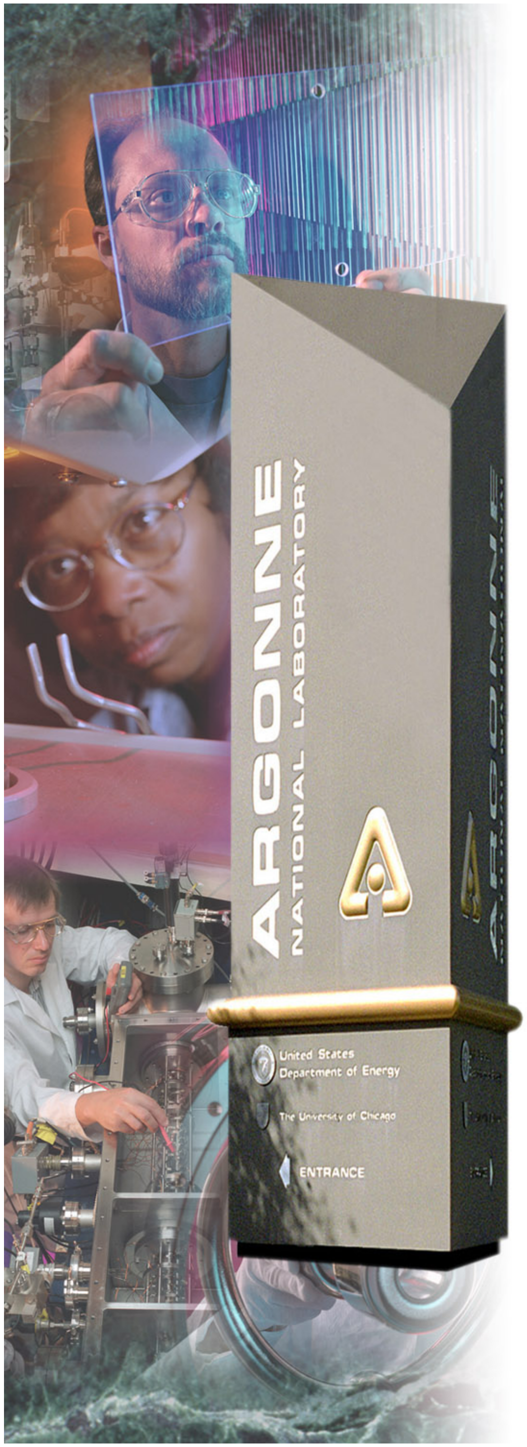

Experimental Nuclear Structure Part II

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kondev@anl.gov

Workshop on "Nuclear Structure and Decay Data: Theory and Evaluation", Trieste, Italy

February 20th-March 3rd, 2006

Argonne National Laboratory

Office of Science
U.S. Department of Energy

A U.S. Department of Energy
Office of Science Laboratory
Operated by The University of Chicago

Outline

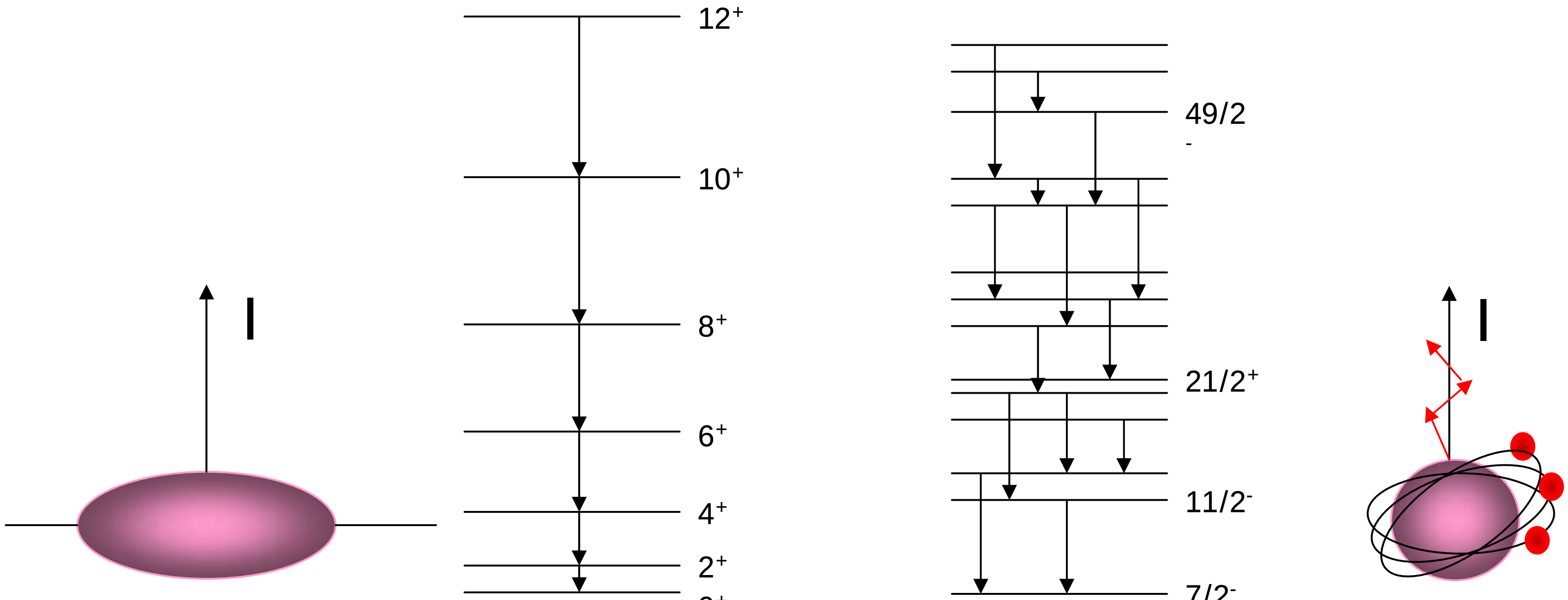
I) **Lecture I: Experimental nuclear structure techniques**

- ☐ Introduction
- ☐ Reactions used to populate excited nuclear states
- ☐ Techniques used to measure the lifetime of a nuclear state
  - ➢ *Coulomb excitation, electronic, activity, indirect*

II) **Lecture II: Contemporary Nuclear Structure Physics at the Extreme**

- ☐ Spectroscopy of nuclear K-Isomers
- ☐ Physics with large γ–ray arrays
- ☐ Gamma-ray tracking – the future of the nuclear γ–ray spectroscopy

Generation of Angular Momentum in Nuclei



$I = J\omega$

^{156}Dy

^{147}Gd

$I = \Sigma\ I_j$

$E_I = \hbar^2/2J\ I(I+1)$

$E_I = \Sigma\ e_j + \Sigma\Sigma\ V_{jk}$

B(E2) ~ 200 W.U.

deformed nucleus

spherical nucleus

What is a Nuclear Isomer?

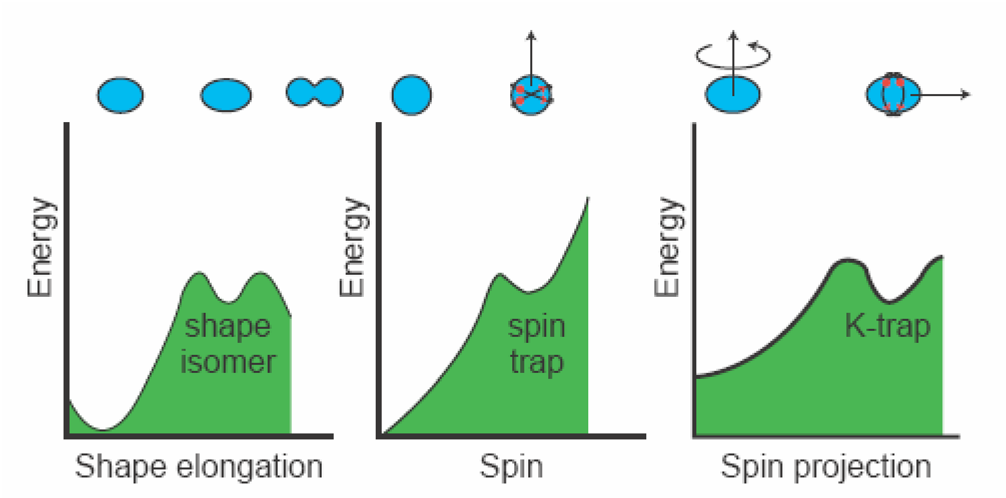
Nuclear Isomer – a *long-lived excited nuclear state* (*$T_{1/2} > 1$ ns*)

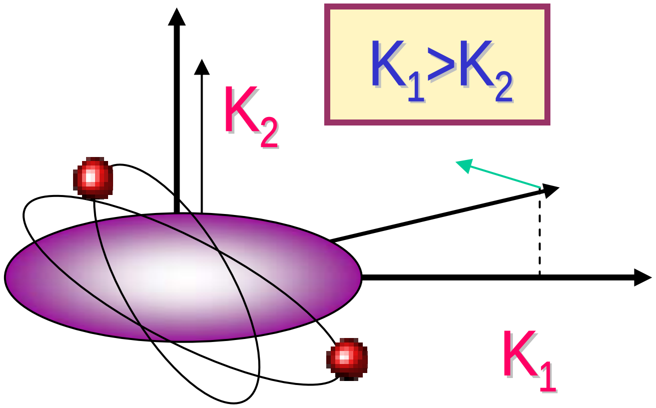
decays by emission of α, β, γ, p, fission, cluster

The first one discovered by O. Hahn in Berlin in 1921 – decay of ^{234}Pa (70 s)

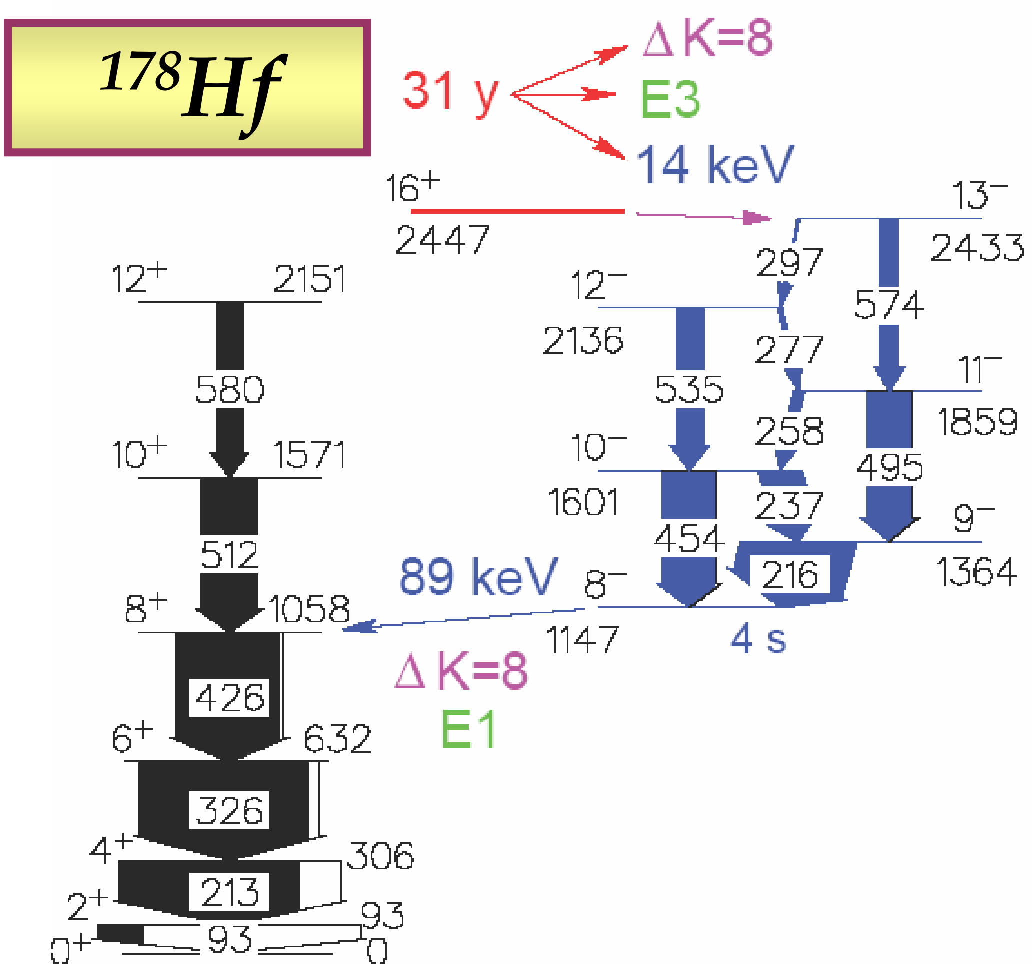
von Weizsacker, A. Bohr & B. Mottelson

$$1/\tau \sim E_\gamma^{\,2\lambda+1}\,|\langle \psi_f \,|\, T \,|\, \psi_i \rangle|$$

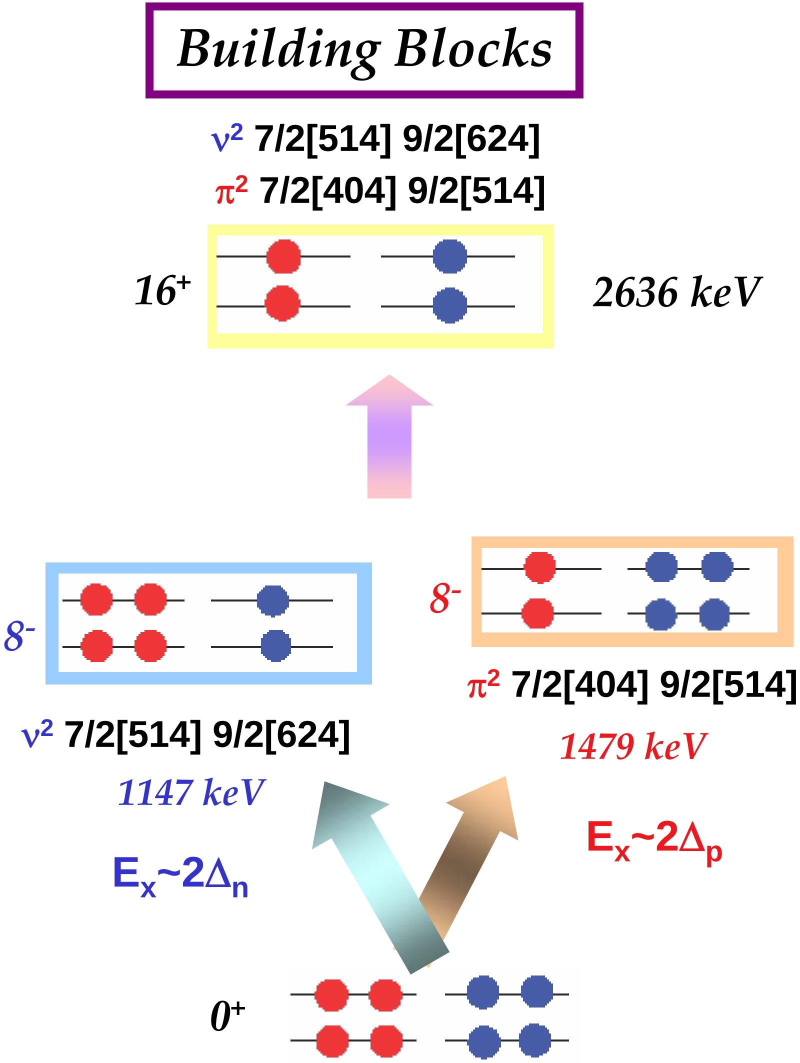




K-Isomers – the building blocks

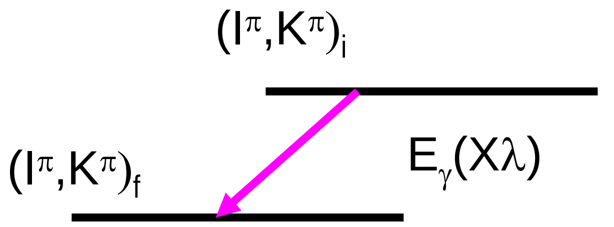


R. Helmer & C. Reich, NP A114 (1968)

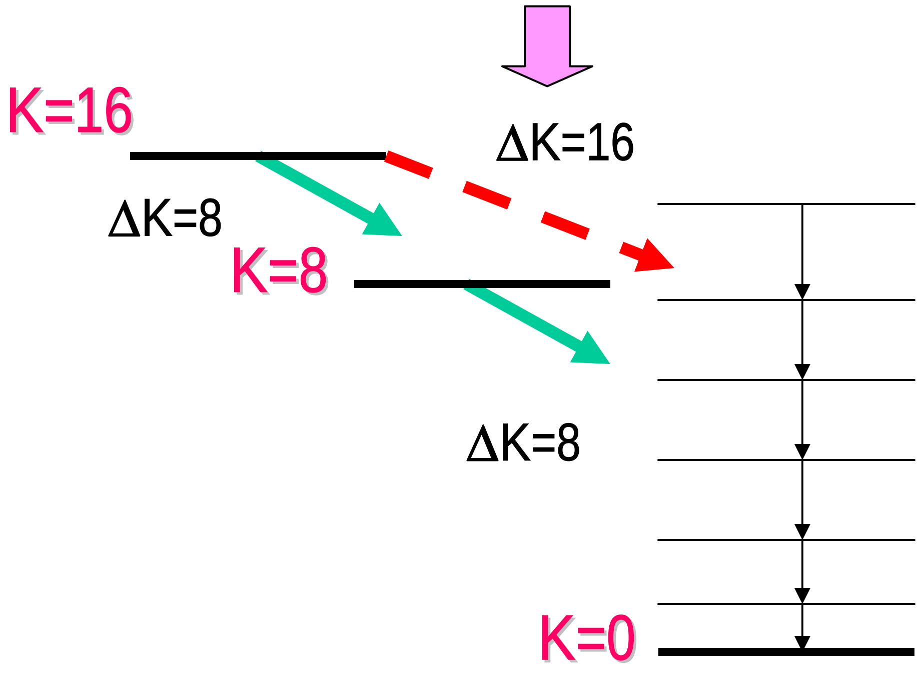


K-Selection Rule and Reduced Hindrance

K-Isomer decay usually proceeds by minimizing ΔK



Usually not this way!



$\nu=\Delta K-\lambda$ – degree of K-forbiddenness

$F=\tau^\gamma(X\lambda)/\tau^W(X\lambda)$ – hindrance factor

$f_\nu=(F)^{1/\nu}$ – reduced hindrance per degree of K-forbiddenness – gives yardstick for "goodness" of K-quantum number

$f_\nu>20$ – K-hindered decay

$f_\nu<10$ - anomalous decay

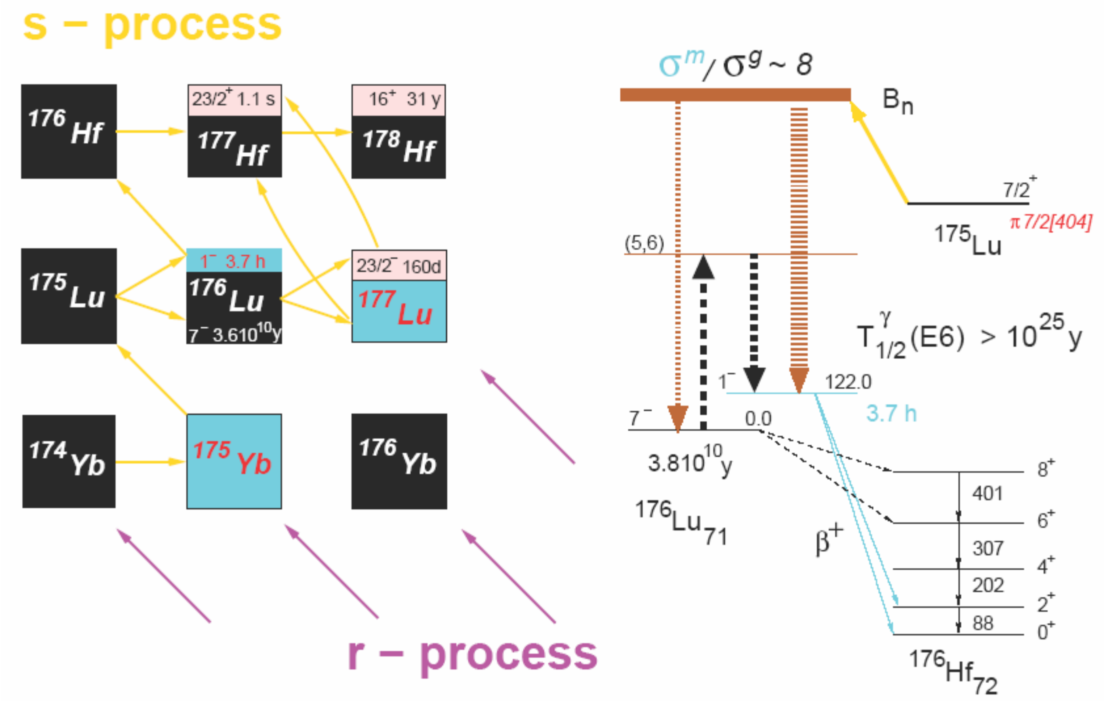
Why Studying Isomers?

- ☐ **Powerful spectroscopy tool - highly selective “devices”**
- ☐ **Advanced physics**
  - ✓ The mapping of intrinsic orbitals close to and remote from the Fermi surface providing an indirect probe of deformation and potentials used in mean-field descriptions.
  - ✓ The limits to the existence of high-K states, both at high excitation energy and as a function of proton and neutron number and the competition between collective and intrinsic excitation.
  - ✓ The question of the dilution of the K-quantum number due to both random interactions in regions of high-level density, and to chance degeneracies in regions of low level density.
  - ✓ As a seniority- and configuration-dependent probe of the major residual interactions in deformed nuclei, specifically pairing and spin-spin interactions.

Why Studying Isomers – cont.?

- Interesting astrophysical applications: stellar thermometers and chronometers

  ✓There is considerable interest in the role of nuclear structure effects (the precise disposition of excited states) and the possible role of the K-quantum number in the formation and possible photo-destruction of isomeric nuclei such as ^{176}Lu, ^{180}Ta and ^{186}Re in hot stellar processes.



Why Studying Isomers? – cont.

Applications

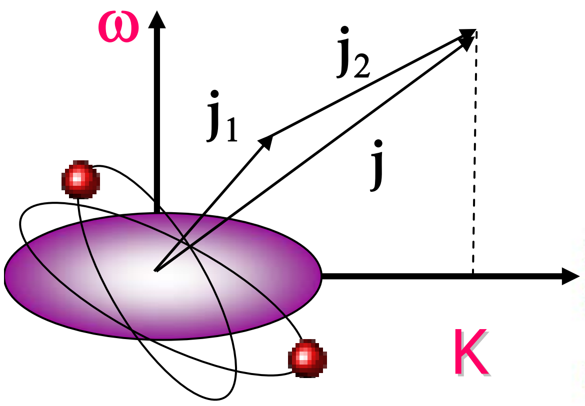
- Activation analysis
- Medicine
- Gamma-ray lasers/batteries?
- Transmutation of nuclear waste?

Exotic Studies

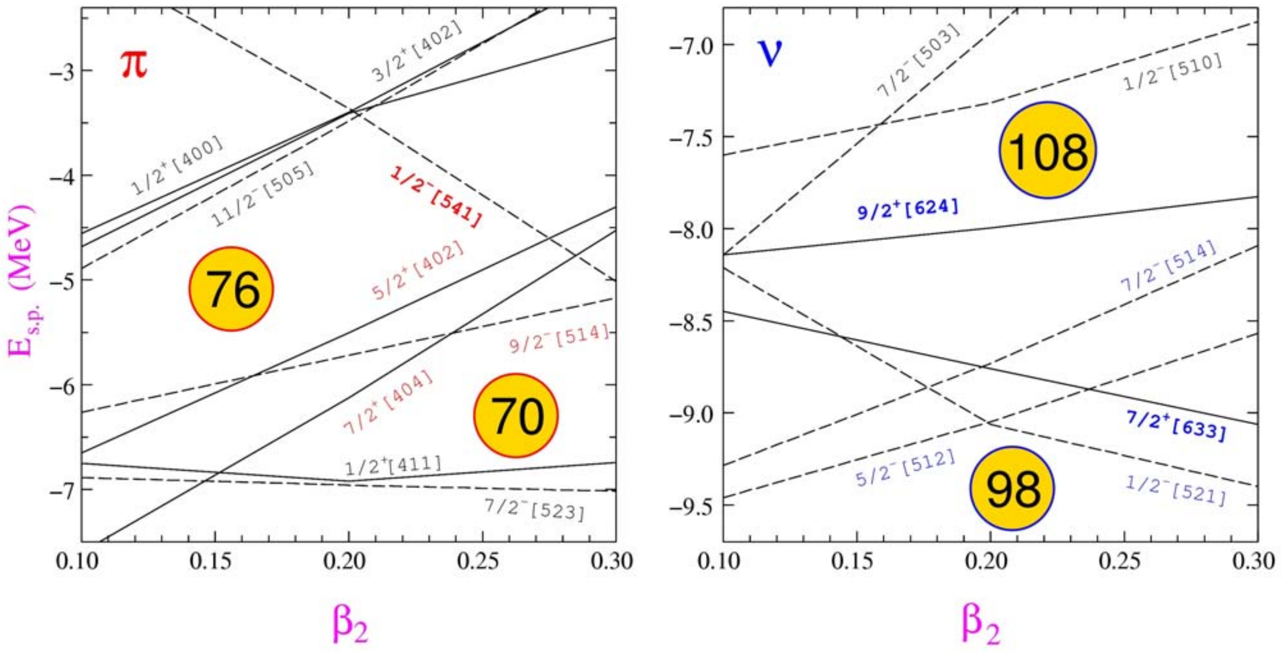
- Radioactive targets – high-spin/seniority, e.g. ^{178m2}Hf, ^{177m}Lu
- Radioactive beams – the future of nuclear knowledge

K Isomers: Where to find them?

