Detectors for High Energy γ-rays

- Scintillator Detectors
- Arrays for Heavy Ion physics:
  - HECTOR (Low energy HI)
  - MEDEA (Intermediate Energy HI)
  - TAPS (Relativistic HI)

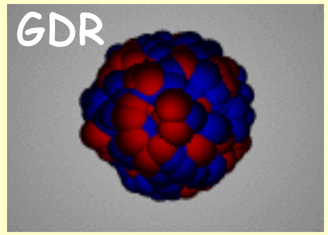
References

➡ **Hector:** A. Maj et al., NPA571(1994)185
➡ **Hector:** M. Mattiuzzi et al., NA612(1997)262
Multiplicity filter: M. Jaaskelainen et al. NIMA204(1983)385
➡ **Medea:** E. Migneco et al., NIMA314(1992)31
Medea: D. Santonocito & Y. Blumenfeld, Eur. Phys. J. A30(2006)183
➡ **Taps:** R. Novotny, IEEE38(1991)379
➡ **Taps:** A.R. Gabler et al., NIMA346(194)168
➡ **Taps:** N. Kalantar-Nayestanaki, NPA631(1998)242c
Taps: J.G. Messchendorp et al., PRL82(1999)2649

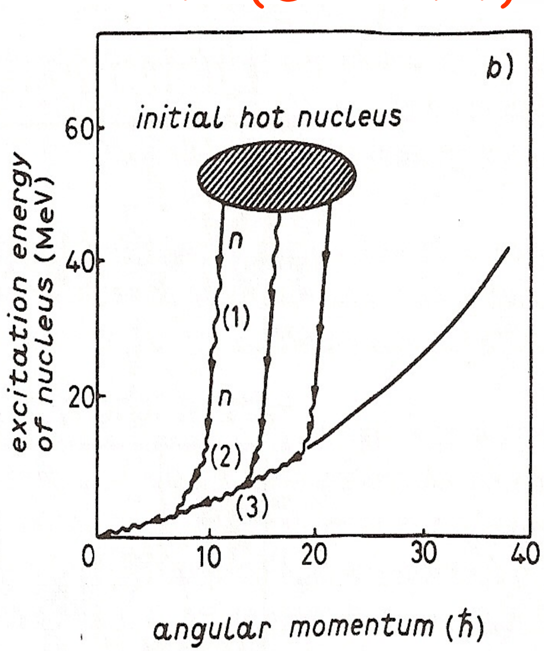
Detection of high-energy γ-rays E_γ>10 MeV

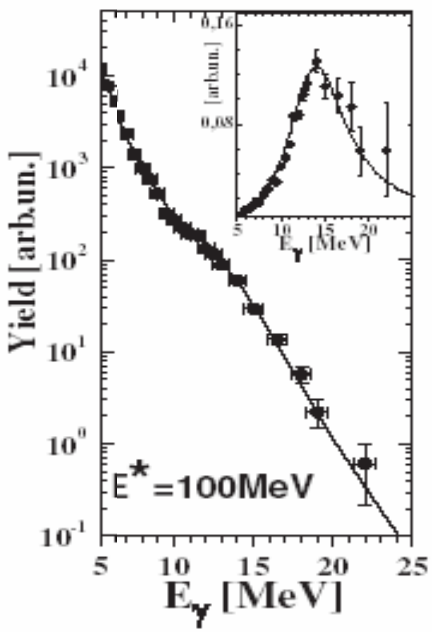
HOT Giant Dipole Resonance

- E_γ ~ 15 MeV
- FWHM ~ 5-7 MeV
- $P_\gamma/P_{part} \approx 10^{-3}$



^{64}Ni (@300MeV) + ^{68}Zn → ^{132}Ce





Experimental requests:

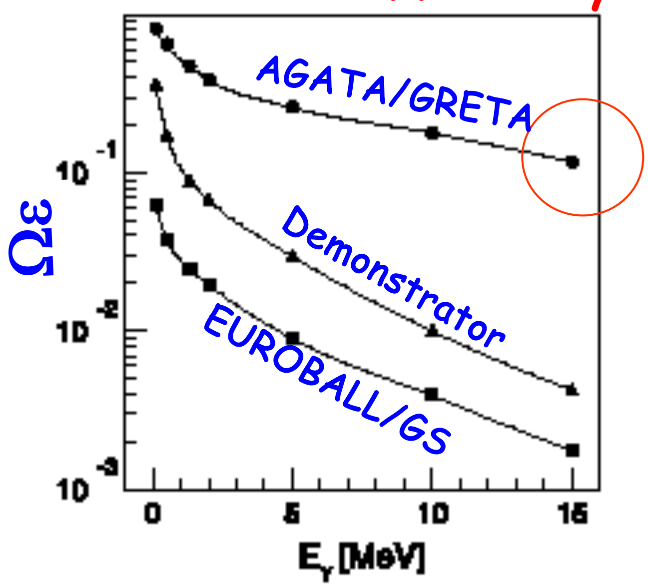
- High efficiency;
- n-γ discrimination;
- energy resolution (not crucial)

at present this can only be achieved with large volume scintillators

Ge Arrays (present status)

large photopeak efficiency
for high-energy γ-rays

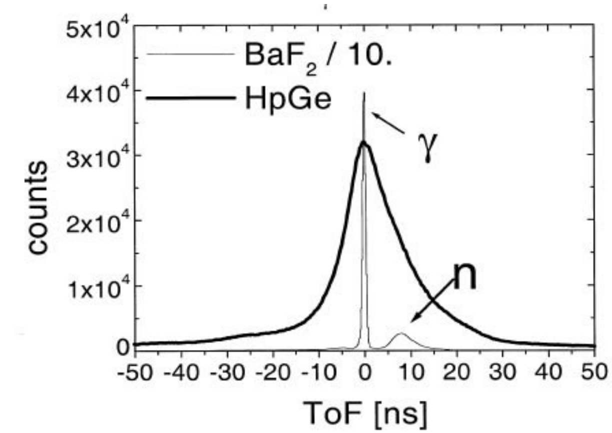
absolute efficiency



comparable wih scintillators arrays

NO γ-n discrimination

- TOF measurement: useless



- Pulse Shape Analysis: useless
  γ and n interactions in Ge produce electric signals with similar shapes

- tracking ? under study
  γ and n should produce different cluster of events

A. Atac et al., NIMA607(2009)554

BaF_2 : the most advantageous scintillator detector

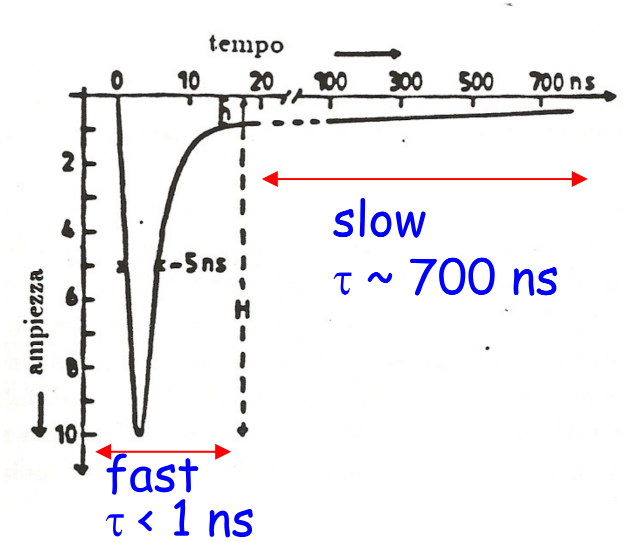
$\Delta E\gamma / E\gamma$ (^{60}Co) ≈ 11%
ΔT < 1 ns
ε_{ph} (15 MeV) ≈ 10%

- 80% light emission in visible
- Largest size: 14cm × 18 cm
  (Merk Factory, Darmstadt)

- Not fragile
- Not igroscopic
- Not damaged by neutrons

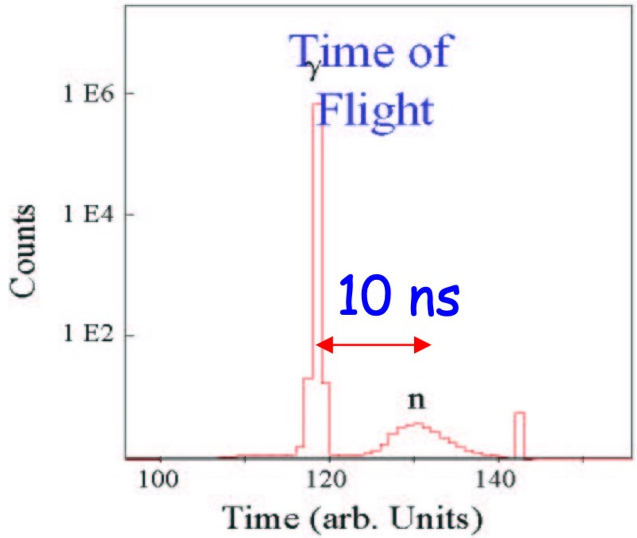
- <u>two components time signal</u>:
  fast (λ ~ 220 nm) τ < 1 ns
  slow (λ ~ 310 nm) τ ~ 700 ns

Fast signal ⇒ time measurement
Fast+Slow signal ⇒ energy



Cristallo	Densitá	ΔT (FWHM)	ΔE/E	Vol Max.
BaF_2	4.88	~ 0.4 ns	~ 11%	> 4 dm^3
NaI	3.67	~ 1.5 ns	~ 7%	> 4 dm^3
BGO	7.13	~ 5.0 ns	~ 15%	> 4 dm^3
HpGe	5.32	~ 3.0 ns	~ 0.2%	< 0.2 dm^3

- excellent n-γ discrimination by TOF



n energy	delay (after 30 cm)
2 MeV	~ 14 ns
4 MeV	~ 10 ns
6 MeV	~ 8 ns
10 MeV	~ 6 ns
14 MeV	~ 5 ns
20 MeV	~ 4 ns

CN neutrons (2 MeV, 4 MeV, 6 MeV)

very good timing (τ < ns) gives the possibility of using the detectors **closer** to the target ($\Rightarrow$ larger $\Omega \Rightarrow$ larger ε)

- low efficiency for neutron capture ($E_{neutron}$ ~ 2-5 MeV)

$$\sigma_n(NaI) \approx 10 \times \sigma_n(BaF_2)$$

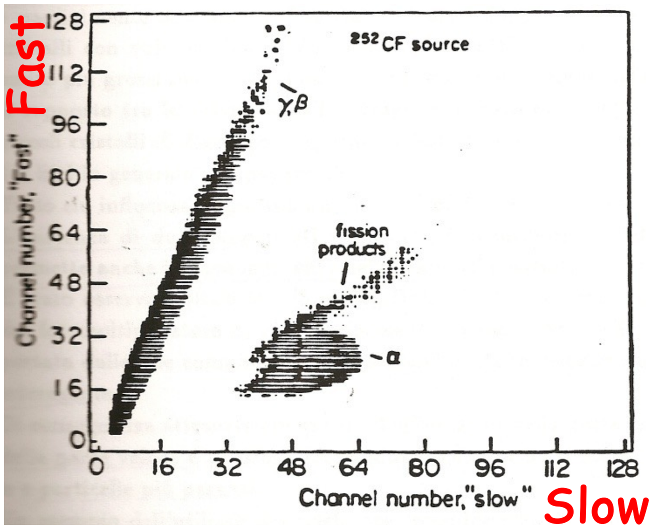
$\Rightarrow$ cleaner spectra with BaF_2

n-capture cross sections

Nucleo(%)	Q-value	$\sigma(1MeV)$	$\sigma(3MeV)$	$\sigma(4MeV)$	$\sigma(5MeV)$	$\sigma(14MeV)$
$^{137}Ba(12)$	8.5 MeV	9.22 mb	2.11 mb	- - -	- - -	- - -
$^{138}Ba(72)$	4.7 MeV	4.52 mb	1.07 mb	0.78 mb	- - -	1.10 mb
$^{23}Na(100)$	7.0 MeV	0.22 mb	- - -	- - -	- - -	0.33 mb
$^{127}I(100)$	6.8 MeV	52.8 mb	8.88 mb	- - -	2.89 mb	1.12 mb
$^{19}F(100)$	6.6 MeV	0.1 mb	- - -	- - -	- - -	- - -

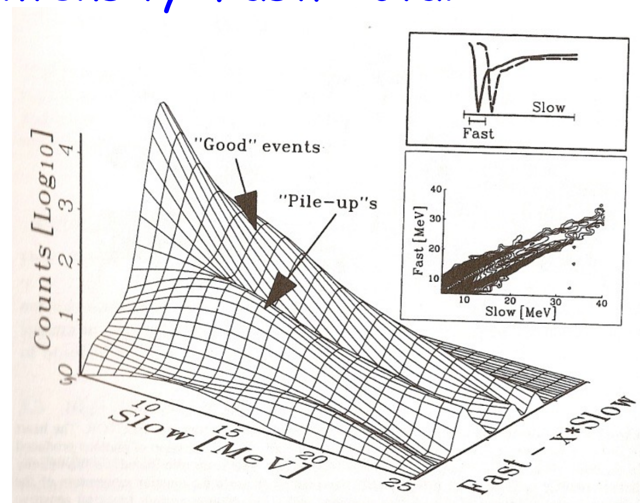
- **particle identification:**

pulse shape of **fast** and **slow** components depends on the type of interacting particles



