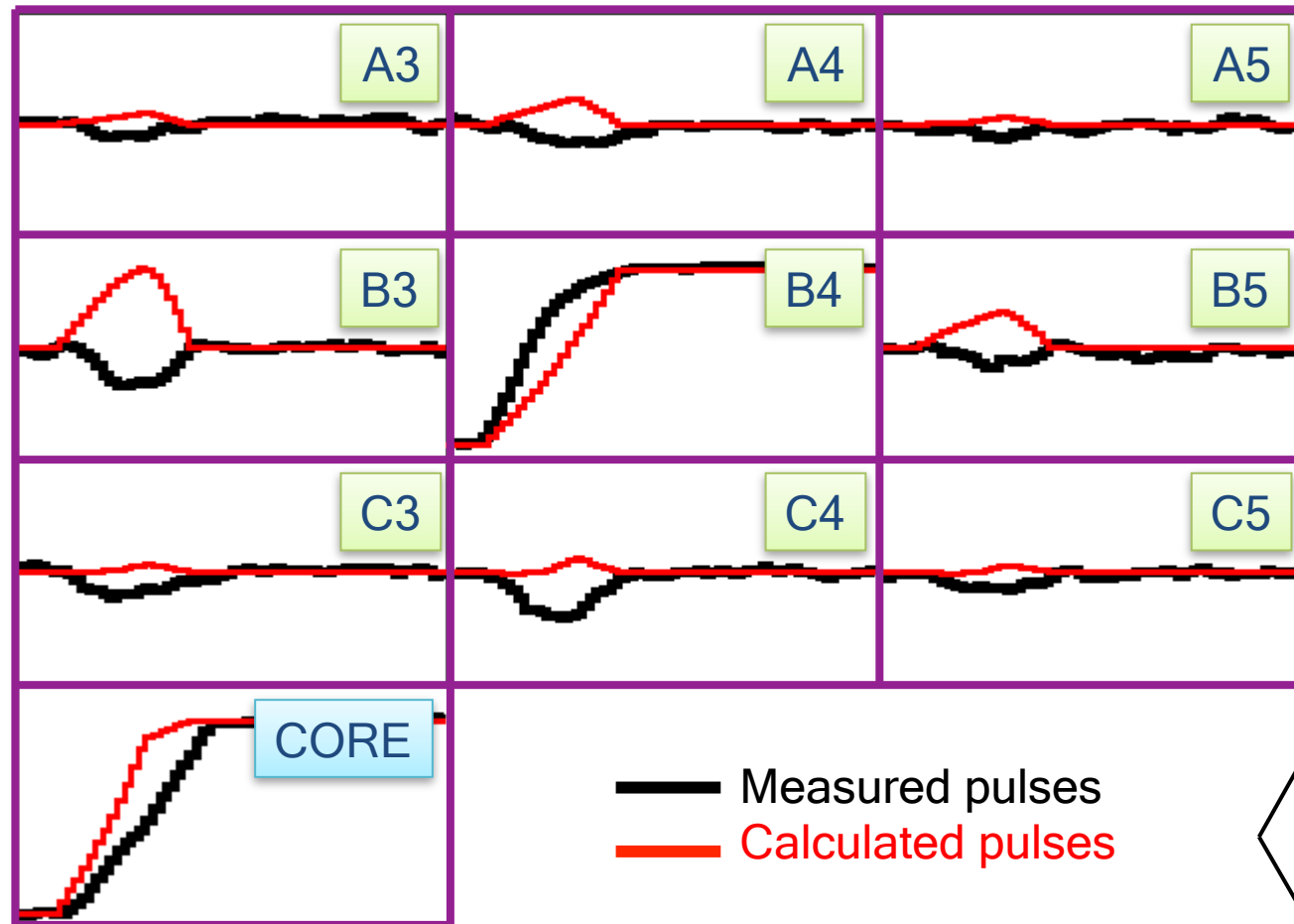


791 keV deposited in segment B4

(10, 10, 46)

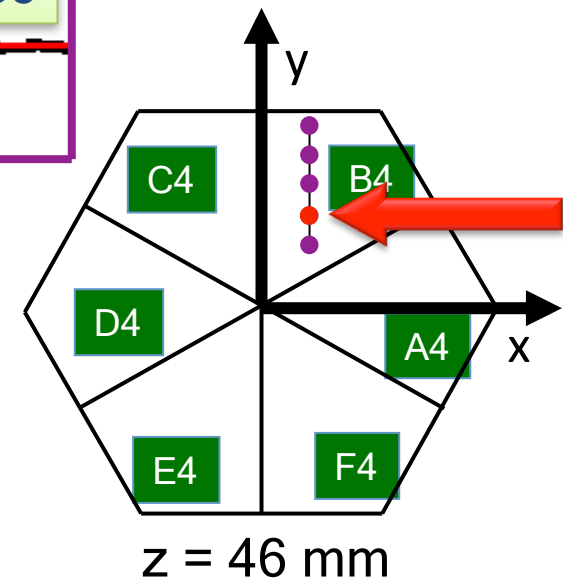


Pulse Shape Analysis Concept

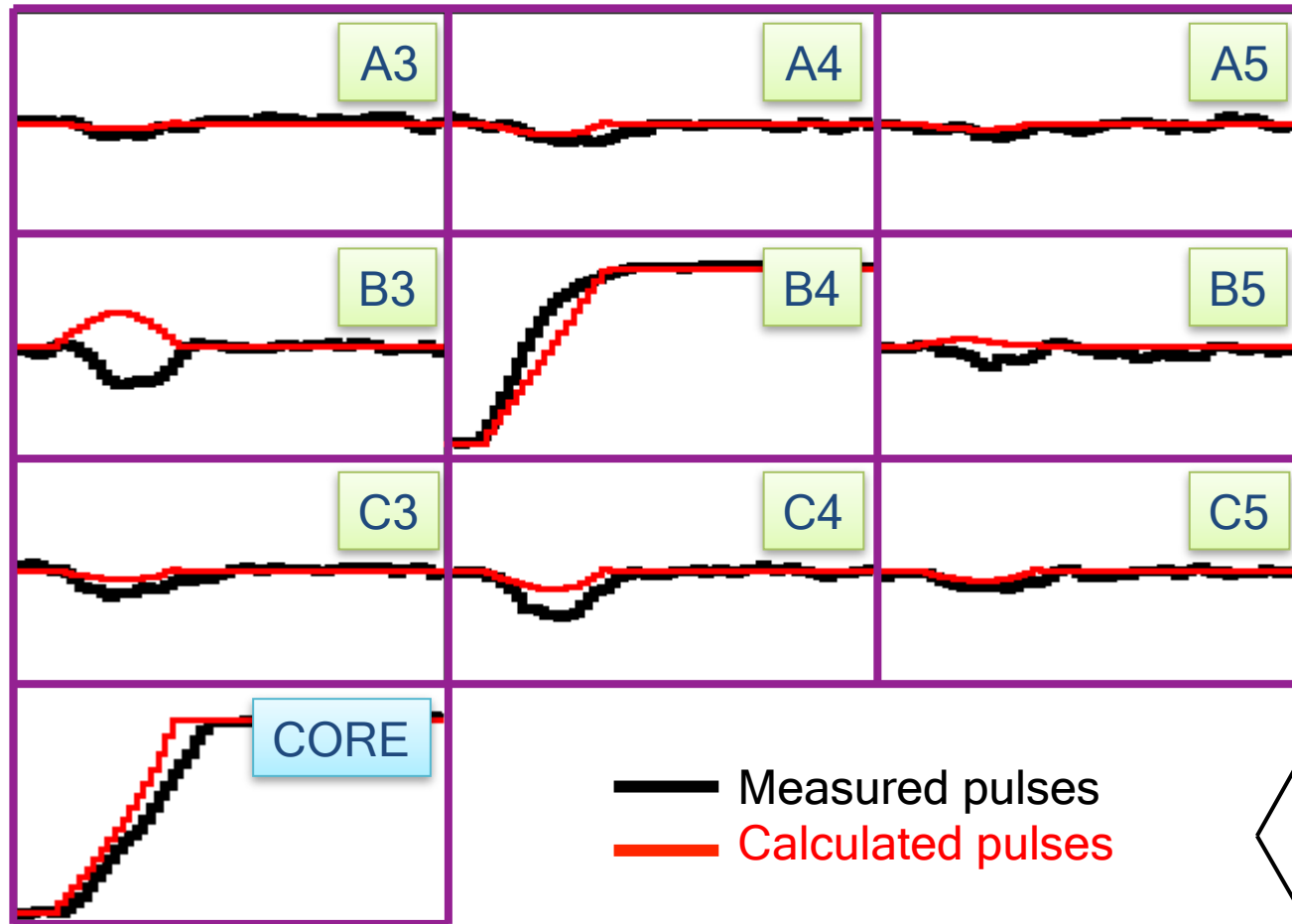


791 keV deposited in segment B4

(10, 15, 46)