- Deformed nuclei with axially-symmetric shape



Mass 180 region : Yb (Z=70)-Ir(Z=77)



- High-K orbitals near the Fermi surface

π 5/2[402], 7/2[404], 9/2[514]

ν 5/2[512], 7/2[514], 7/2[633], 9/2[624]

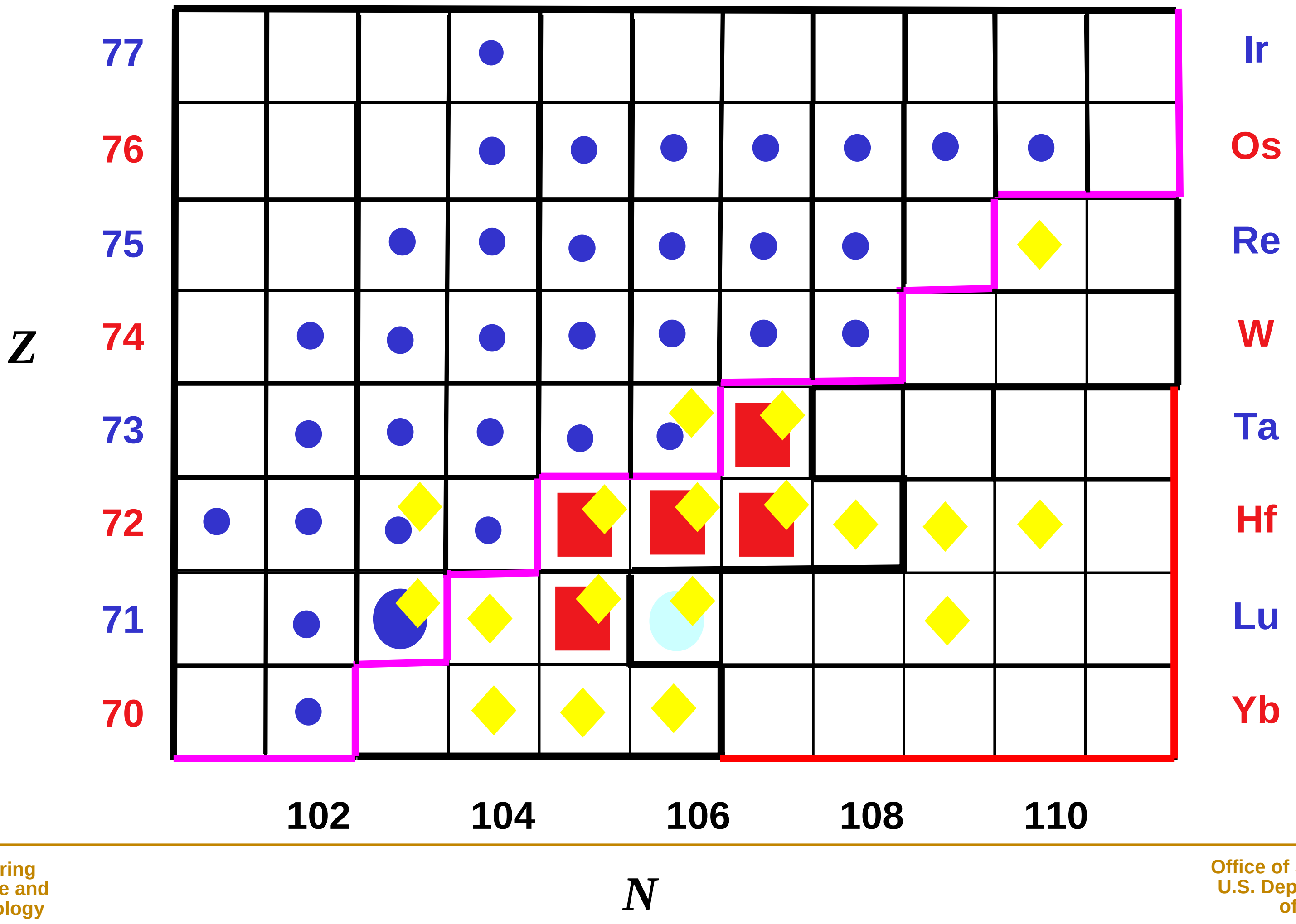
7-qp

K=49/2

K-Isomers in the A~180 Region

- Seniority 2 and higher
- $T_{1/2} < 1$ s (small) / $T_{1/2} > 1$ s (large)

● *HI,xn – fusion evaporation*
◆ *Deep-inelastic collisions*
■ *Incomplete fusion*

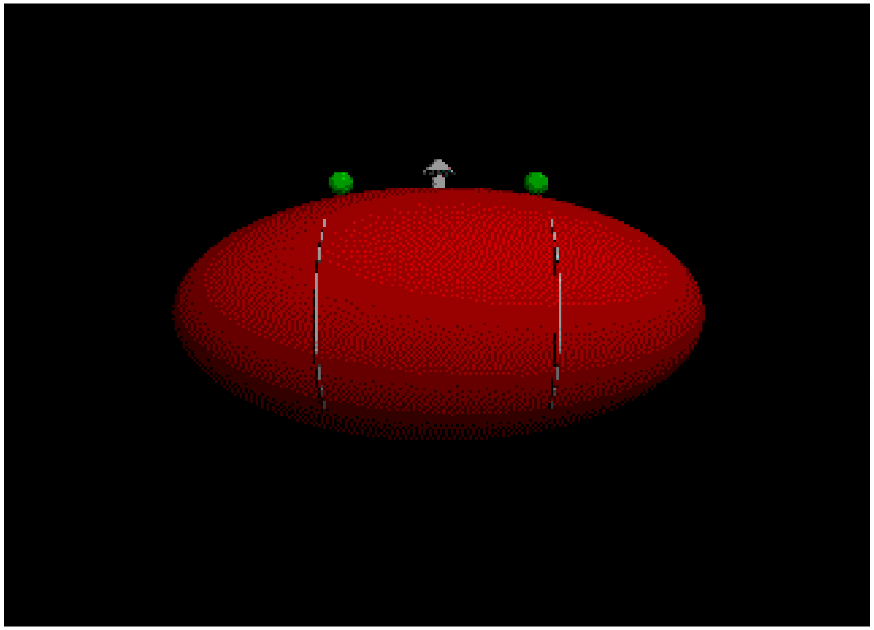


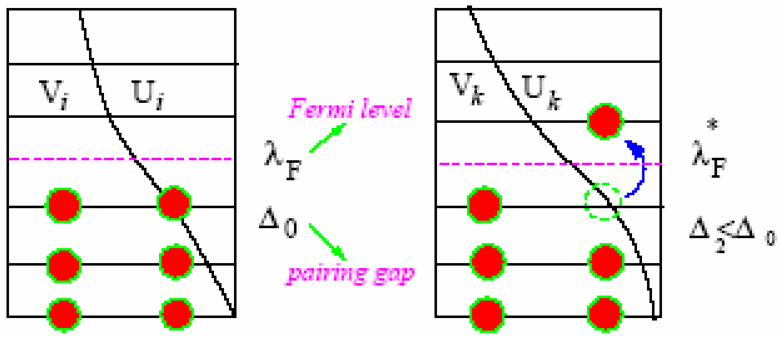
Pairing Destruction in Nuclei

In general there are **two** anti–pairing mechanisms :

(a) Coriolis anti–pairing – induced by the fast rotation

(b) Blocking – occupation of level(s) by unpaired nucleon(s)

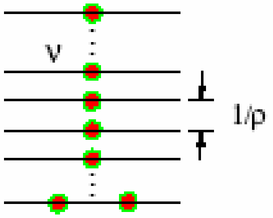




$V^2_{i(k)}$ $U^2_{i(k)}$ the probability that a given state is or is not occupied

uniform levels distribution

$$\Delta_\nu = [\Delta_0(\Delta_0 - \nu/\rho)]^{1/2}$$



ν – the number of blocked particles (seniority)

ρ – level density near the Fermi surface

$1/\rho \sim 300$ keV and $\Delta_0 \sim 900$ keV

$\nu \sim 3$ $\Delta = 0$!

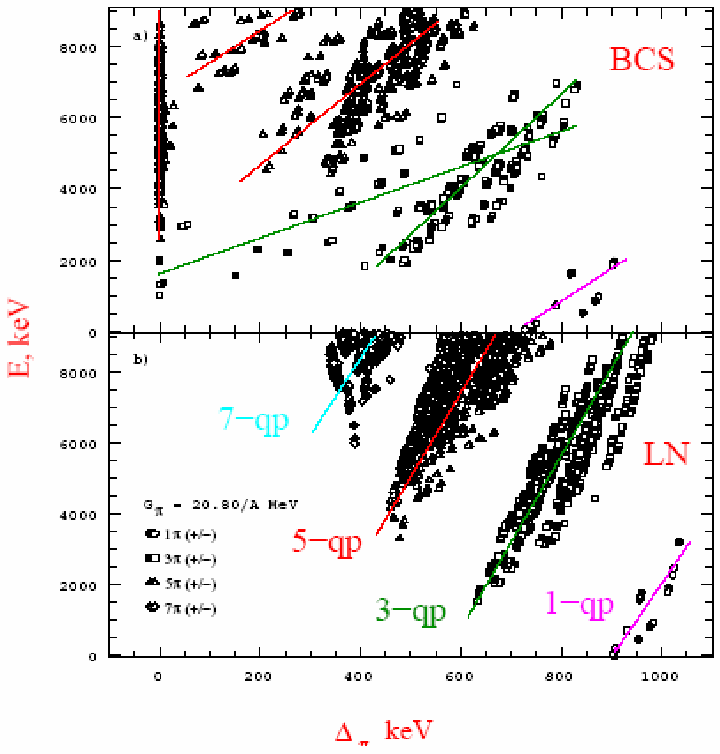
Pairing Gap & Seniority

illustrative example: blocked multi−quasiparticle calculations − protons $^{177}_{73}\mathrm{Ta}_{104}$

mean field − Nilsson potential

pairing − BCS model
LN model

LN: *W. Nazarewicz et al. NP A512 (1990)*
W. Satula et al. NP A578 (1994)

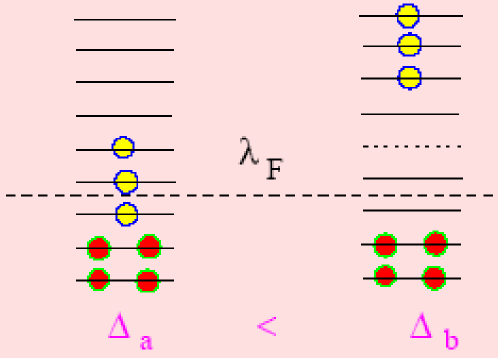


(a) Has the pairing really gone ?

(i) the number of blocked levels

seniority dependence

(ii) their location



configuration dependence

(iii) the single−particle density

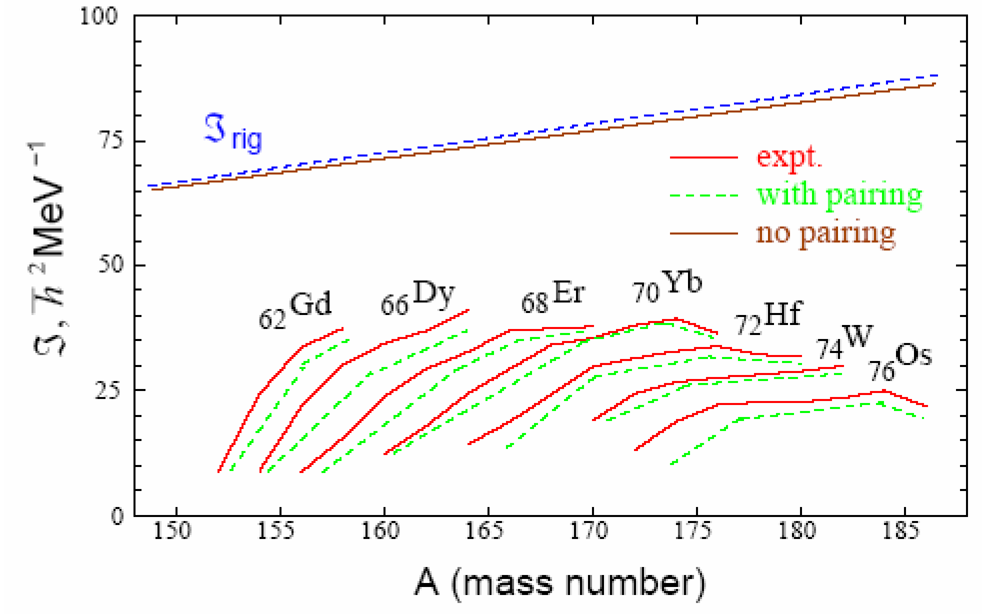
$\Delta \sim exp\,[-1/G\,\rho\,]$

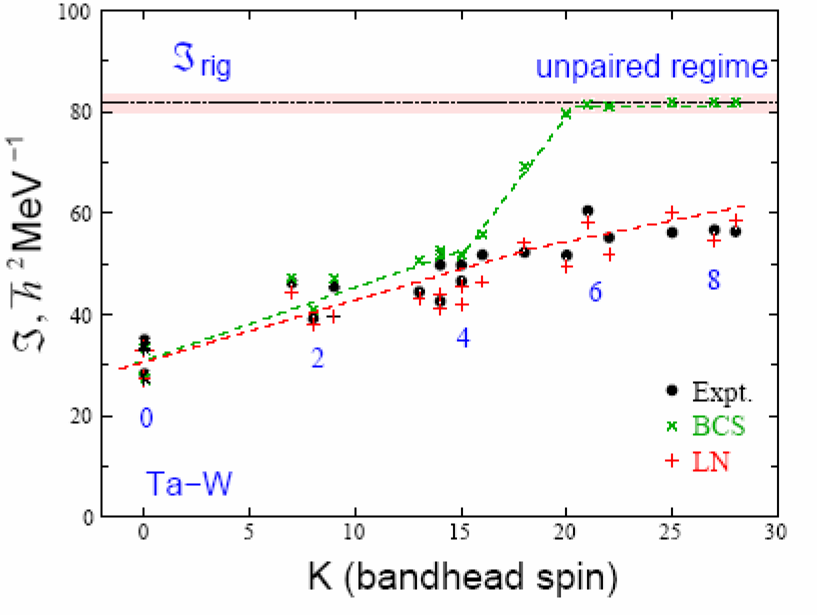
shell structure dependence

(b) How to prove it?

rotation of the MQP state comes to the rescue

Pairing & Moment of Inertia





- *Implication:* yet higher seniority states would not show marked decrease in pairing

  G.D. Dracoulis et al., Phys. Lett. B419 (1998)

- *Is the rigid rotation a signature of quenched pairing?*

  $\Im$ is smaller than $\Im_{rig}$ due to shell effects

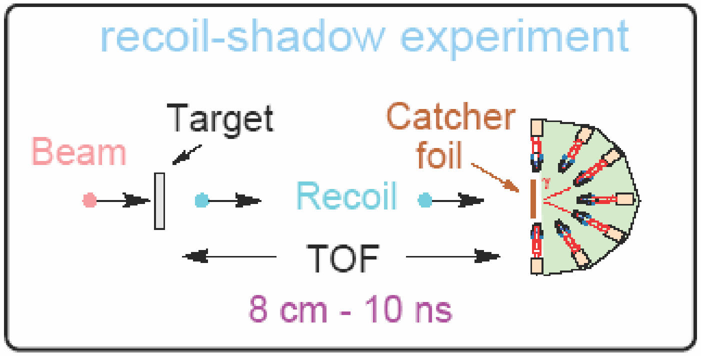
  S. Frauendorf et al., Phys. Rev. C61 (2000)

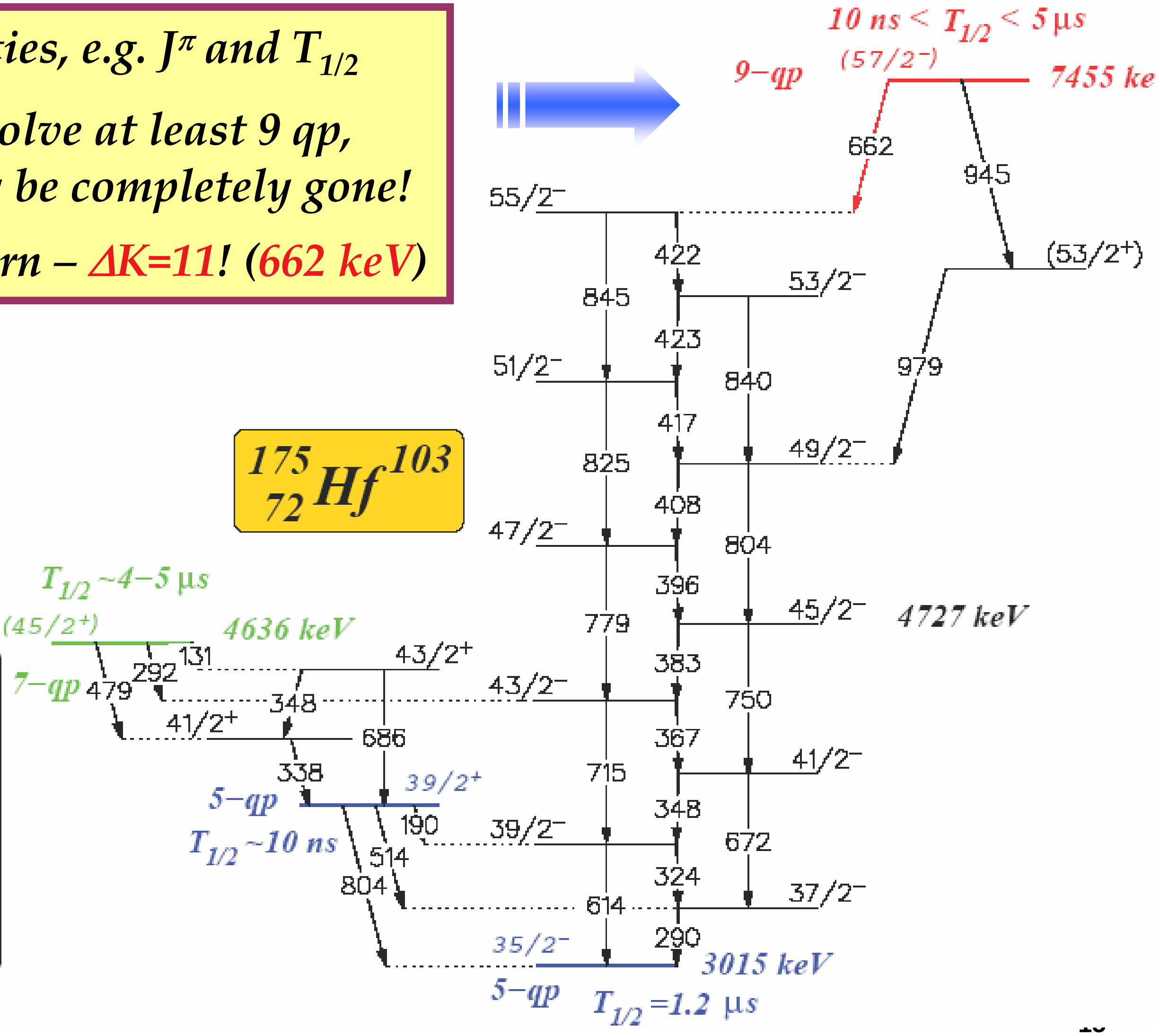
- *Needs an experimental confirmation !*

… at Extreme of Seniority – the case of ^{175}Hf

- ☐ *Tentative quantum properties, e.g. J^{π} and $T_{1/2}$*
- ☐ *Exotic structure - must involve at least 9 qp, a case where the pairing may be completely gone!*
- ☐ *Unprecedented decay pattern – ΔK=11! (662 keV)*

$^{48}Ca + {}^{130}Te \xrightarrow{3n}$ @195 MeV



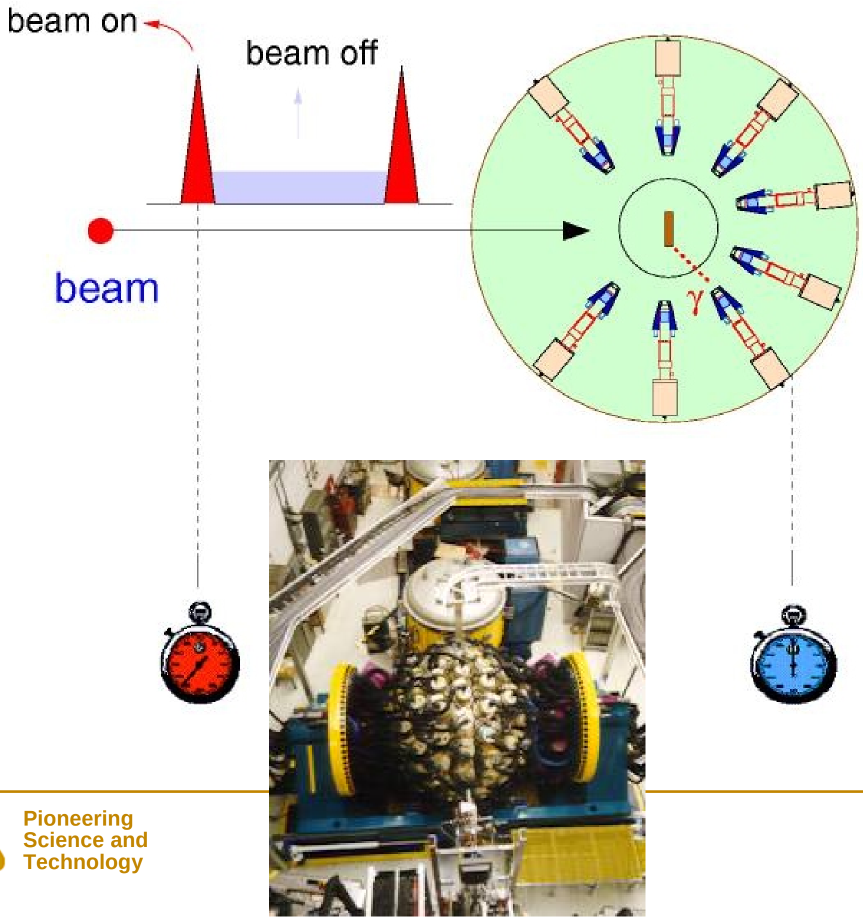


N.L. Gjorup et al., Z. Phys. A337 (1990)

^{175}Hf Experiments at ANL and ANU/Canberra

Pulsed Beam Technique

- Well defined "clock"
- Sensitive to in-beam and decay events



ANL Experiment

^{48}Ca(^{130}Te,3n)@194 MeV

- Pulsed beam & Gammasphere
  1 ns on / 825 ns off
- Thin target
  1 ns on / 82.5 ns off

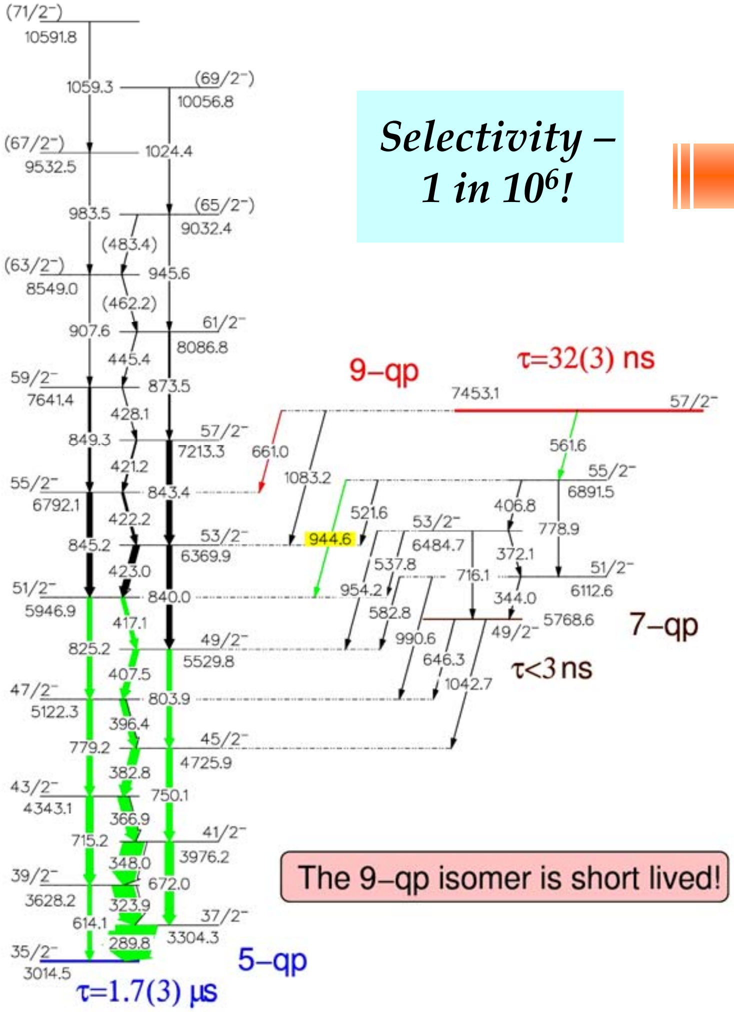
Complementary Experiment at ANU

^{9}Be(^{170}Er,4n)@50 MeV

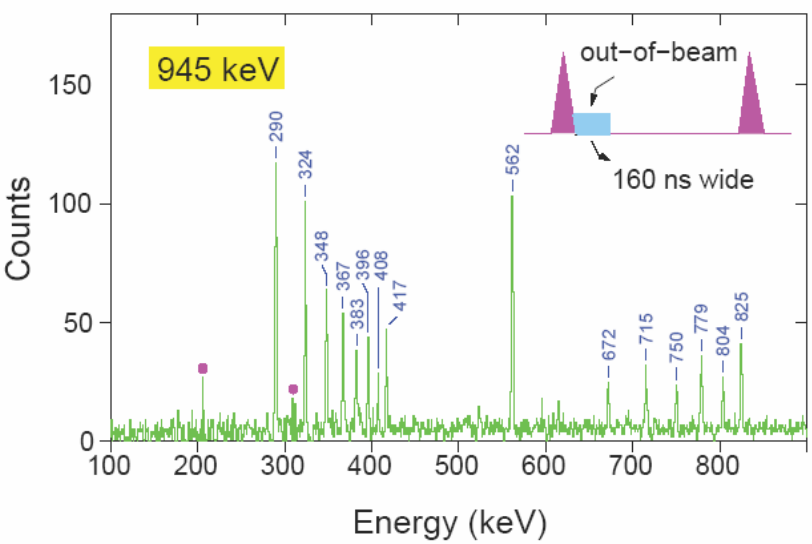
- Pulsed beam & CAESAR array
  (8 CS Ge detectors)
  4 μs on/60 μs off

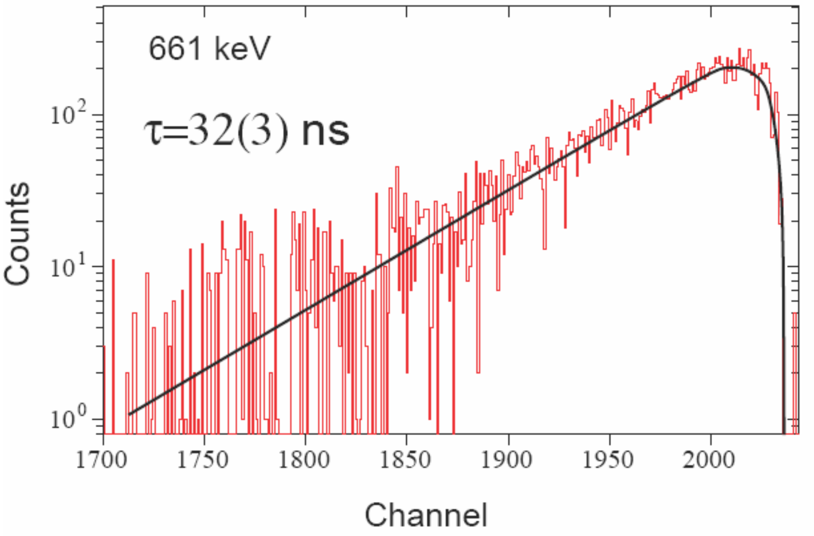
Decay of the 57/2- Isomer

Selectivity –
1 in 10^6!

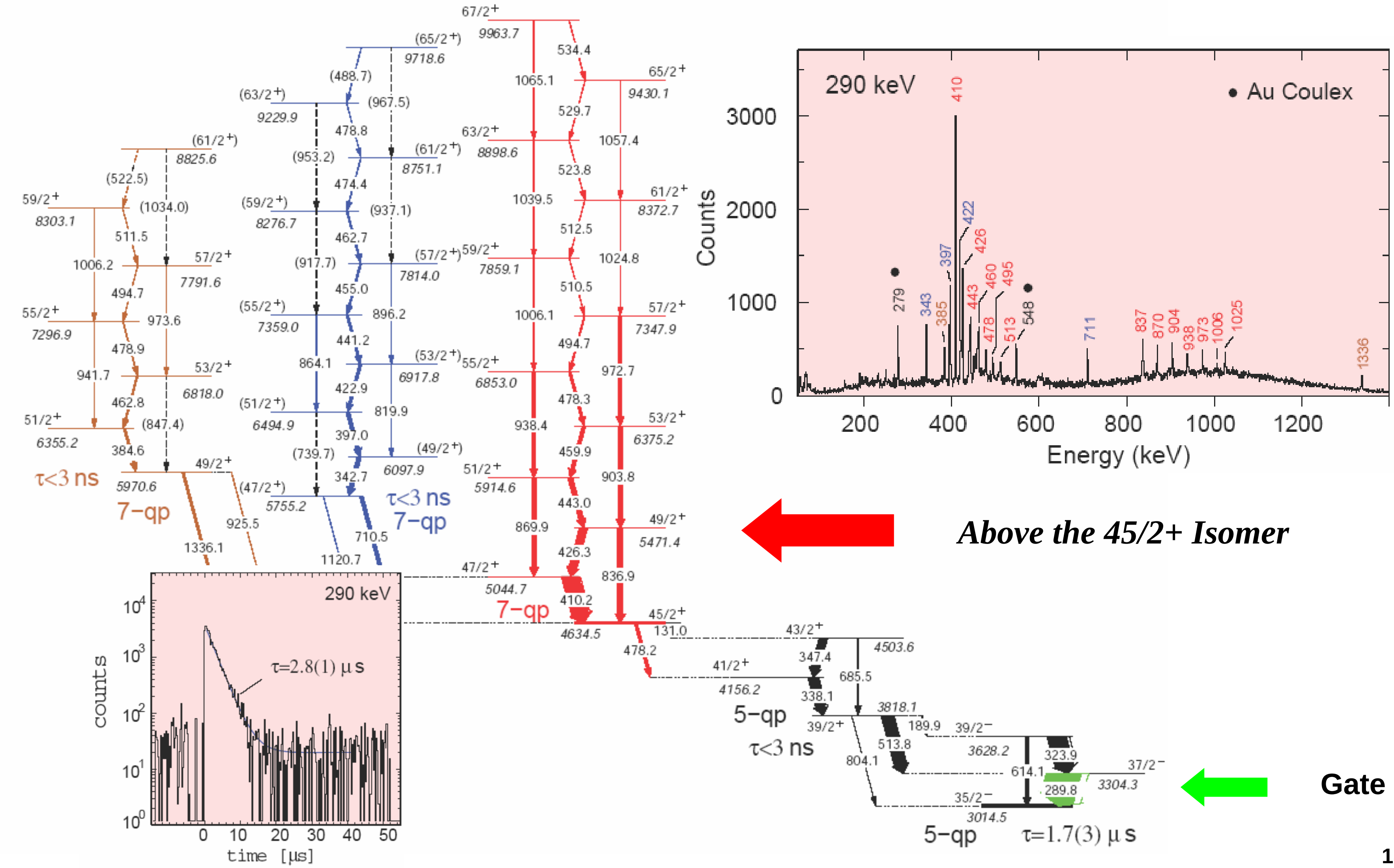


The 9–qp isomer is short lived!