- **pile-up rejection:**

piled-up events have a different ratio of intensity Fast/Total



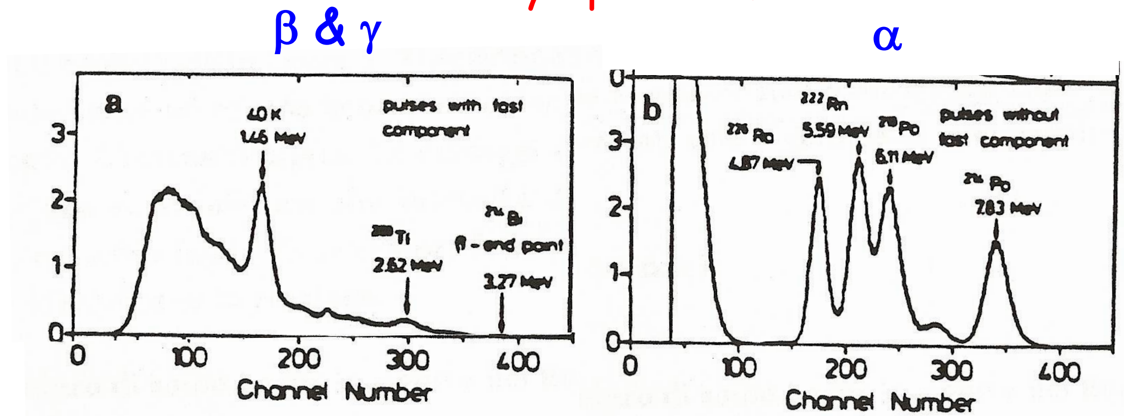
when operating in **air**, charge particles contribution is modest and pulse-shape discrimination is used for **pile-up rejection**

- **internal radioactivity:**

BaF_2 contains small % of Ra
(typically 600cts/l)

it can be used for calibration
(Energy < 8 MeV)

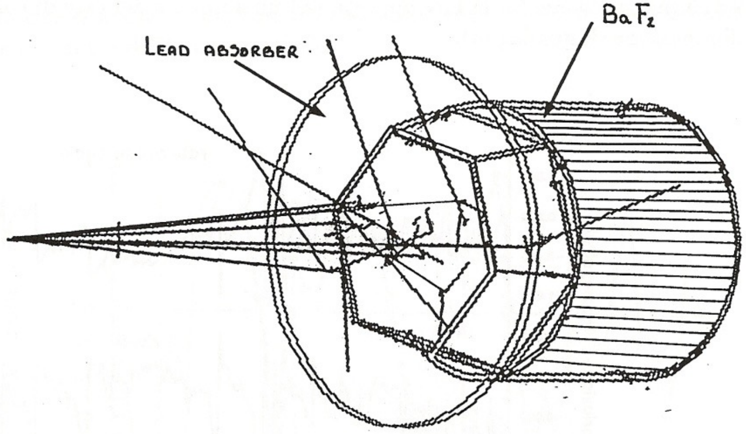
internal radioactvity spectrum AFTER PSA

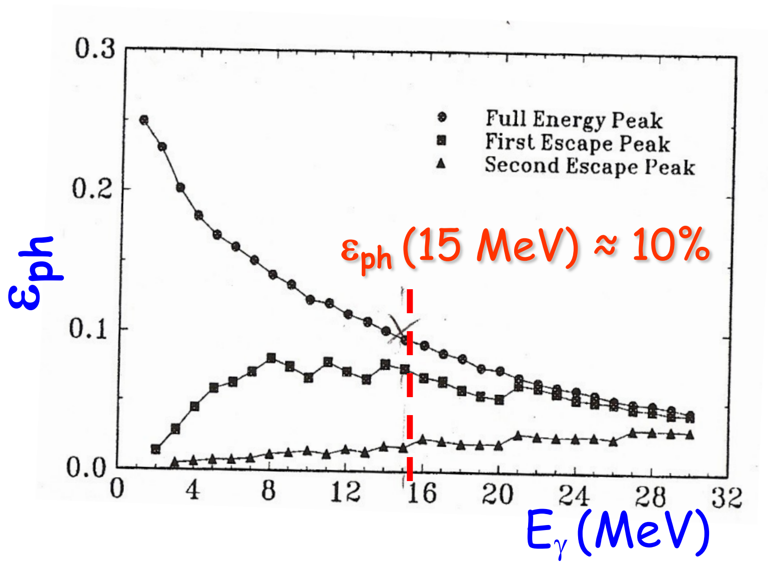


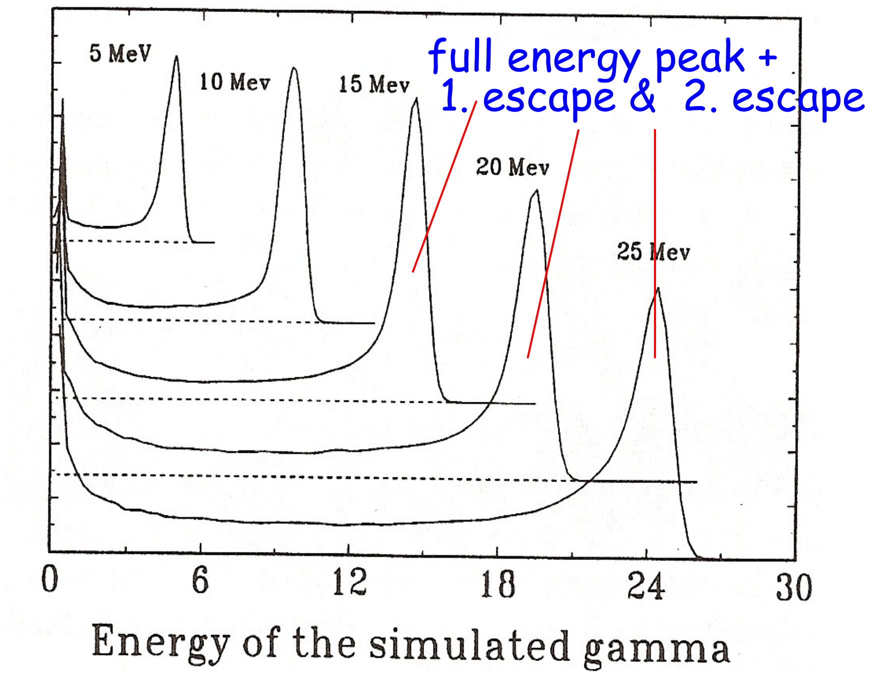
- efficiency & response function:

the γ-ray interactions in the BaF_2 detector can be simulated by the MonteCarlo code GEANT based on

- type of crystal (Z, A, ρ, … of BaF_2)
- detector geometry: Ø= 14.5 cm, L = 17.5 cm
- surroundings materials:
  housing: C&H 2mm, r~1 g/cm³
  absorbers: Pb, 6mm thick
- source distance: 30 cm
- energy resolution: ~ $1/\sqrt{E_\gamma}$
  (extrapolated from meaured values)



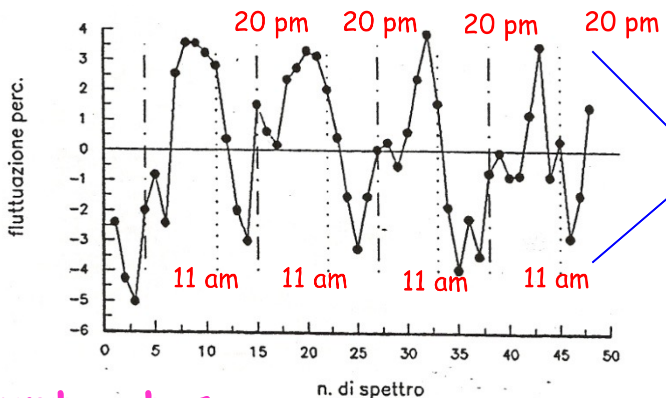




- energy gain fluctuations:

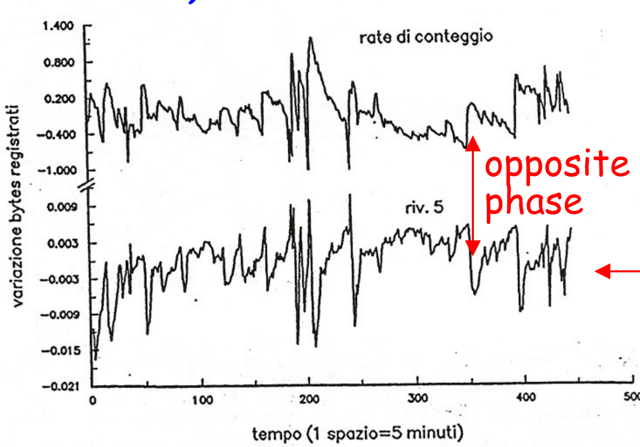
fluctuations in **temperature** and **count rate** are sources of instability in the energy gain

temperature:
change of chemical/physical properties of BaF_2 (transparency) and photocatods + dinodes (amplification factor)



4%

count rates:
plasma formation among last dinodes
(⇒ E decrease)



gain monitor
[count rate fluctuations]

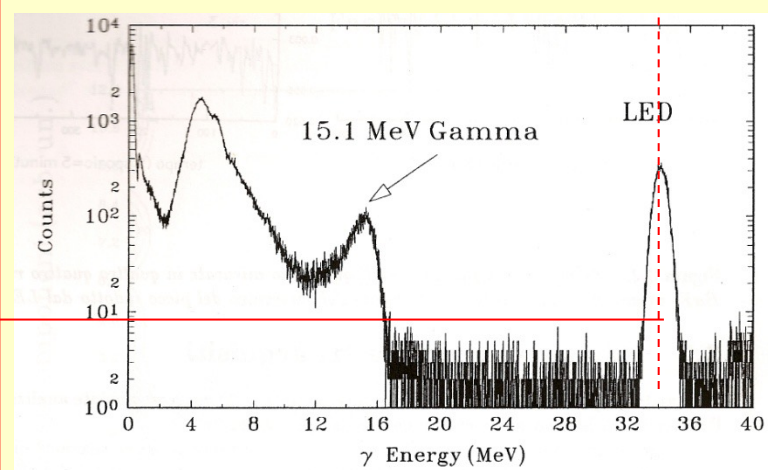
LED source

$\nu \sim$ 1 Hz - 10 kHz
$\lambda \sim$ 568 nm
$E_\gamma \sim$ 25-30 MeV ←

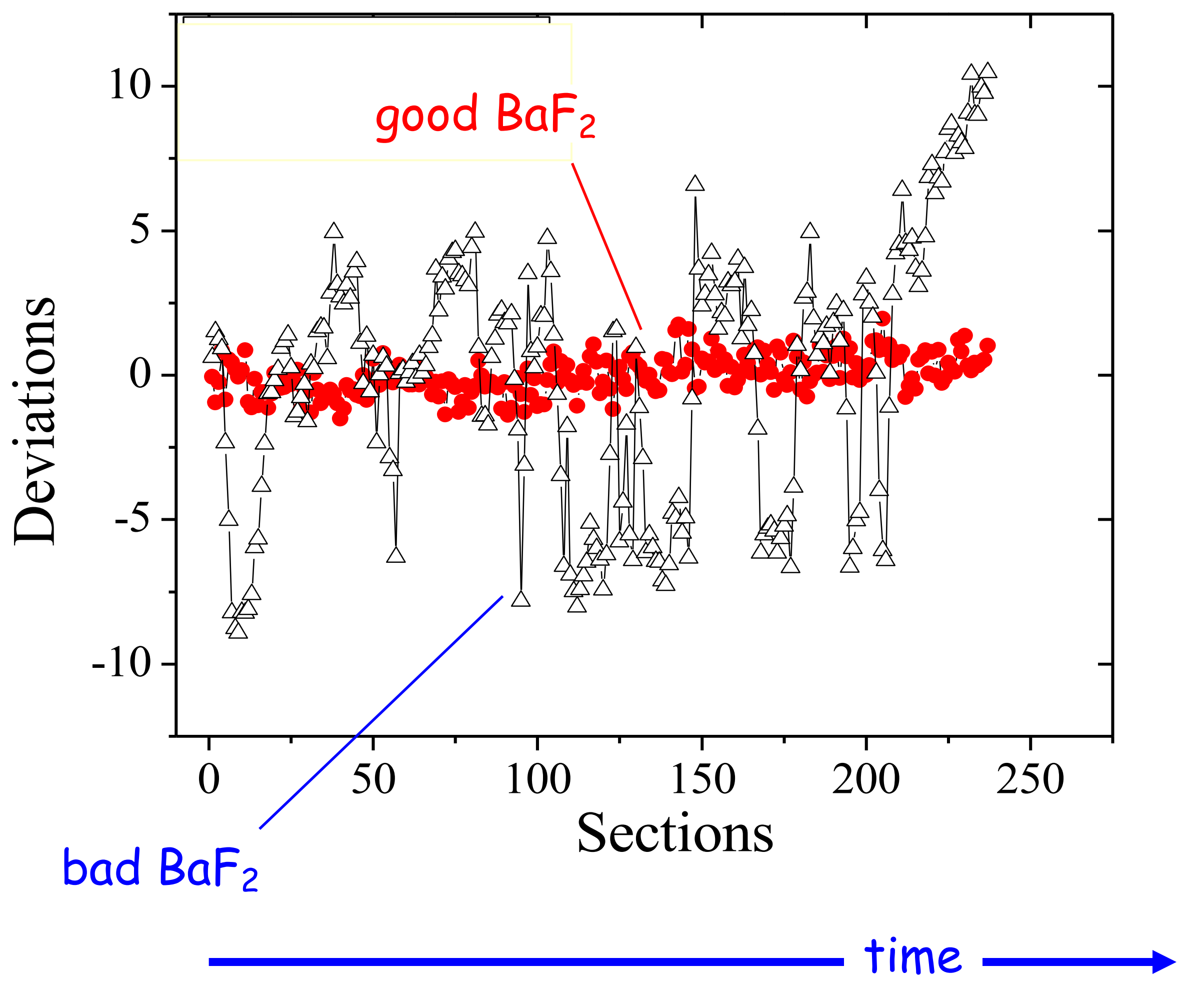
calibration spectrum

$^{11}B + {}^{2}D \rightarrow {}^{12}C^* + n$

γ-decay of ^{12}C:
- 15.1 MeV (M1, 90%)
- 17.1 & 4.4 MeV (2%)



LED gain monitor



Large Volume Scintillators can be used as:

- **Dedicated arrays:**

  - HECTOR (Low-energy Heavy-Ions : $E_{beam} \sim 5$ MeV/A)
  - MEDEA (Intermediate Energy Heavy-Ions: $E_{beam} \sim 20$-40 MeV/A)

    ➔ evolution of collective motion (GDR) with excitation energy

  - TAPS (Relativistic Energy Heavy-Ions: E_{beam} up to 1 GeV/A)

    ➔ reaction dynamics with relativistic heavy ions

- **Ancillary detectors:**

  - Large BaF_2 in EUROBALL/AGATA

    ➔ Hot GDR built on specific residues
    (i.e. superdeformed nuclei)

Dedicated Arrays: HECTOR

GDR studies (E_γ= 10-25 MeV)

Moderately excited CN

E*~ 30-100 MeV, T ≤ 4 MeV

low energy region

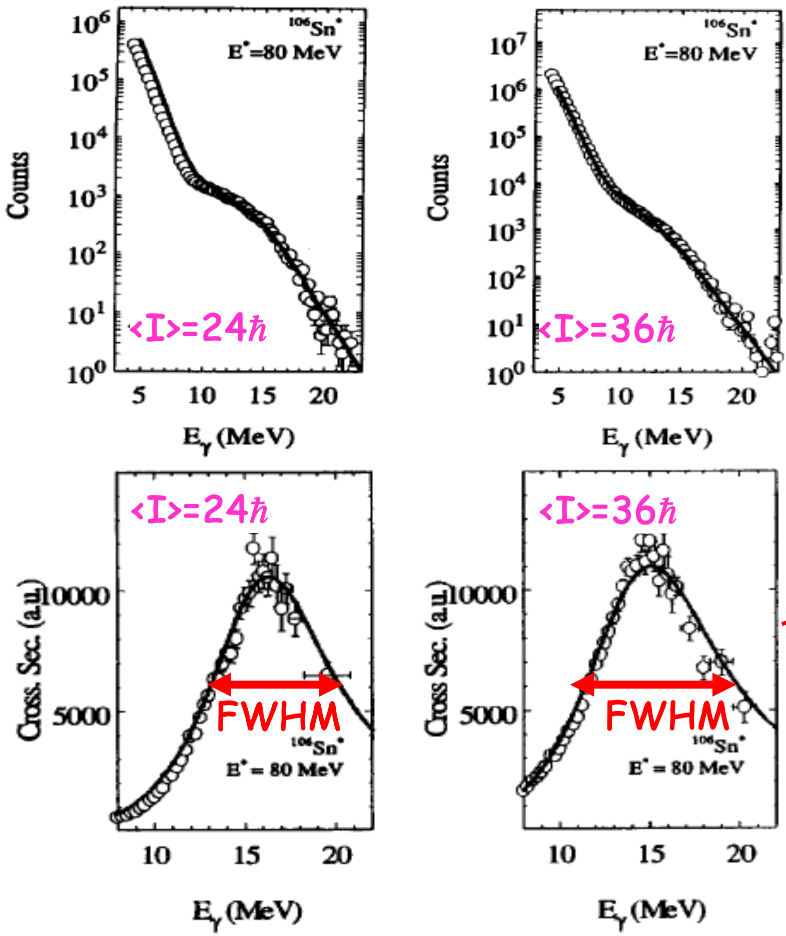
E_{beam} ~ 5 MeV/A

complete fusion reactions

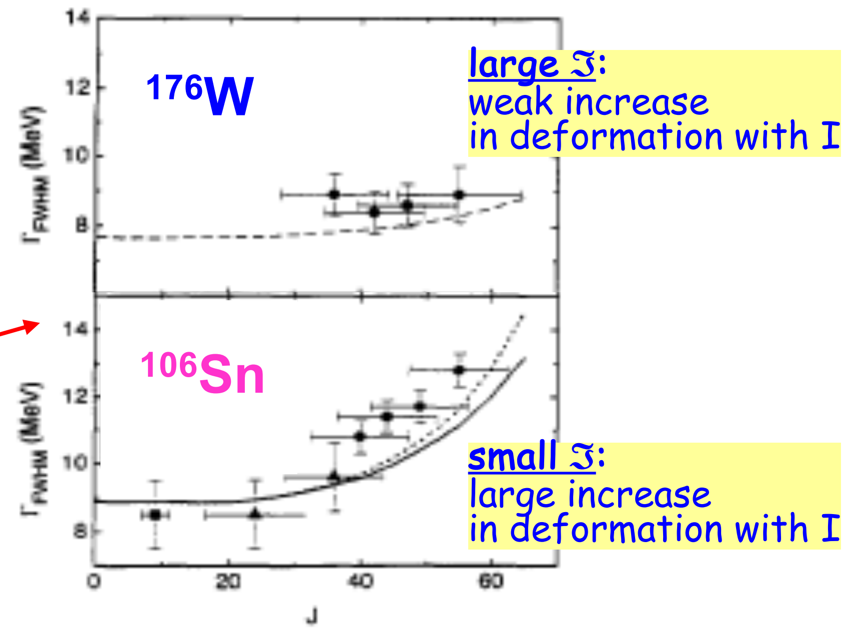
- small variety of emitted particles
  γ-rays, n, p, α
- small energy range
  ~ 1- 25 MeV

^{58}Ni (@260MeV) + ^{48}Ti

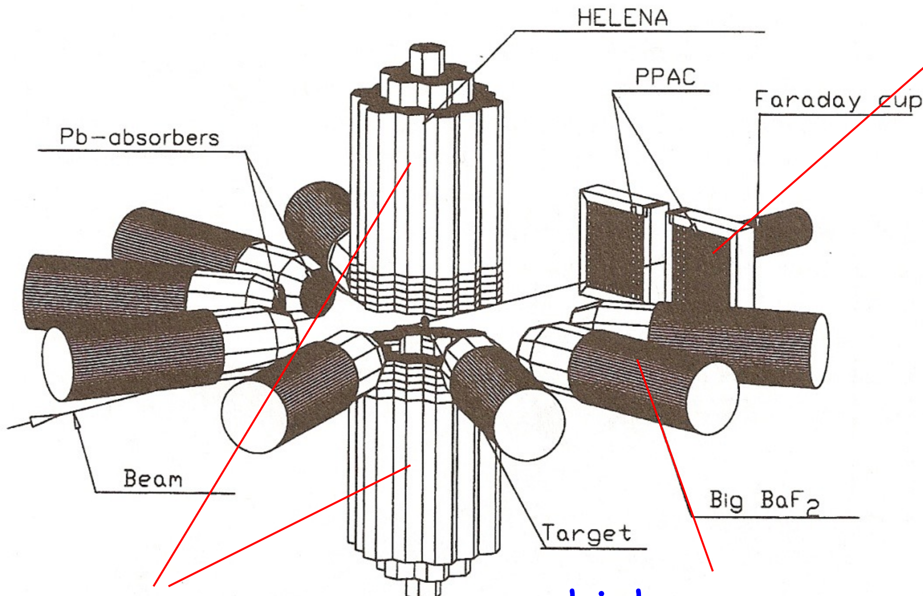
→ ^{106}Sn (E*=80MeV, T~1.8MeV)



Angular Momentum Dependence of GDR width



HECTOR
High Energy Detector (NBI-LNL)



heavy charged fragments

PPAC: gas counter
position sensitive
parallel plate
avalanche counters

low-energy γ-rays

Helena: 38 small BaF_2
Ø= 5.06 cm, L = 7.62 cm
exagnal base
Δt~350 ps

Tipo Fotocatodo	Bialk/B
ø Fotocatodo	~ 51 mm
Numero Dinodi	10
Tempo di Salita	1.3 ns
Tempo di Transito	28 ns
Sensib. Spettrale	150 - 600 nm

Ω_{total} > 90%

high-energy γ-rays

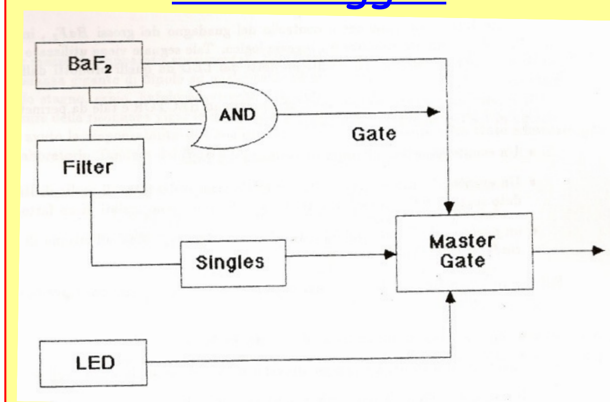
Hector: 8 Big BaF_2
Ø= 14.5 cm, L = 17.5 cm
Δt~600 ps
LED gain monitor

Tipo Fotocatodo	Bialk/B
Dia. Fotocatodo	~ 130 mm
Numero Dinodi	14
Tempo di Salita	2.7 ns
Tempo di Transito	55 ns (FWHM 3.8 ns)
Sensib. Spettrale	150 - 600 nm

Ω_{total} ~ 10%

Master Gate

main trigger

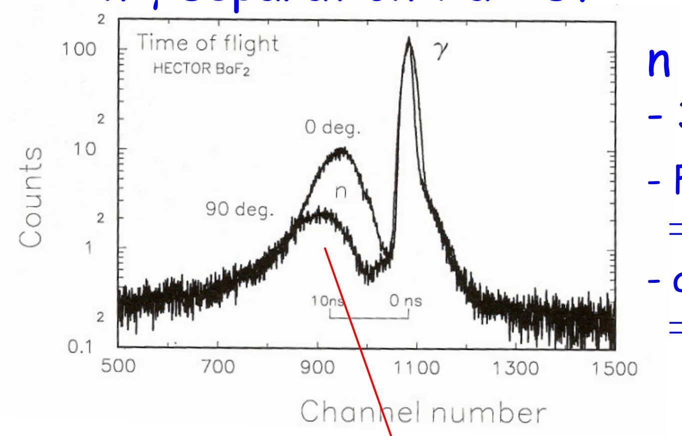


accepted events:

≥ 1γ in Hector (GDR)
.AND.
≥ nγ in Helena
(rotational cascade)

HECTOR: detection of high-energy γ-rays

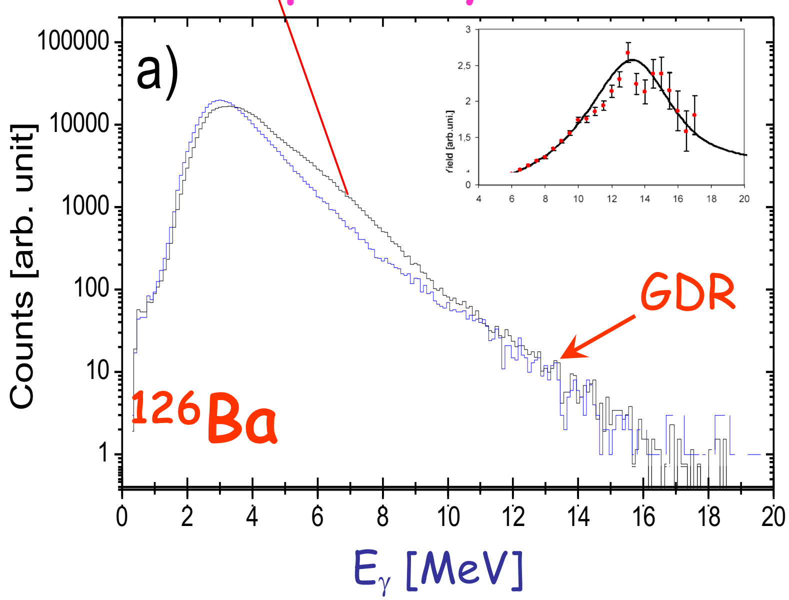
n-γ separation via TOF



n peak:

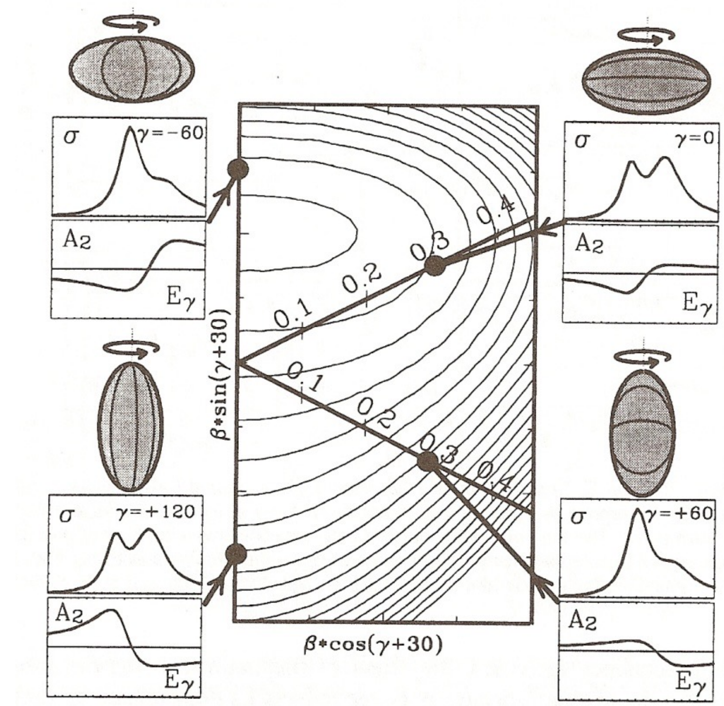
- 30% of total events
- FWHM
  ⇒ n's velocity distribution
- angular distribution
  ⇒ kinematic effect