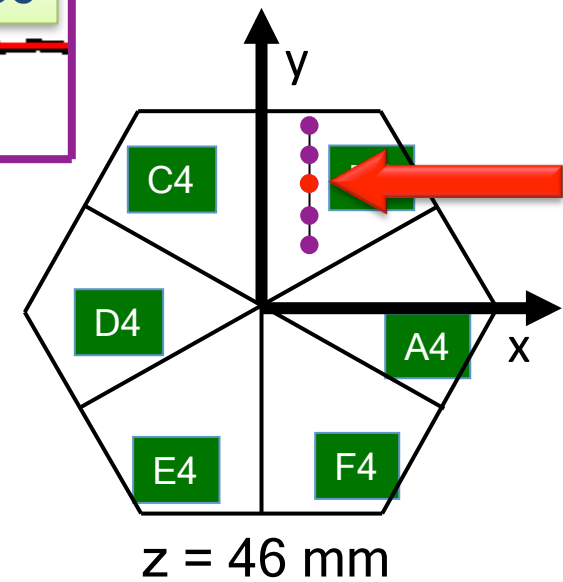


Pulse Shape Analysis Concept

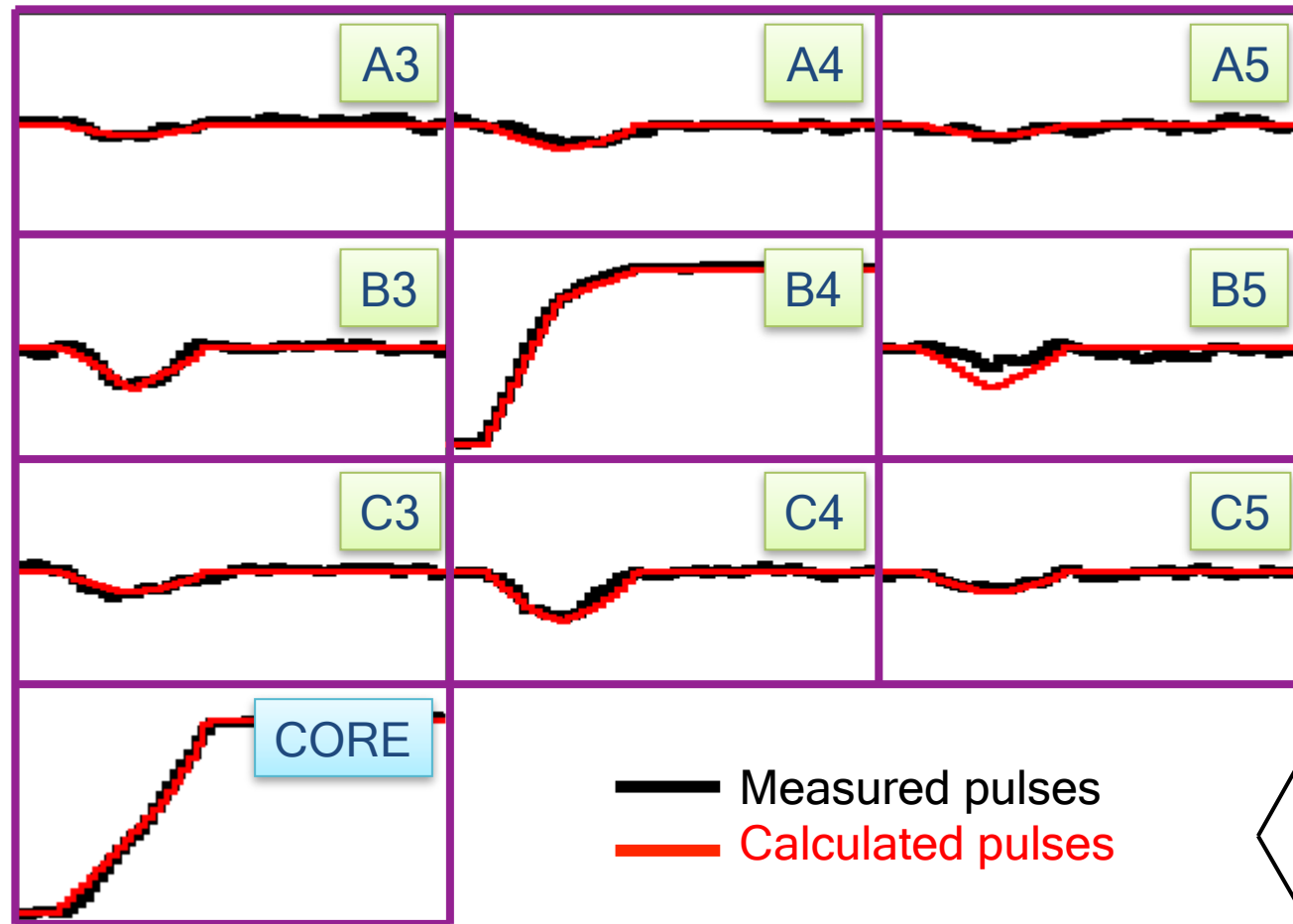


791 keV deposited in segment B4

(10, 20, 46)



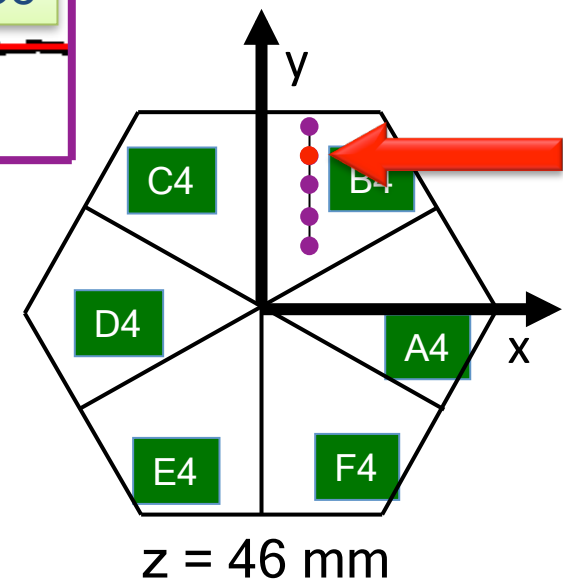
Pulse Shape Analysis Concept



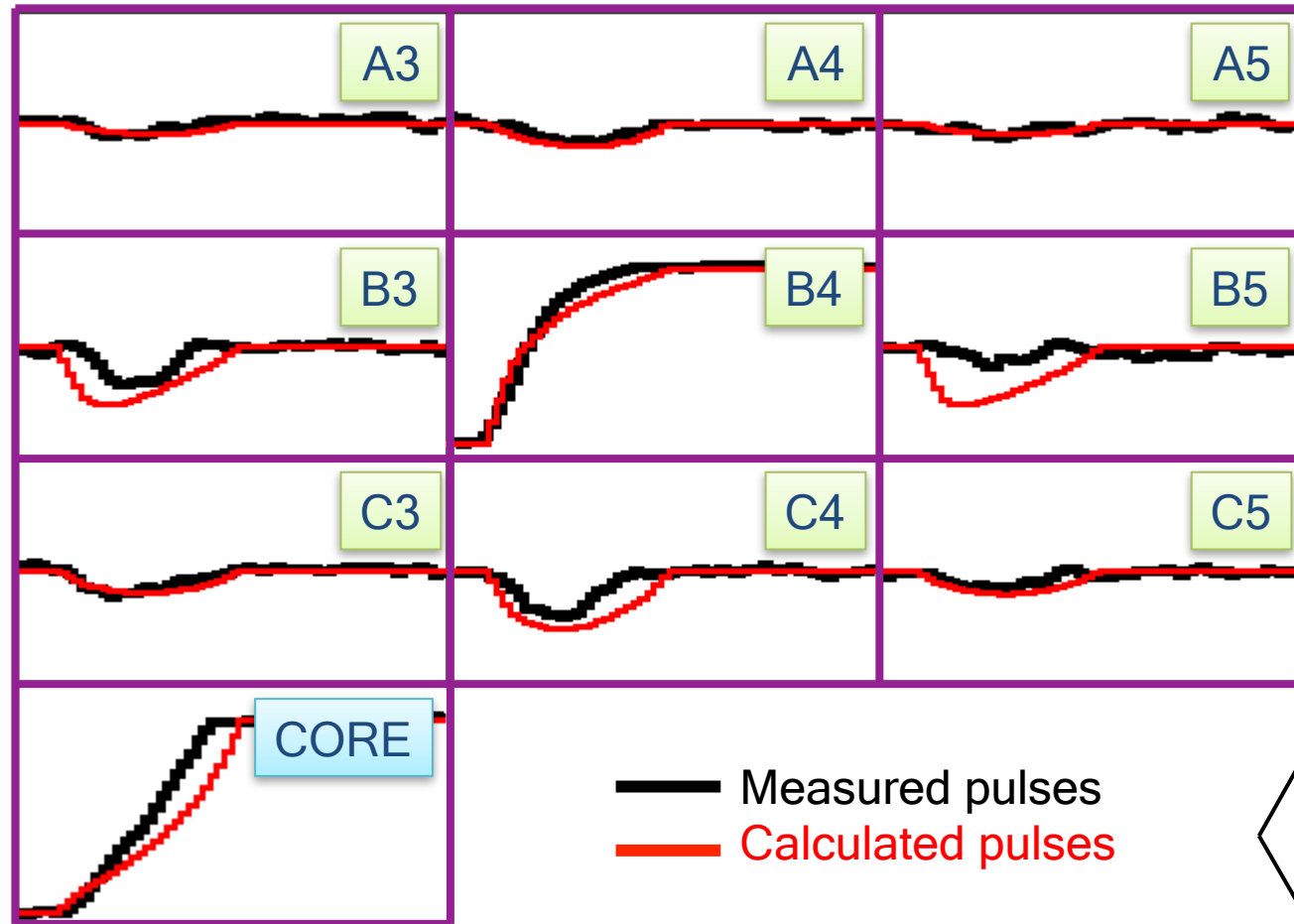
— Measured pulses
— Calculated pulses

791 keV deposited in segment B4

(10, 25, 46)