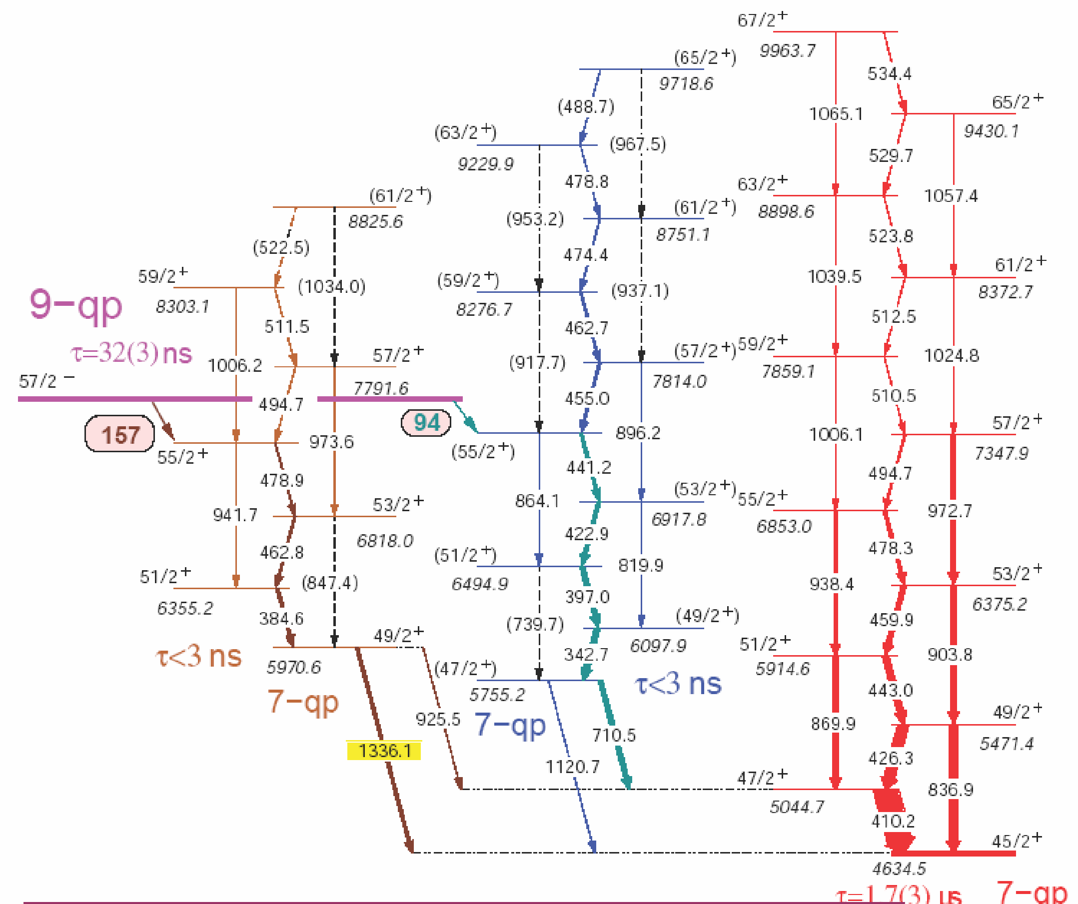
Structures above the 45/2+ Isomer

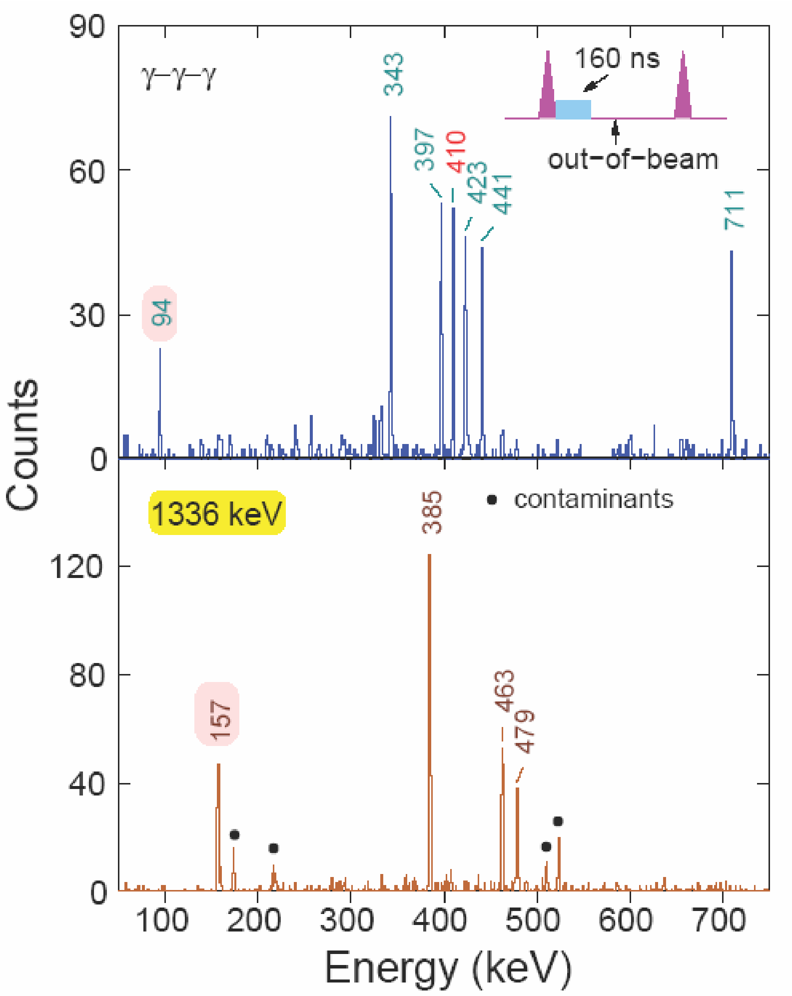


Above the 45/2+ Isomer

Gate

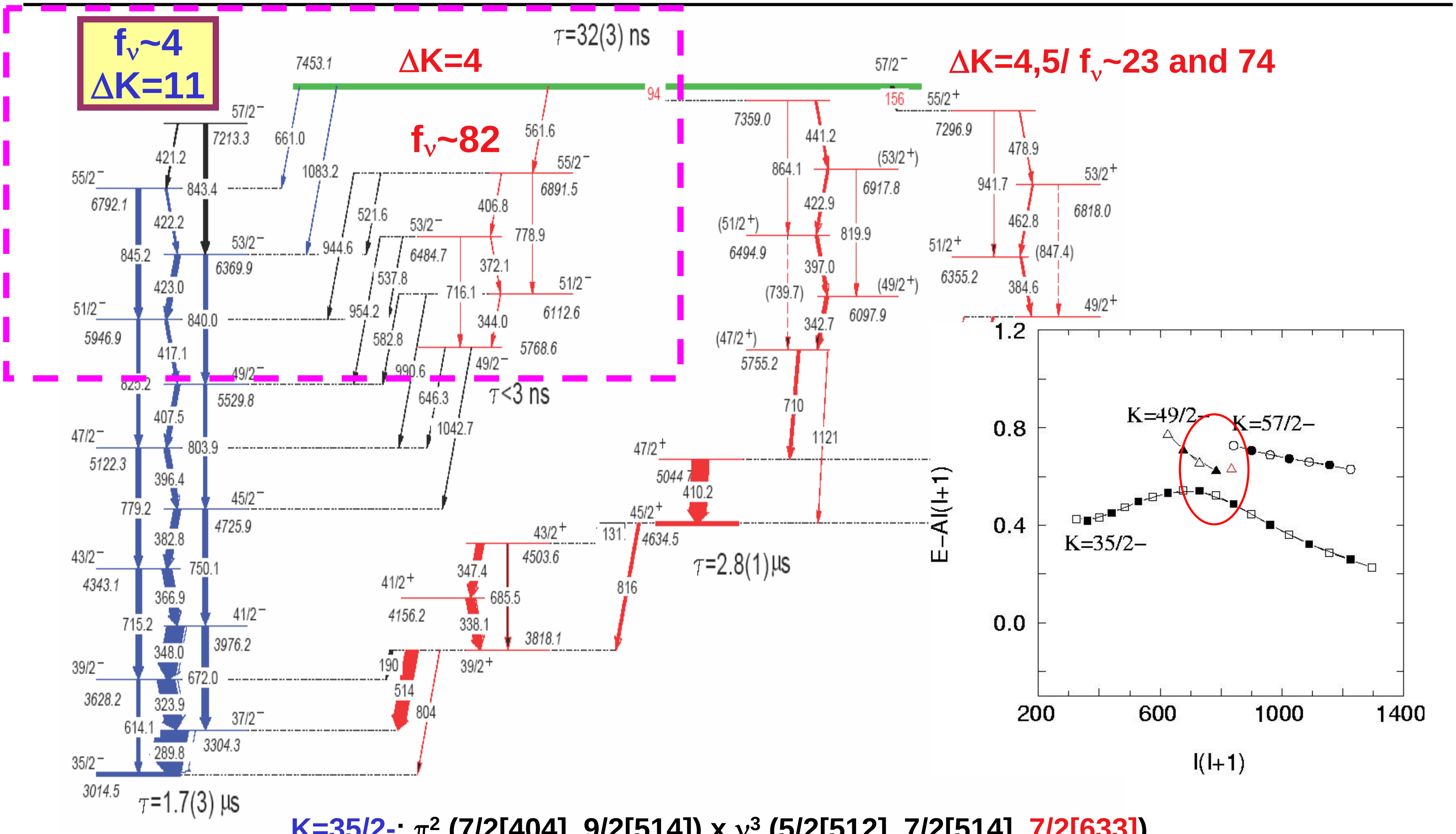
“Normal” Decay Branches





- ☐ ***94 keV Mult: E1 - 18% branch***
- ☐ ***157 keV Mult: E1 – 17% branch***

K-hindrances in the decay of the 57/2- Isomer



fν~4
ΔK=11

ΔK=4

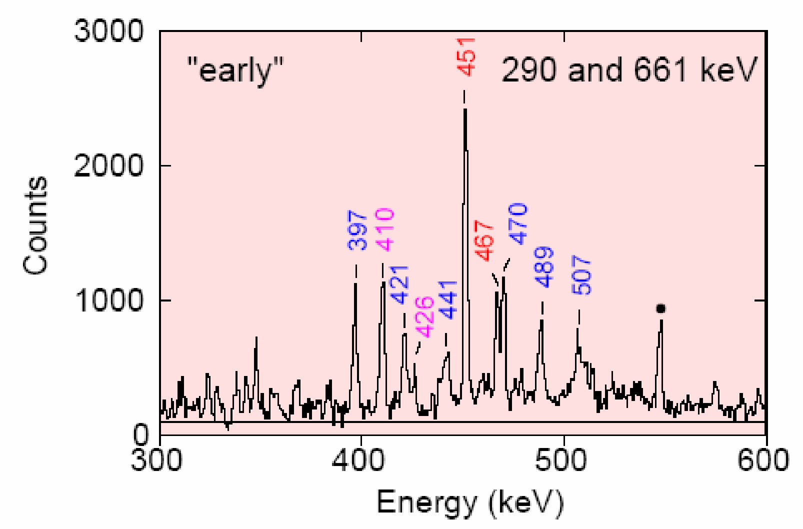
fν~82

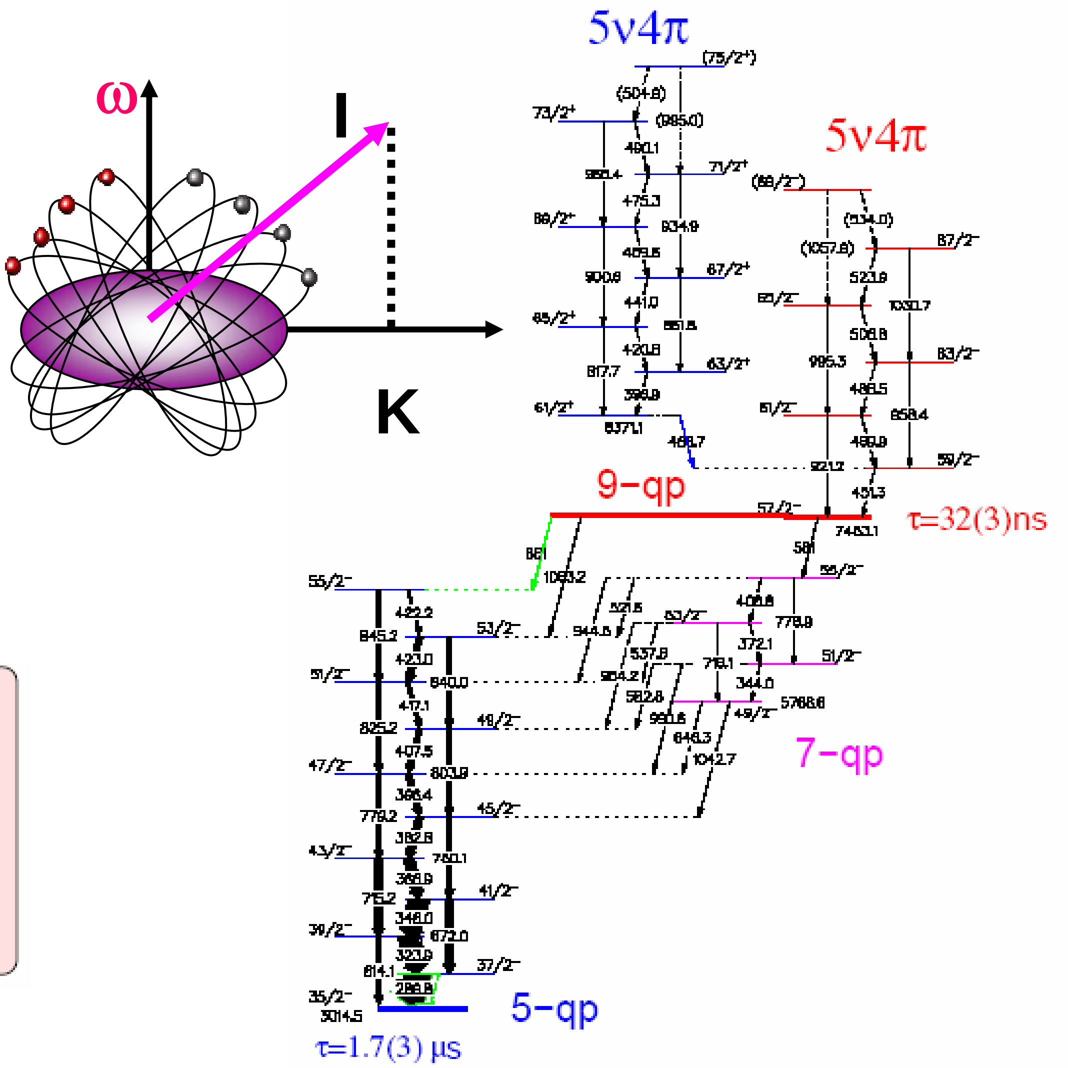
ΔK=4,5/ fν~23 and 74

K=35/2-: **π² (7/2[404], 9/2[514]) x ν³ (5/2[512], 7/2[514], 7/2[633])**

K=49/2-: **35/2- x ν² (5/2[642], 9/2[624])**

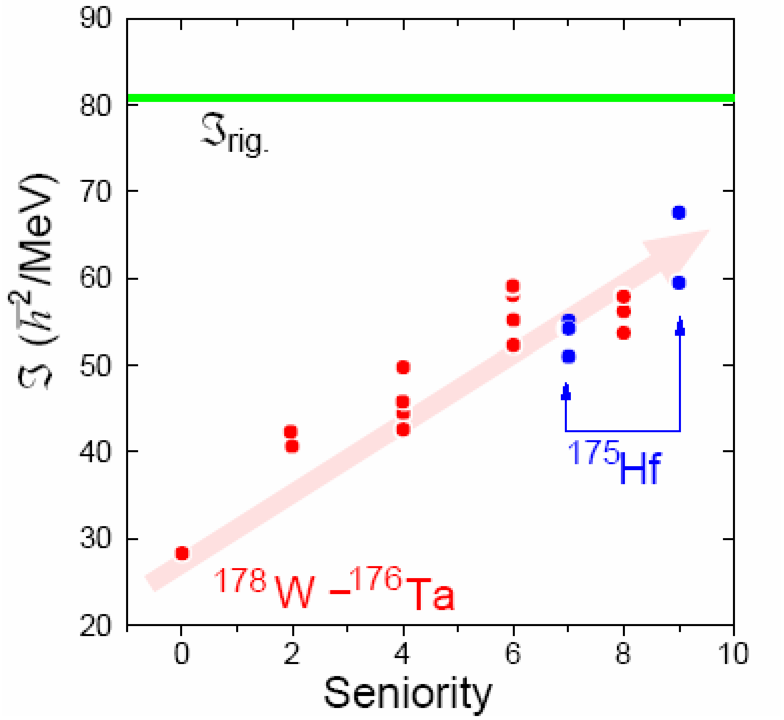
Rotation of the 57/2- Isomer

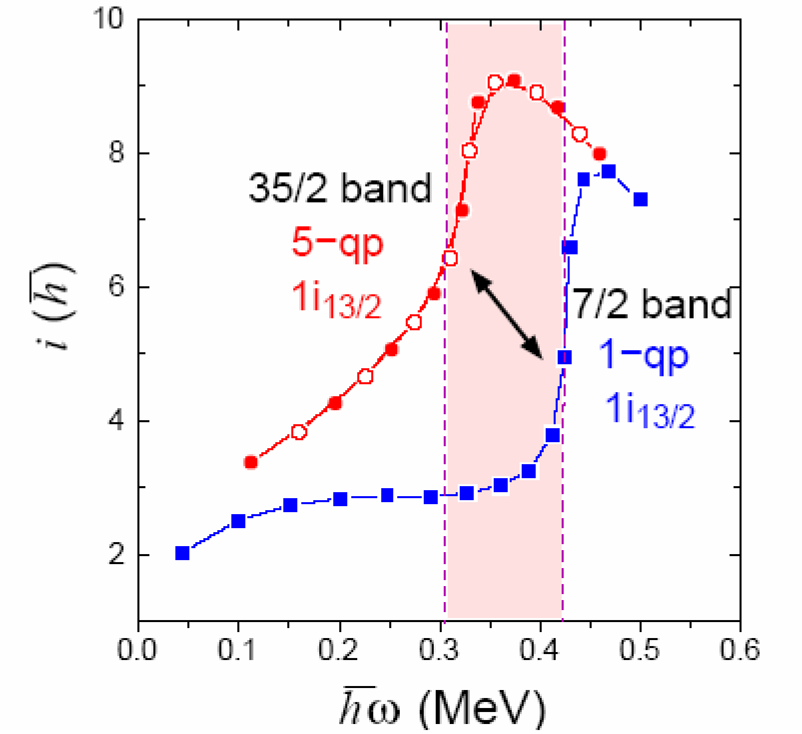




- two new 9−qp structures
- collectivity still persists
- $g_K - g_R$ − configurations

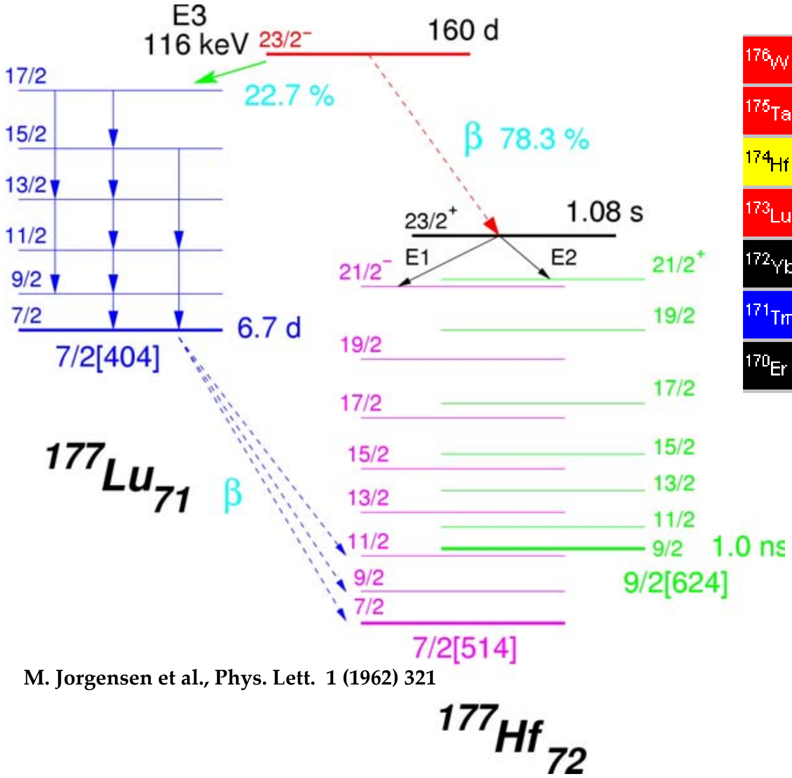
Has the Pairing Really Gone?



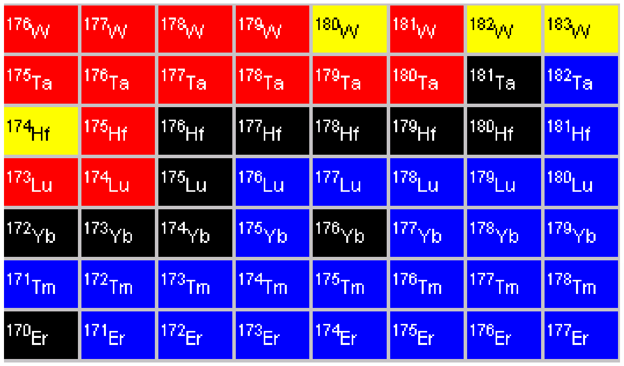


- even at 9−qp $\Im < \Im_{rig.}$
  - pairing is still important
    - "dynamic" vs. "static"

… at Extreme of Neutron number – the case of ^{177}Lu



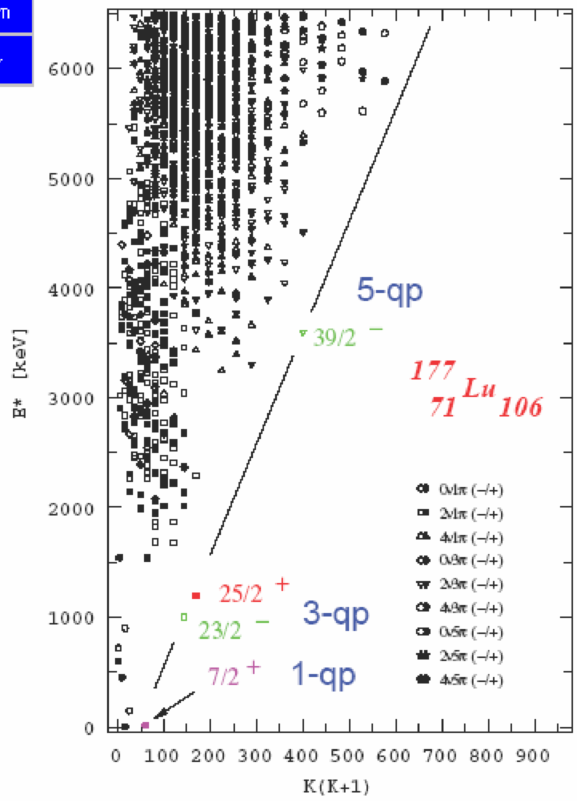
M. Jorgensen et al., Phys. Lett. 1 (1962) 321



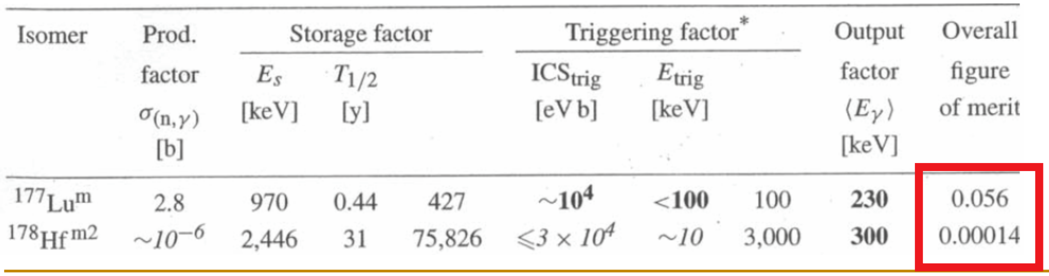
^{176}W	^{177}W	^{178}W	^{179}W	^{180}W	^{181}W	^{182}W	^{183}W
^{175}Ta	^{176}Ta	^{177}Ta	^{178}Ta	^{179}Ta	^{180}Ta	^{181}Ta	^{182}Ta
^{174}Hf	^{175}Hf	^{176}Hf	^{177}Hf	^{178}Hf	^{179}Hf	^{180}Hf	^{181}Hf
^{173}Lu	^{174}Lu	^{175}Lu	^{176}Lu	^{177}Lu	^{178}Lu	^{179}Lu	^{180}Lu
^{172}Yb	^{173}Yb	^{174}Yb	^{175}Yb	^{176}Yb	^{177}Yb	^{178}Yb	^{179}Yb
^{171}Tm	^{172}Tm	^{173}Tm	^{174}Tm	^{175}Tm	^{176}Tm	^{177}Tm	^{178}Tm
^{170}Er	^{171}Er	^{172}Er	^{173}Er	^{174}Er	^{175}Er	^{176}Er	^{177}Er

Deformed shell-model

- *Nilsson s.p. levels*
- *Pairing - LN prescription*



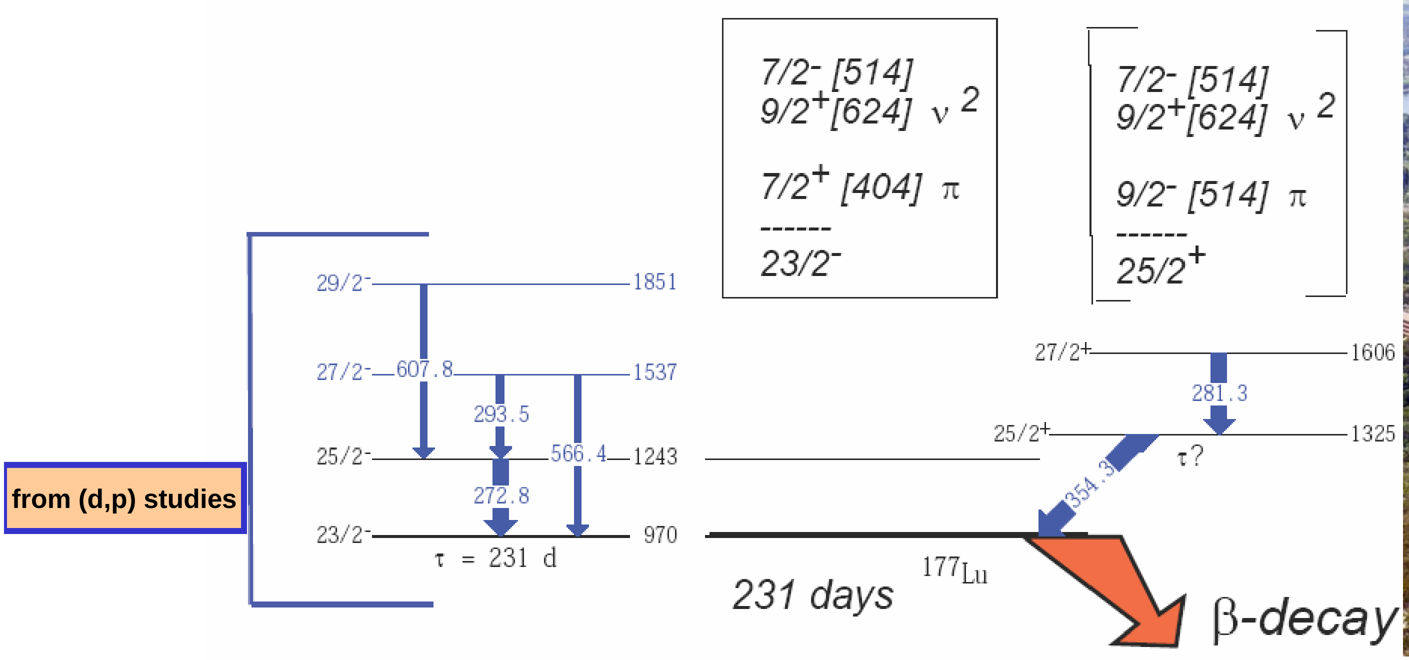
J.J. Carroll *et al.*, *Hyp. Int.* 135 (2001) 3

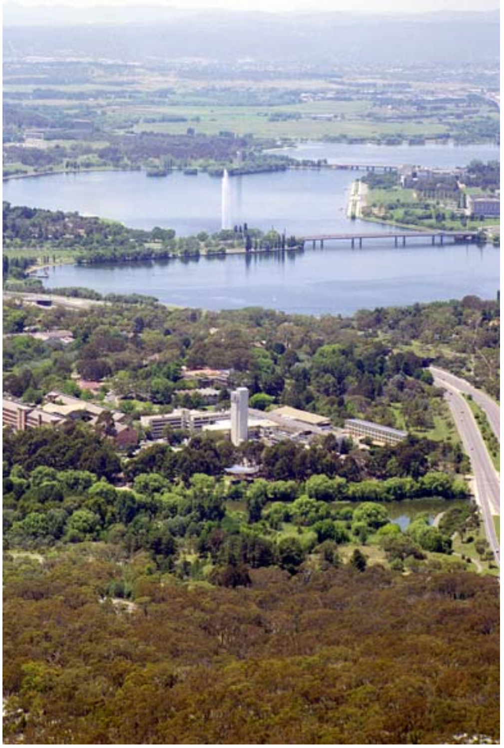


Isomer	Prod. factor $\sigma_{(n,\gamma)}$ [b]	Storage factor			Triggering factor*			Output factor $\langle E_\gamma \rangle$ [keV]	Overall figure of merit
		E_s [keV]	$T_{1/2}$ [y]		ICS$_{\text{trig}}$ [eV b]	E_{trig} [keV]			
^{177}Lu^m	2.8	970	0.44	427	**$\sim 10^4$**	**<100**	100	**230**	0.056
^{178}Hf^{m2}	$\sim 10^{-6}$	2,446	31	75,826	$\leqslant 3 \times 10^4$	~ 10	3,000	**300**	0.00014

Structures Above the K^{π}=23/2- isomer

^{177}Lu from incomplete fusion





α–γ–γ–time coincidences 4p particle-detector array;
37 MeV 7Li ; angular momentum in 6-13 h - breakup-compound

^{176}Yb(^{7}Li,α2n) McGoram ANU PhD; to be published

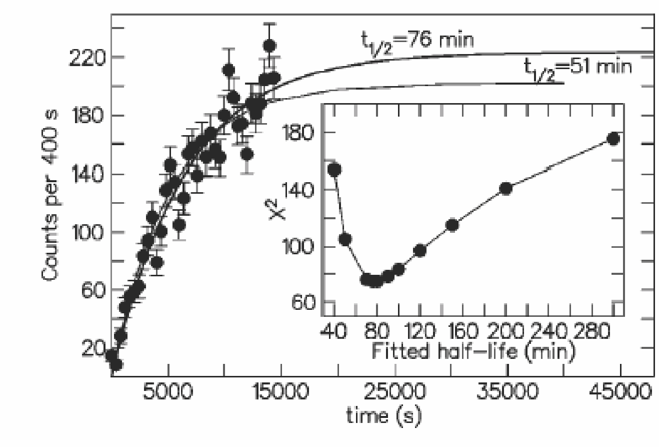
An evidence for a β– decaying isomer?