Line-shape analysis: E_{GDR}, Γ_{GDR}



angular distribution: $a_2(E_\gamma)$

$$W(E_\gamma) = W_0[1 + a_2(E_\gamma)P_2(\cos\theta)]$$



measurements of γ-ray spectra at **different angles** allows to deduce

- nuclear shape
- nuclear orientation

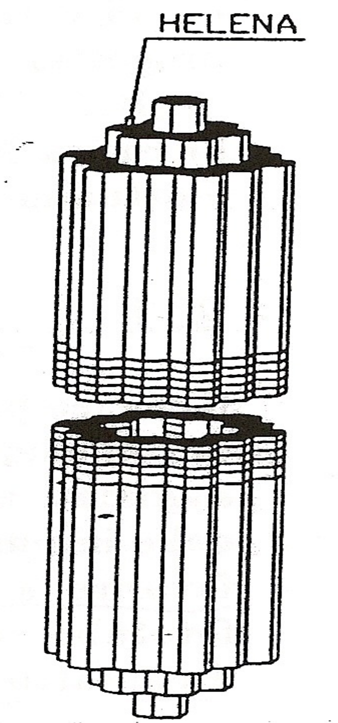
(collective or non collective rotation)

HELENA: detection of low-energy γ-rays

multiplicity filter

4π geometry

crucial to avoid selection of γ-rays
with specific oriented angular momentum



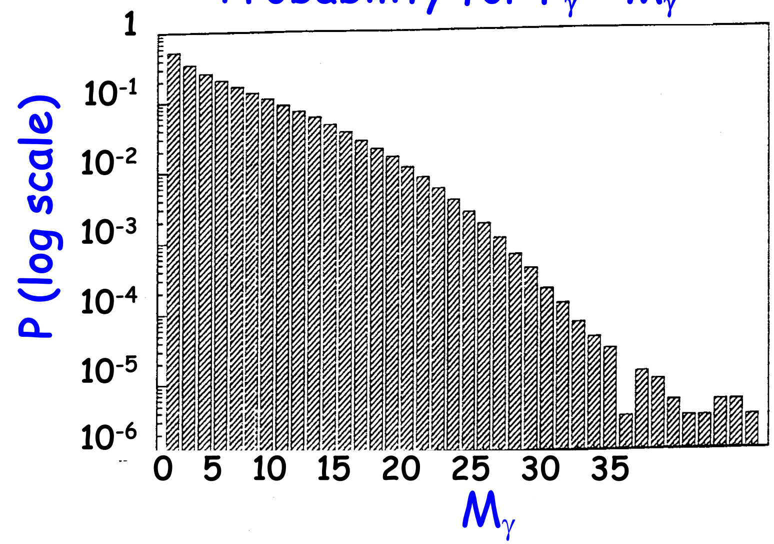
Fold F_γ
(# of γ detected)
↓
Multiplicity M_γ
(# of γ emitted)
↓
Spin I

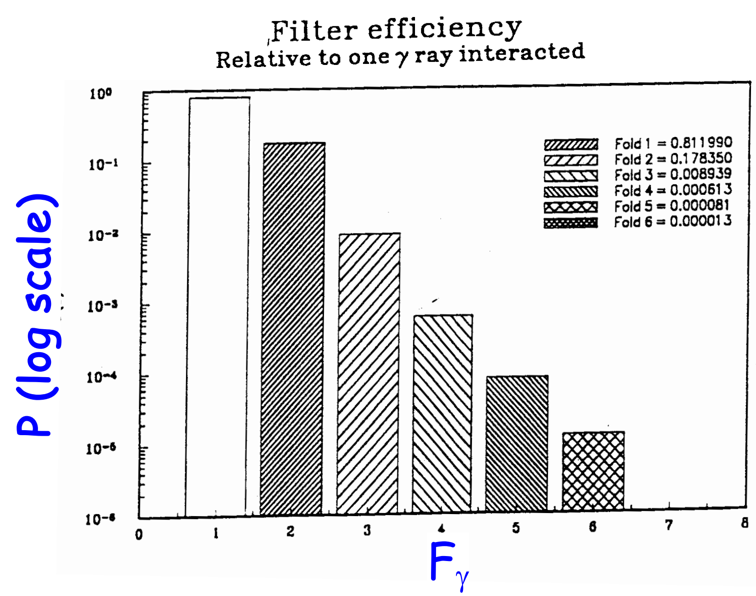
$$I = 2 \times M_\gamma + C$$

particle contribution

2 hemispheres of
3 rings of 1, 6, 12 detectors
38 detectors
honeycomg geometry

Probability for $F_\gamma = M_\gamma$



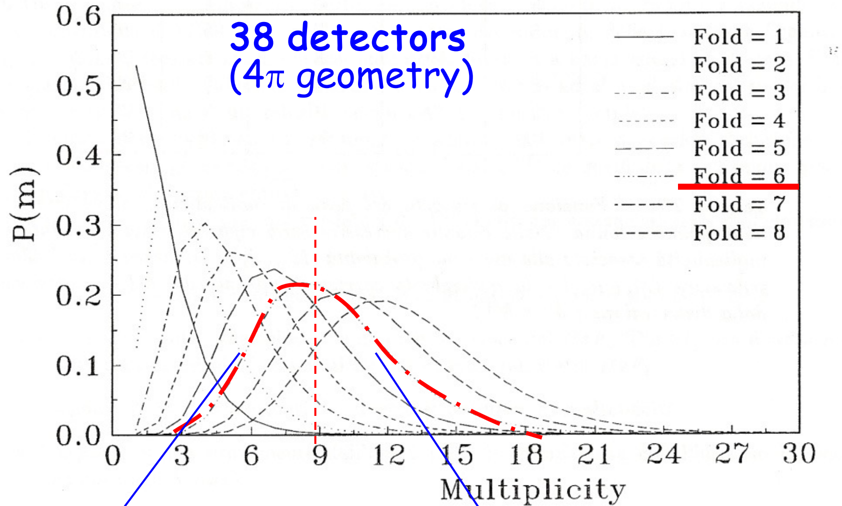


➔ *detailed study of F_γ vs. M_γ is needed*

HELENA: multiplicity filter response

multiplicity distribution

^{60}Co calibration



Fold	M_{max}	M_{FWHM}
1	1	3
2	2	5
3	4	5
4	5	6
5	7	6
6	9	7
7	10	8
8	12	9
9	13	10
10	15	11

low-M_γ tail

$F_\gamma > M_\gamma$

- spurius signals
  (i.e. evaporated n's, ...)
- multiple
  Compton scattering

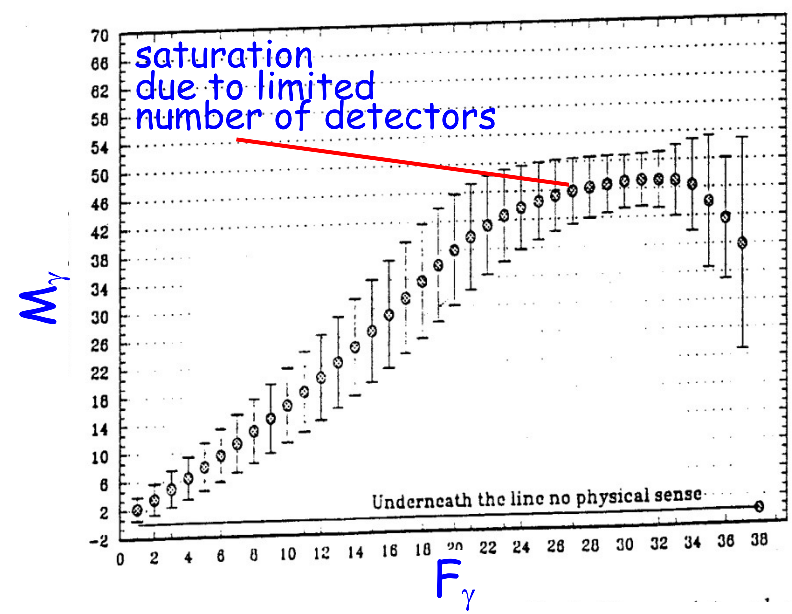
high-M_γ tail

$F_\gamma < M_\gamma$

since $P(F_\gamma = M_\gamma) < 1$

- $\Omega < 4\pi$
- $\varepsilon_{ph} < 100\%$
- $E_\gamma <$ electronic threshold
- multiple hits in 1 detector

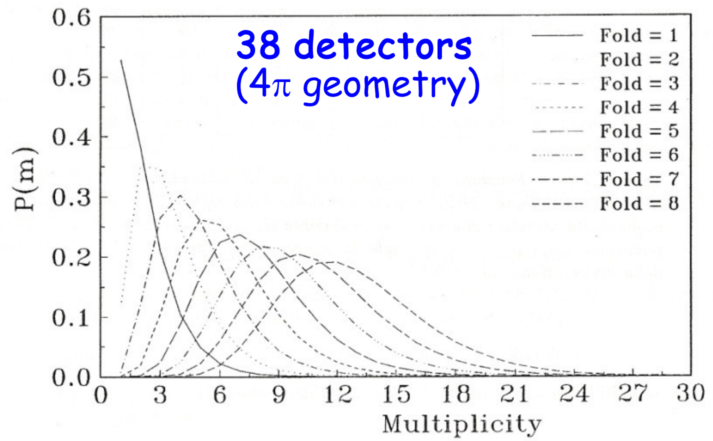
$$P_{double} = \left(\frac{\varepsilon_{ph}\Omega}{4\pi}\right)^2 \frac{1}{N}$$



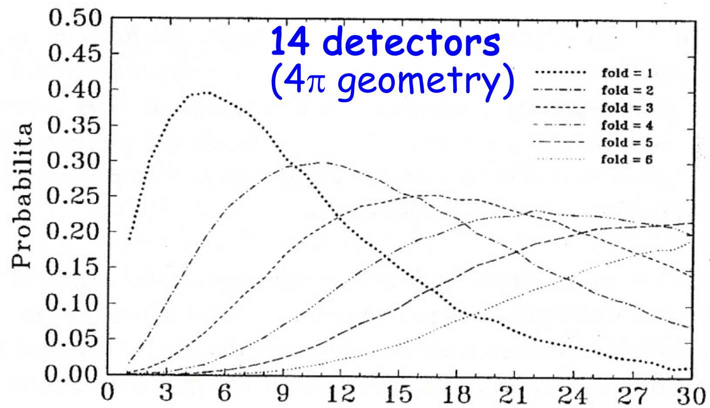
HELENA: multiplicity filter response

multiplicity distribution

^{60}Co calibration



Fold	M_{max}	M_{FWHM}
1	1	3
2	2	5
3	4	5
4	5	6
5	7	6
6	9	7
7	10	8
8	12	9
9	13	10
10	15	11



Fold	M_{max}	M_{FWHM}
1	5	12
2	11	18
3	17	25
4	23	>30
5	30	>30

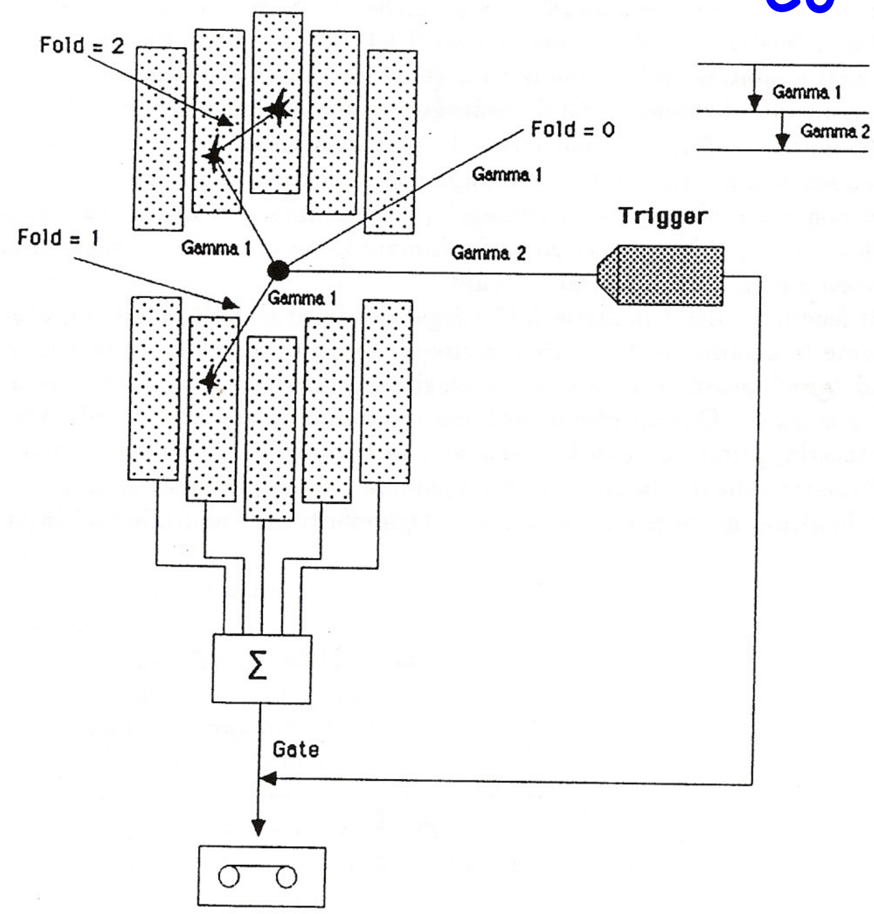
# det	Angolo solido	Efficienza	Single Hit	Cross Talk Double Hit	Cross Talk Triple Hit
14 →	~ 39%	~ 20%	18.5%	1.3%	0.25%
38 →	~ 90%	~ 71%	57.5%	12.6%	0.6%

Low-efficiency ⇒ large uncertainty in M_γ

Calibration of the multiplicity filter:

determination of **response function matrix R(M_γ,F_γ)**
[probability that an event of multiplicity M_γ gives
a signal in F_γ detectors]

^{60}Co



- Source (^{60}Co): 2 coincident γ-rays
  100% branching
- $M_\gamma = 1$: coincident **measurement**
  trigger detector & filter
- $M_\gamma > 1$: **simulation** of the event
  random selection of N events of
  M_γ = 1 gives events of M_γ = N