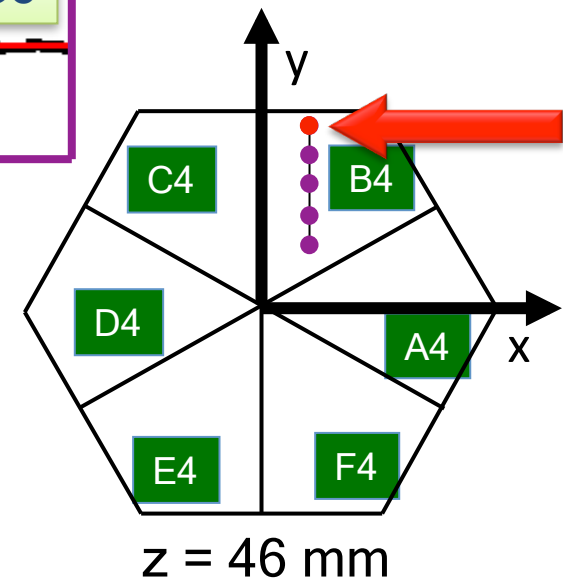


Pulse Shape Analysis Concept

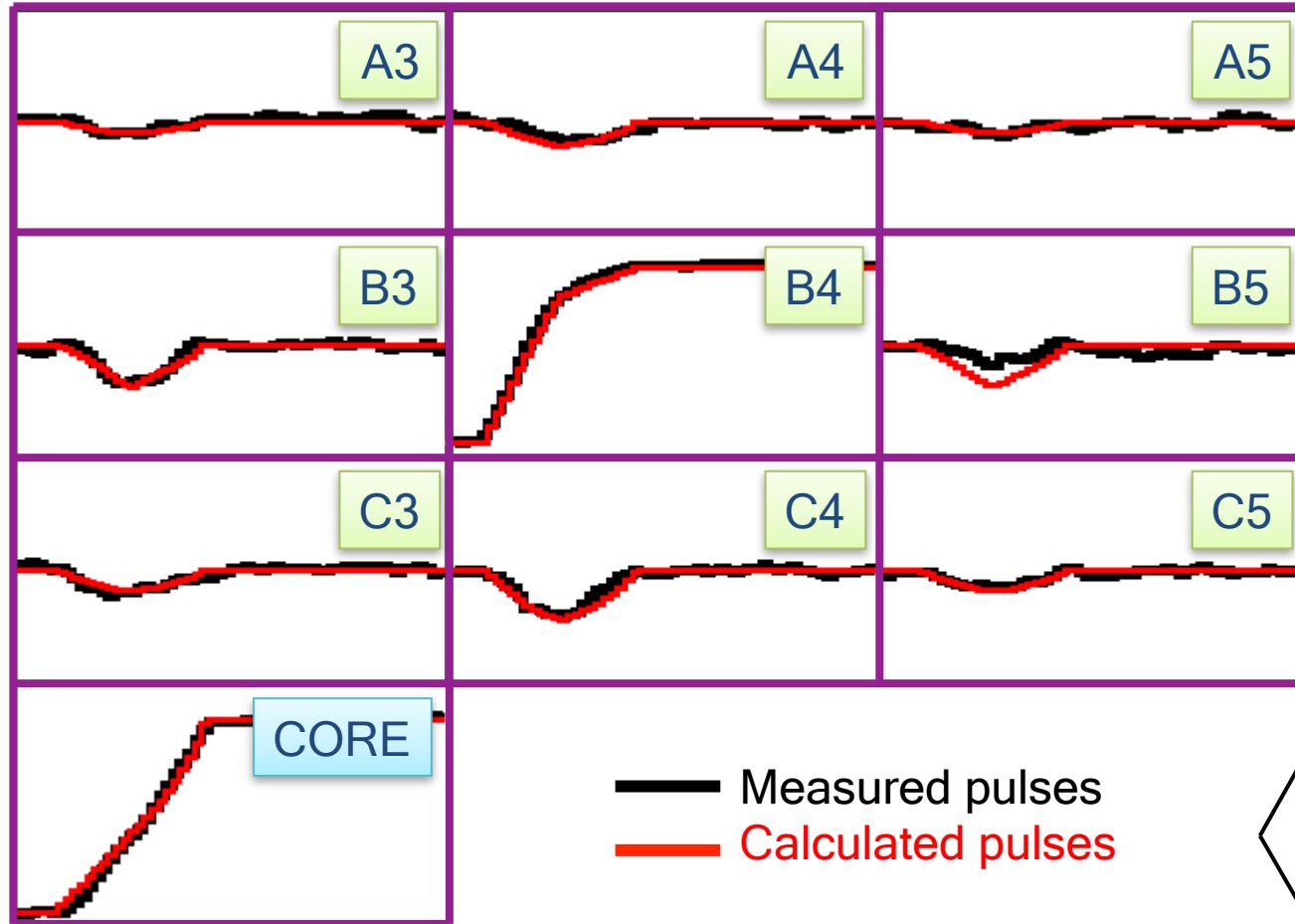


791 keV deposited in segment B4

(10, 30, 46)



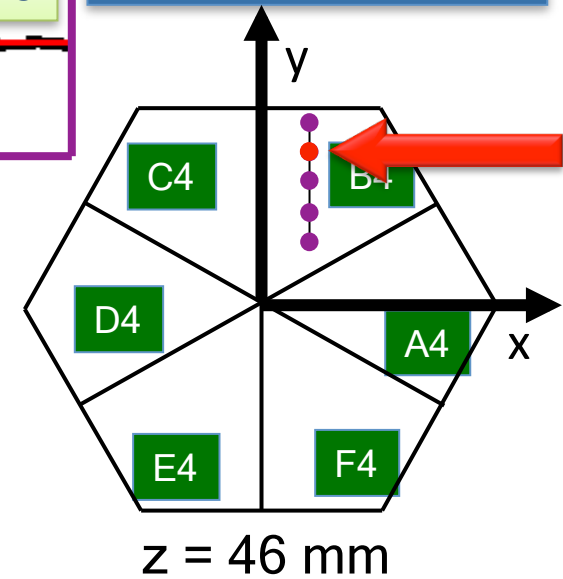
Pulse Shape Analysis Concept



Result of
Grid Search
algorithm

R. Venturelli

(10, 25, 46)



791 keV deposited in segment B4

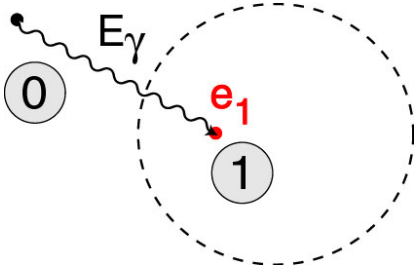
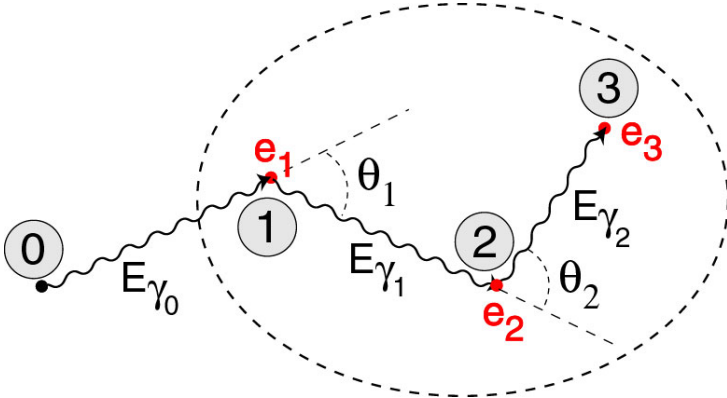
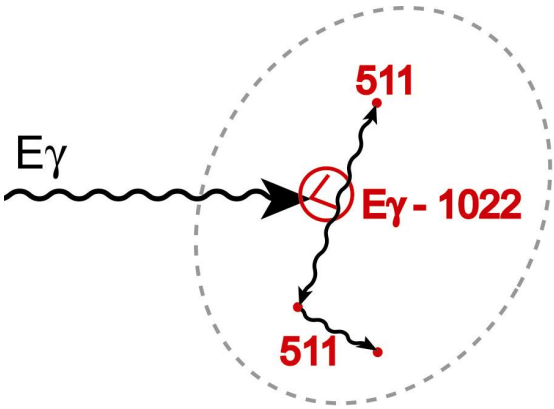
Set of Energies +
Interaction Positions



Tracking

R.Venturelli, D.Bazzacco

Interaction - Reconstruction Mechanisms

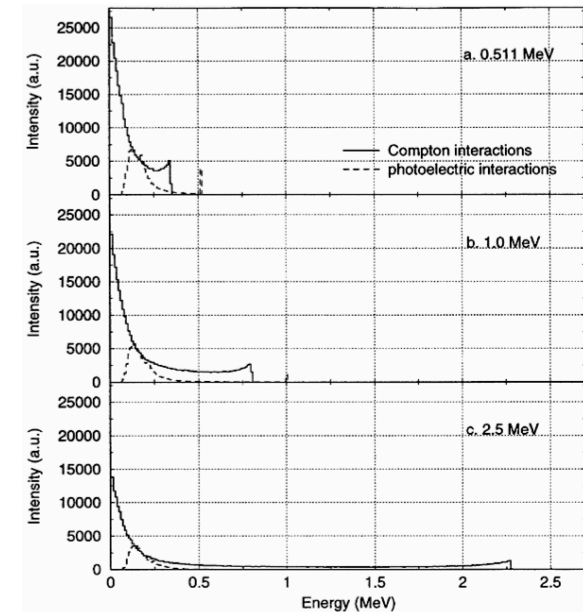
~ 100 keV ~1 MeV ~ 10 MeV γ-ray energy			
Photoelectric	Compton Scattering	Pair Production	
			
Isolated hits	Angle/Energy	Pattern of hits	
Probability of interaction depth	$E_{\gamma'} = \frac{E_{\gamma}}{1 + \frac{E_{\gamma}}{m_0 c^2} (1 - \cos\theta)}$		$E_{1st} = E_{\gamma} - 2 mc^2$

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

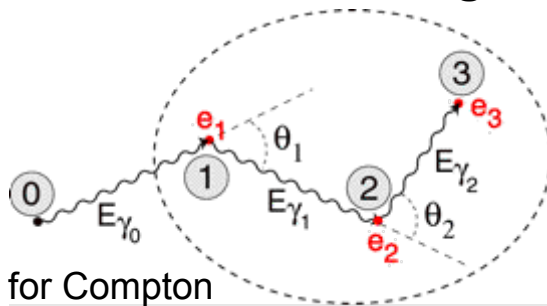
The tracking Algorithms in AGATA

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



Forward-tracking



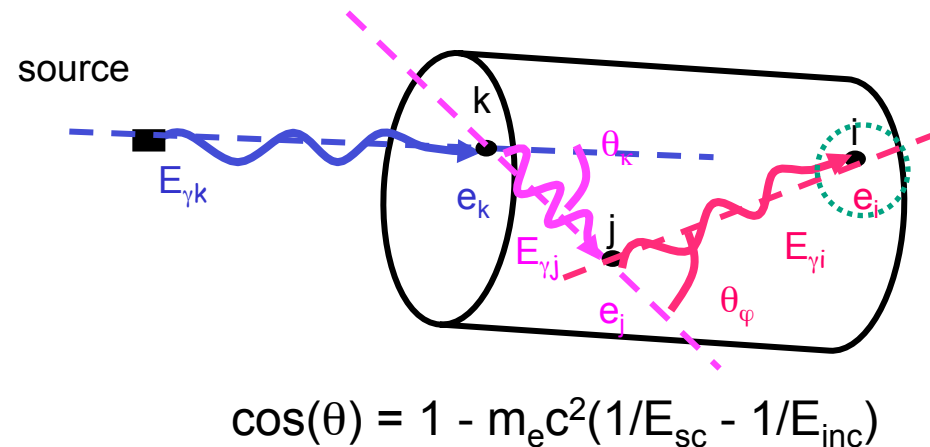
Probability for Compton or photoelectric and for the path in Germanium

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

Likelihood

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

Back-tracking



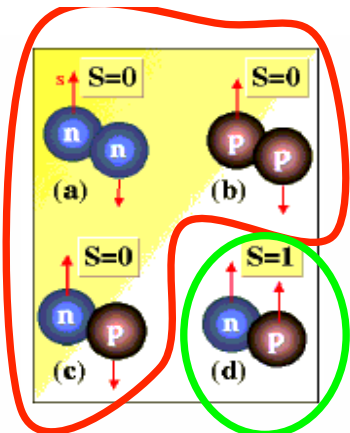
$$\cos(\theta) = 1 - m_e c^2 (1/E_{sc} - 1/E_{inc})$$

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

What can we learn from atomic nuclei with high-resolution γ -ray spectroscopy techniques?