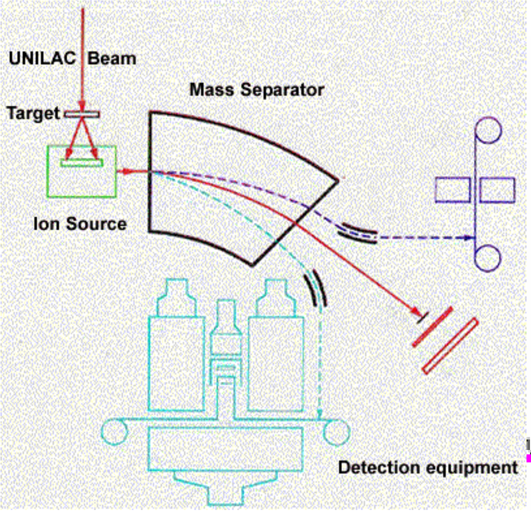
PHYSICAL REVIEW C **69**, 024320 (2004)

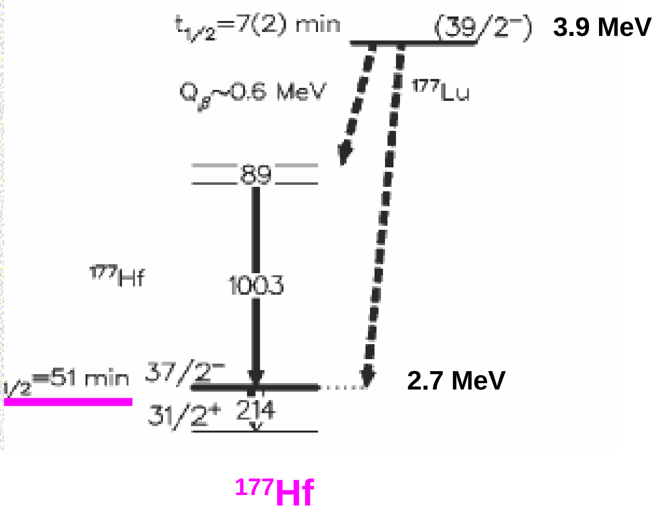
Evidence for a high-spin β-decaying isomer in ^{177}Lu

Sareh D. Al-Garni,[1,*] P. H. Regan,[1,†] P. M. Walker,[1] E. Roeckl,[2] R. Kirchner,[2] F. R. Xu,[3] L. Batist,[2,4] A. Blazhev,[2,5] R. Borcea,[2] D. M. Cullen,[6,7] J. Döring,[2] H. M. El-Masri,[1] J. Garces Narro,[1] H. Grawe,[2] M. La Commara,[2,8] C. Mazzocchi,[2,9] I. Mukha,[2,10] C. J. Pearson,[1] C. Plettner,[2] K. Schmidt,[2] W.-D. Schmidt-Ott,[11] Y. Shimbara,[12] C. Wheldon,[1,2,6] R. Wood,[1] and S. C. Wooding[1,2]

11.4 MeV/nucleon ^{136}Xe beam on ^{186}W target; thermal ion source; mass separation

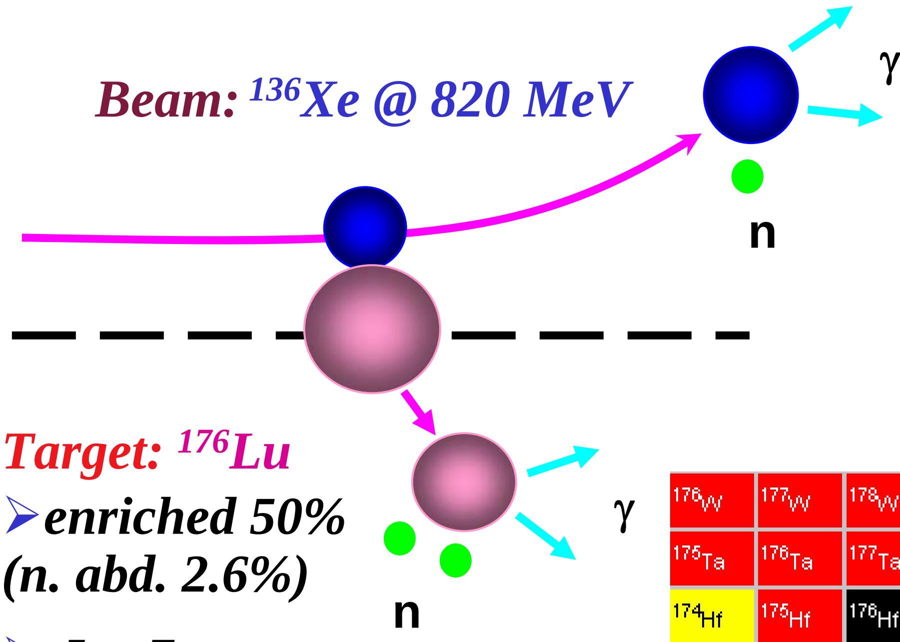






Deep Inelastic Experiment at ANL

Pulsed beam & Gammasphere at ANL

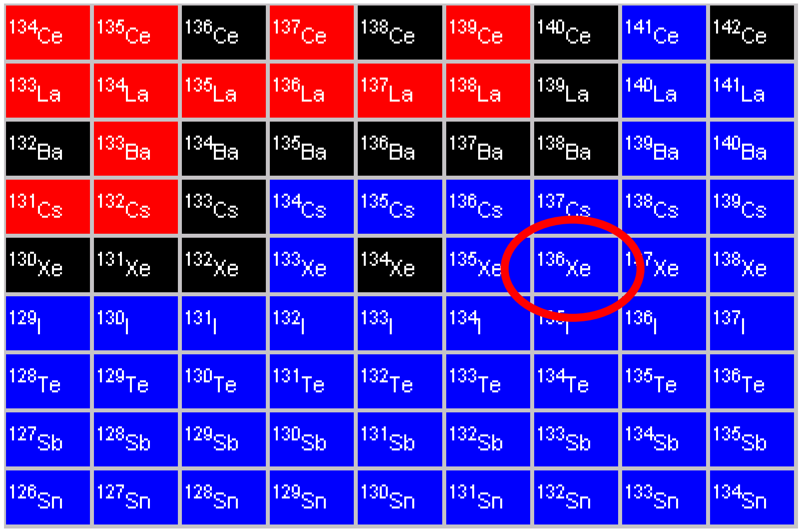


Beam: ***^{136}Xe @ 820 MeV***

Target: ***^{176}Lu***

- ***enriched 50% (n. abd. 2.6%)***
- ***J^{π} =7-***

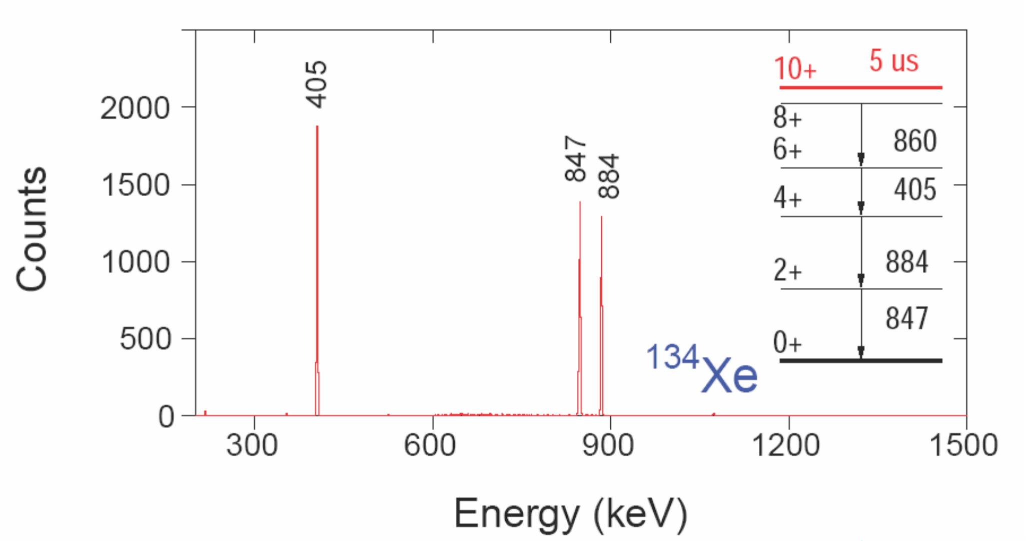
Target: ***^{175}Lu, ^{174}Yb***

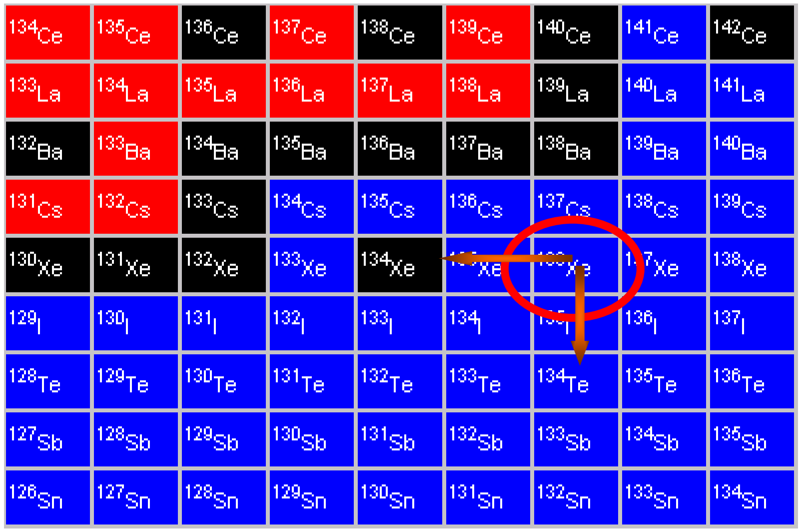


^{134}Ce	^{135}Ce	^{136}Ce	^{137}Ce	^{138}Ce	^{139}Ce	^{140}Ce	^{141}Ce	^{142}Ce
^{133}La	^{134}La	^{135}La	^{136}La	^{137}La	^{138}La	^{139}La	^{140}La	^{141}La
^{132}Ba	^{133}Ba	^{134}Ba	^{135}Ba	^{136}Ba	^{137}Ba	^{138}Ba	^{139}Ba	^{140}Ba
^{131}Cs	^{132}Cs	^{133}Cs	^{134}Cs	^{135}Cs	^{136}Cs	^{137}Cs	^{138}Cs	^{139}Cs
^{130}Xe	^{131}Xe	^{132}Xe	^{133}Xe	^{134}Xe	^{135}Xe	^{136}Xe	^{137}Xe	^{138}Xe
^{129}I	^{130}I	^{131}I	^{132}I	^{133}I	^{134}I	^{135}I	^{136}I	^{137}I
^{128}Te	^{129}Te	^{130}Te	^{131}Te	^{132}Te	^{133}Te	^{134}Te	^{135}Te	^{136}Te
^{127}Sb	^{128}Sb	^{129}Sb	^{130}Sb	^{131}Sb	^{132}Sb	^{133}Sb	^{134}Sb	^{135}Sb
^{126}Sn	^{127}Sn	^{128}Sn	^{129}Sn	^{130}Sn	^{131}Sn	^{132}Sn	^{133}Sn	^{134}Sn

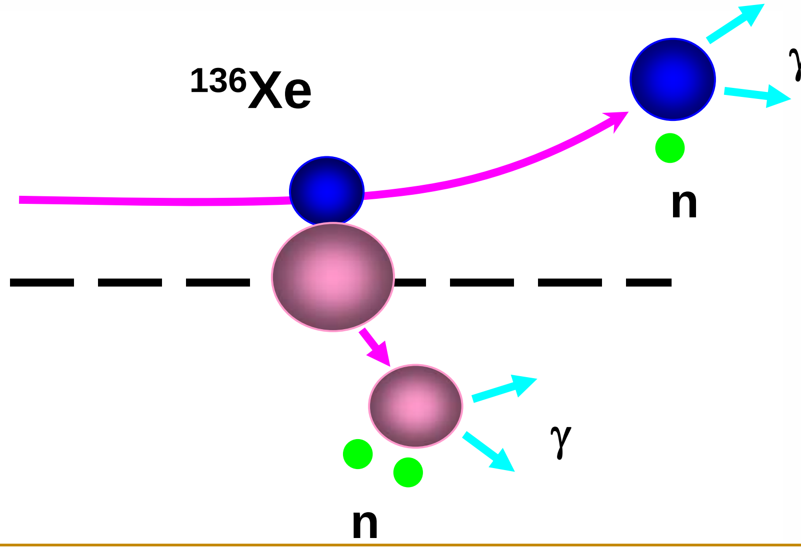
^{176}W	^{177}W	^{178}W	^{179}W	^{180}W	^{181}W	^{182}W	^{183}W
^{175}Ta	^{176}Ta	^{177}Ta	^{178}Ta	^{179}Ta	^{180}Ta	^{181}Ta	^{182}Ta
^{174}Hf	^{175}Hf	^{176}Hf	^{177}Hf	^{178}Hf	^{179}Hf	^{180}Hf	^{181}Hf
^{173}Lu	^{174}Lu	^{175}Lu	^{176}Lu	^{177}Lu	^{178}Lu	^{179}Lu	^{180}Lu
^{172}Yb	^{173}Yb	^{174}Yb	^{175}Yb	^{176}Yb	^{177}Yb	^{178}Yb	^{179}Yb
^{171}Tm	^{172}Tm	^{173}Tm	^{174}Tm	^{175}Tm	^{176}Tm	^{177}Tm	^{178}Tm
^{170}Er	^{171}Er	^{172}Er	^{173}Er	^{174}Er	^{175}Er	^{176}Er	^{177}Er

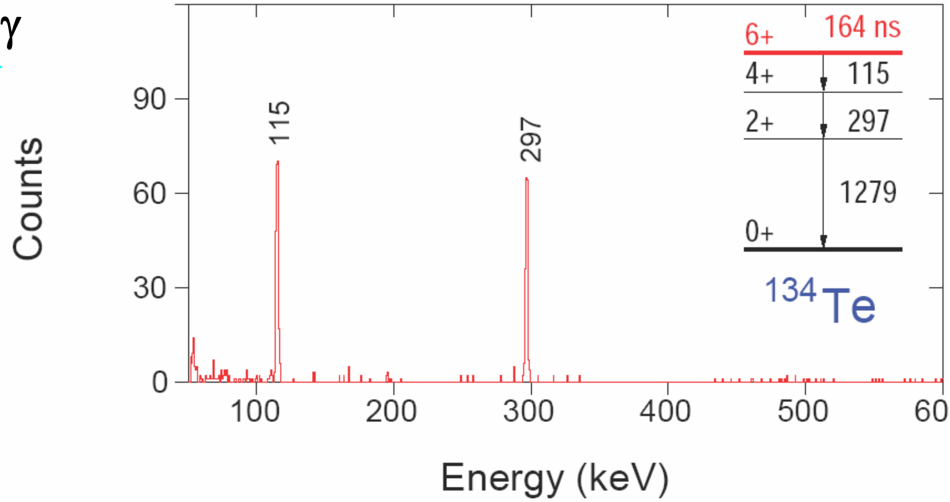
Projectile-like nuclei



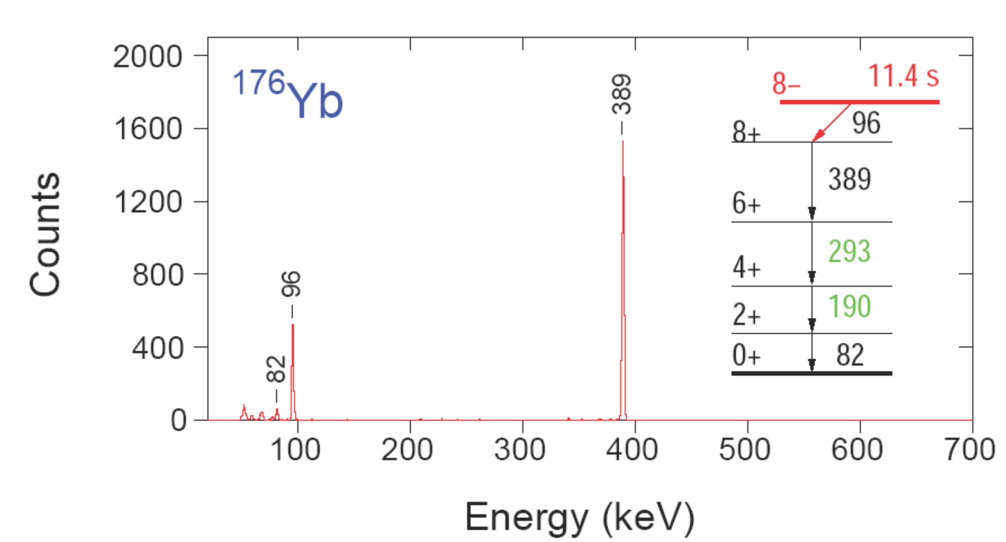


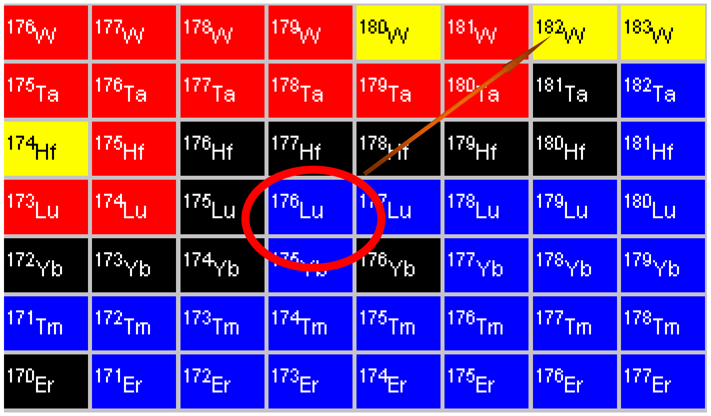
^{134}Ce	^{135}Ce	^{136}Ce	^{137}Ce	^{138}Ce	^{139}Ce	^{140}Ce	^{141}Ce	^{142}Ce
^{133}La	^{134}La	^{135}La	^{136}La	^{137}La	^{138}La	^{139}La	^{140}La	^{141}La
^{132}Ba	^{133}Ba	^{134}Ba	^{135}Ba	^{136}Ba	^{137}Ba	^{138}Ba	^{139}Ba	^{140}Ba
^{131}Cs	^{132}Cs	^{133}Cs	^{134}Cs	^{135}Cs	^{136}Cs	^{137}Cs	^{138}Cs	^{139}Cs
^{130}Xe	^{131}Xe	^{132}Xe	^{133}Xe	^{134}Xe	^{135}Xe	^{136}Xe	^{137}Xe	^{138}Xe
^{129}I	^{130}I	^{131}I	^{132}I	^{133}I	^{134}I	^{135}I	^{136}I	^{137}I
^{128}Te	^{129}Te	^{130}Te	^{131}Te	^{132}Te	^{133}Te	^{134}Te	^{135}Te	^{136}Te
^{127}Sb	^{128}Sb	^{129}Sb	^{130}Sb	^{131}Sb	^{132}Sb	^{133}Sb	^{134}Sb	^{135}Sb
^{126}Sn	^{127}Sn	^{128}Sn	^{129}Sn	^{130}Sn	^{131}Sn	^{132}Sn	^{133}Sn	^{134}Sn



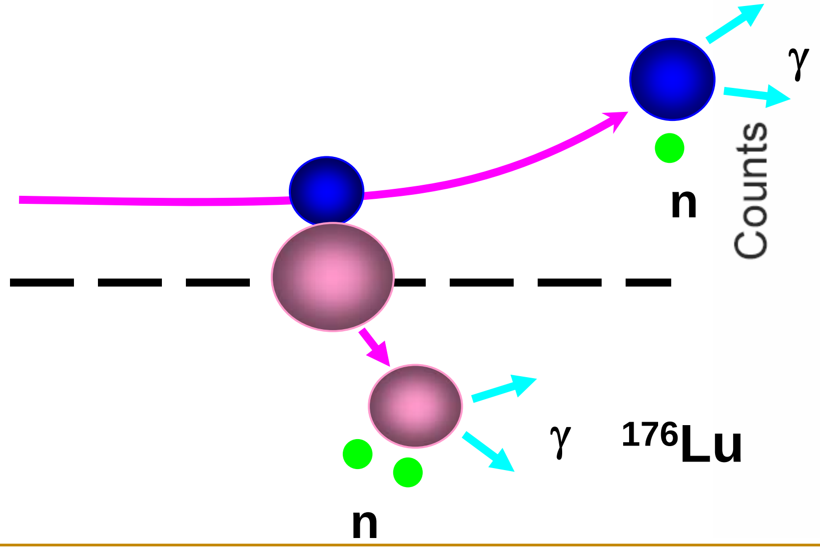


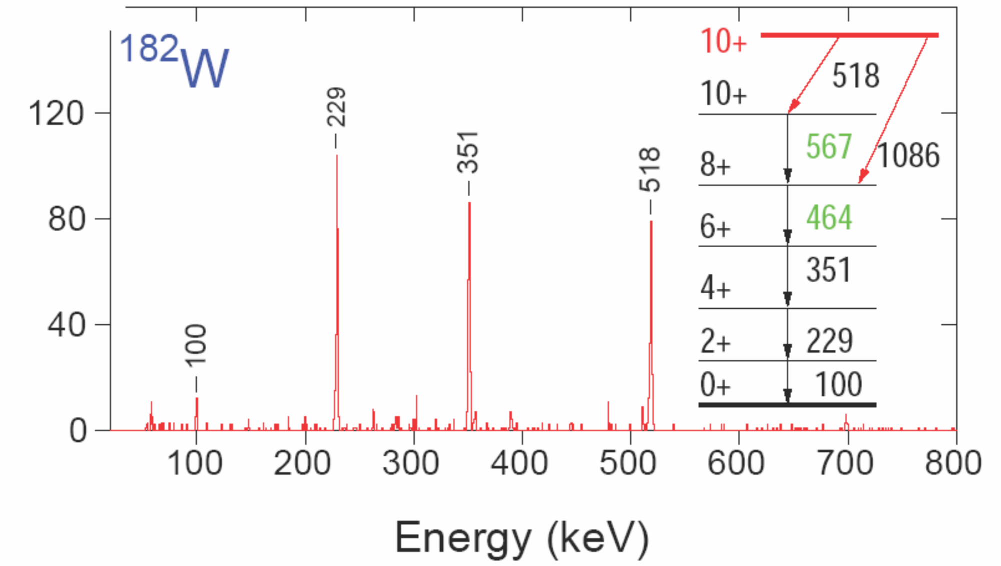
Target-like nuclei



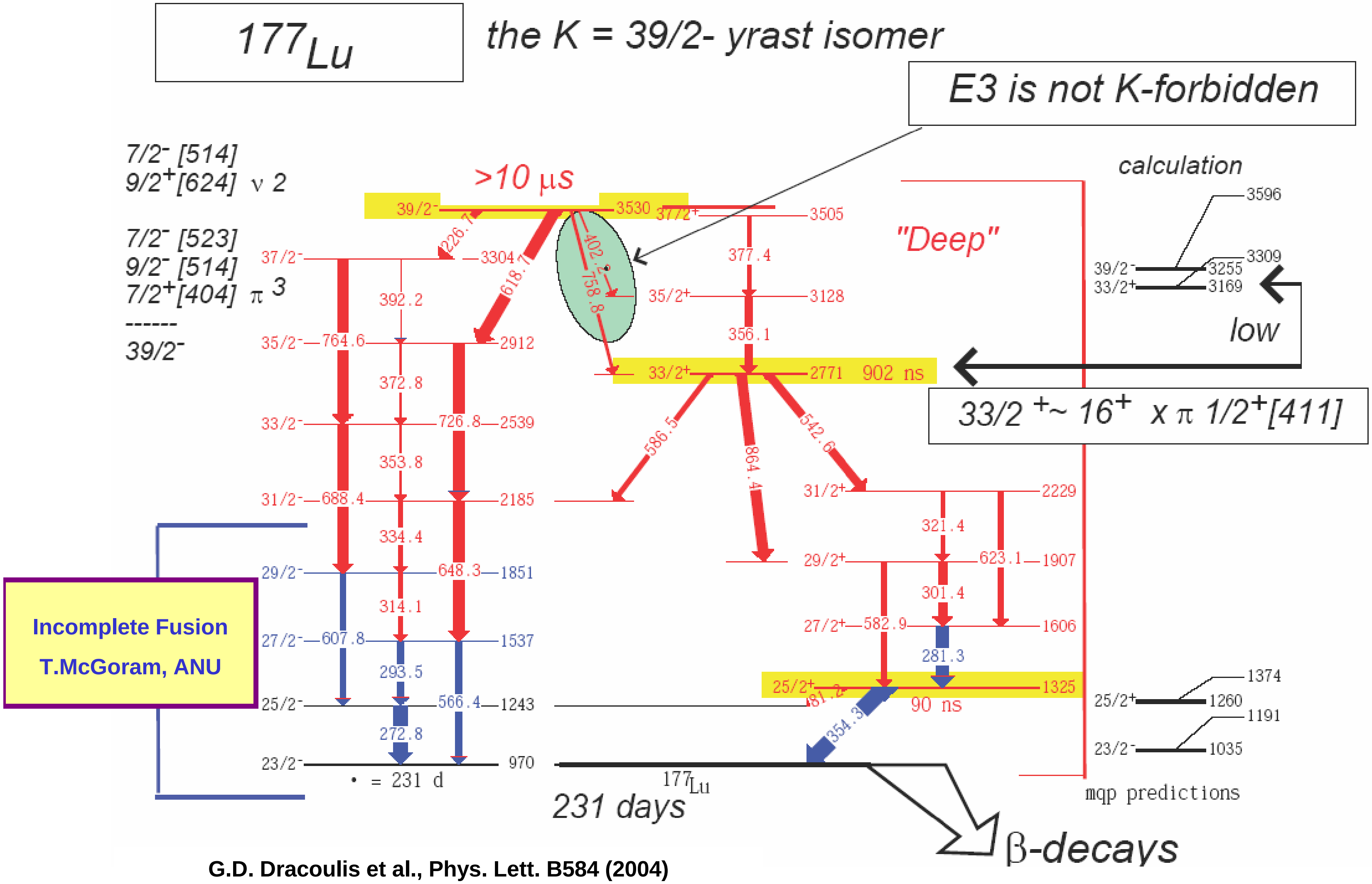


^{176}W	^{177}W	^{178}W	^{179}W	^{180}W	^{181}W	^{182}W	^{183}W
^{175}Ta	^{176}Ta	^{177}Ta	^{178}Ta	^{179}Ta	^{180}Ta	^{181}Ta	^{182}Ta
^{174}Hf	^{175}Hf	^{176}Hf	^{177}Hf	^{178}Hf	^{179}Hf	^{180}Hf	^{181}Hf
^{173}Lu	^{174}Lu	^{175}Lu	^{176}Lu	^{177}Lu	^{178}Lu	^{179}Lu	^{180}Lu
^{172}Yb	^{173}Yb	^{174}Yb	^{175}Yb	^{176}Yb	^{177}Yb	^{178}Yb	^{179}Yb
^{171}Tm	^{172}Tm	^{173}Tm	^{174}Tm	^{175}Tm	^{176}Tm	^{177}Tm	^{178}Tm
^{170}Er	^{171}Er	^{172}Er	^{173}Er	^{174}Er	^{175}Er	^{176}Er	^{177}Er