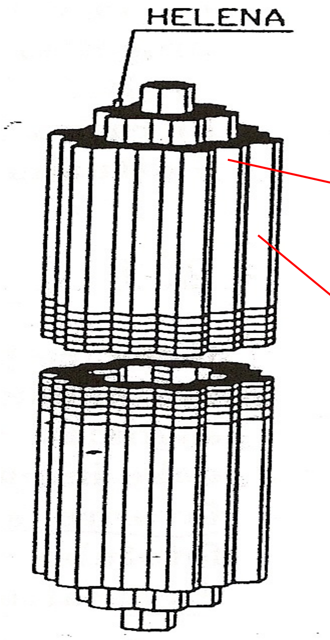
$$F_\gamma(M_\gamma = N) = \sum_{n=1}^{N} F_\gamma(M_\gamma = 1)$$

- corrections for:
  - background radiation
    (filter response in coincidence with background event in trigger detector)
  - multiple hit
    (MonteCarlo simulation)

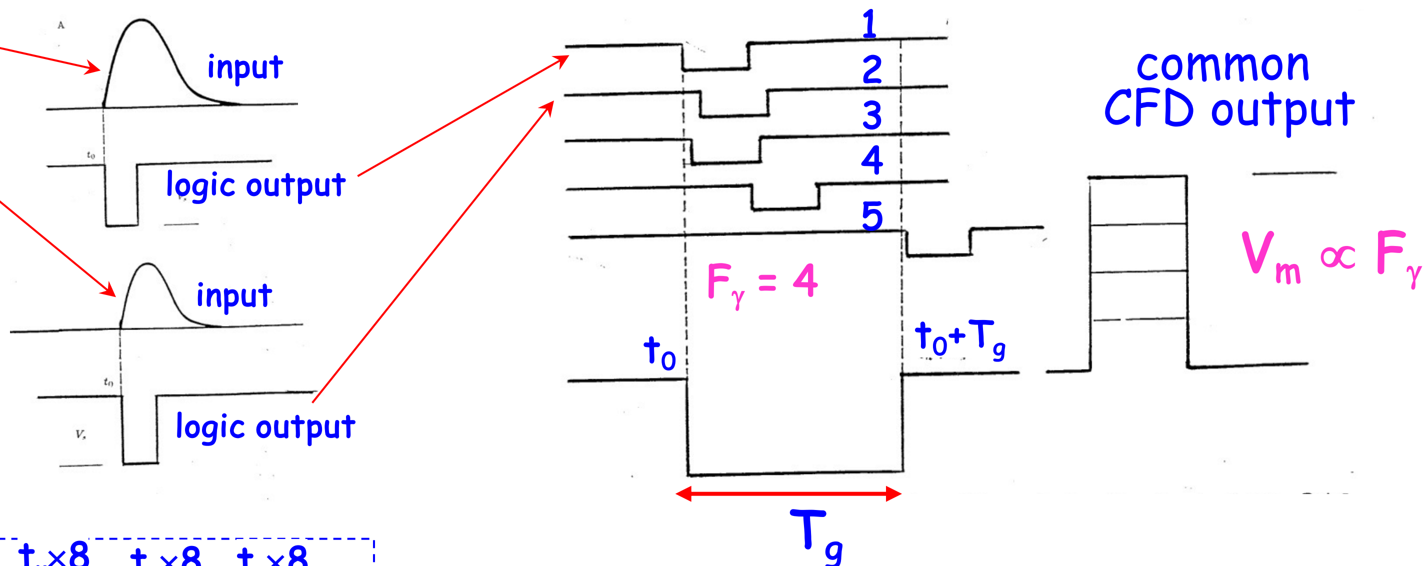
Jaaskelainen et al., NIMA204 (1983)385
M. Mattiuzzi, PhD Thesis

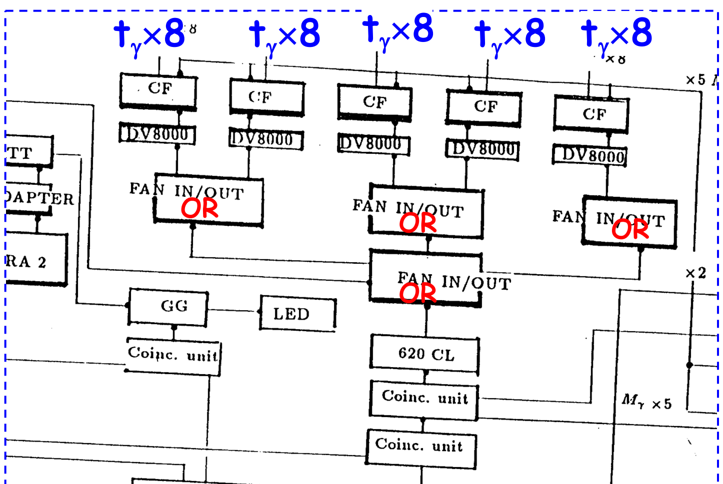
Formation of coincidence (fold F_γ) signal

constant fraction technique



each anode signal (38 detectors)
is sent to a CFD (8 channels input)
⇒ infos on arrival time





T_g ~ 20 ns
- must be ~1/10 single rate (between 1-10 kHz)
- must be > delay rotational cascade (~ ns)

Energy threshold ~ 250 keV
To reduce low intensity events from
- noise
- Coulomb excitation projectile and target

EUROBALL multiplicity filter

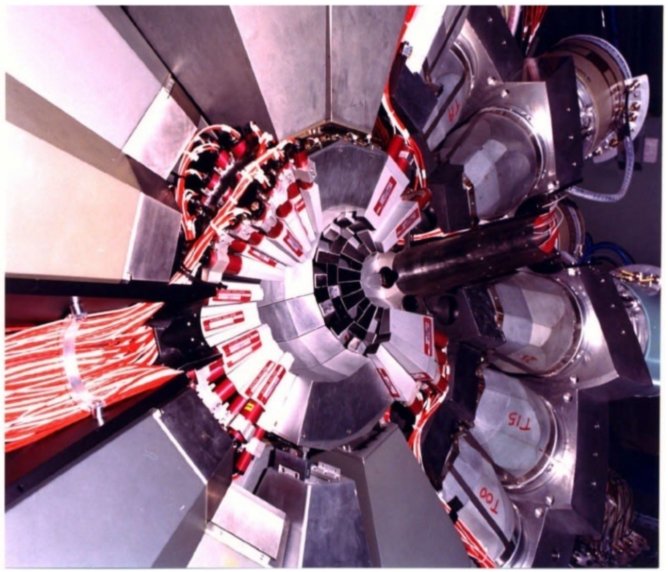
BGO InnerBall

[210 elements of different shapes]

Full Ball

Ge + InnerBall ≈ 4π

40%   60%



To take into account the different **detector efficiency** and **solid angles** the concept of ***equivalent detectors*** is used:

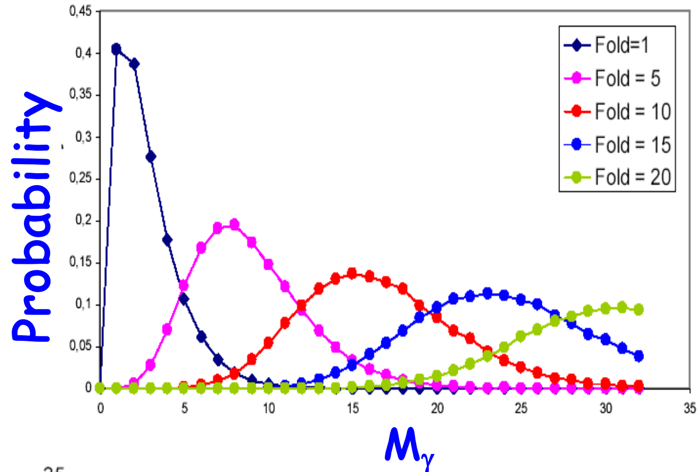
1 BGO ~ 1 Ge Clover

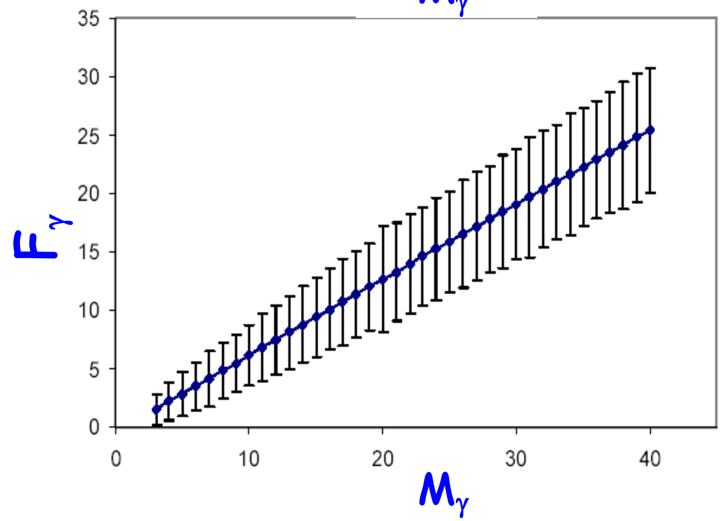
1 BGO ~ 1.5 Ge Cluster

$$F_{eq} = F_{IB} + F_{clo} + 1.5*F_{clu}$$

Response function

3/4 InnerBall + Ge detectors





Fold	<Multiplicty>	FWHM
1	2.8	3.5
5	8.9	7.5
10	16.5	11
20	30.7	17
25	34.6	.....

comparable with HELENA but **NO saturation** (more detectors!!!)

InnerBall can also be used as calorimeter

⇒ focus on specific regions of phase space (E_{exc} vs. I)

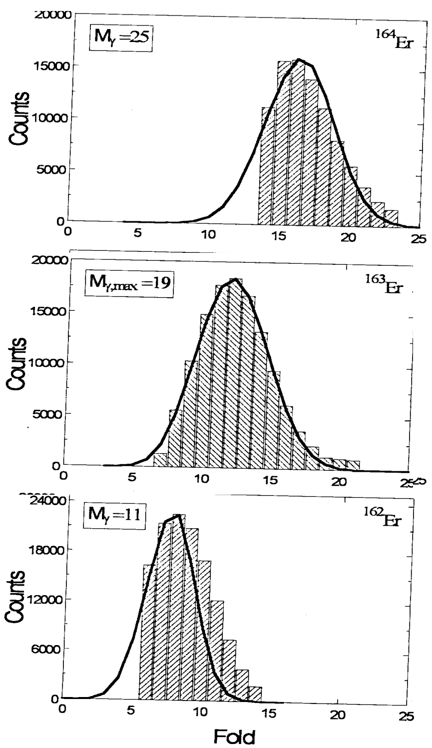
N.B. InnerBall detectors need to be
- energy calibrated
- gain matched

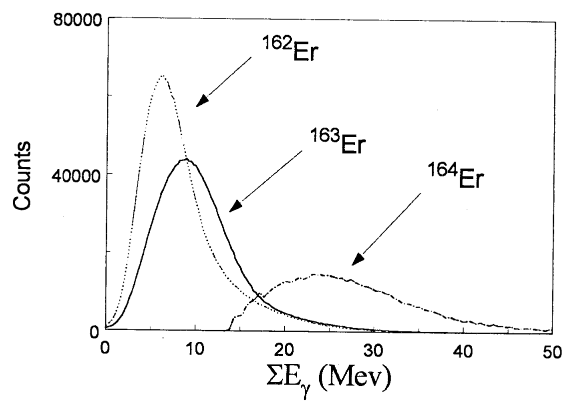
^{18}O (@87MeV) + $^{150}Nd \rightarrow {}^{168}Er^*$

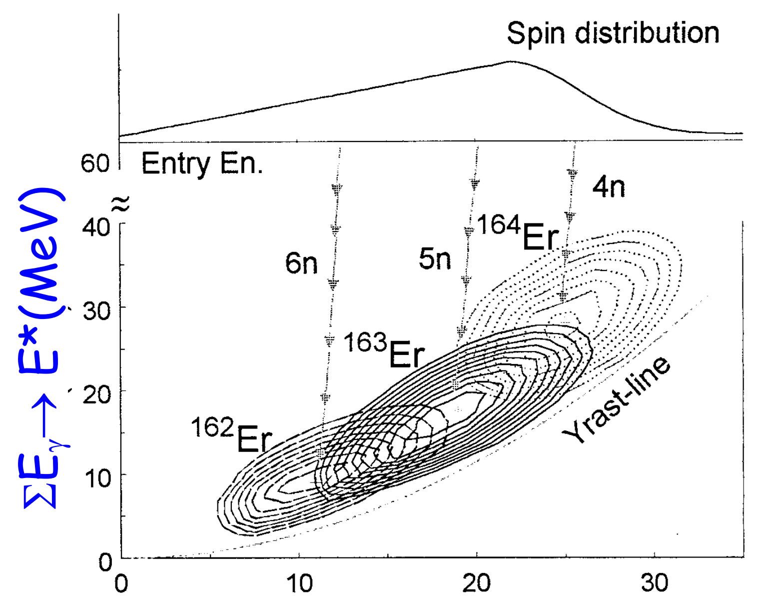
γ-multiplicity
$M_\gamma \rightarrow I$

Reaction channel selection

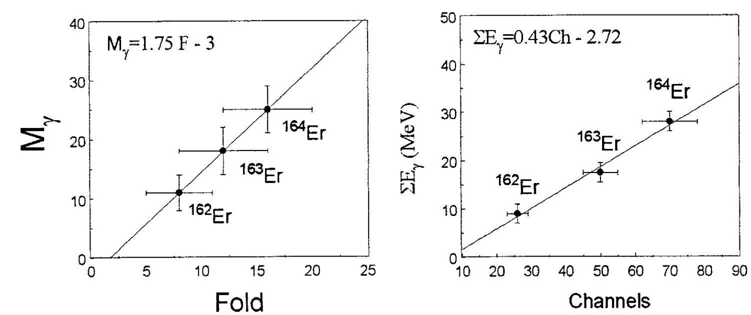
γ-sum energy
$\Sigma E_\gamma \rightarrow E^*$