Some Examples on:

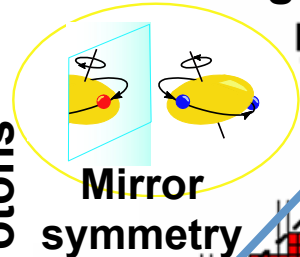
- Nuclei in the vicinity of $N=Z$ (equilibrated nuclear matter)
- Neutron-rich nuclei (large isospin values)
- Macroscopic/microscopic behavior of nuclei (collective modes)



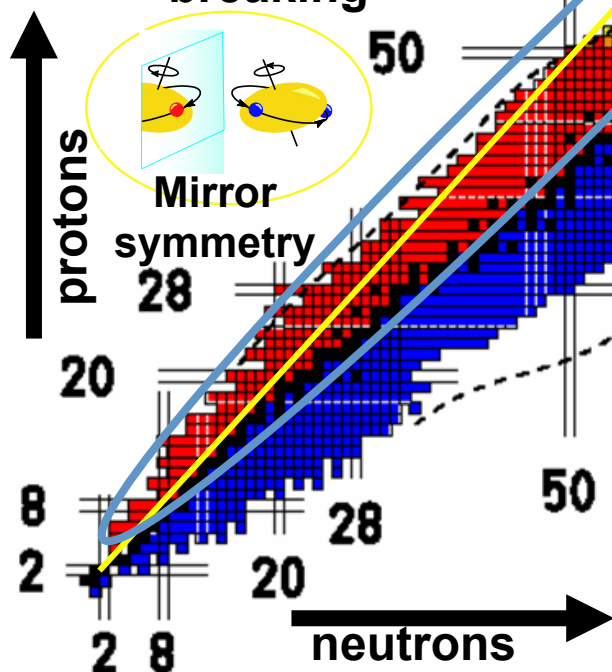
$J=0 \ T=1$ $J=1 \dots 2j$
 $T=0$

Isospin $T=0$ np -pairing

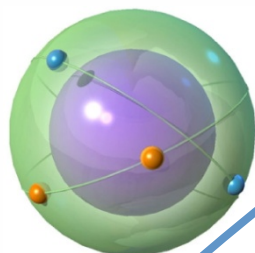
Isospin symmetry breaking



Mirror symmetry

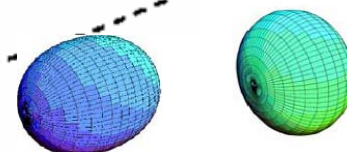


Single-particle and collective states around doubly close shell $N=Z$ nuclei

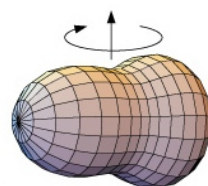


The demise of isospin purity: heavier Mirror nuclei are less similar

Shape coexistence and collectivity in $N \sim Z$ nuclei ($A \sim 70$)



Exotic structures along the $N=Z$ line: p - n enhancement of collective properties



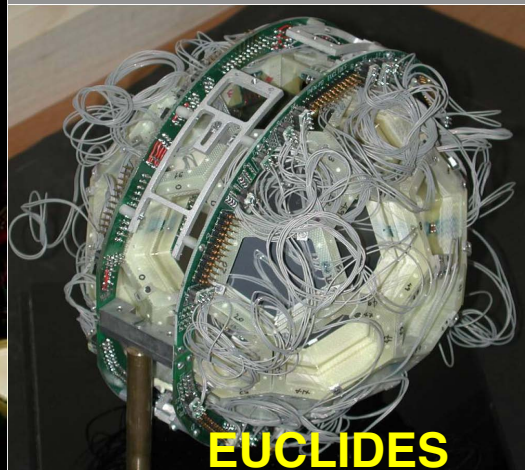
Spectroscopy at large isospin and exotic (particle) decays: multidimensional quantum tunneling

Proton "Islands of Inversion"

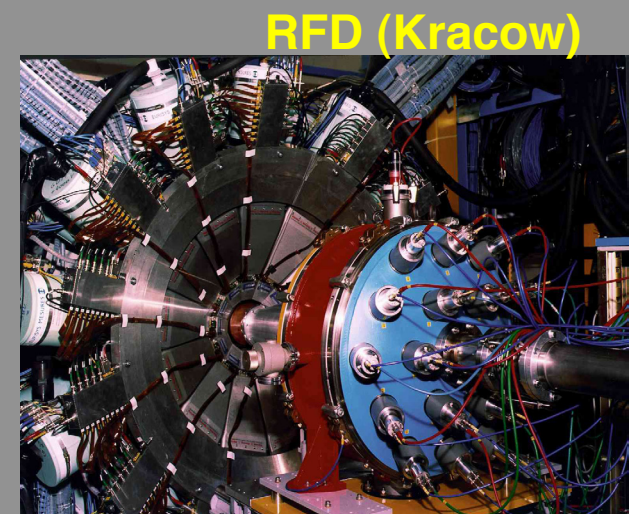
Mainly Populated in Fusion-Evaporation reactions

The GASP array

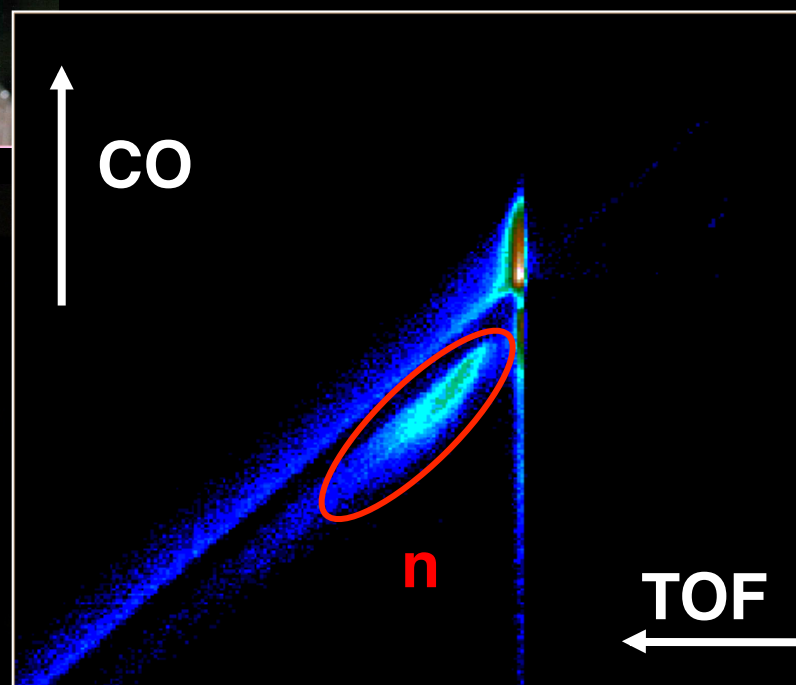
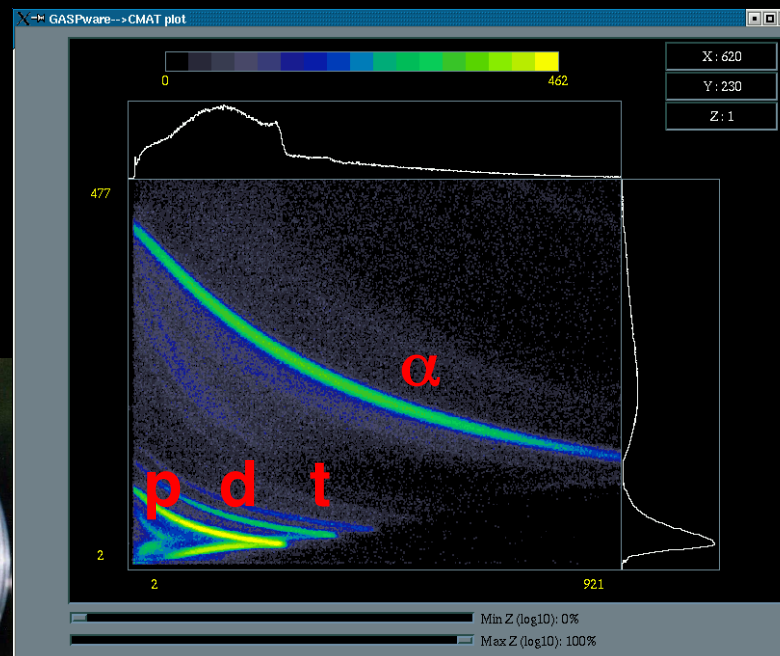
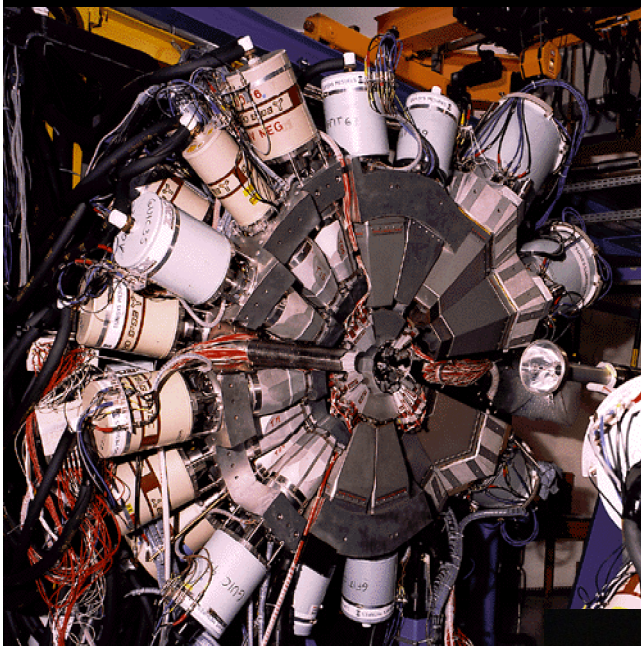
Configuration I & II with ancillary detectors



40 Ge+AC
I $\epsilon \sim 3\%$
II $\epsilon \sim 5\%$
80 BGO
 $\Omega \sim 80\%$
40 DE-E Si
(EUCLIDES)
Plunger
N-detectors
RFD ...