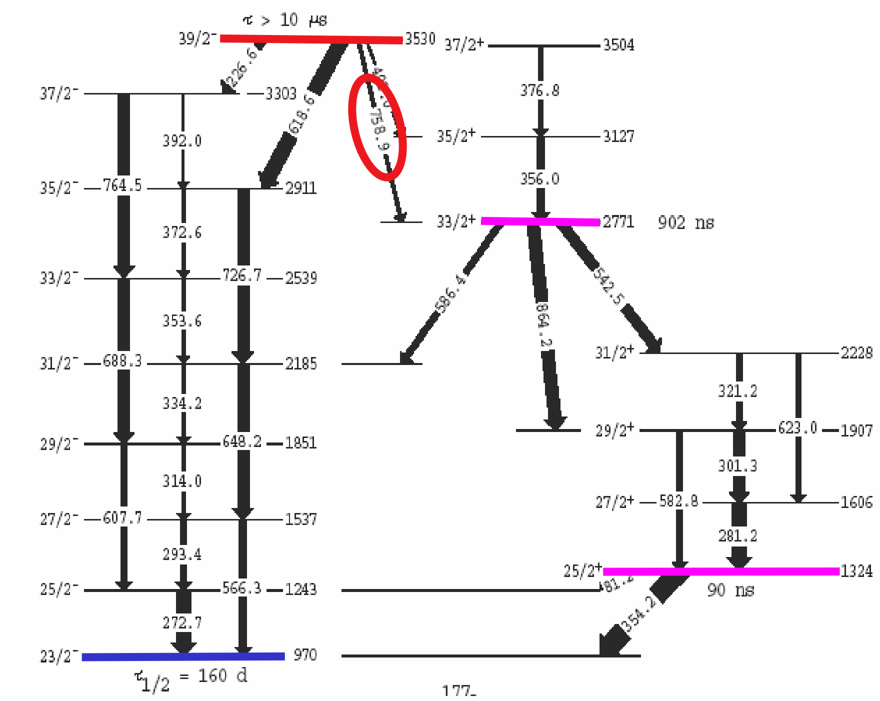


K^{π}=39/2- isomer in ^{177}Lu



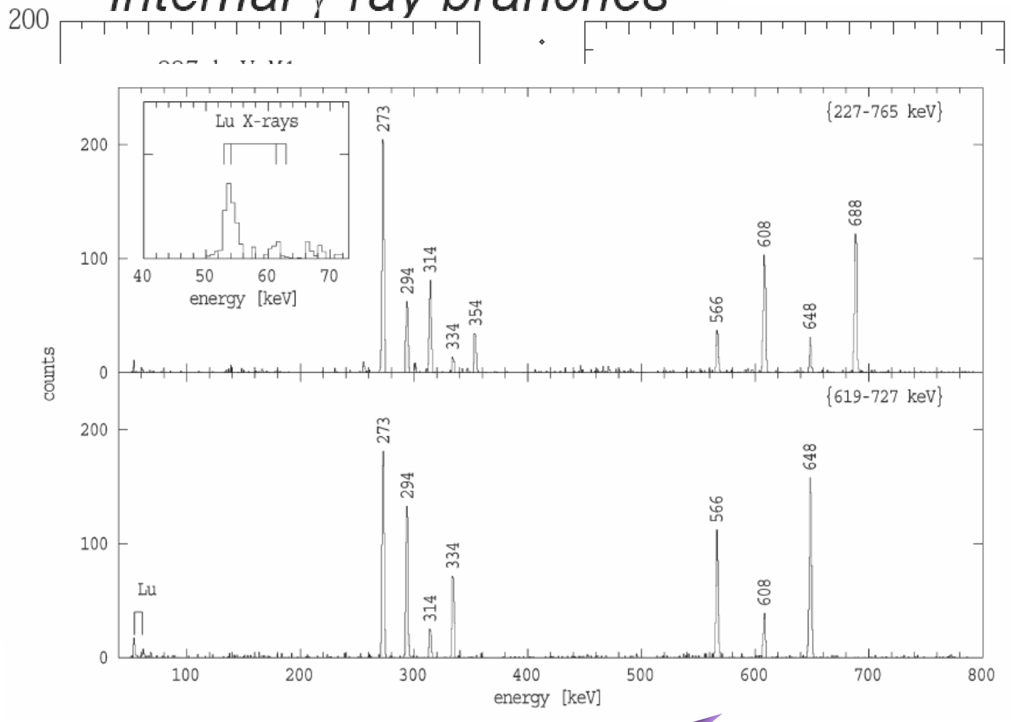
G.D. Dracoulis et al., Phys. Lett. B584 (2004)

Is this the claimed β- decaying isomer?



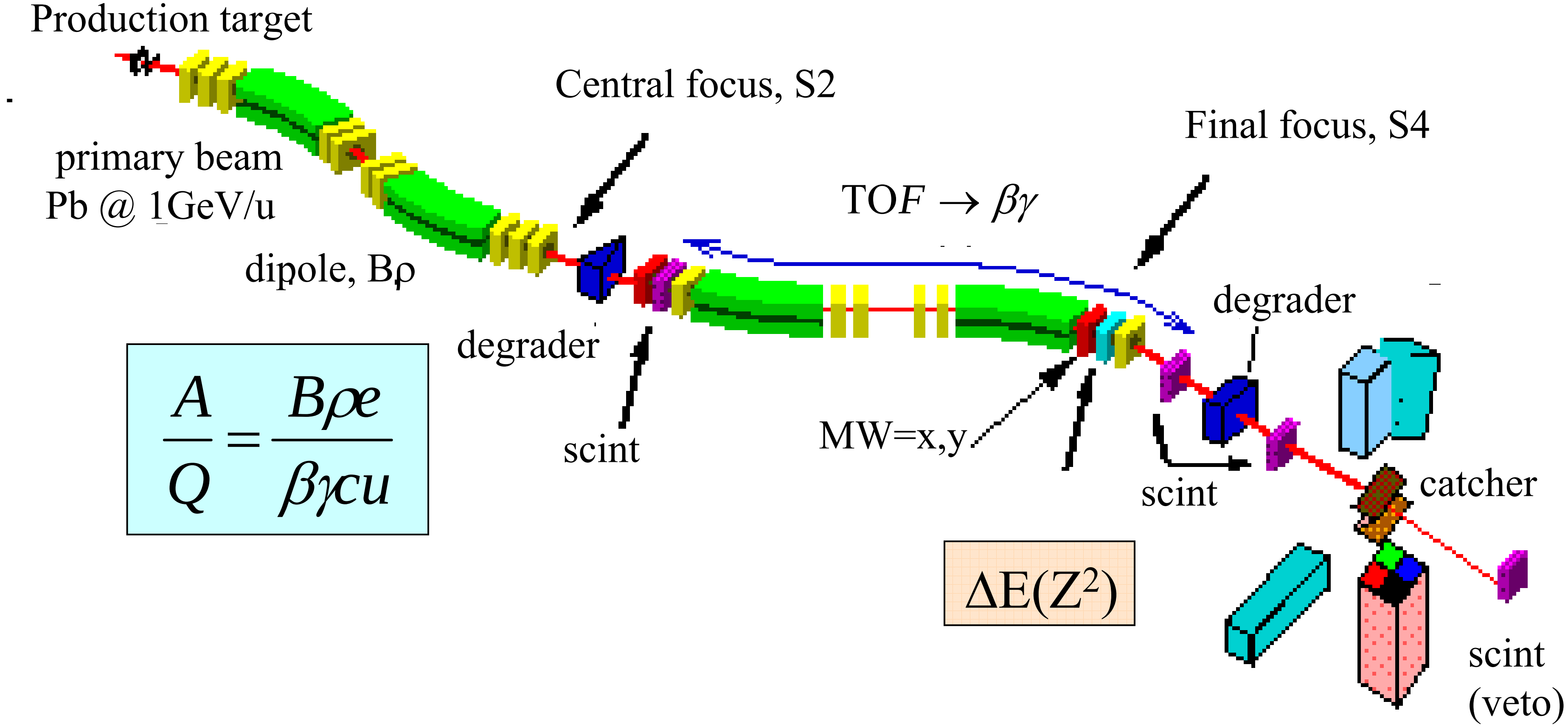
Dracoulis et al Phys Lett B 584(2004)22

Q$_\beta$ - *logft & strength of internal γ-ray branches*



- *Ex=3.5 MeV (3.9 MeV)*
- *unambiguous γ–ray decay signature (no such gammas in the spectrum)*
- *unprecedented transition strength for the 759 keV, non K-forbidden, E3 transition (10^9! times retarded compared to W.u. if $T_{1/2}$=7 min)*

In-Flight Technique Using Projectile Fragmentation



Production target

primary beam
Pb @ 1GeV/u

dipole, Bρ

Central focus, S2

degrader

scint

$$\frac{A}{Q} = \frac{B\rho e}{\beta\gamma c u}$$

$\mathrm{TOF} \rightarrow \beta\gamma$

Final focus, S4

MW=x,y

degrader

scint

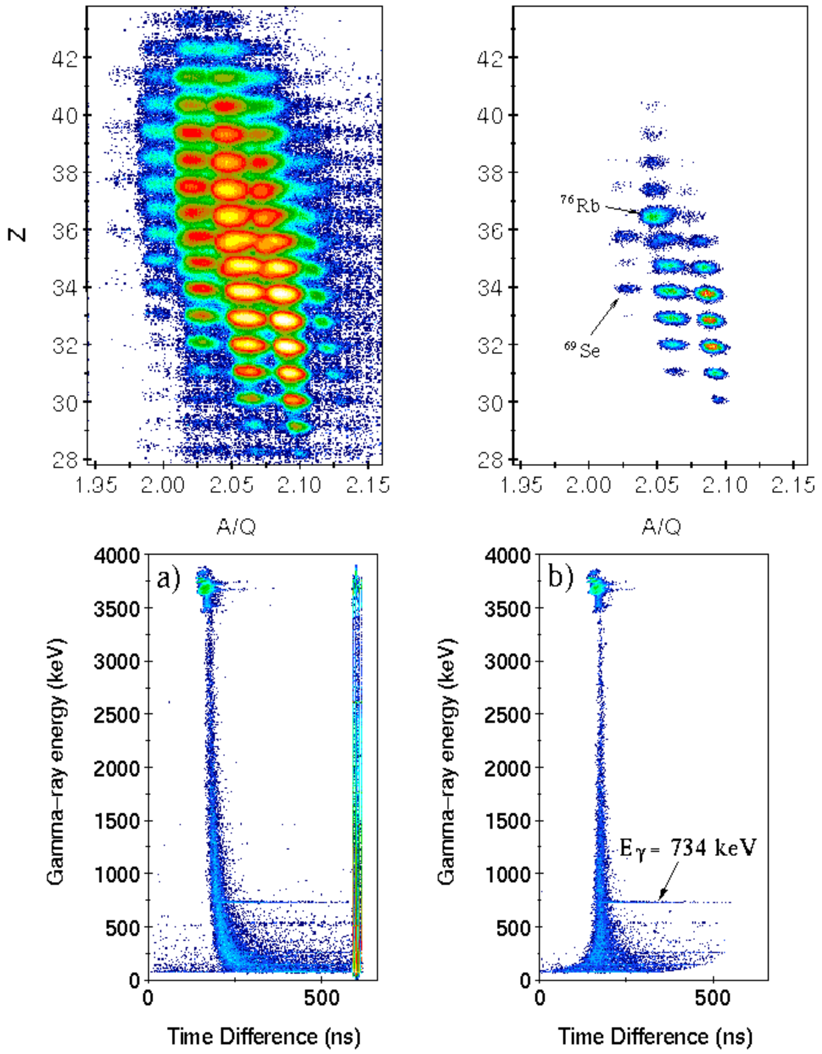
catcher

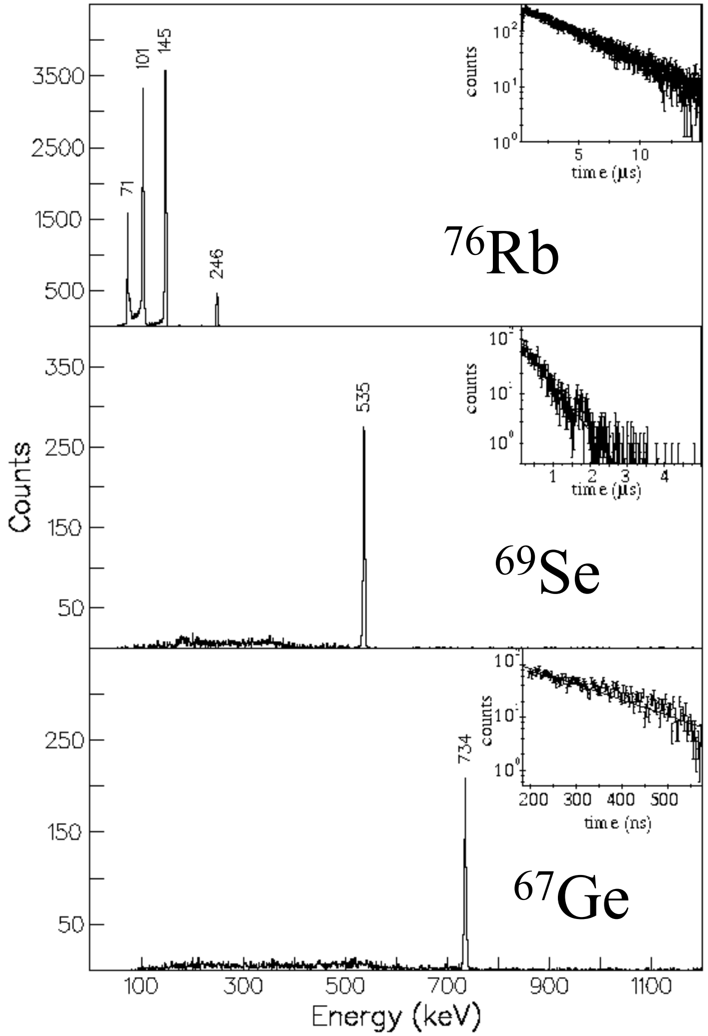
$\Delta E(Z^2)$

scint
(veto)

Use FRS@GSI or LISE3@GANIL to ID nuclei.
Transport some in isomeric states (TOF~ 300 ns).
Stop and correlate isomeric decays with nuclei id.

^{92}Mo fragmentation on ^{nat}Ni target





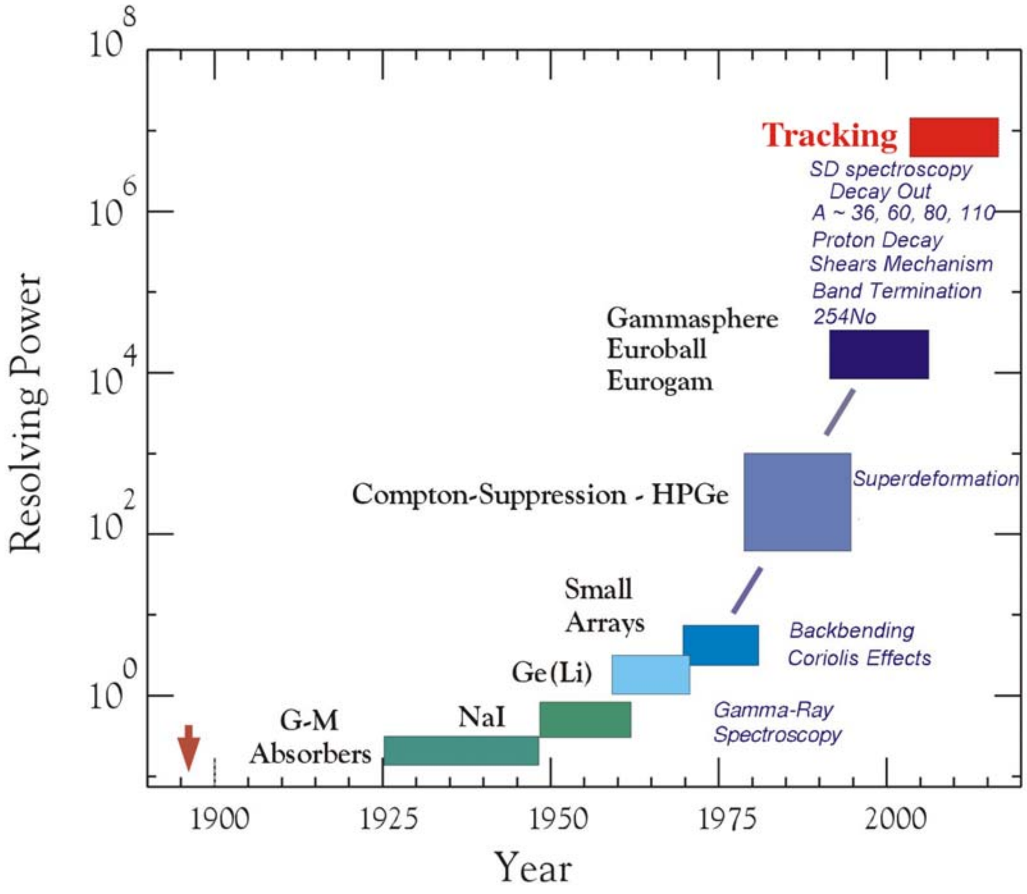
C. Chandler et al. Phys. Rev. **C61** (2000) 044309

The future of γ–ray spectroscopy

- ☐ Historical perspective
- ☐ Principle of gamma ray tracking
- ☐ Physics opportunities
- ☐ Technical challenges
- ☐ Status of project

Gamma-ray Detector Development

Crucial to Nuclear Physics Research



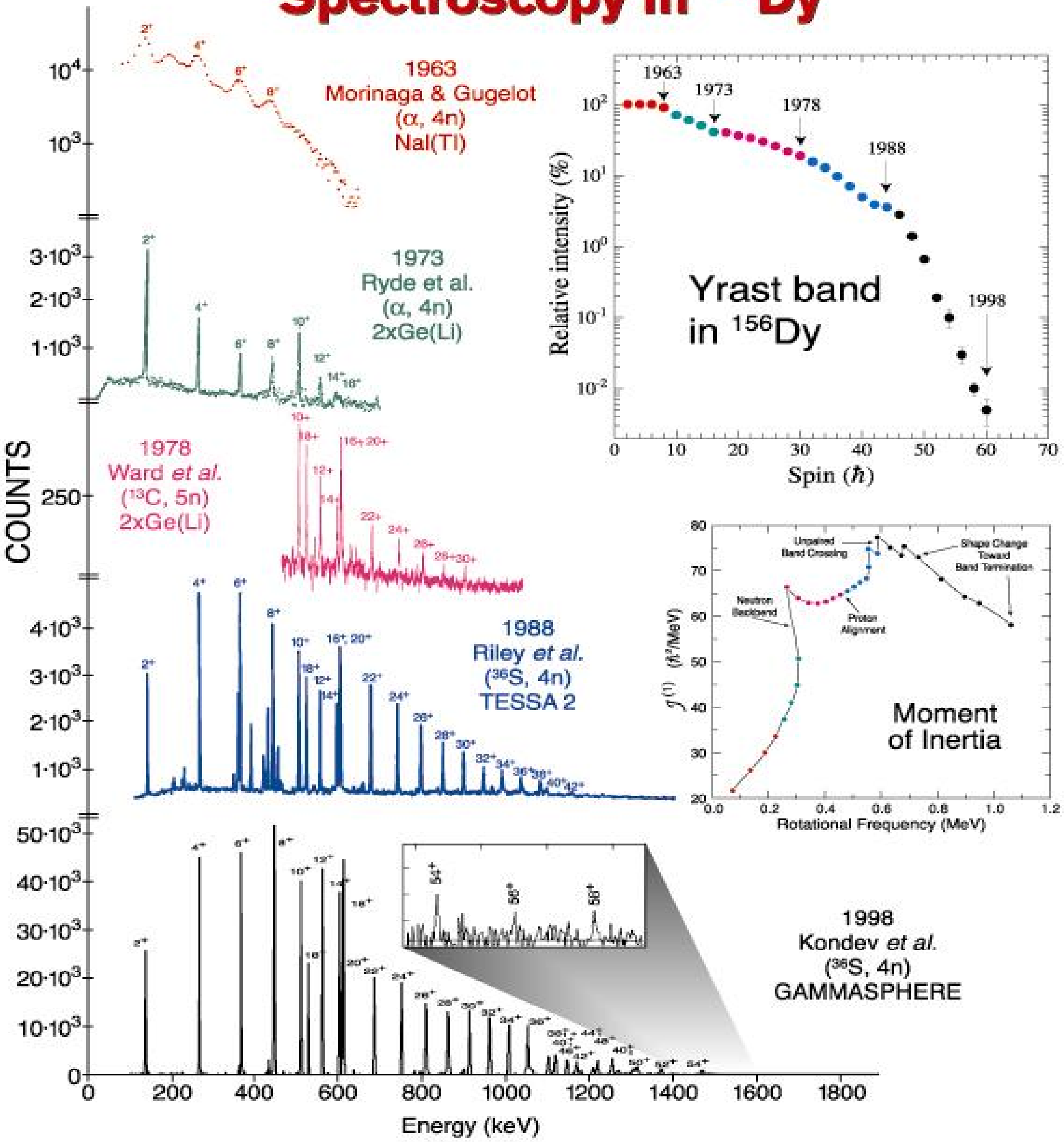
- Advances in detector technology have resulted in new discoveries.
- Innovations have improved detector performance.
  - **Energy resolution**
  - **Efficiency**
  - **Peak-to-total ratio**
  - **Position resolution**
  - **Directional information**
  - **Polarization**
  - **Auxiliary detectors**
- Tracking is feasible, will provide new opportunities and meet the challenges of new facilities.

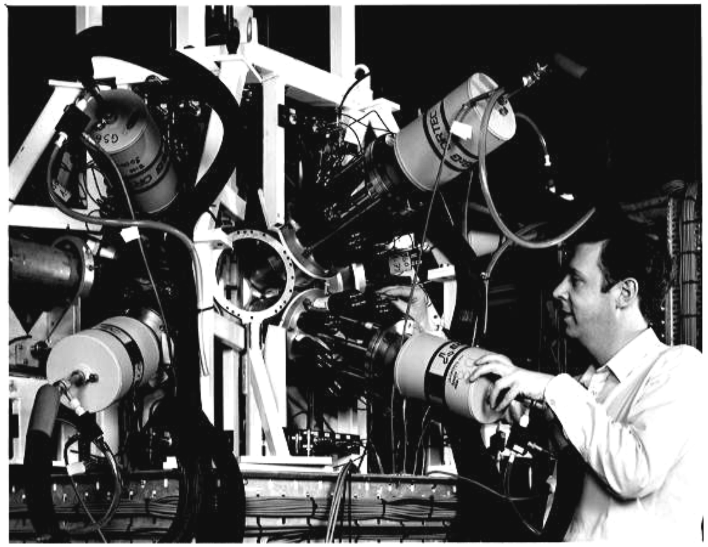
$$R \sim \left[\frac{P}{T} \times \varepsilon \times \frac{E_{spacing}}{\Delta E} \right]^n$$

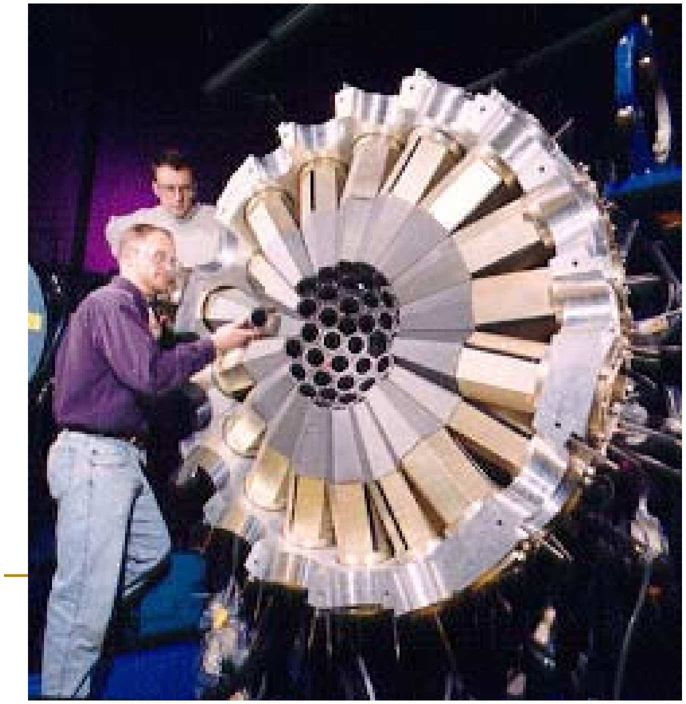
Why gamma-ray arrays?