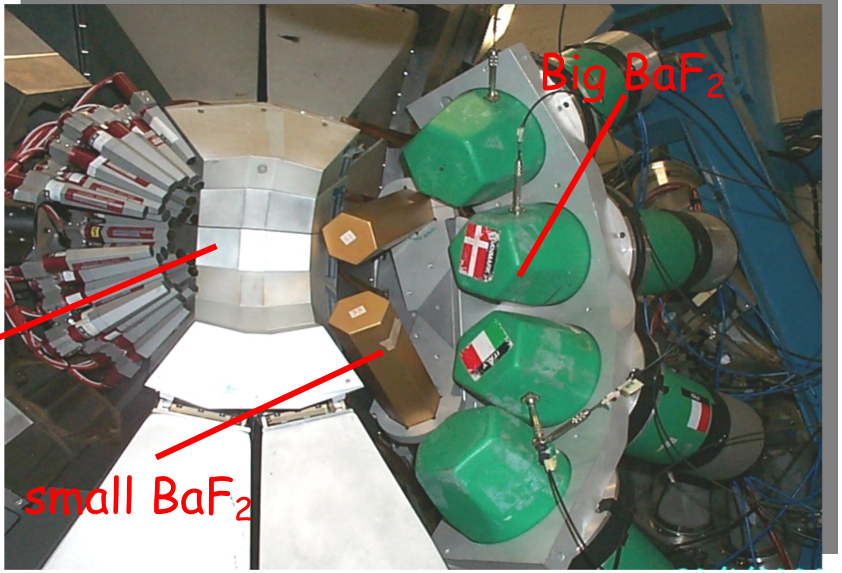




$M_\gamma \rightarrow I(\hbar)$

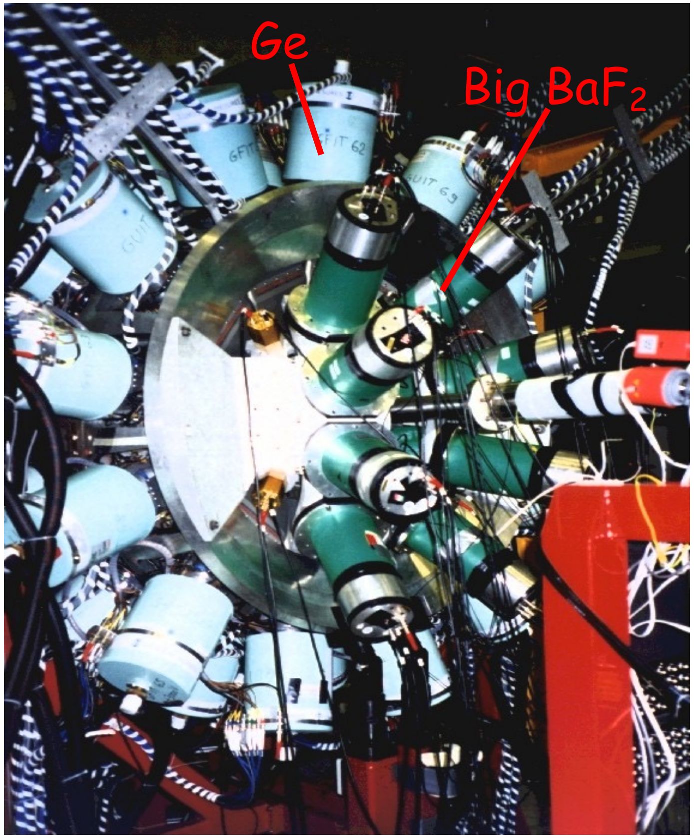


HECTOR (8 Big BaF_2 + 4 small BaF_2) as EUROBALL ancillary



at 10-15 MeV

$\varepsilon_a = 8 \times \varepsilon_{ph}\Omega \sim 8\times0.1\times0.01 \sim 1\%$



EUROBALL IV:

Ge: 26 Clover + 15 Cluster

75%IB (BGO) for high-spin selection

- Energy threshold for BaF_2: ~ 3-5 MeV
  to reduce low-energy events of higher-multiplicity (~10^3)
- Lead absorbers in front of BaF2:
  pile-up reduction of low-energy, high-rate signals
- Monitor of energy gain by LED

Master trigger

2 clean Ge
.AND.
(1 big BaF .AND. 1 small BaF)
.OR.
(1 big BaF .AND. IB fold >11)

Rates

1 Ge $\leq$ 10 kHz
1 BaF_2 ~ 2-3 kHz
Trigger ~ 5 kHz

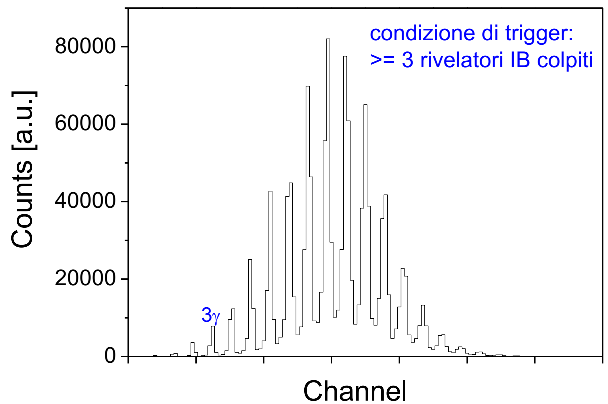
Fold distribution in EUROBALL & HECTOR detectors

$^{30}Si + ^{170}Er \rightarrow ^{200}Pb^*$, E_{beam} = 150 MeV

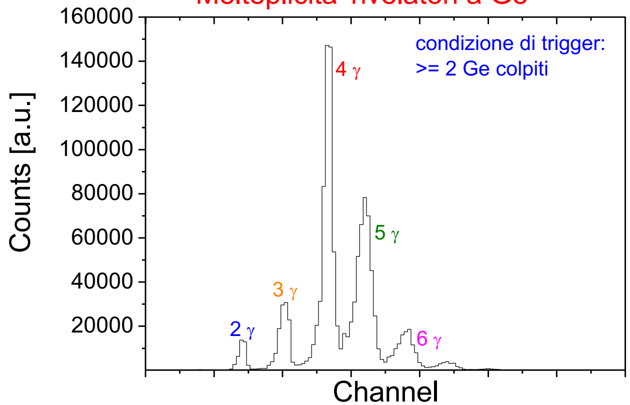
$\beta \approx 1.45$ %

0.6 mg/cm^2 target di ^{170}Er

Euroball IV array



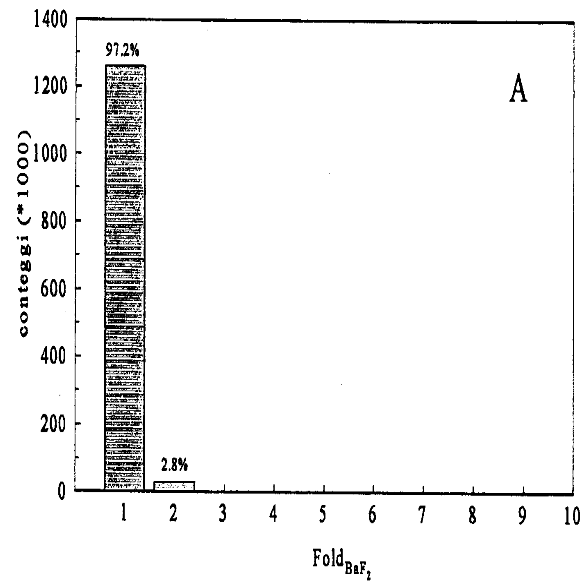
Molteplicita' rivelatori a Ge



Low-energy γ-rays

E_γ < 4 MeV

HECTOR array (8 BaF_2)



~ 95% F_γ = 1

~ 5% F_γ = 2

High-energy γ-rays (GDR)

E_γ > 10 MeV

Precursors of Modern γ-Multi-detector Arrays:

- The Spin Spectrometer (Oak-Ridge, USA)
- The Crystal Ball (GSI, Germany)
- ...

The Spin Spectrometer (mid' 80's)

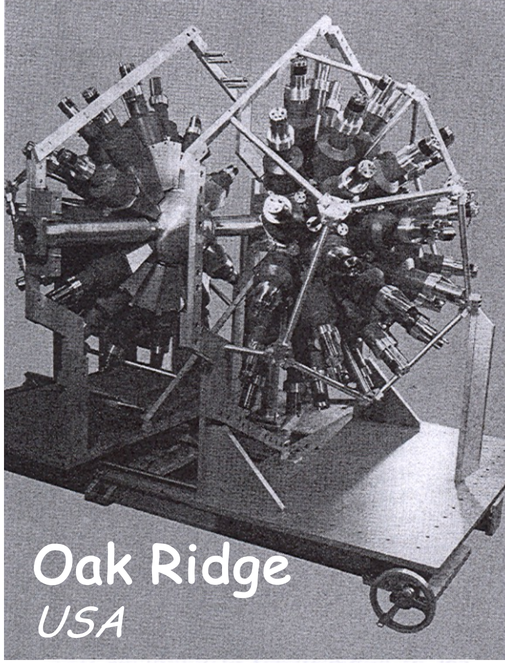
Nuclear Structure at high-angular momentum
following Heavy Ions induced reactions

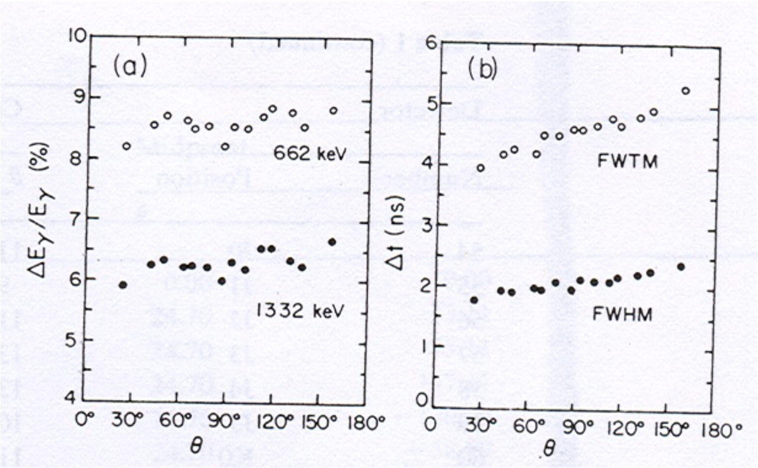
72 NaI(Tl) detectors in 4π geometry

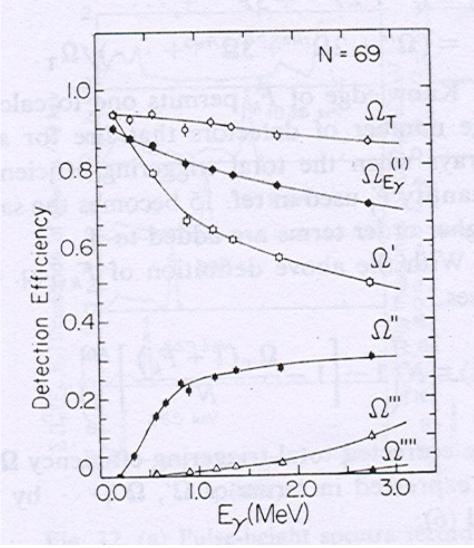
Inner radius ~ 32 cm

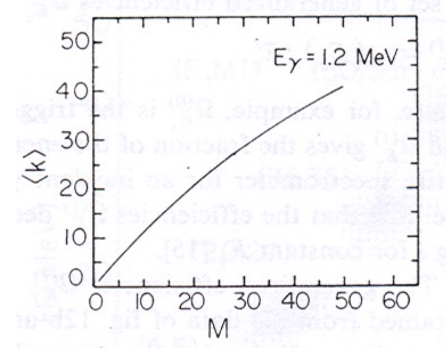
recorded signals for each detector:
- ID number
- pulse height
- time of flight
- pulse width

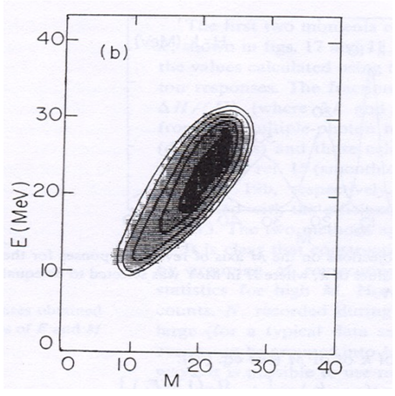
⇒ M_γ, γ-ΣE_γ, $M_{neutron}$
⇒ angular correlations