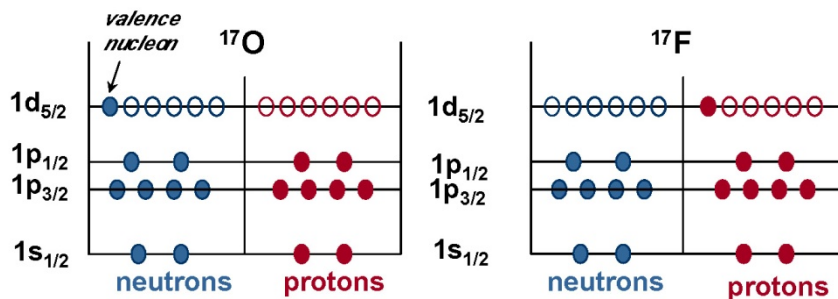
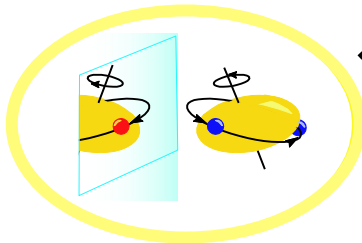
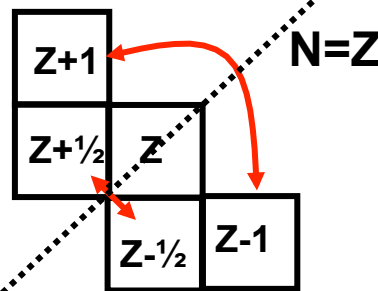
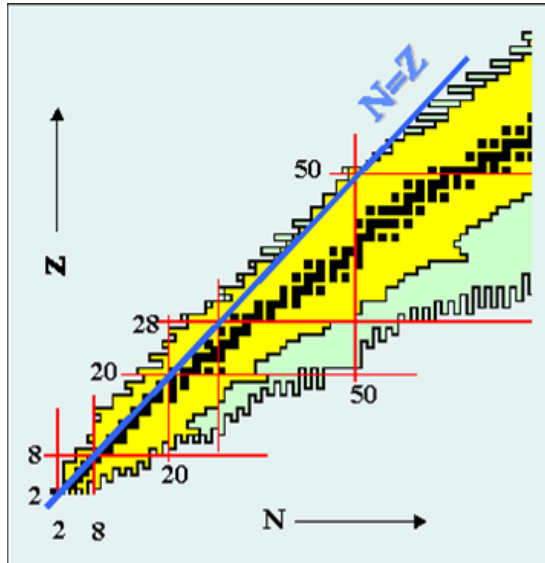


EUROBALL with Ancillary Detectors

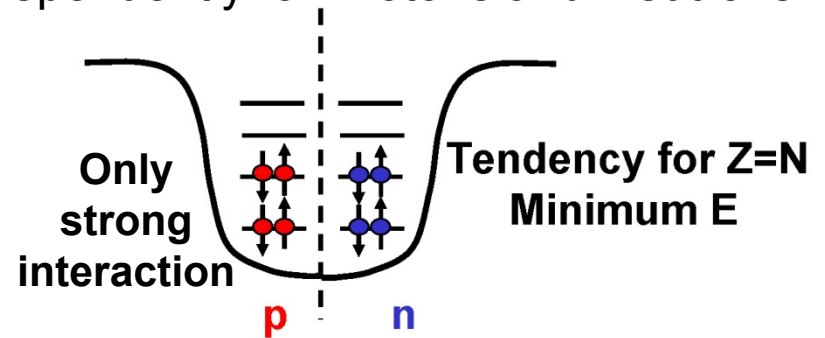


Mirror Symmetry in nuclei

Isospin symmetry is only approximate in strong interaction

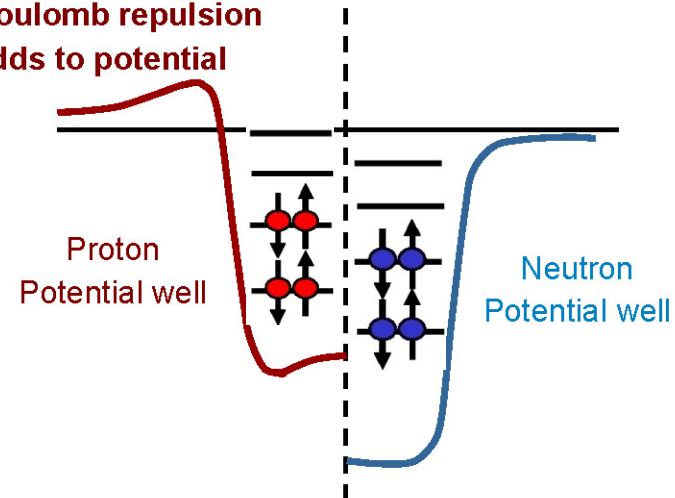


The Pauli principle operates independently for Protons and Neutrons



In reality

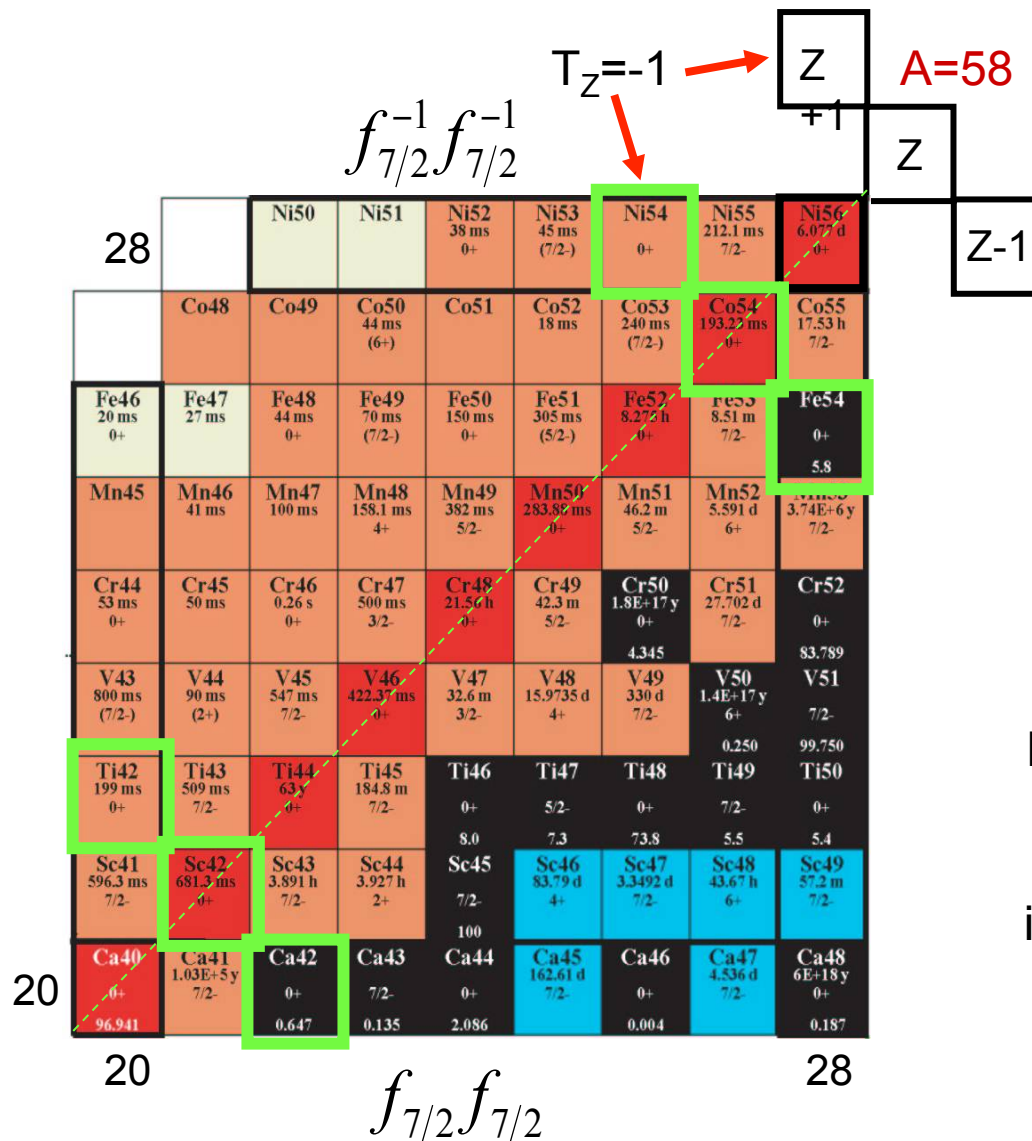
Coulomb repulsion adds to potential



Mirror energy differences

From odd mirror nuclei is possible to get the isovector energy differences.

From mass triplets is possible to get both isovector and isotensor..



•MDE (Mirror Displacement Energies): binding energy difference between mirror nuclei ($MDE = BE(Z, A_N) - BE(N, A_Z)$).
→ from few to tens of MeV.

•MED (Mirror Energy Differences): differences in excitation energies of yrast bands in mirror nuclei ($MED_J = E_J(Z+2T, A_{N-2T}) - E_J(Z-2T, A_{N+2T})$). → from tens to hundreds of keV.

Due to shell effects coming from the Coulomb and Isospin symmetry breaking potentials.

For a $T=1$ triplet:

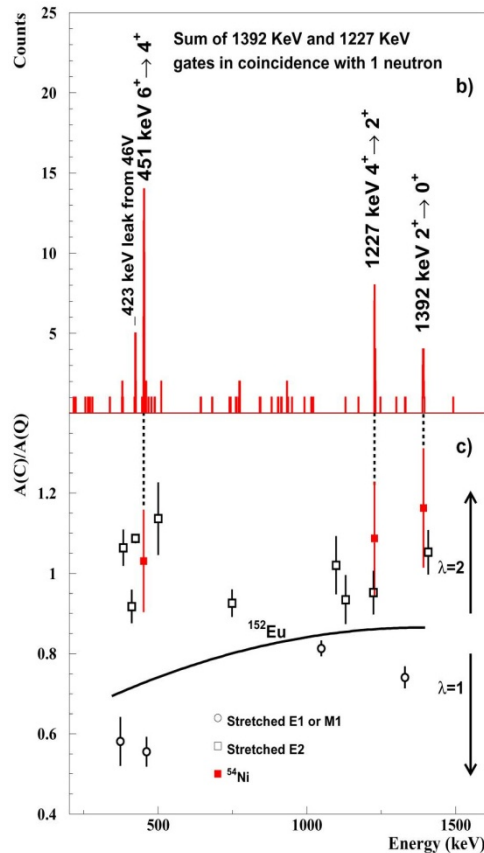
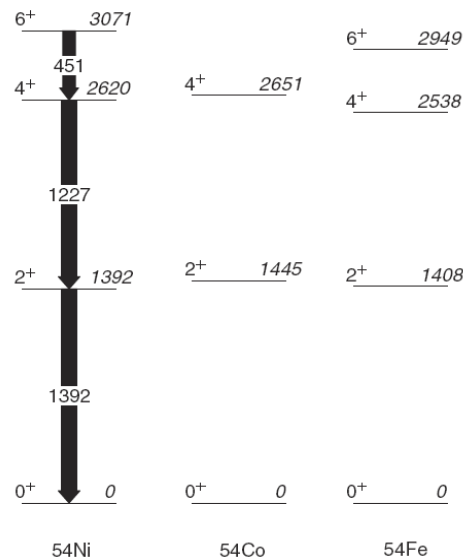
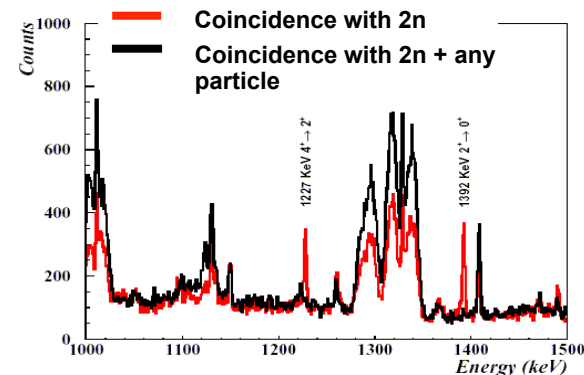
$$MED_J = E_J(Z+1) - E_J(Z-1)$$