High energy resolution	ΔE_{γ}=2.5 keV @1.3 MeV
Large P/T ratio	~60%
Large photopeak efficiency	10% @ 1.3 MeV
Good timing resolution	<10 ns
Wide energy range	~30 keV – 20 MeV
Large solid angle	~ 4π
High granularity	high fold coincidences
High resolving power	ability to isolate a given sequence of γ rays

Evolution of High-Spin γ-ray Spectroscopy in ^{156}Dy



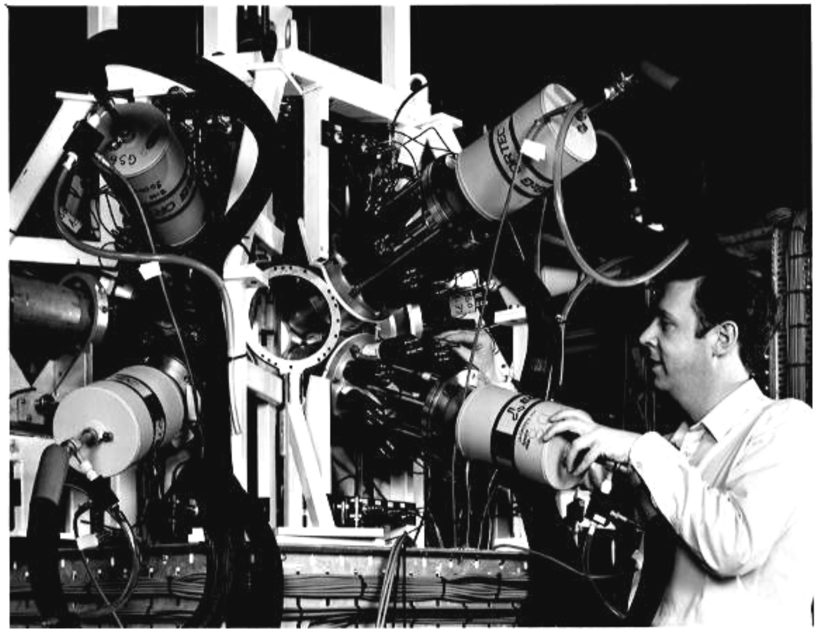




Historical Perspective

~1980 states to spin ~30

naked Ge arrays



~1980-1982 TESSA

Escape suppressed array at NBI

1983 TESSA to Daresbury

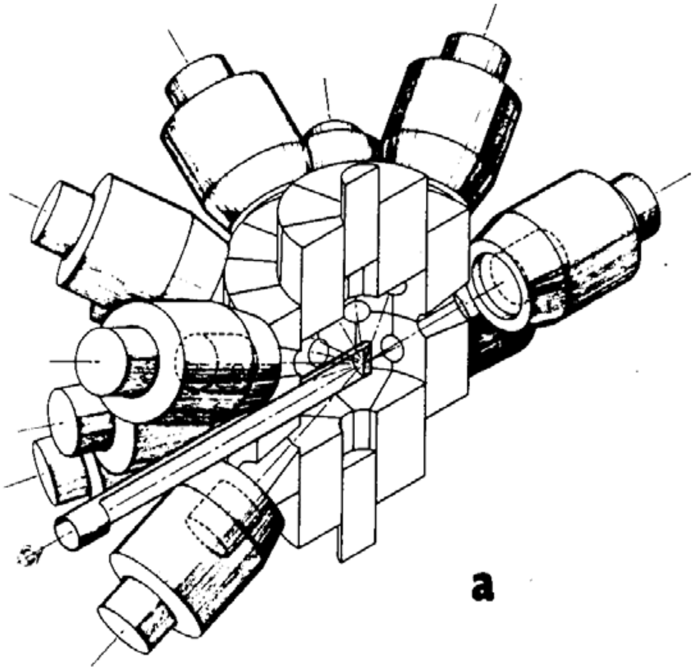
Heavier Ion beams

6 ESS using NaI(Tl)

Channel selection included, 50 element inner BGO ball

I ~ 1% sensitivity

Historical Perspective – era of large arrays

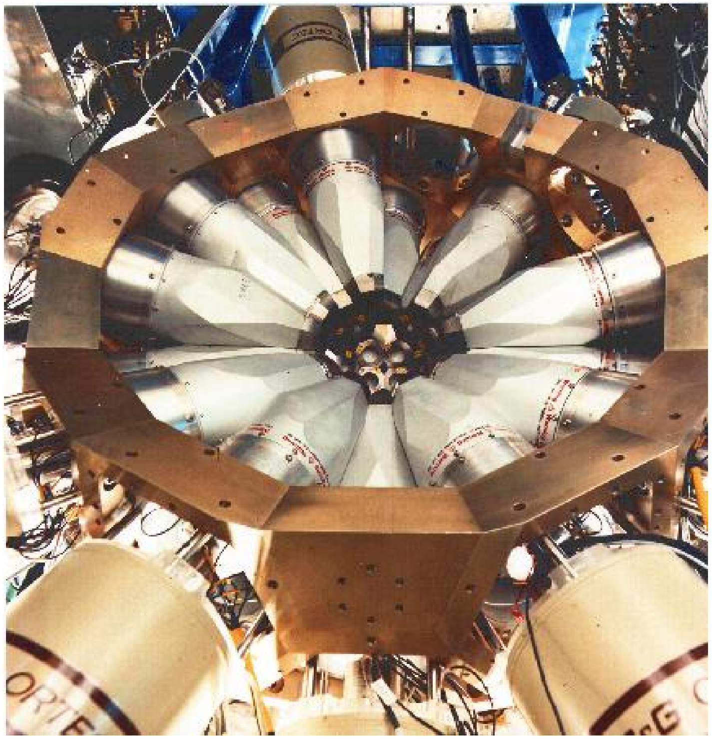


~1987

BGO replaces NaI(Tl)

HERA, TESSA3

I ~ 0.1% sensitivity



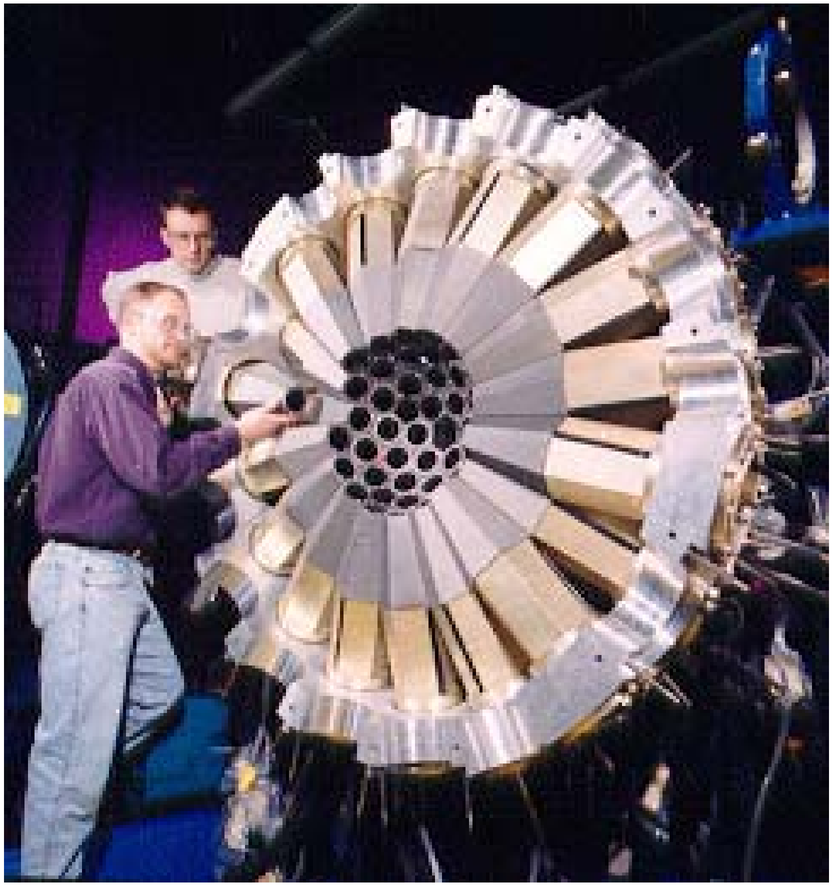
~1995

Large γ–ray arrays

Eurogam, Gammasphere,
Euroball's, GASP

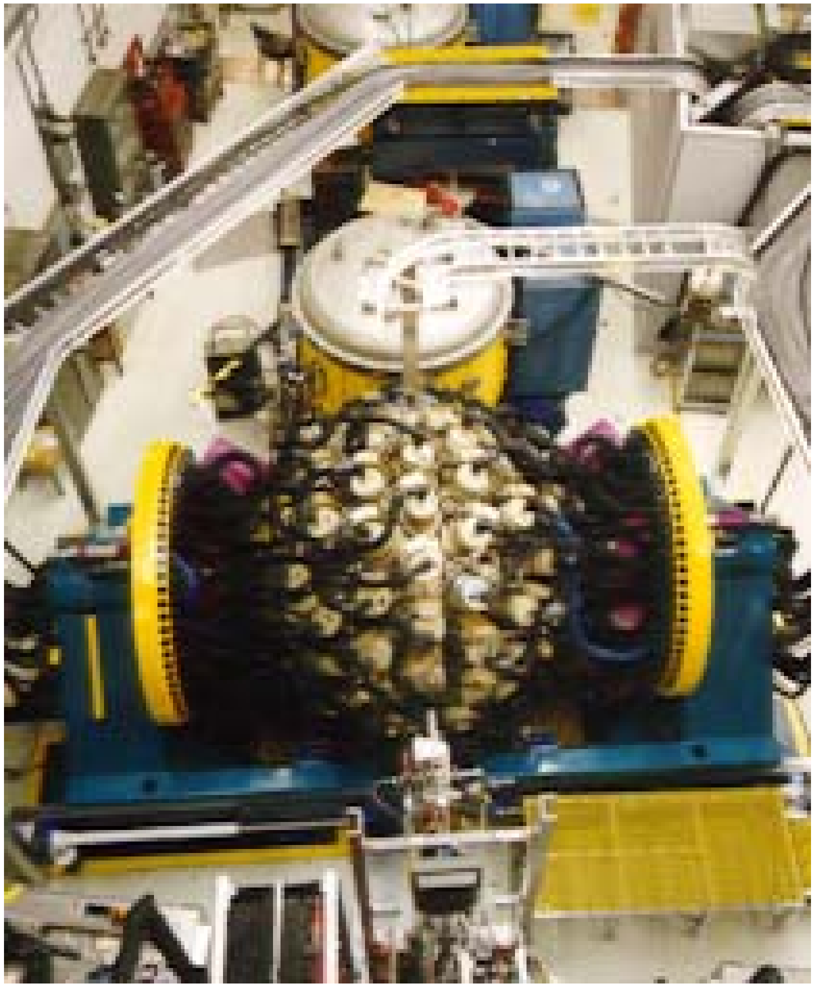
I ~ 0.001% sensitivity

Gammasphere spectrometer



- ☐ A spectrometer with high detection sensitivity to nuclear electromagnetic radiation due to its high **resolution**, granularity and efficiency
- ☐ Consists of a spherical shell of 110 large volume HpGe detectors each enclosed in a BGO shield
- ☐ Funded by DOE, US

Gammasphere operation



- ❑ From 1993 to 1997 GS was constructed and sited at the 88-Inch Cyclotron, LBNL

  130 experiments

  super deformation

- ❑ From 1998 to 2000 GS operated at ATLAS, ANL

  101 experiments

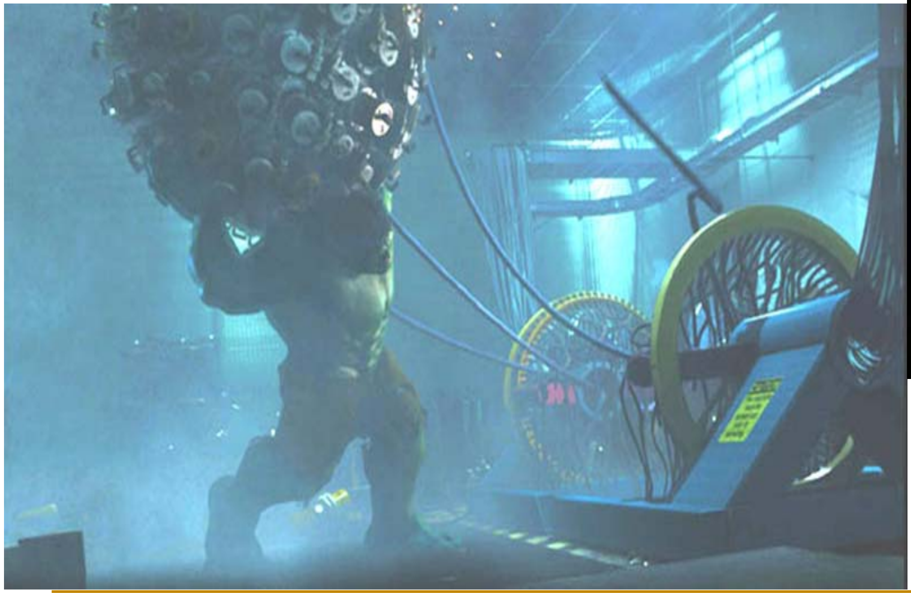
  nuclei far from stability

- ❑ From March 2000 till January 2002 at LBNL
- ❑ Since March 2002 till now GS is back at ANL

How we do research with Gammasphere …

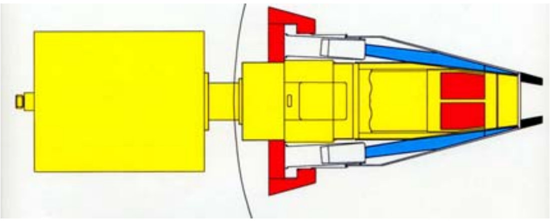
"Gammasphere in Action … "

Universal Studio Picture

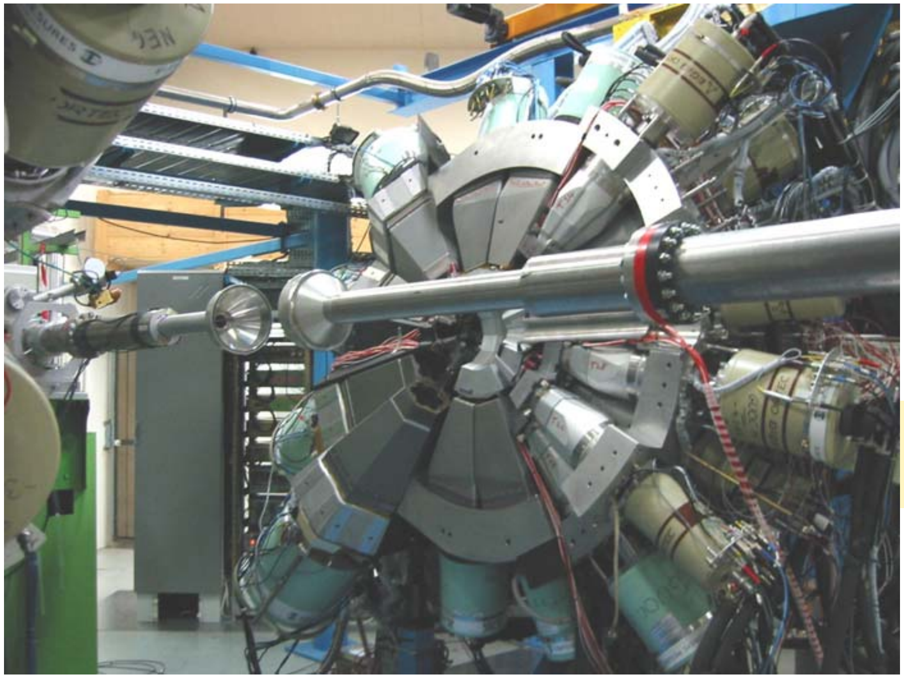


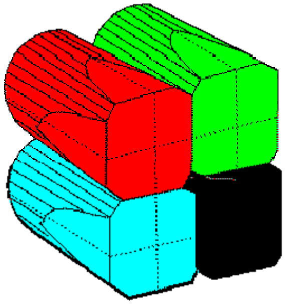
Euroball

European collaboration
France, Denmark, Germany, Italy, Sweden and the UK



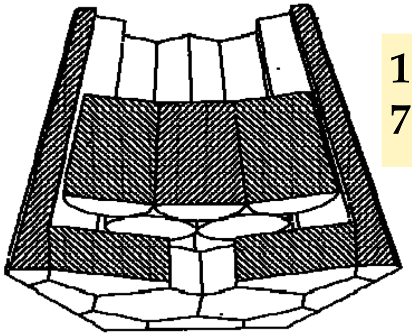
30 Large single crystal
Ge detectors





26 Clover Ge detectors
4 crystals per cryostat

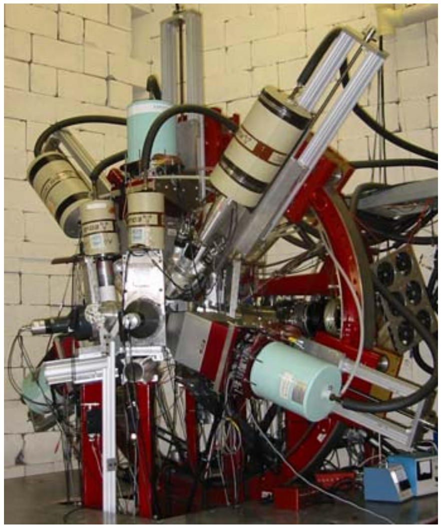
239 Ge crystals
Suppression shields
Total peak efficiency ~9.4%
Intensity limit ~ 10^{-5}



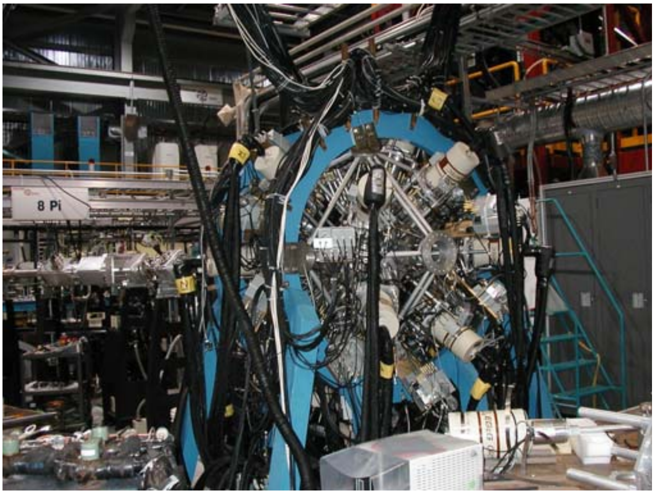
15 Cluster Ge detectors
7 encapsulated Ge crystals per cluster

Gamma-ray arrays in US & Canada

Yrast Ball, Yale University
10 Clover
17 Ge



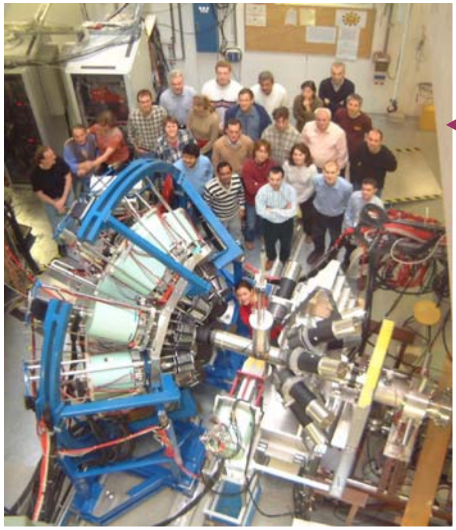
FSU Array, USA



8π, TRIUMF
~100 Ge detectors

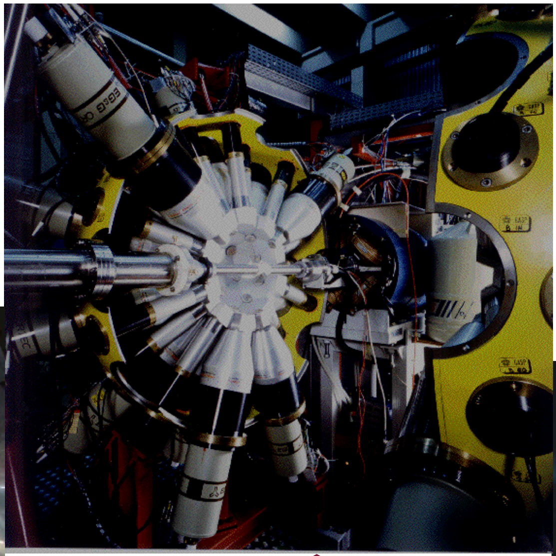
CLARION, ORNL

Gamma-ray arrays in Europe

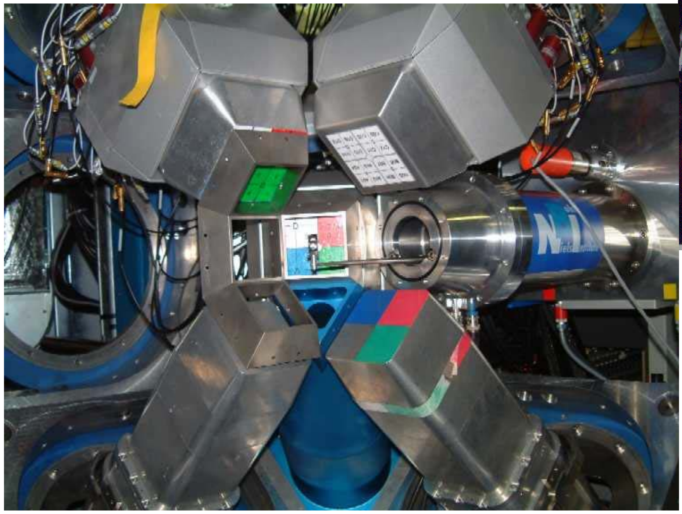


RISING, GSI

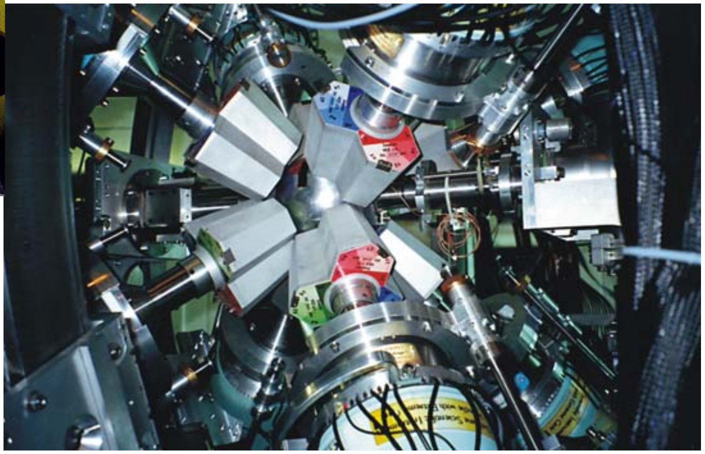
JUROGAM, JYFL



GASP, INFN

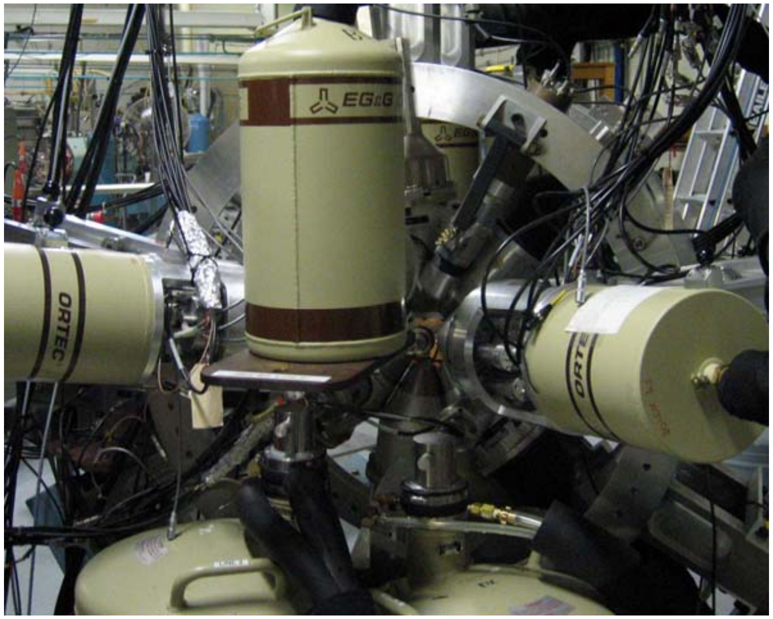


EXOGAM, Ganil

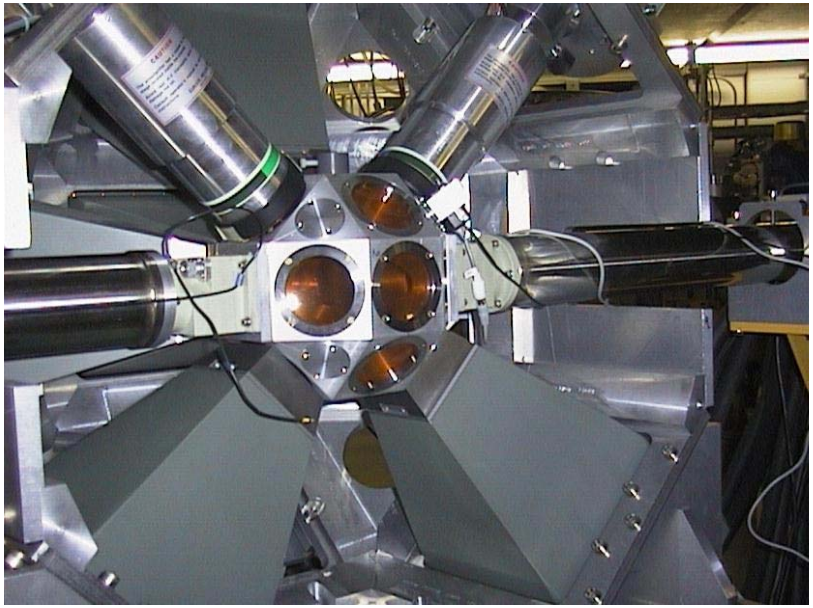


MINIBALL, RexIsolde

Australia, Asia & Africa



CAESAR, Australia



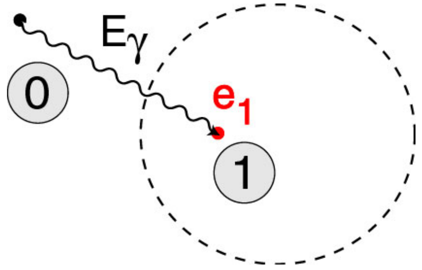
Afrodite, South Africa

Smaller arrays operate in India, China and Japan

Interaction of gamma rays with matter

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

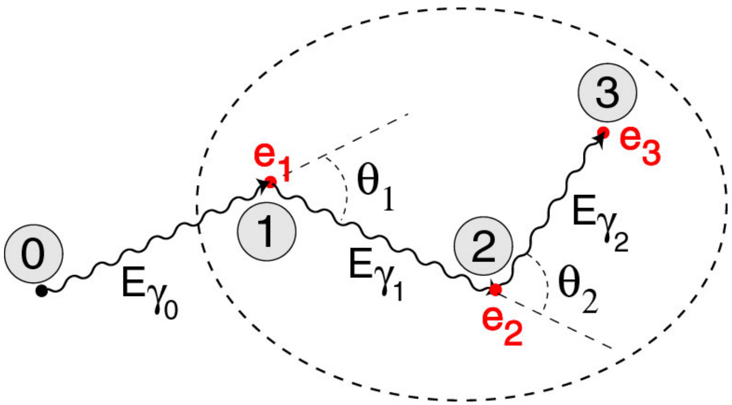
Photoelectric



Isolated hits

Probability of interaction depth

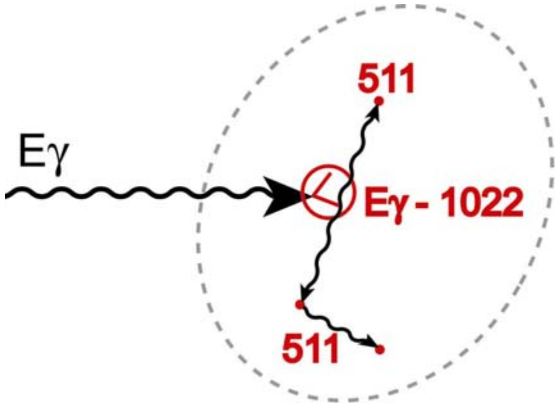
Compton Scattering



Angle/Energy

$$E_{\gamma'} = \frac{E_\gamma}{1+\frac{E_\gamma}{m_0c^2}\left(1-\cos\theta\right)}$$

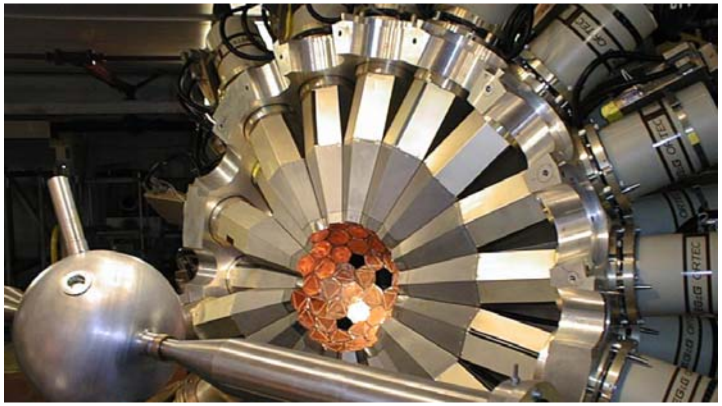
Pair Production

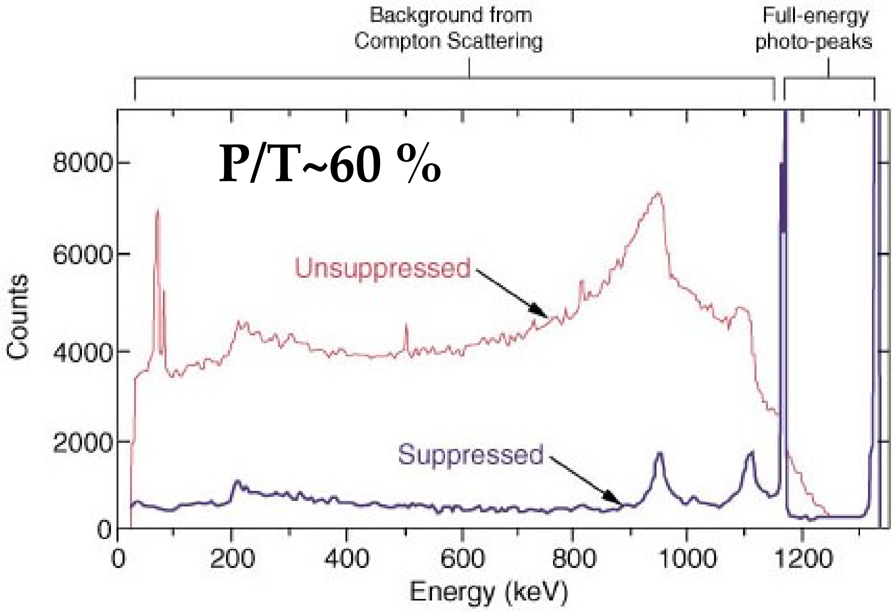


Pattern of hits

$$E_{1st} = E_\gamma - 2\ mc^2$$

Compton Suppression – improving the peak to background ratio

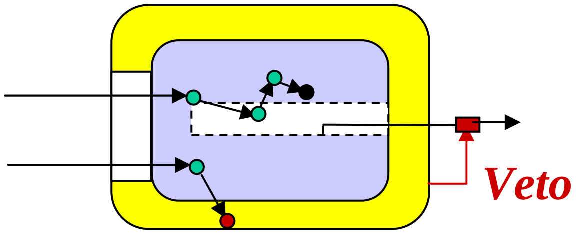




$$R \sim \left[\frac{P}{T} \times \varepsilon \times \frac{E_{spacing}}{\Delta E} \right]^{n}$$