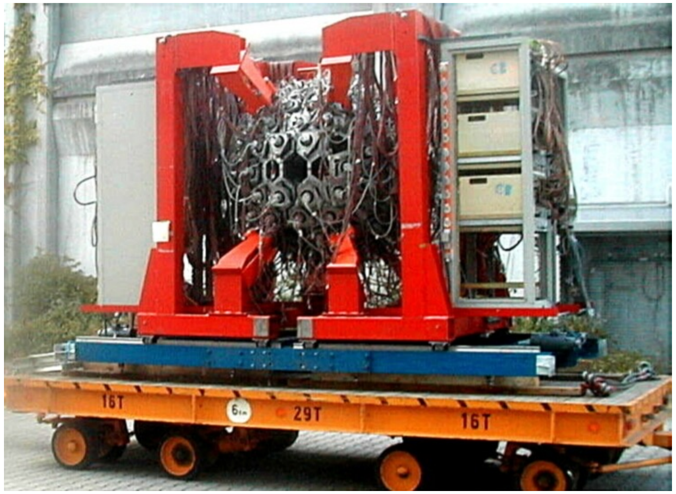




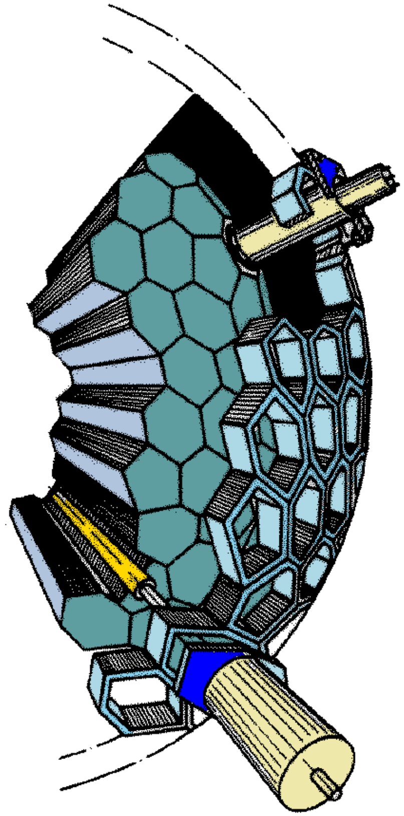


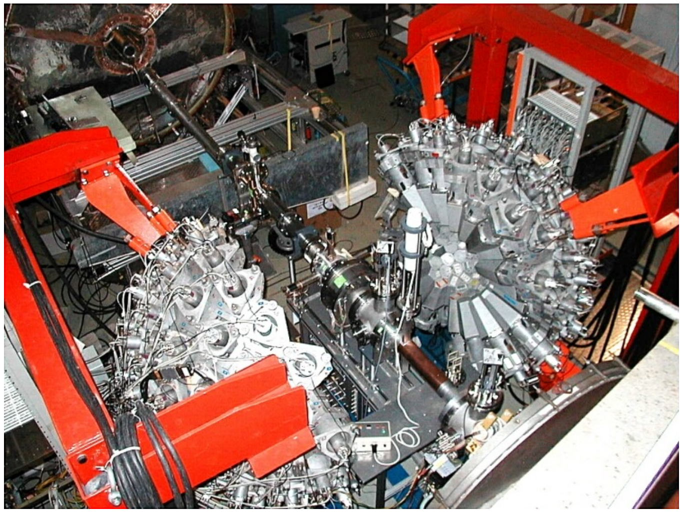
5 keV/ch gain
⇒ 10 MeV range

The Crystal Ball (mid’ 80’s)



GSI
Germany





162 NaI crystals
Sphere of inner radius of 25 cm and thickness of 20 cm.

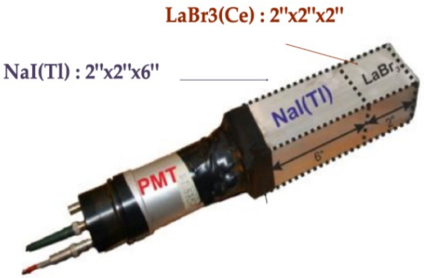
Each crystal covers the same solid angle of **77 msr**.
Four different shapes of crystals:
regular hexagon (12 crystals), three kinds of irregular pentagons (60 + 60 + 30).

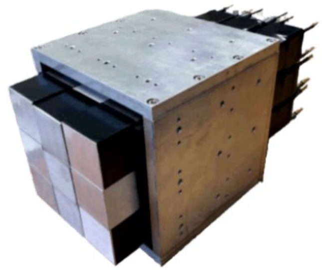
MODERN Scintillators BALL (2020's)

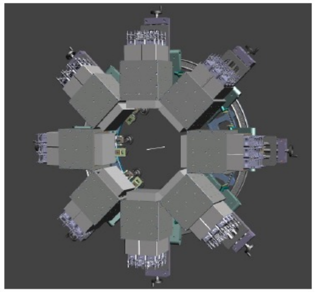
the PARIS array

under construction –
for the physics with Radioactive beams

Poland-France-Italy, …





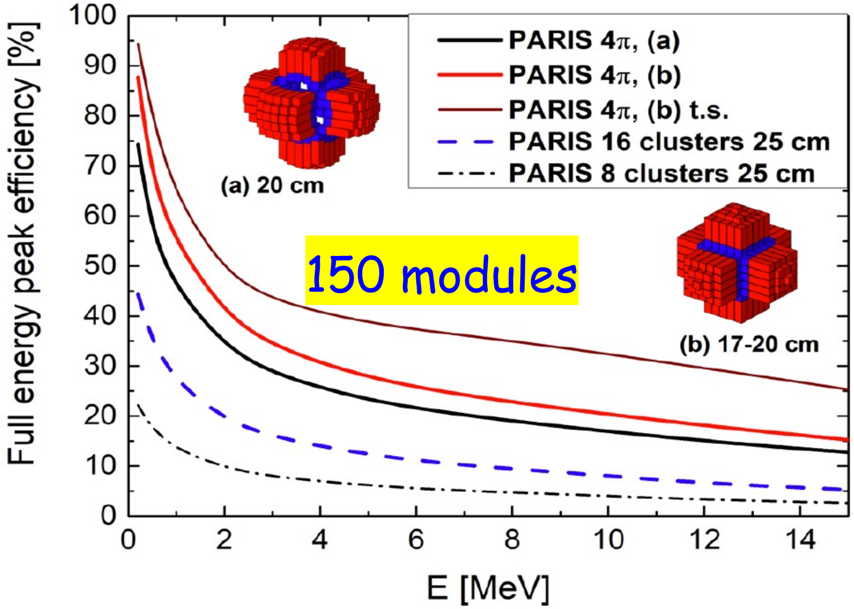


Phoswich solution

LINK to the paper

Status (2021)
- 8 clusters (72 Phoswiches) ready

In 2022
~ 10 clusters (90 phoswiches)

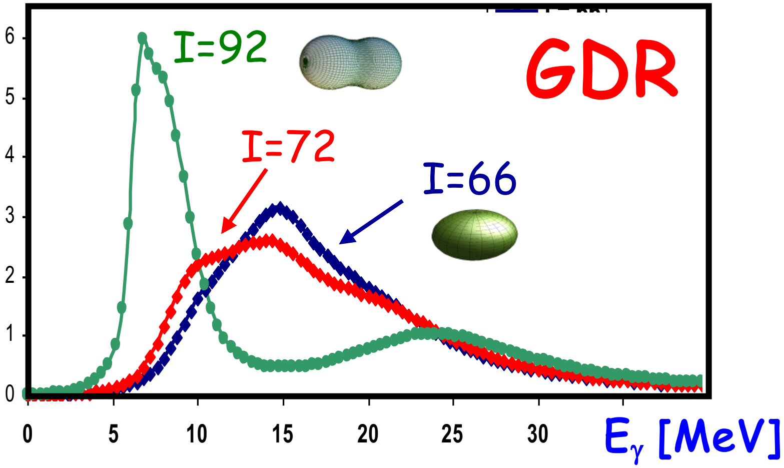


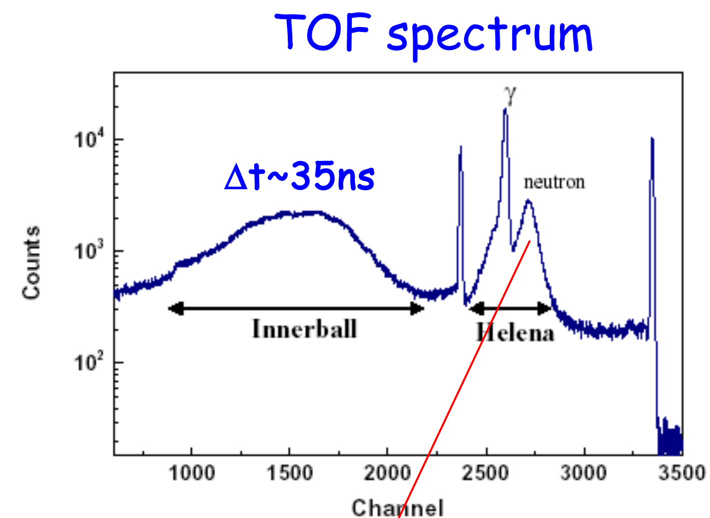
Additional Examples from EUROBALL Experiments and GDR Studies …

Search for GDR built on highly-elongated nuclei

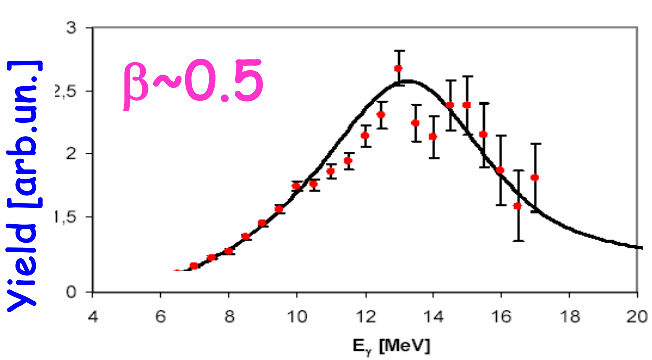
EUROBALL Experiment:
search for hyperdeformation

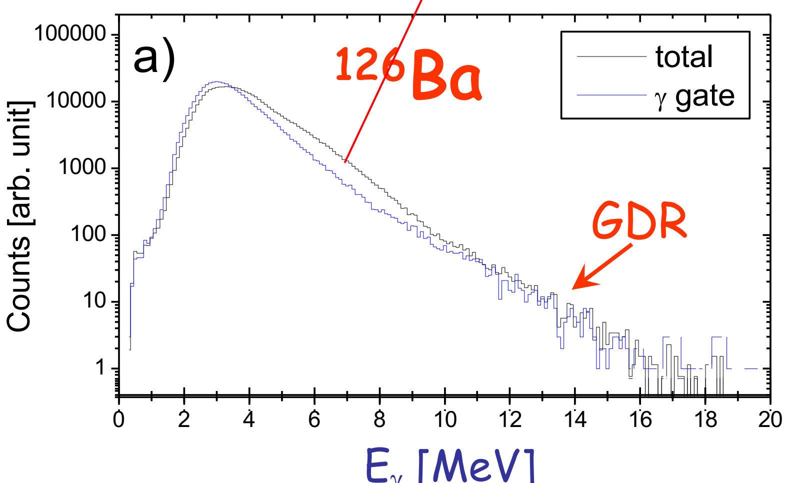
$^{64}Ni + ^{64}Ni - 2n \Rightarrow ^{126}Ba$, @ 255 MeV, $L_{max} = 76\ \hbar$





- 4 small BaF_2 : Reaction time definition (TOF)
- BGO InnerBall: Multiplicity selection