information on CSB terms ($V^{pp} - V^{nn}$)

$$TED_J = E_J(Z+1) + E_J(Z-1) - 2E_J(Z)$$

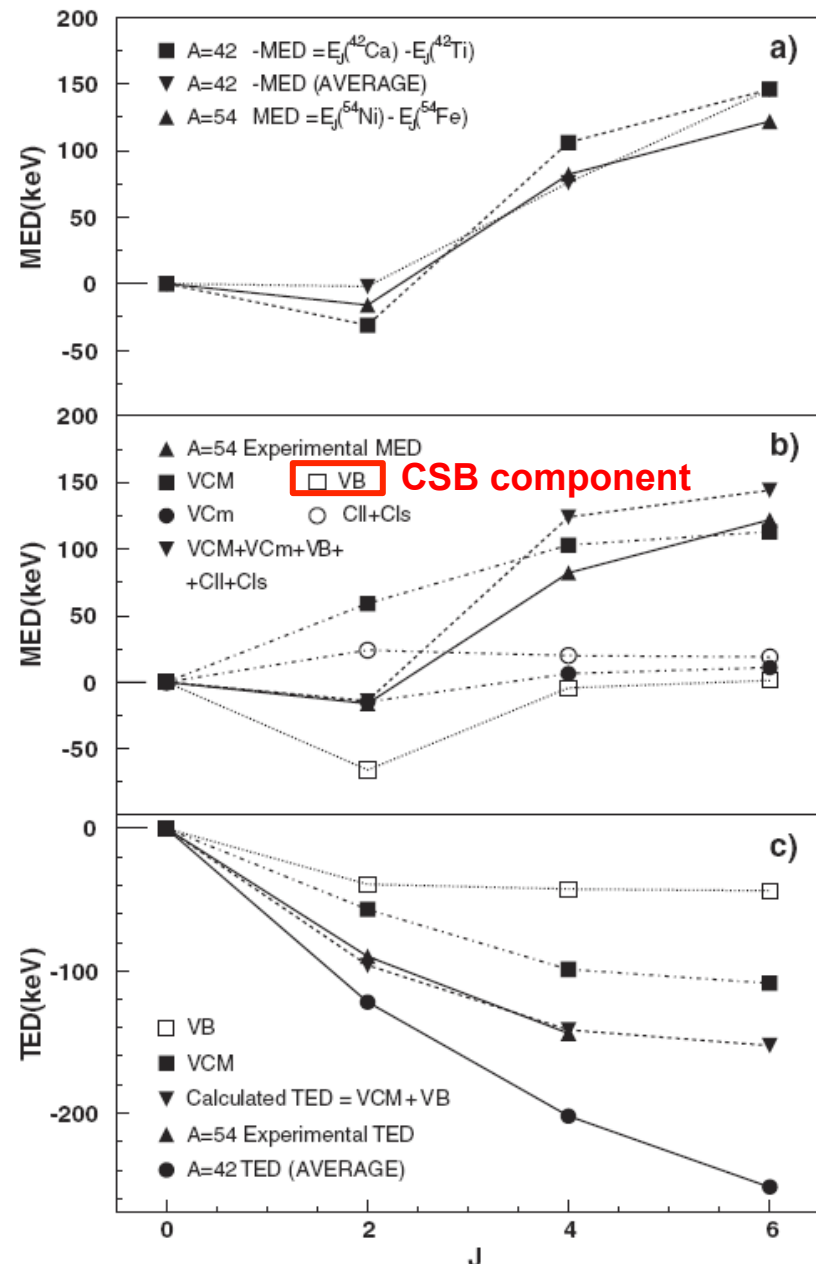
information on CSB & CIB (V^{pn}) terms

MED and TED in the A=54 Triplet



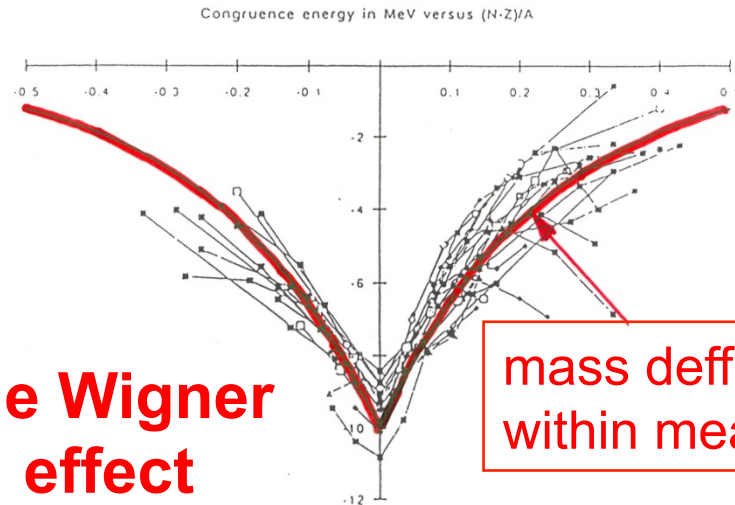
Conclusions:

- Good agreement with the $A=42 \rightarrow \text{CCS}$ works!!!
- MED trend mainly due to V_{CM} and V_B
- The 2^+ anomaly present and of the same order for the $A=42$ and $A=54$
- **Required CSB component to reproduce**



Fingerprints of Proton-Neutron Pairing

W.D. Myers, W.J. Swiatecki / Nuclear Physics A 612 (1997) 249-261

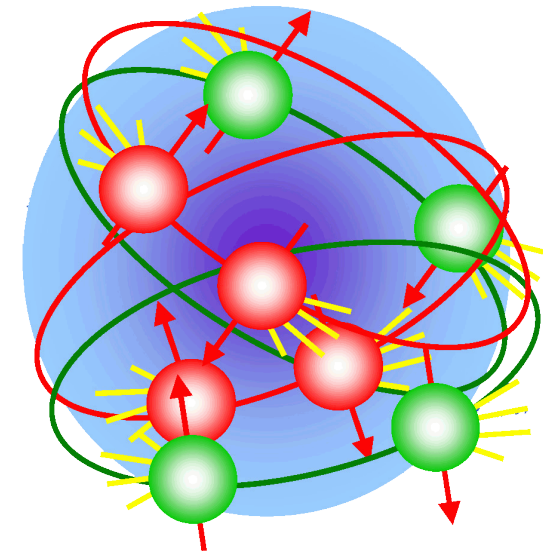
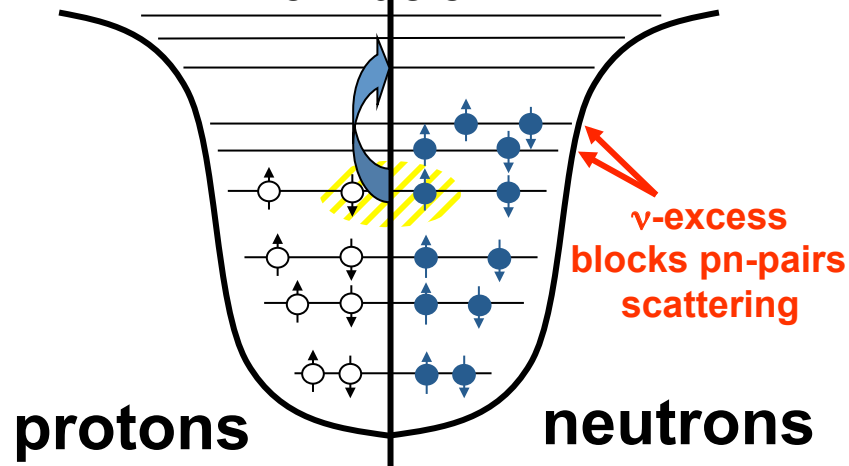


The Wigner effect

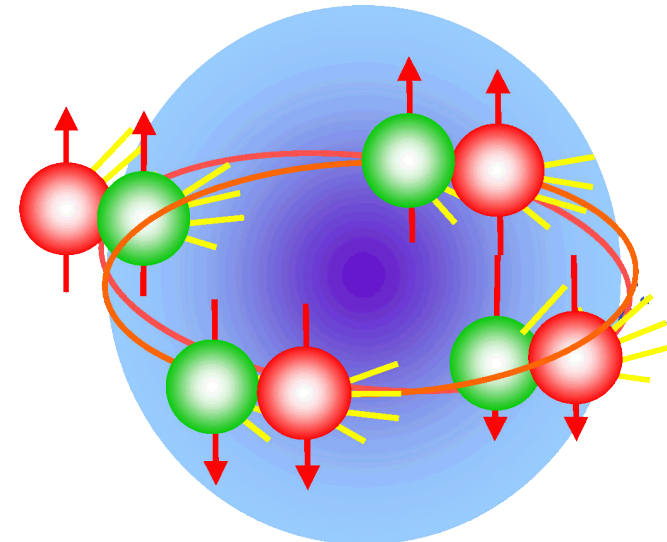
mass defect
within mean-field

Fig. 1. The difference between measured binding energies and those calculated using the shell- and pairing-corrected Thomas-Fermi model of Ref. [5]. The points (denoted by a variety of symbols) refer to the 28 isobaric chains with $A = 6, 8, \dots, 60$ that straddle the locus $N = Z$ in the chart of nuclei. The curve is the semi-empirical fit $C(I) = \sim 10 \exp(-4.2|I|)/\text{MeV}$.