Gamma-ray Tracking Concepts

- **Compton Suppressed Ge**

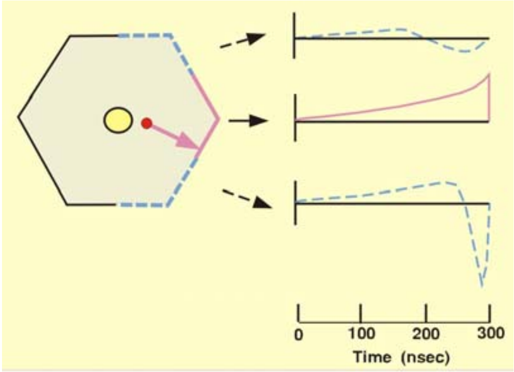


$N_{det} = 100$

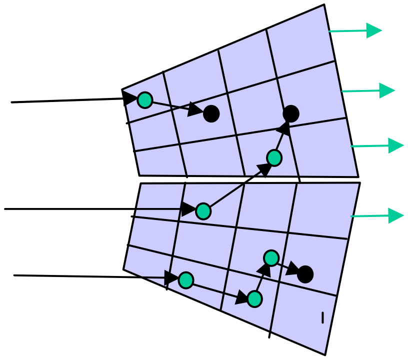
Peak efficiency = 8-10%

Efficiency limited

Pulse shape analysis in segments ➔ 3D position



- **Gamma Ray Tracking**

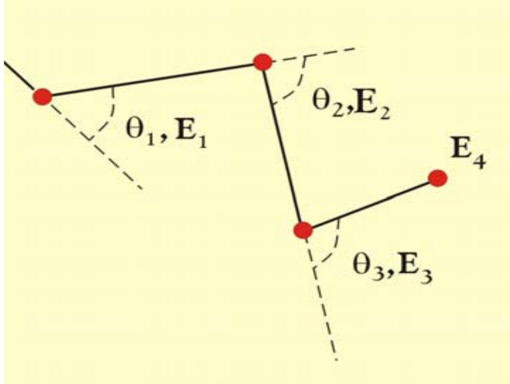


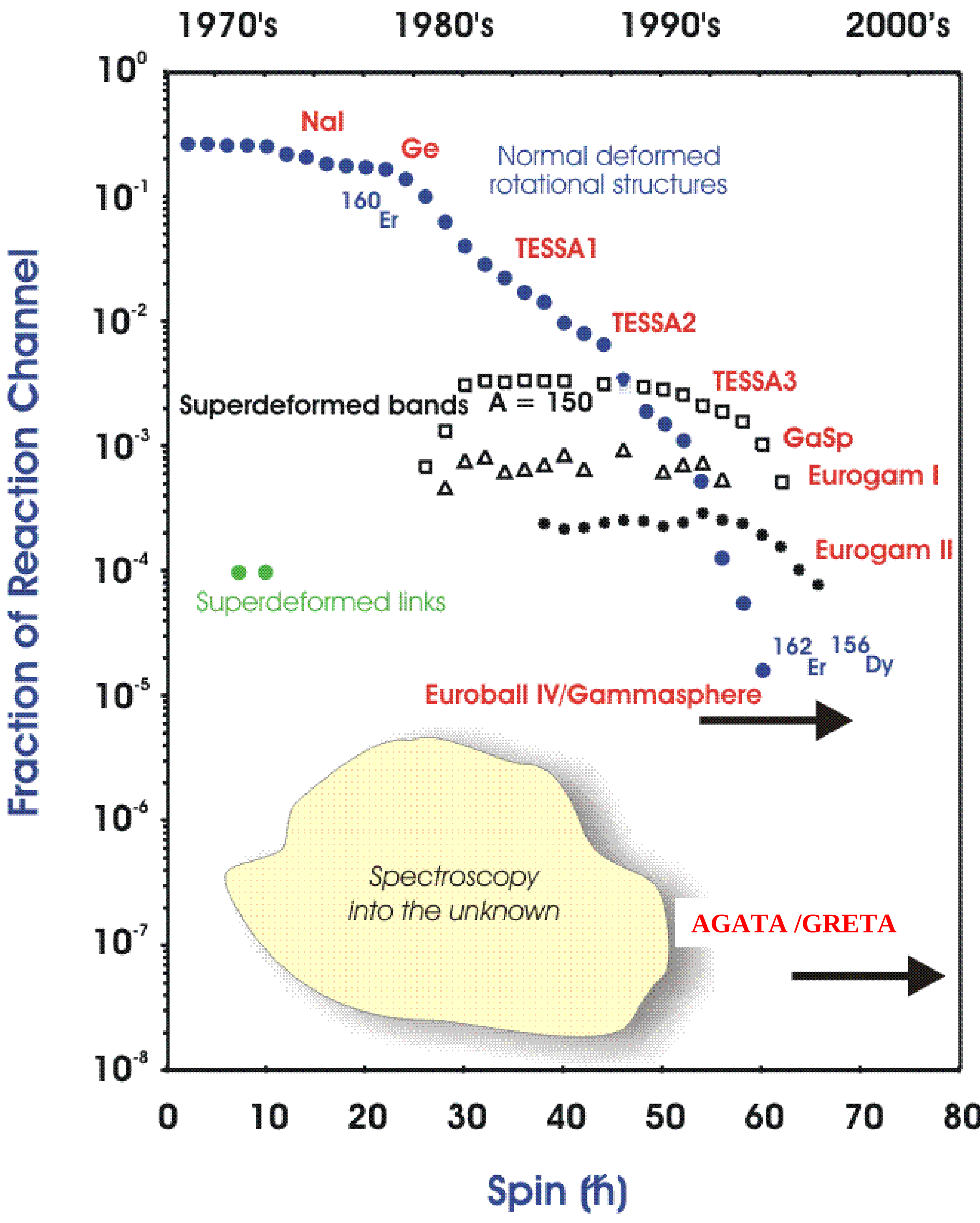
$N_{det} = 100$

Peak efficiency = 60 %

Segmentation

Tracking of photon interaction points ➔ energy, position

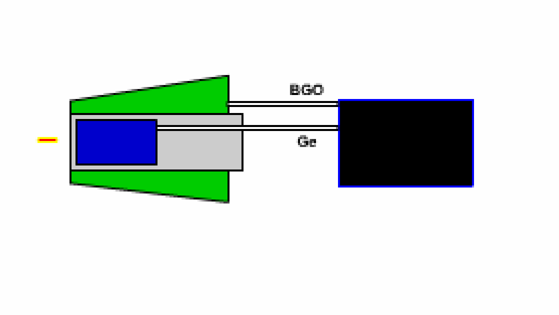


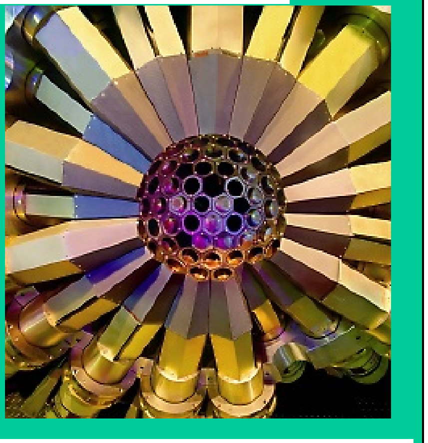


GRETINA

AGATA
ADVANCED GAMMA
TRACKING ARRAY

Large Gamma Arrays based on Compton Suppressed Spectrometers



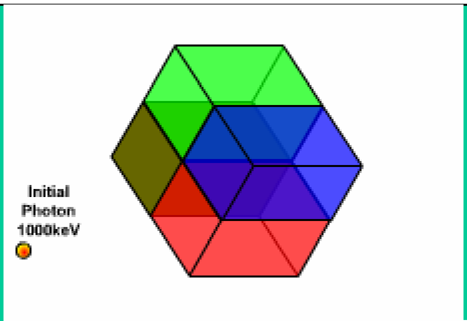


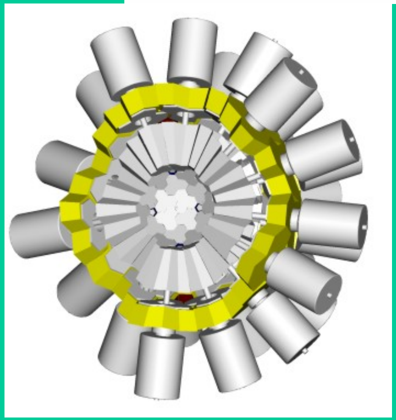
EUROBALL GAMMASPHERE

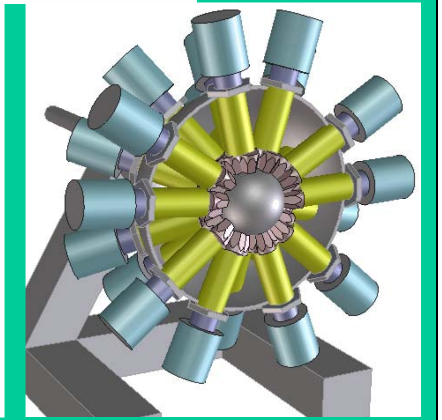
$\varepsilon \sim$ 10 — 5 %

(M_γ=1 — M_γ=30)

Tracking Arrays based on Position Sensitive Ge Detectors







AGATA GRETA

$\varepsilon \sim$ 60 — 40 %

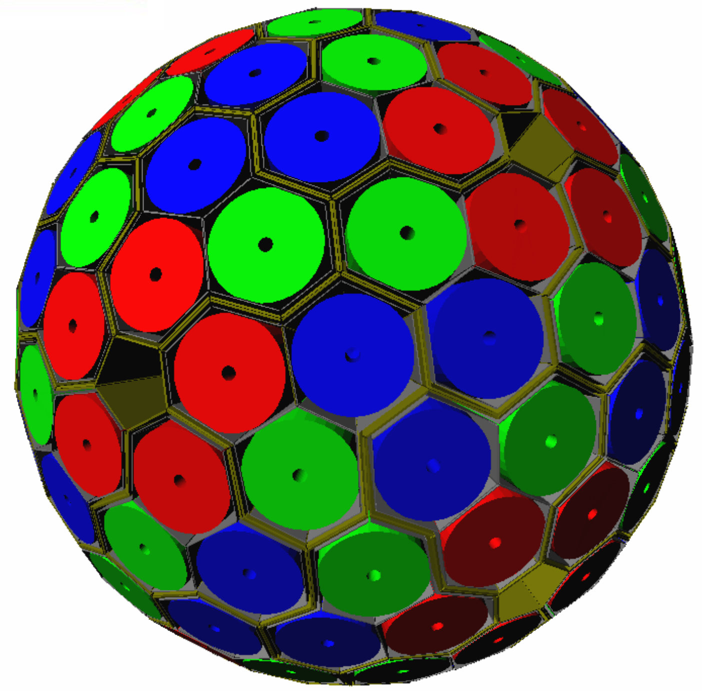
(M_γ=1 — M_γ=30)

Exogam, Miniball, SeGa: optimized for Doppler correction at low γ-multiplicitiy → ε up to 20%

GRETA/GRETINA

- **Resolving power: 10^7 vs. 10^4**
  - Cross sections down to ~1 nb
    - *Most exotic nuclei*
    - *Heavy elements (e.g. ^{253,254}No)*
    - *Drip-line physics*
    - *High level densities (e.g. chaos)*
- **Efficiency (high energy) (23% vs. 0.5% at E_γ=15 MeV)**
  - Shape of GDR
  - Studies of hypernuclei
- **Efficiency (slow beams) (50% vs. 8% at E_γ =1.3 MeV)**
  - Fusion evaporation reactions
- **Efficiency (fast beams) (50% vs. 0.5% at E_γ =1.3 MeV)**
  - Fast-beam spectroscopy with low rates -> RIA
- **Angular resolution (0.2° vs. 8°)**
  - N-rich exotic beams
    - *Coulomb excitation*
  - Fragmentation-beam spectroscopy
    - *Halos*
    - *Evolution of shell structure*
    - *Transfer reactions*
- **Count rate per crystal (100 kHz vs. 10 kHz)**
  - More efficient use of available beam intensity
- **Linear polarization**
- **Background rejection by direction**

AGATA
(Advanced GAmma Tracking Array)



Main features of AGATA

Efficiency: 40% (M_γ=1) 25% (M_γ=30)
today's arrays ~10% (gain ~4) 5% (gain ~1000)

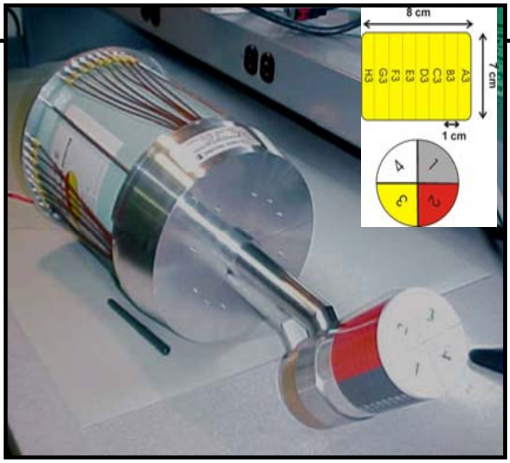
Peak/Total: 55% (M_γ=1) 45% (M_γ=30)
today ~55% 40%

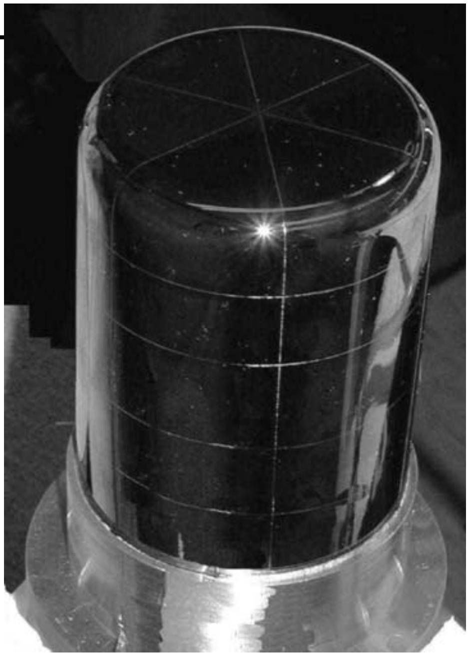
Angular Resolution: ~1° →
FWHM (1 MeV, v/c=50%) ~ 6 keV !!!
today ~40 keV

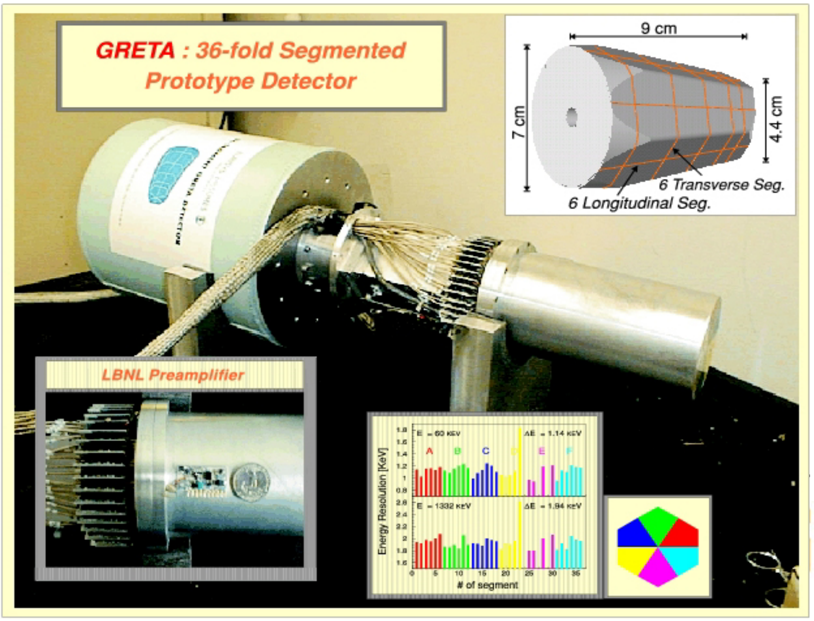
Rates: 3 MHz (M_γ=1) 300 kHz (M_γ=30)
today 1 MHz 20 kHz

- 180 large volume 36-fold segmented Ge crystals in 60 triple-clusters
- Digital electronics and sophisticated Pulse Shape Analysis algorithms allow
- Operation of Ge detectors in position sensitive mode → γ-ray tracking

Highly segmented Ge Detectors







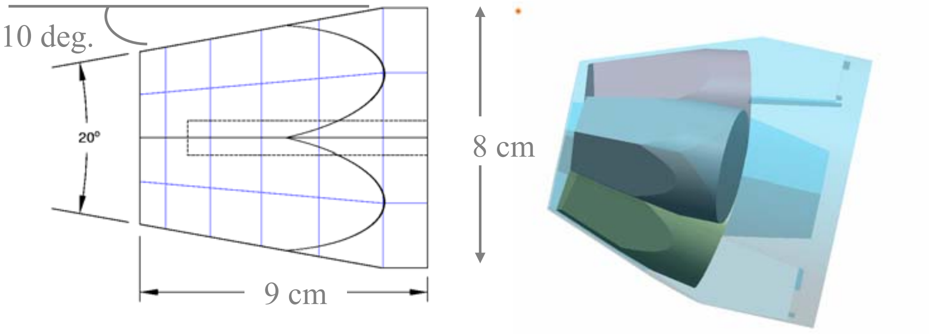
Canisters AGATA and EUROBALL

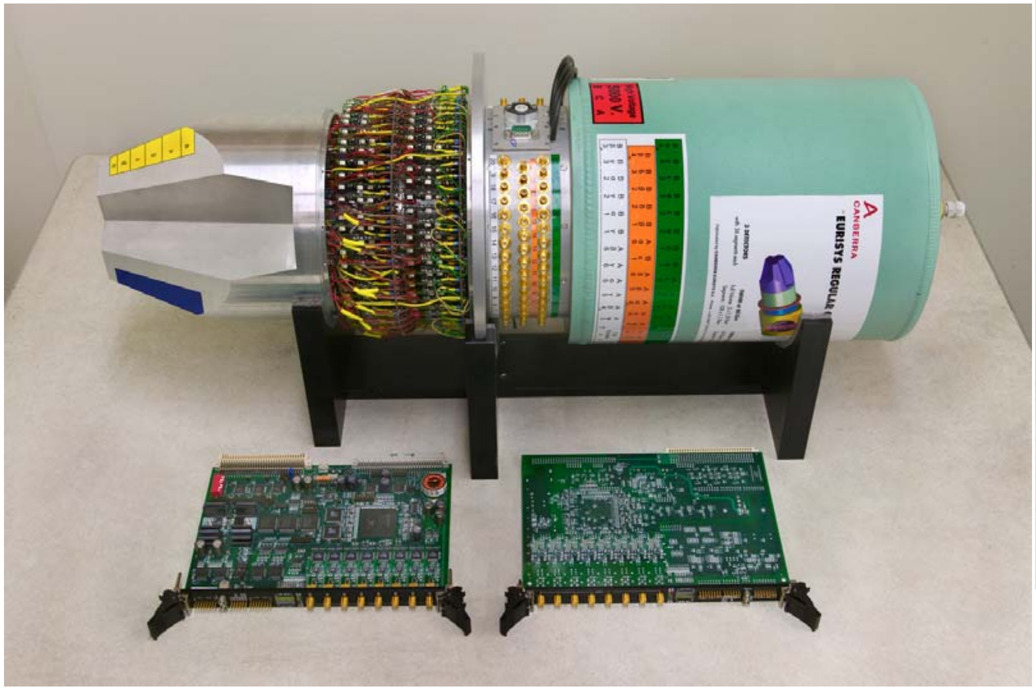
AGATA

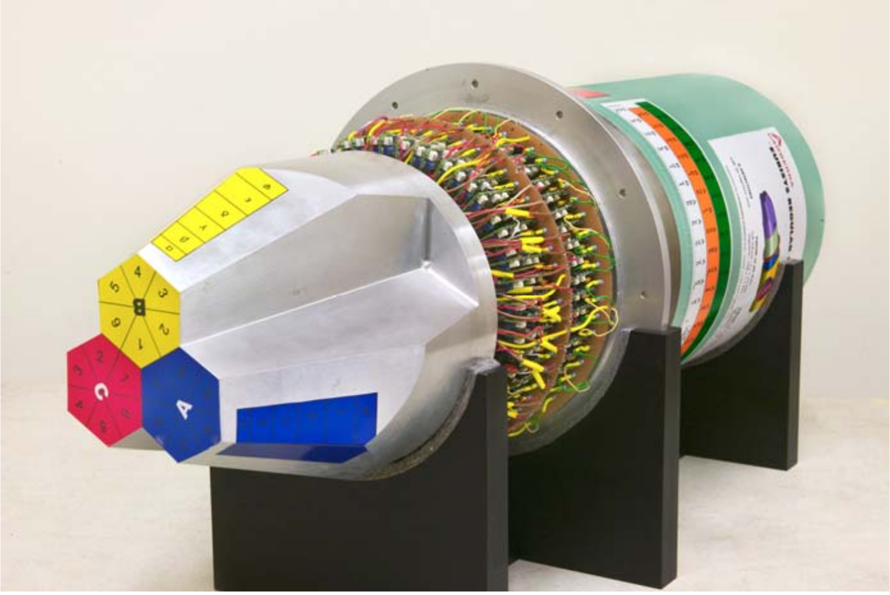
EUROBALL

GRETINA Detectors

- **Tapered hexagon shape**
- **Highly segmented 6 × 6 = 36**
- **Close packing of 3 crystals**
- **111 channels of signal**

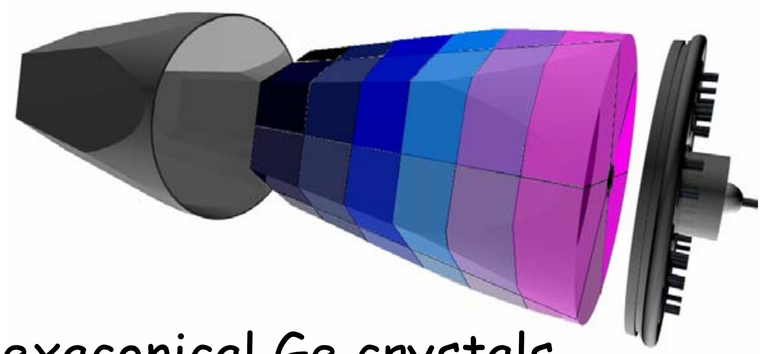




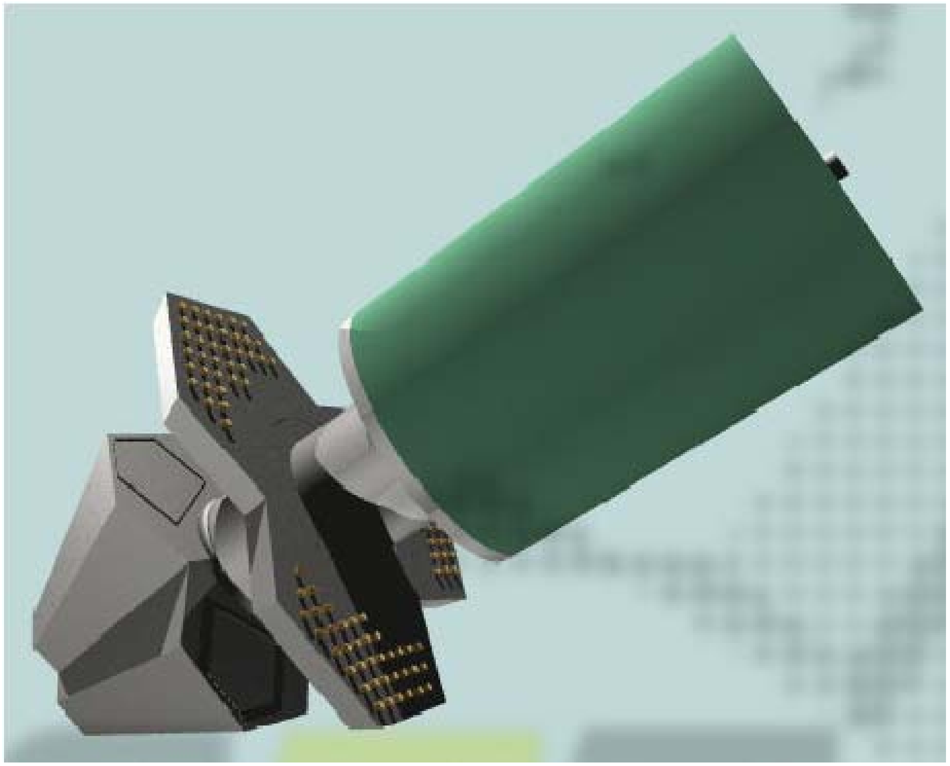


Received June 4, 2004

AGATA Detectors



Hexaconical Ge crystals
90 mm long
80 mm max diameter
36 segments
Al encapsulation
    0.6 mm spacing
    0.8 mm thickness
37 vacuum feedthroughs

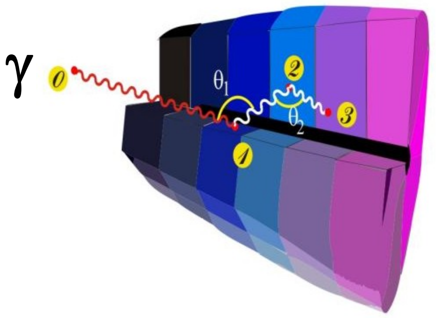


3 encapsulated crystals
111 preamplifiers with cold FET
~230 vacuum feedthroughs
LN_2 dewar, 3 litre, cooling power ~8 watts

Ingredients of γ–ray Tracking

1

Highly segmented HPGe detectors



2

Digital electronics to record and process segment signals

3

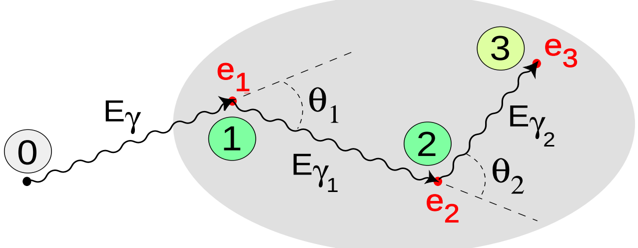
Pulse Shape Analysis to decompose recorded waves

Identified interaction

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

4

Reconstruction of tracks e.g. by evaluation of permutations of interaction points

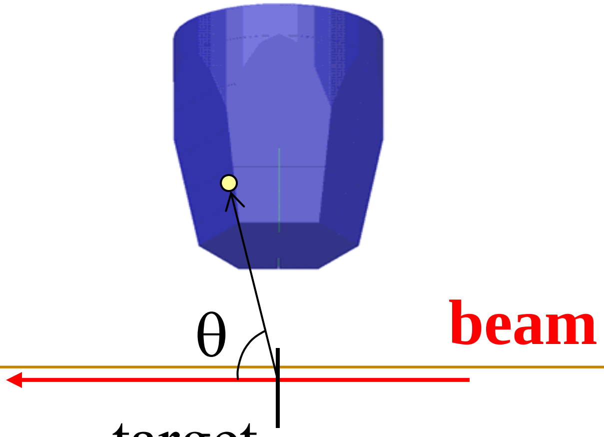


reconstructed γ-rays

In-beam test

Experiment

- LBNL 88” Cyclotron
- Prototype II detector
- ^{82}Se + ^{12}C @ 385 MeV
- ^{90}Zr nuclei ($\beta \sim 8.9\%$)
- 2055 keV ($10^+ \rightarrow 8^+$) in ^{90}Zr
- Detector at 4 cm and 90°
- Three 8-channels LBNL signal Digitizer modules (24 ch.)