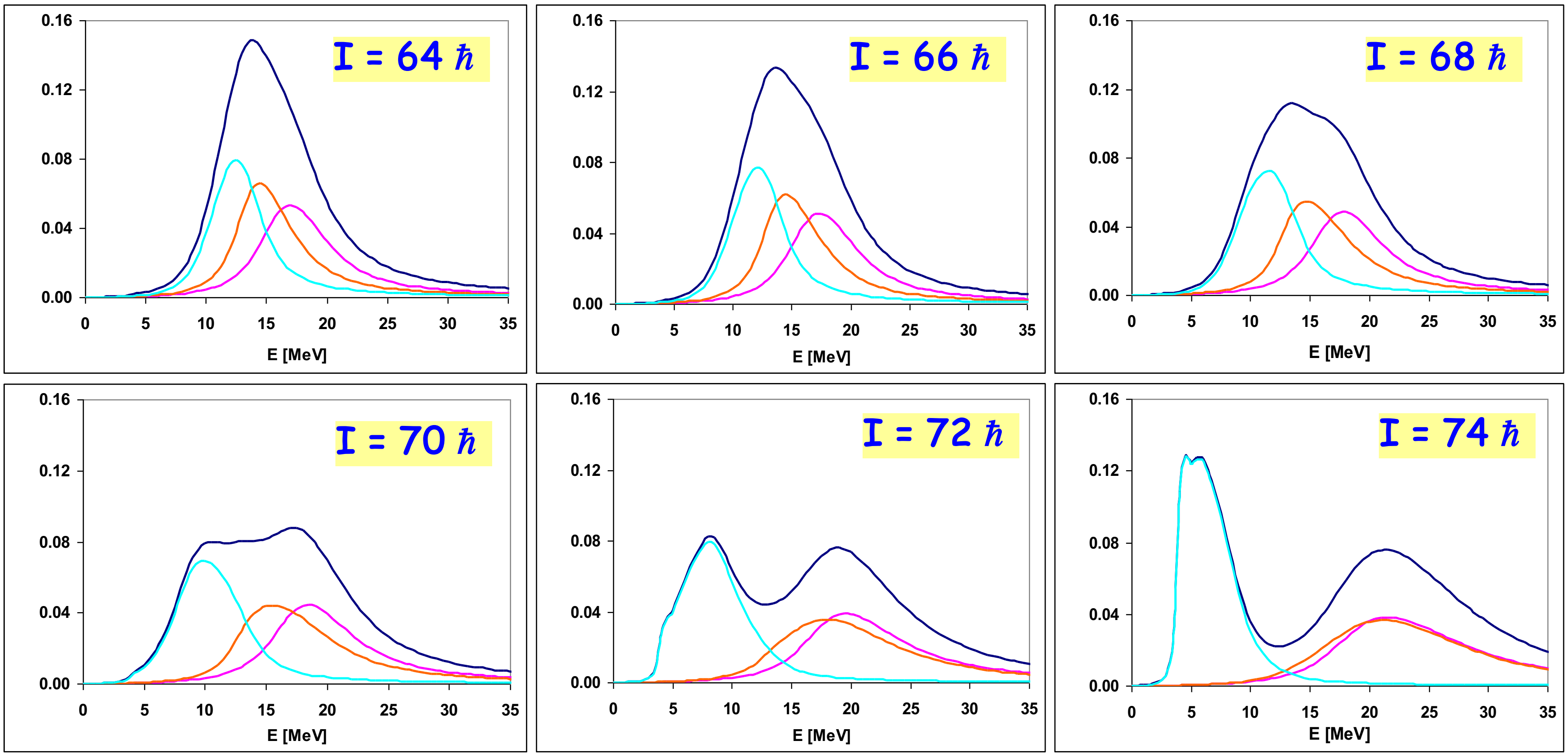




How to detect a Hyperdeformation

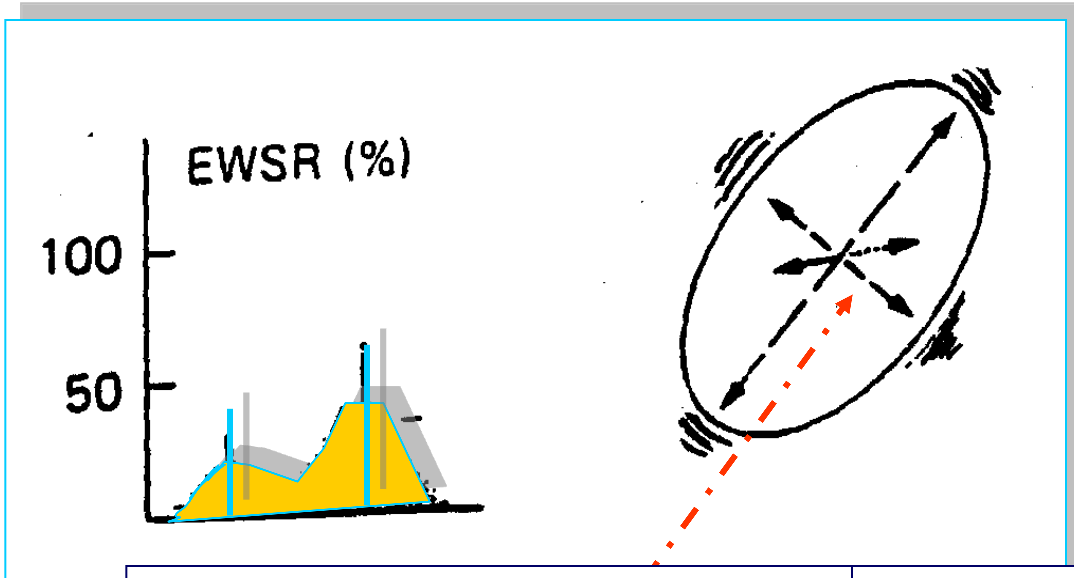
Evolution of GDR shape with angular momentum (Jacobi transition)

$$f_{GDR} = \sum_{x,y} f_{GDR}(x,y) * \exp[(E-E_{yrast})/T]$$

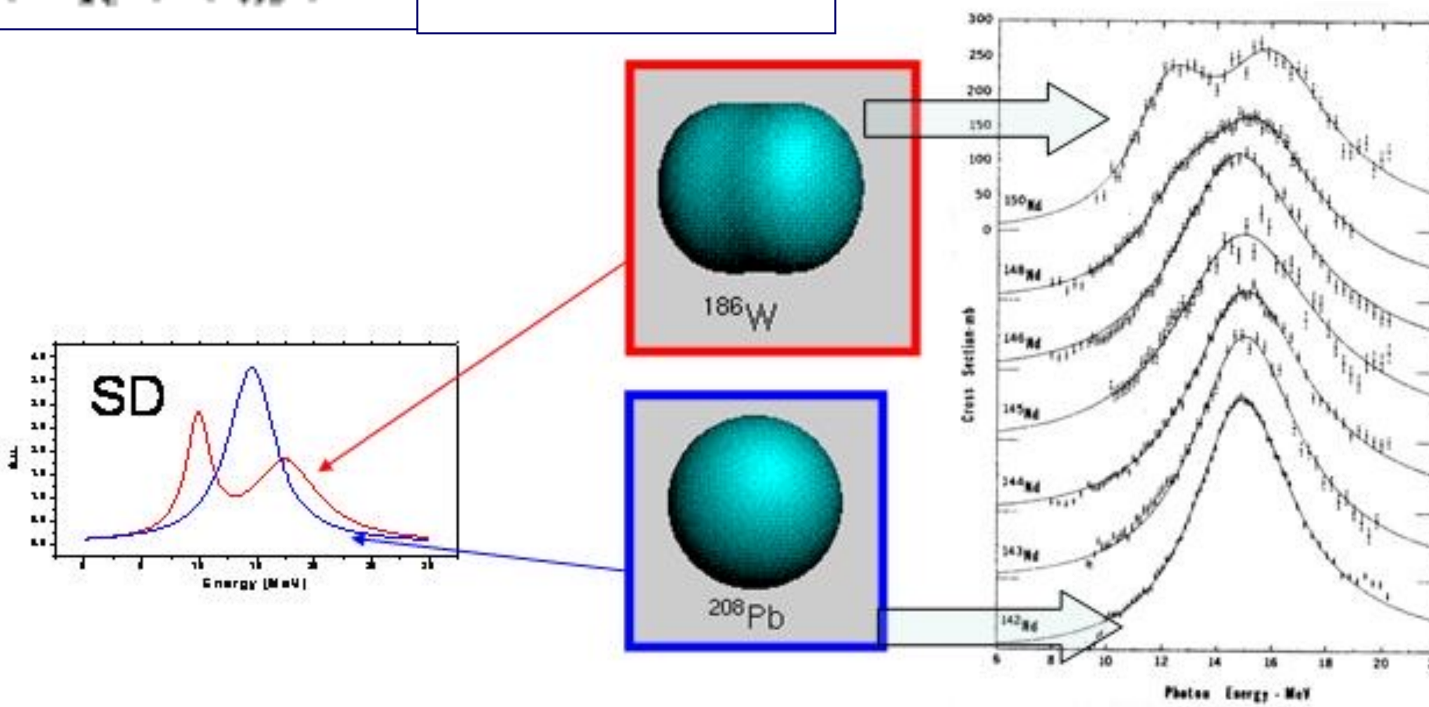


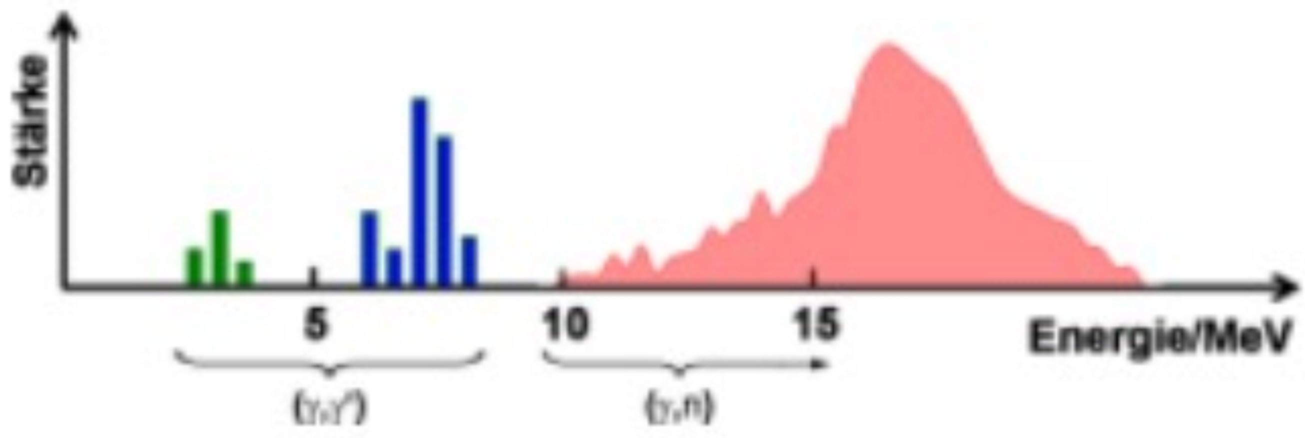
Courtesy of M. Kmiecik & A. Maj

Accoppiamento alla forma del nucleo



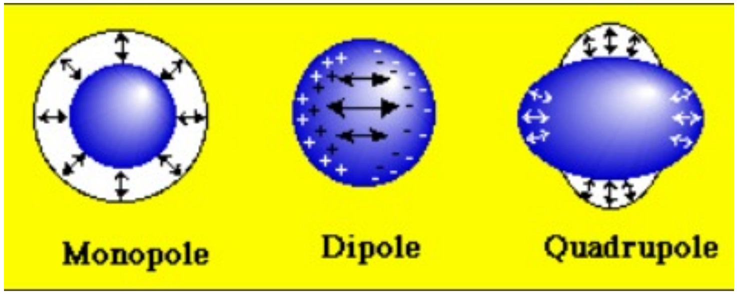
$$E_x^{IVGDR} = \left(\hbar\frac{2.08}{R}\right)\left(\frac{b_{vol}}{m}\right)^{1/2} \simeq 80A^{-1/3}\ \mathrm{MeV}$$





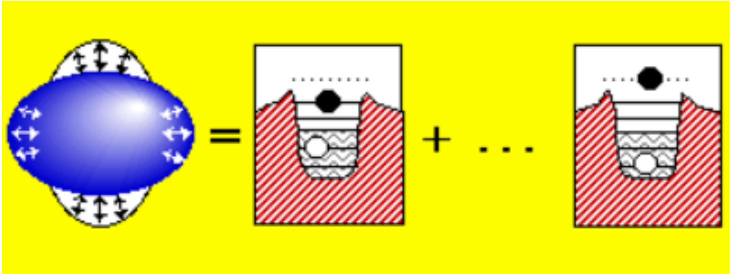
Macroscopically:

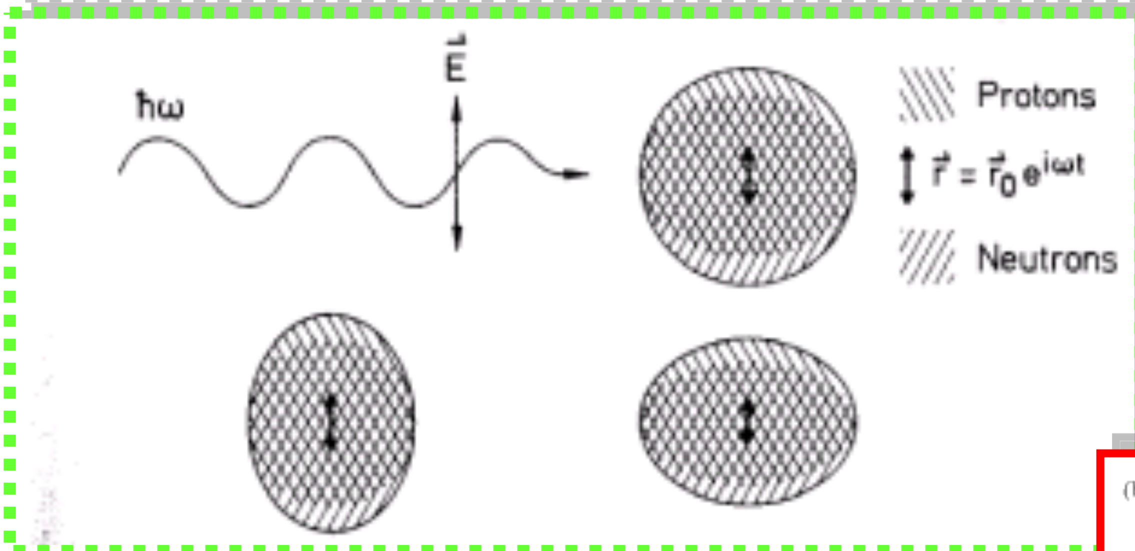
vibrations of the various nuclear fluids (protons/neutrons or spin-up/down).



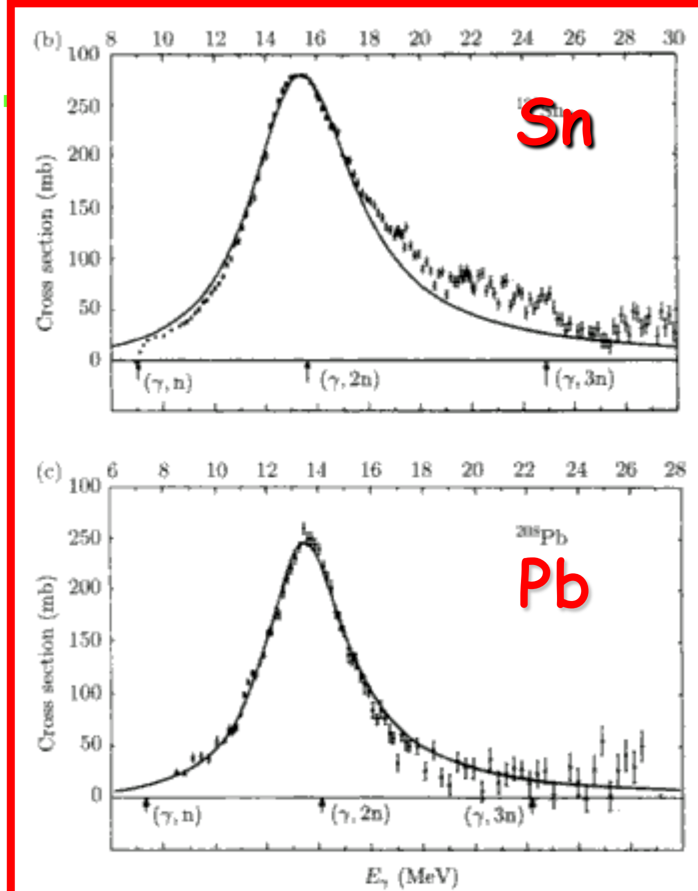
Microscopicamente:

le risonanze giganti sono interpretate come eccitazioni coerenti di particella-buco (1p-1n), determinate della interazione efficace nucleone-nucleone.





$$\sigma(E) = \frac{\sigma_m}{1 + [(E^2 - E_m^2)^2 / E^2\Gamma^2]}$$



Oscillazione dipolare
Si vede nel fotoassorbimento
corrisponde a una frequenza la cui energia associata e' *maggiore* dell' *energia di legame*.

Stato nel continuo ***Collettivo***
(partecipano quasi tutti i nucleoni):

Risonanza gigante di dipolo