**The pn-pairing effects vanish
for nuclei $N \neq Z$**



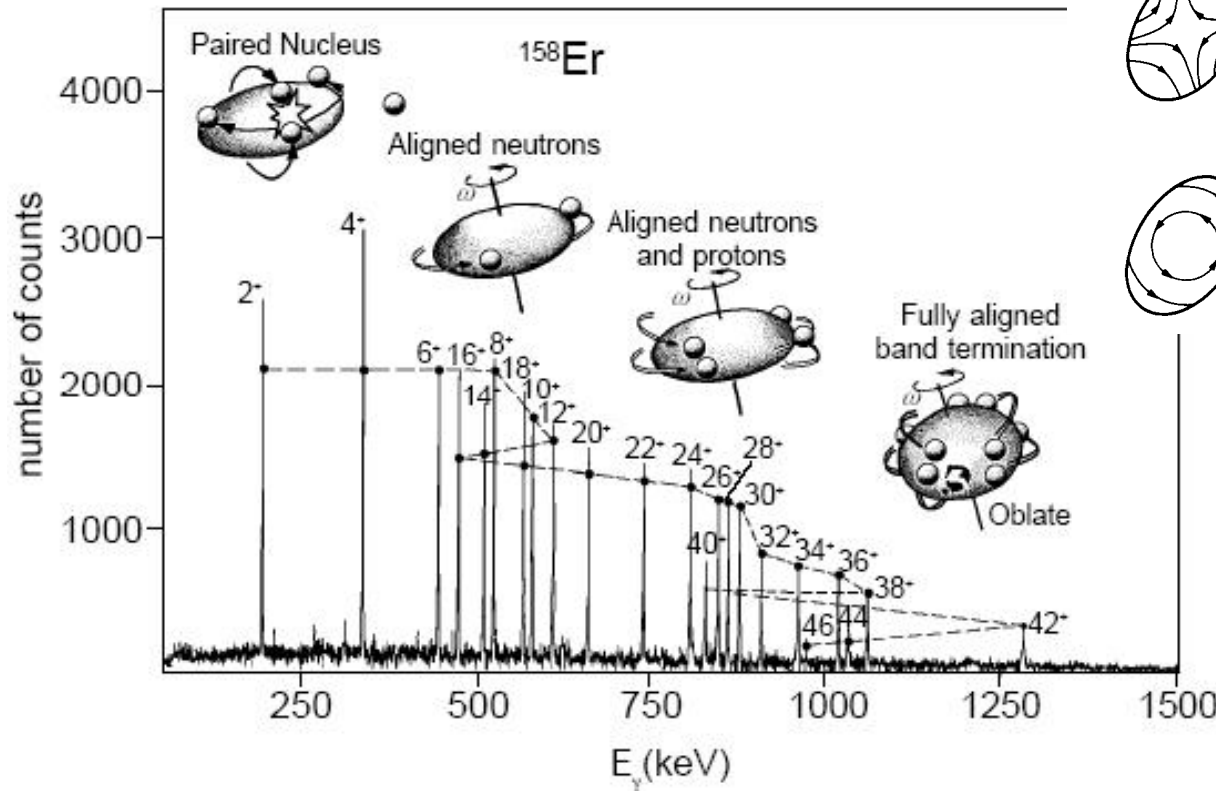
T=1 J=0 Pairing



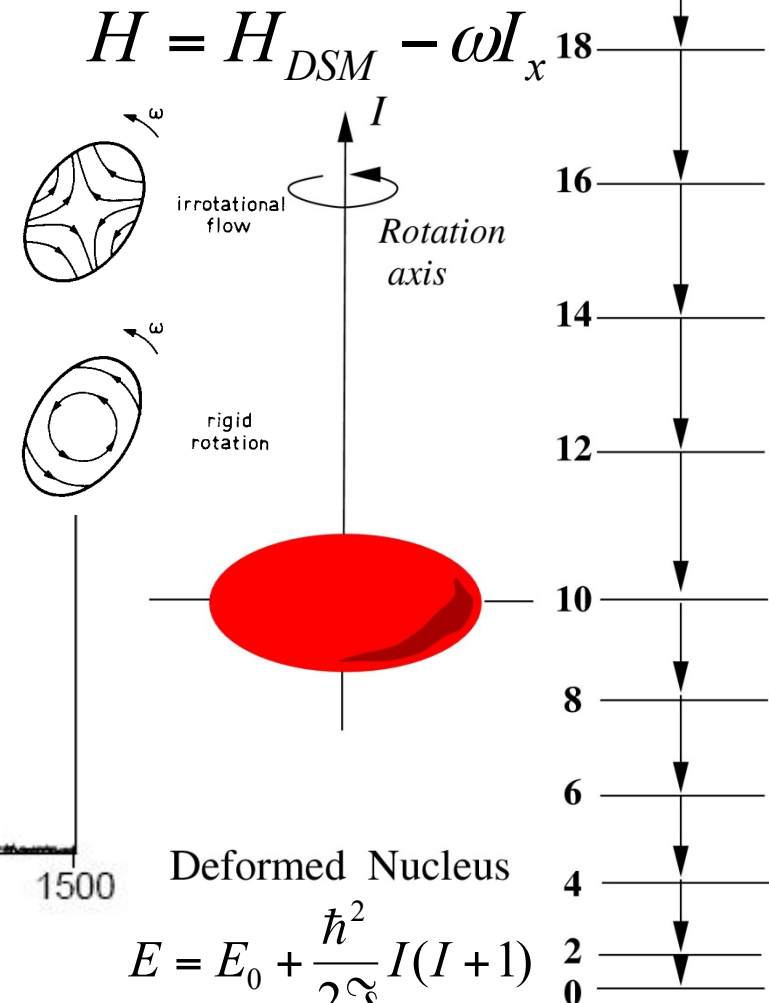
T=0 J>0 Pairing

Deformed Nuclei and Pairing

The “Backbending” phenomena:
nucleon pairs breaking and alignment



Proton-Neutron T=0 (J>0)
pairs do not need to break to
produce angular momentum:
→ Pairing preserved



$$E = E_0 + \frac{\hbar^2}{2\mathfrak{I}} I(I+1)$$

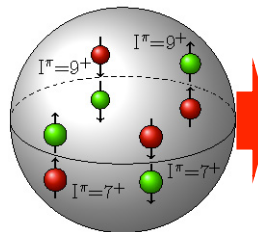
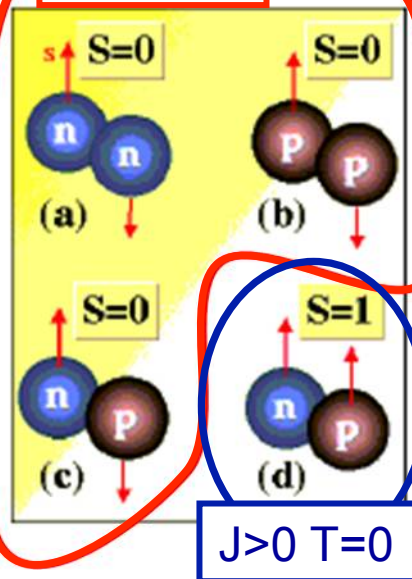
$$\omega = \frac{dE}{dI} \sim \frac{\Delta E}{\Delta I_x} = E_\gamma / 2$$

$$\mathfrak{I} = \frac{dI_x}{d\omega} \sim \frac{\Delta I_x}{\Delta E_\gamma} = \frac{2}{\Delta E_\gamma}$$

Isoscalar (T=0) proton-neutron pairing

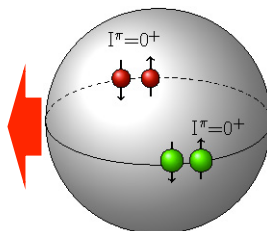
The Spin-Isospin symmetry family

$J=0 \ T=1$



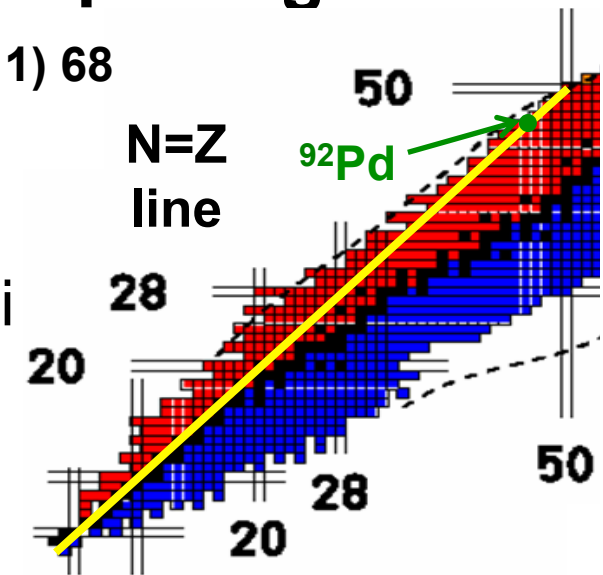
T=0 pair
Condensate

T=1 pair
Condensate



B. Cederwall et al., Nature 469 (2011) 68

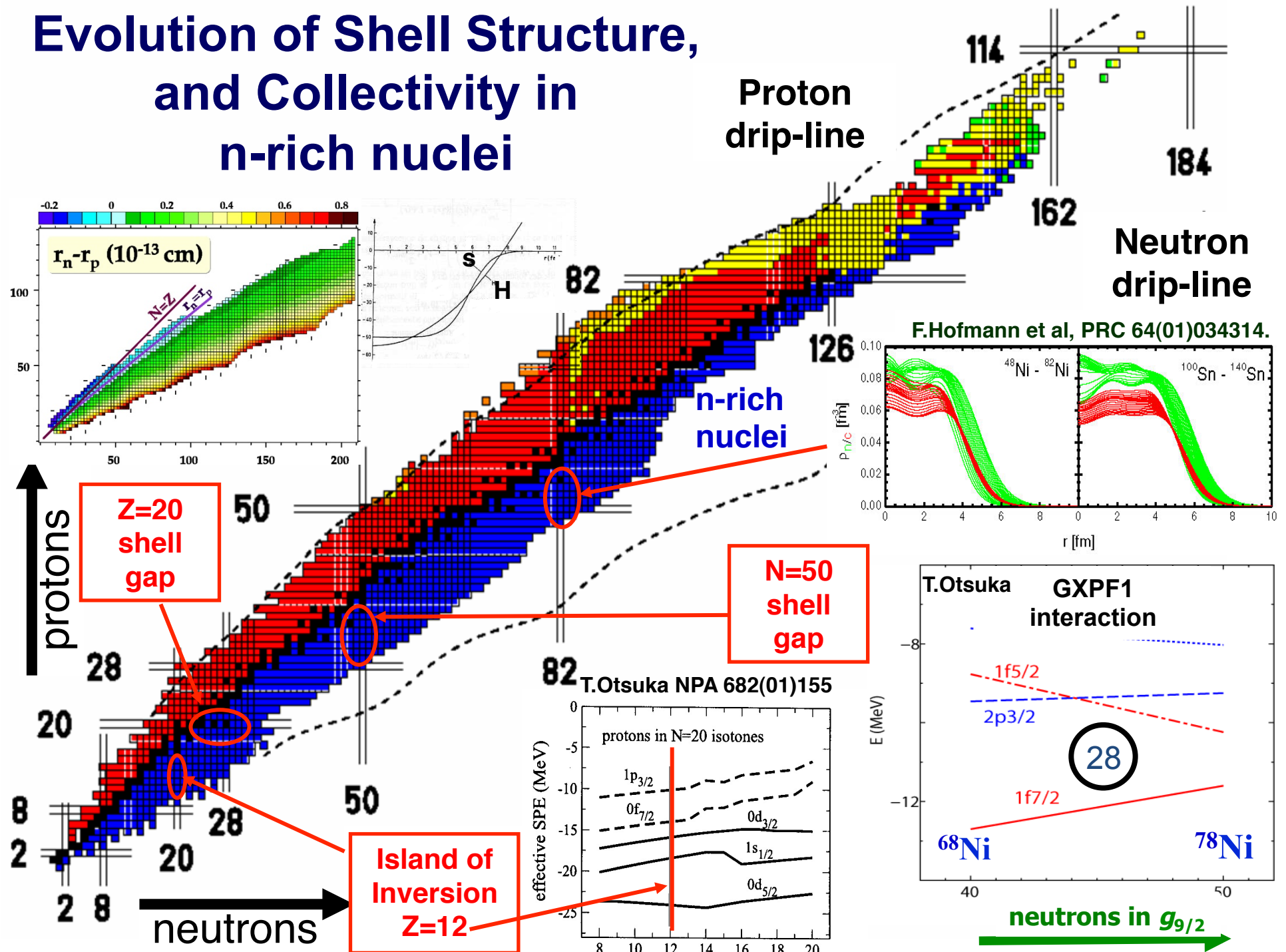
Pairing is a fundamental concept in nuclear physics. Since long heavy N=Z nuclei are seen as candidates to study phenomena related with the T=0 pairing.



Effects of p-n pairing in Structure: T=0 needed in SM

T=0+T=1 $8^+ \quad 3127$					T=1	
$(6^+) \quad 2536$	$6^+ \quad 2466$	$8^+ \quad 2600$	$8^+ \quad 2749$	$8^+ \quad 2633$	$8^+ \quad 2636$	$8^+ \quad 2530$
		$6^+ \quad 2110$	$6^+ \quad 2079$	$6^+ \quad 2212$	$6^+ \quad 2224$	$6^+ \quad 2099$
$(4^+) \quad 1786$	$4^+ \quad 1708$	$4^+ \quad 1518$		$4^+ \quad 1417$	$4^+ \quad 1460$	$4^+ \quad 1415$
			$2^+ \quad 1171$			
$(2^+) \quad 874$	$2^+ \quad 878$	$2^+ \quad 797$				
$0^+ \quad 0$	$0^+ \quad 0$	$0^+ \quad 0$	$0^+ \quad 0$	$0^+ \quad 0$	$0^+ \quad 0$	$0^+ \quad 0$
$^{92}\text{Pd}_{\text{exp}}$	$^{92}\text{Pd}_{\text{SM}}$	$^{92}\text{Pd}_{T=0}$	$^{92}\text{Pd}_{T=1}$	$^{92}\text{Pd}_{\text{no np}}$	$^{96}\text{Pd}_{\text{SM}}$	$^{96}\text{Pd}_{\text{exp}}$

Evolution of Shell Structure, and Collectivity in n-rich nuclei

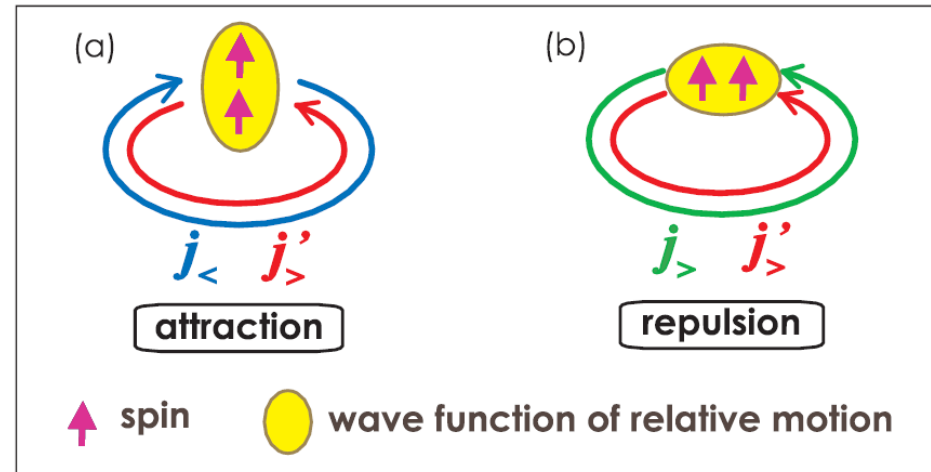
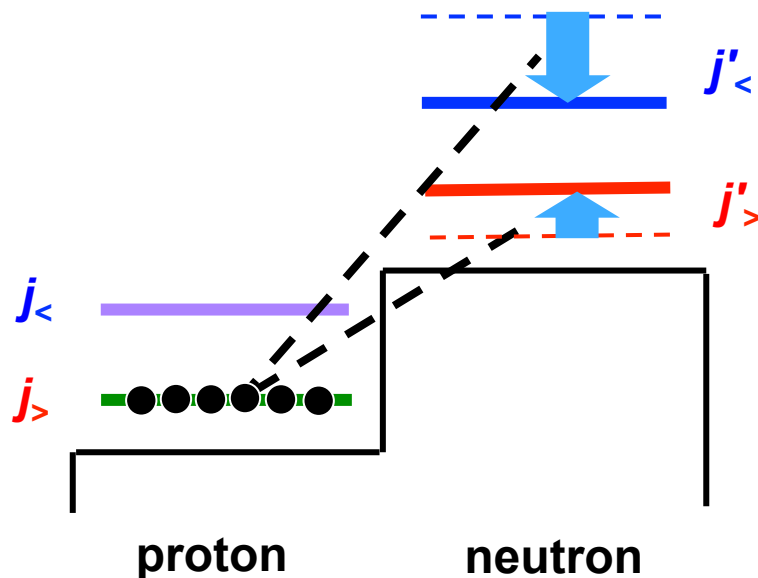


Monopole interaction

Tensor interaction ($\pi + \rho$ meson)
may be responsible for the
modification of the shell gaps

- Monopole energy of the tensor interaction $\sigma\tau$

$$V_{j,j'}^T = \frac{\sum_J (2J+1) \langle jj' | V | jj' \rangle_{JT}}{\sum_J (2J+1)}$$

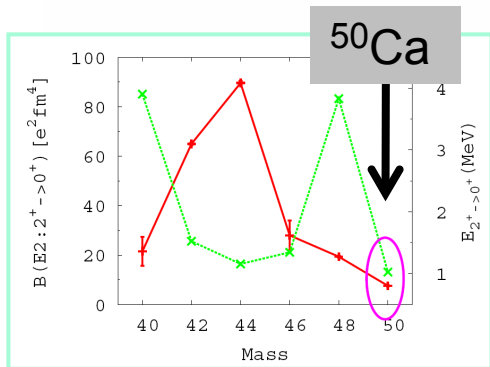


The single-particle orbits may migrate
leading to a possible change in shell
structure.

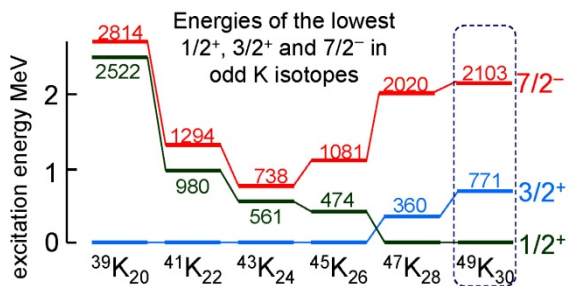
[Otsuka et al., *PRL* **95** (05) 232502]

[Otsuka et al., *PRL* **97** (06) 162501]

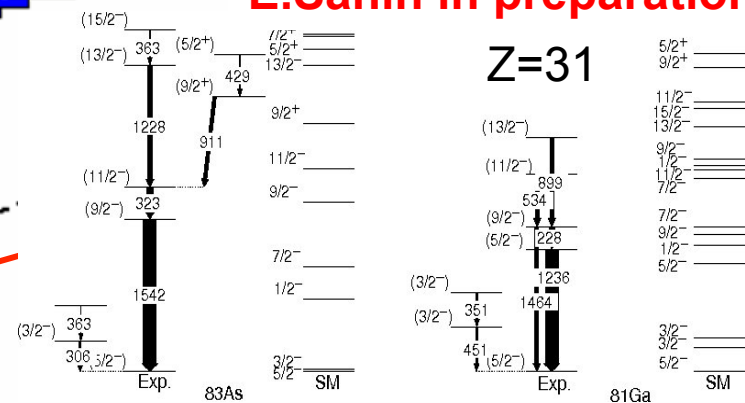
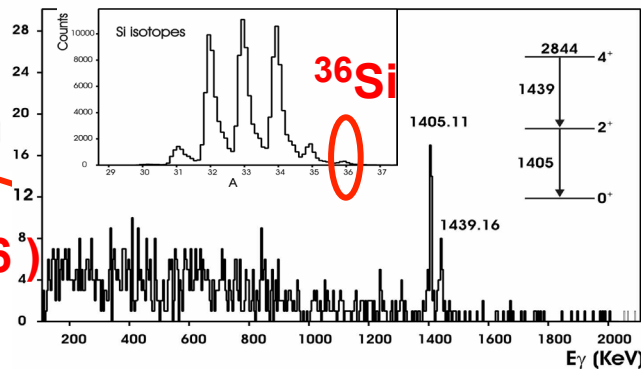
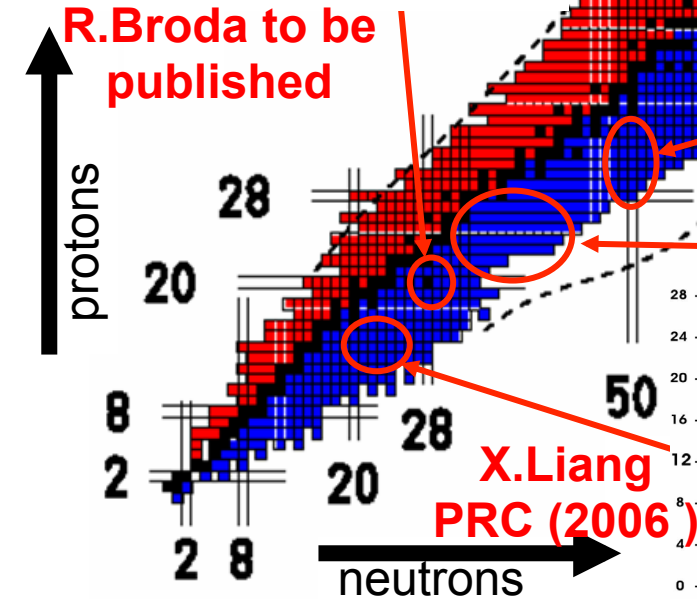
Nuclear Structure in n-rich nuclei



RDDS Lifetimes with the Köln Plunger



R.Broda to be published



S.M.Lenzi to be published