Analysis

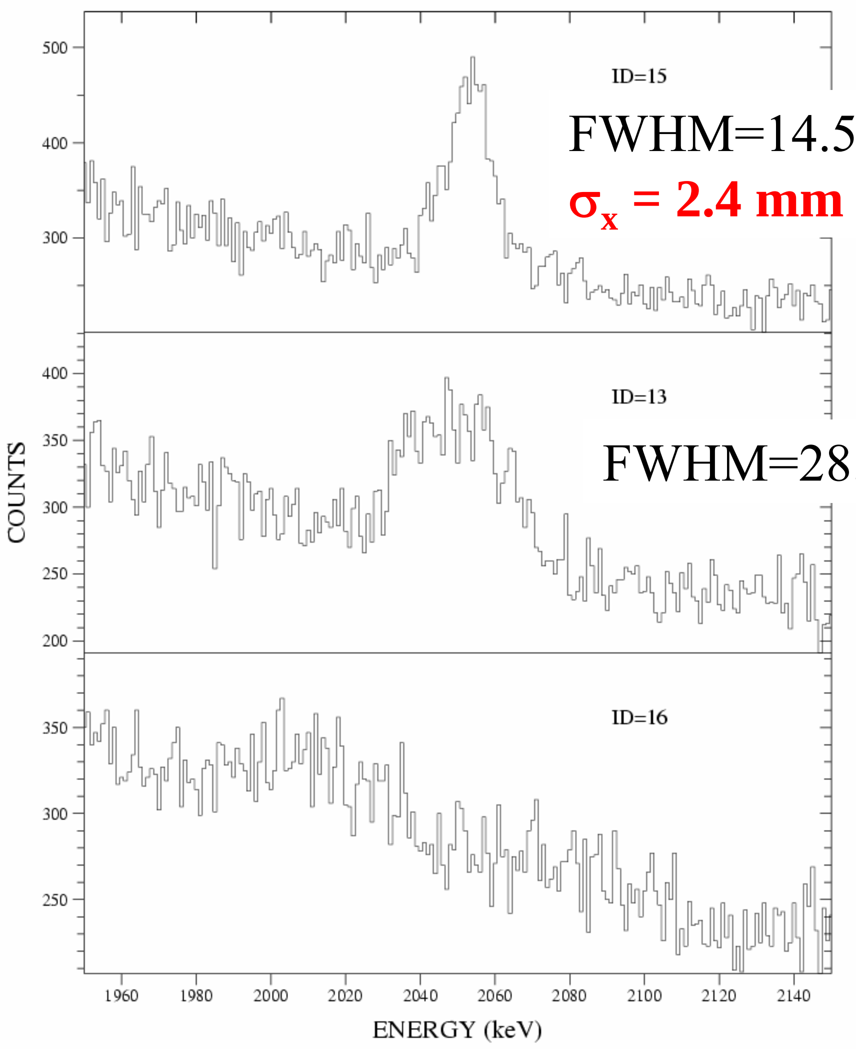
- Event building
- Calibration : cross talk
- Signal decomposition
- Doppler correction

In-beam test Results

Doppler Corrected using first hit position determined by signal decomposition

Corrected using center of segment only

No correction

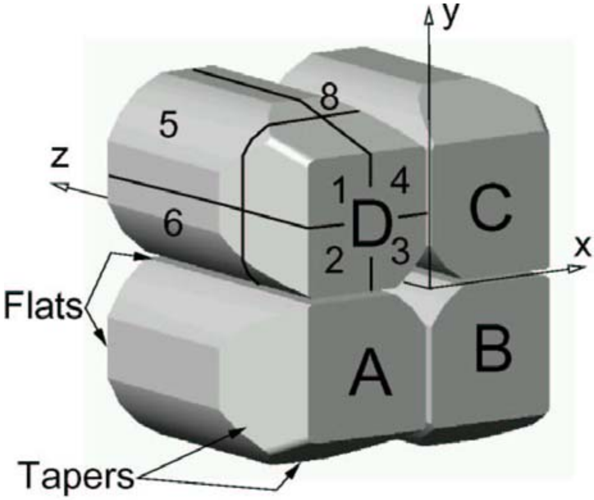


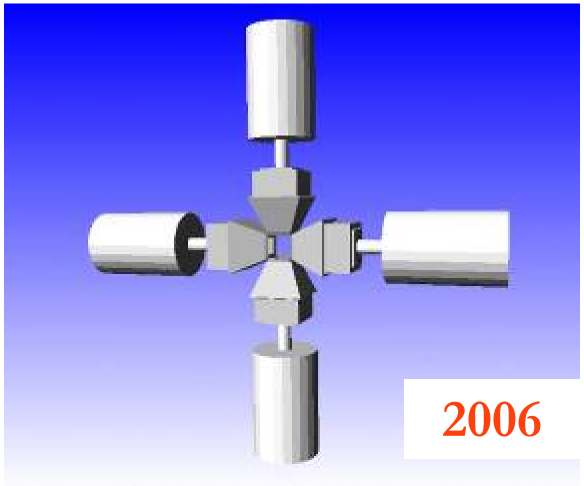
FWHM=14.5 keV

σ_x = 2.4 mm (rms)

FWHM=28.3 keV

TIGRESS TRIUMF, CANADA

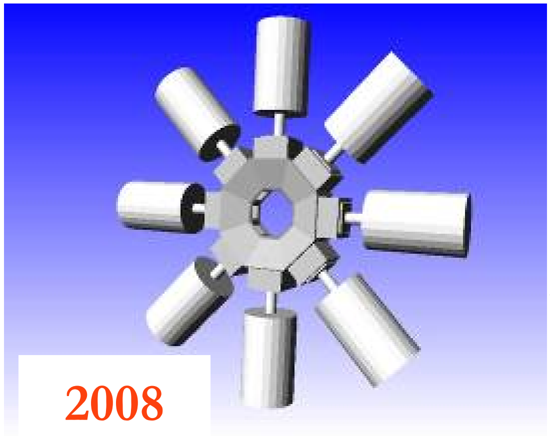



2006

ISAC II

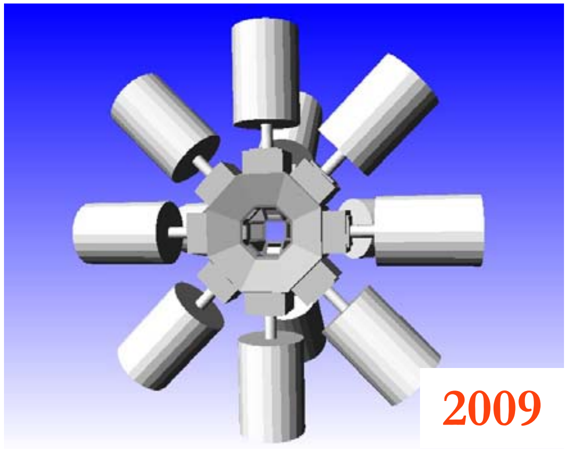
Nuclear Structure:

Evolution of Nuclear Shell Structure
Pairing Correlation far from Stability
Mirror Nuclei and Isospin Symmetry
oulomb Excitation with Bragg/PPAC
Fusion Evaporation reactions with
CsI(Tl) and neutron detector arrays

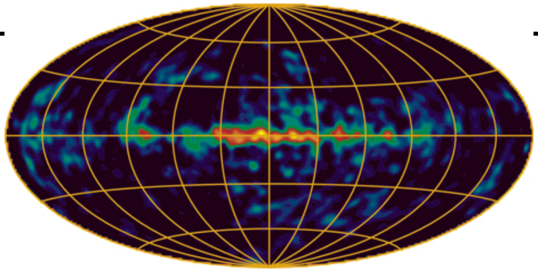

2008

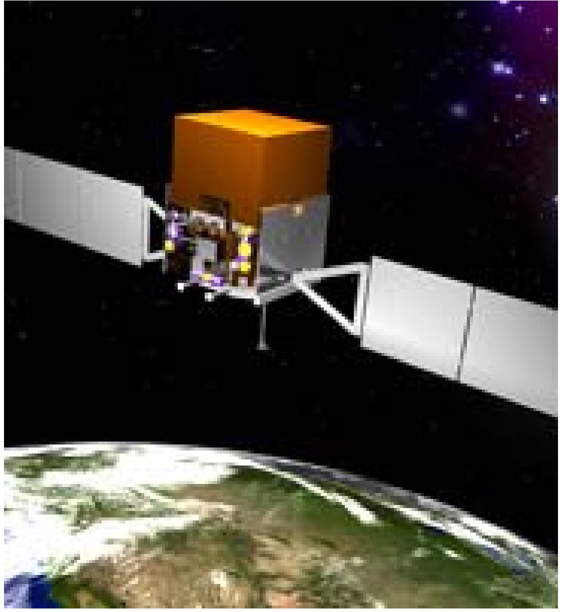
Nuclear Astrophysics:

Structure studies of astrophysically
important states
Transfer reactions with EMMA/Si Array


2009

Gamma Ray Lines of the Cosmos





Science Objective	Isotopes and Lines (MeV)
Understand Type Ia SN explosion mechanism and dynamics	^{56}Ni (0.158, ***0.812***, …) ^{56}Co (***0.847, 1.238***, …) ^{57}Co (0.122)
Understand Core Collapse SN explosion mechanism and dynamics	^{56}Ni (0.158, ***0.812***, …) ^{56}Co (***0.847, 1.238***, …) ^{57}Co (0.122), ^{26}Al (***1.809, 0.511***)
Map the Galaxy in nucleosynthetic radioactivity	^{26}Al (***1.809, 0.511***) ^{60}Fe, ^{60}Co (***1.173, 1.332***) ^{44}Ti (0.068, 0.078, ***1.16***)
Map Galactic positron annihilation radiation	e^+–e^- annihilation (***0.511***, 3 photon continuum) SN Ia ^{56}Co positrons (***0.511***) ^{26}Al and ^{44}Ti positrons (***0.511***)
Understand the dynamics of Galactic Novae	^{13}N, ^{14,15}O, ^{18}F positrons (***0.511***) ^{7}Be (***0.478***), ^{22}Na (***1.275, 0.511***)
Cosmic Ray Interactions with the ISM	^{12}C (4.4), ^{16}O (6.1), ^{20}Ne(***1.634***), ^{24}Mg(***1.369***,2.754),^{28}Si(***1.779***), ^{56}Fe(***0.847,1.238***)
Neutron Star Mass-Radius	p-n (***2.223***)

The Concept

Position sensitive gamma ray detectors have been under development for many years

- In Space Science
- In Medical Imaging
- In Basic Nuclear Research
- In Homeland Security and Verification.

Scintillator: NaI, CsI, LSO

Semi-conductor: Si, CdZnTe, CdTe

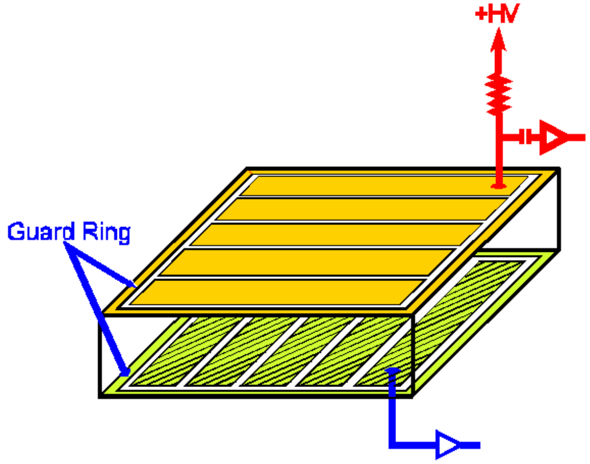
High Purity Germanium: offers the best energy resolution and timing for intermediate (40-2500 keV) radiation. Very large and efficient detectors can now be fabricated.

Key Question:

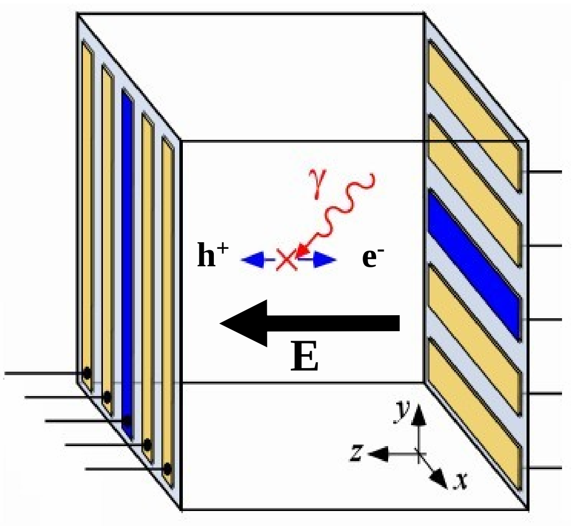
Can reliable, efficient, high resolution *position sensitive* germanium detectors be produced and incorporated into practical devices?

Ge Strips Detectors – an excellent choice!

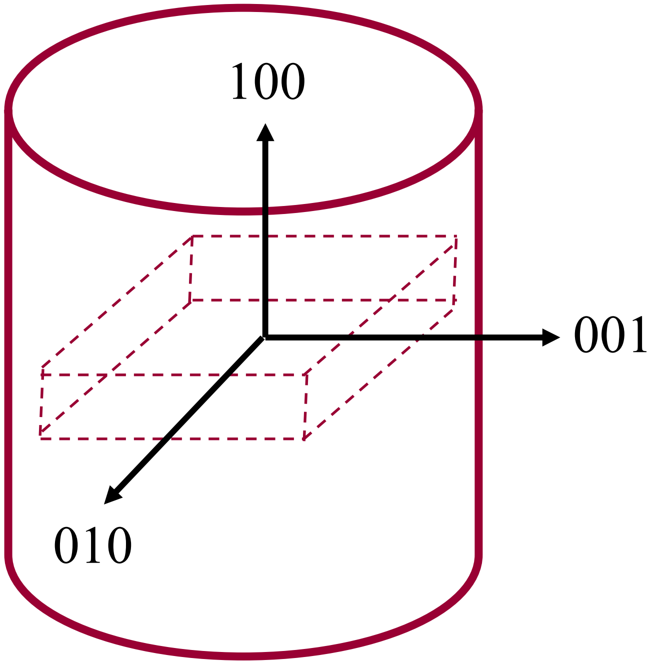
- based on the HpGe planar detector technology
- have orthogonal electrodes (strips) that provide position localization of the interactions
- operates like a conventional p-i-n diode
- pulse-shape analysis – the depth of the interactions

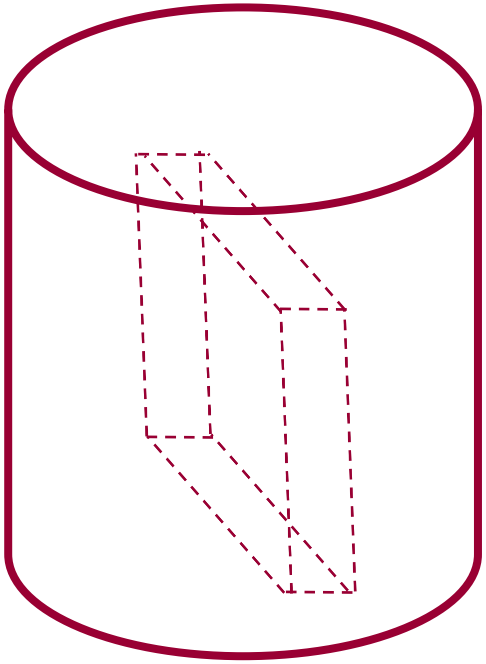


X-Y STRIP DETECTOR



Technology: Wafer Selection





<u>Across Boule</u>

Uniform Impurities

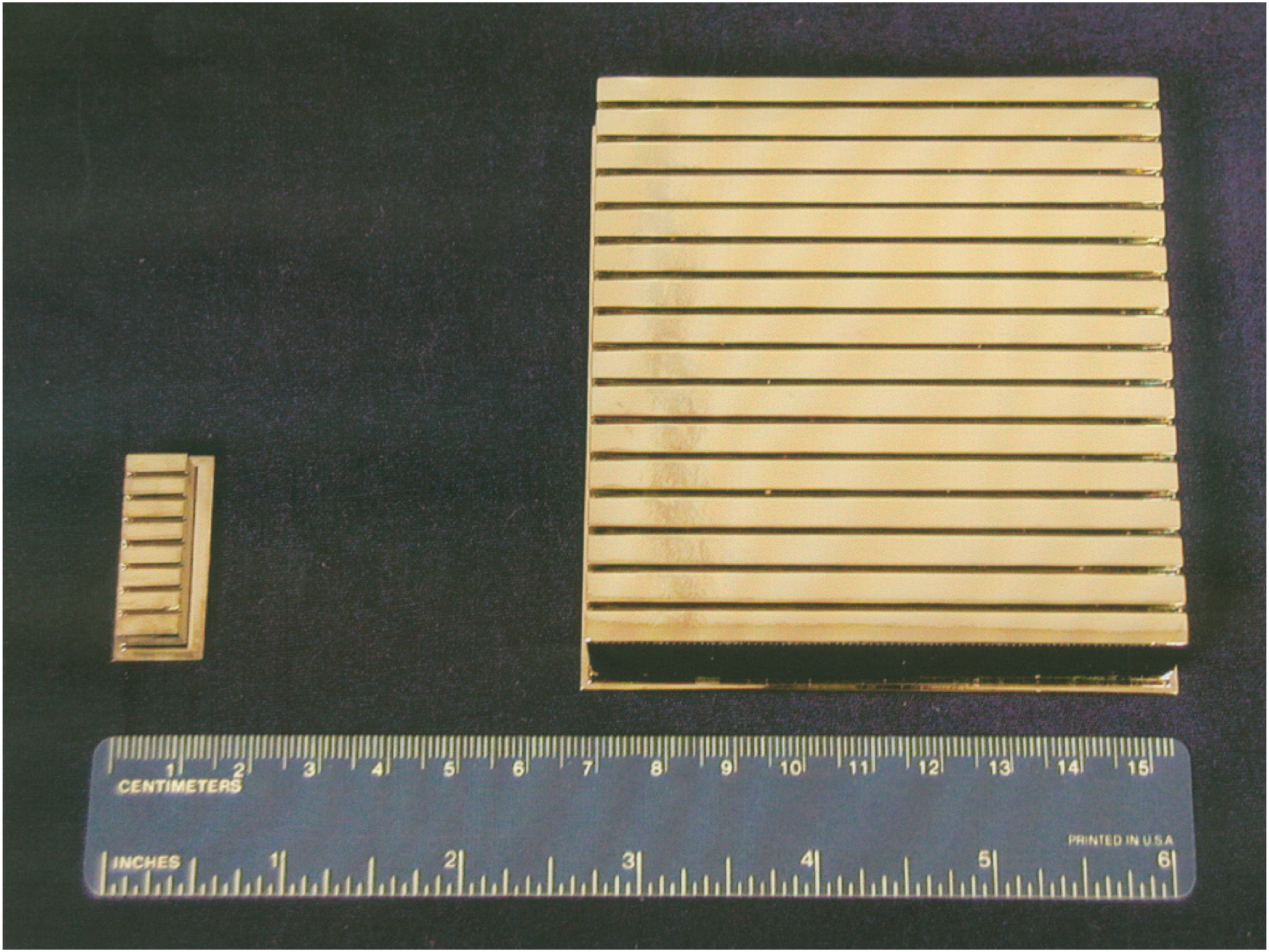
LIMITED SIZE

<u>Along Boule</u>

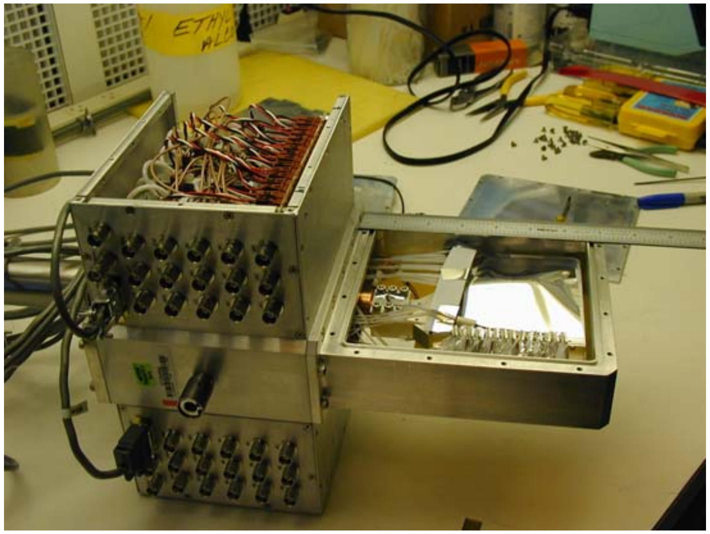
LARGEST SIZE

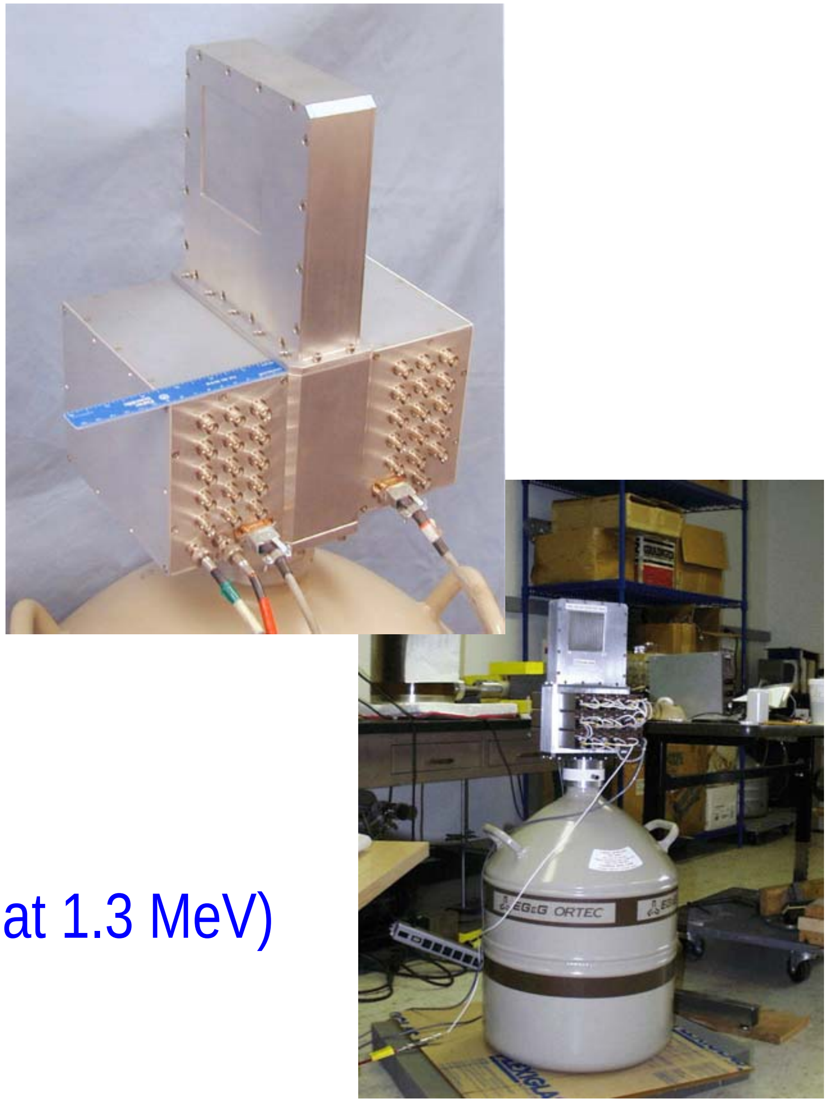
Impurity Gradients

REAL NEED FOR FINANCING OF FACILITY TO GROW BIGGER BOULES.......(15cms)


1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
CENTIMETERS
PRINTED IN U.S.A
INCHES
1 2 3 4 5 6

ANL HpGe Strips Detector



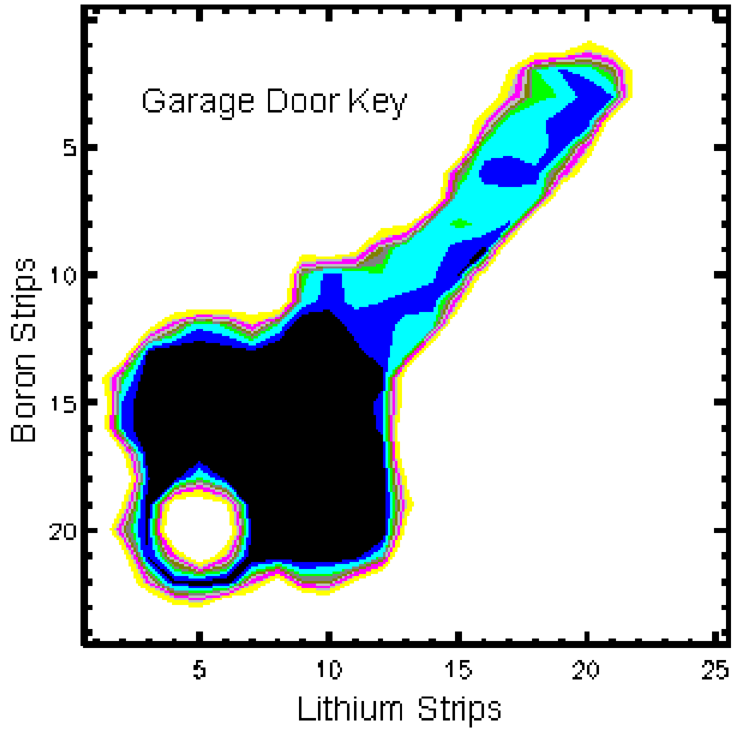


With the premier US germanium detector manufacturer, Ortec, we have built

- ***the biggest*** (~90 mm x 90 mm x 20 mm)
- ***the best*** (~1.0 keV at 122 keV, ~2.0 keV at 1.3 MeV)

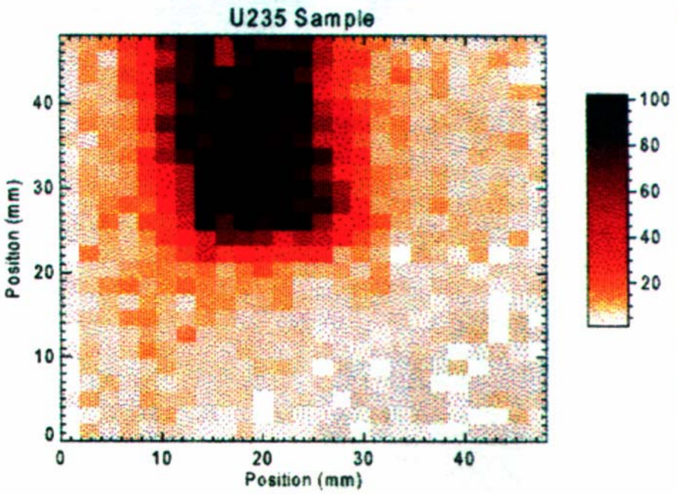
Ge strips detector in the world!

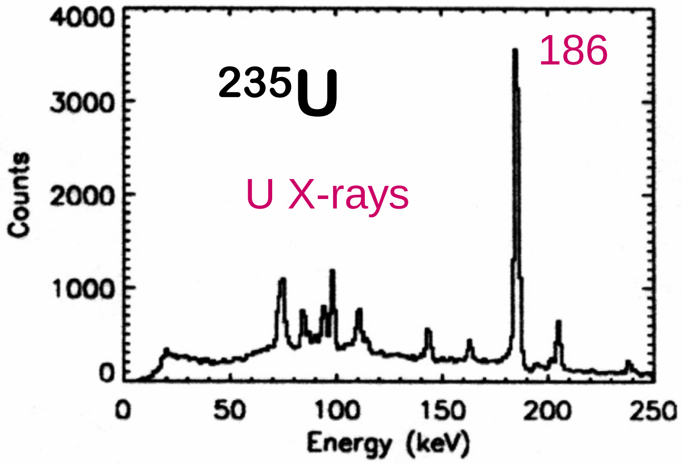
2D Imaging Capabilities



25 x 25 strip HpGeDSSD
60 keV γ-rays from ^{241}Am source

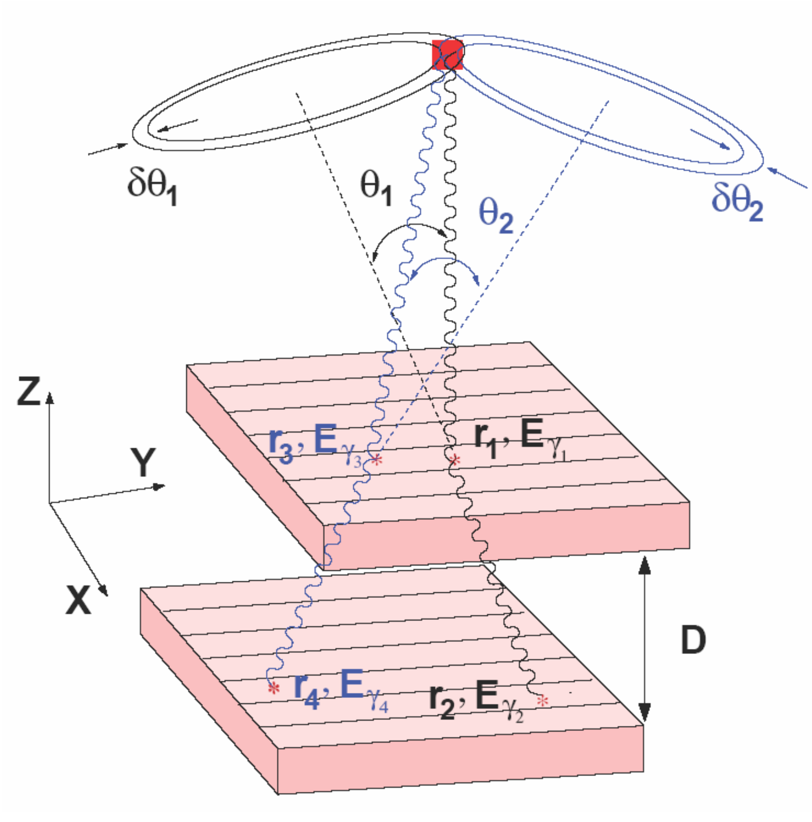
S.E. Inderhees et al., IEEE 43 (1996) 1467





Imaging and characterization

Compton Camera



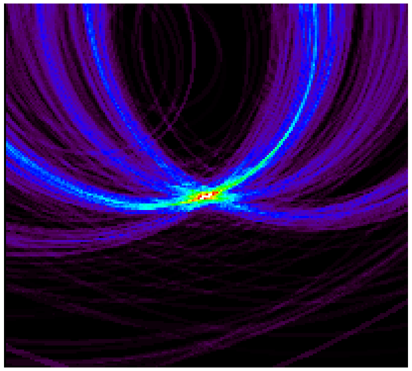
$$\cos\theta_1 = [1 - m_e c^2 ((E_\gamma - E_{\gamma 1}) / E_\gamma E_{\gamma 1})]$$

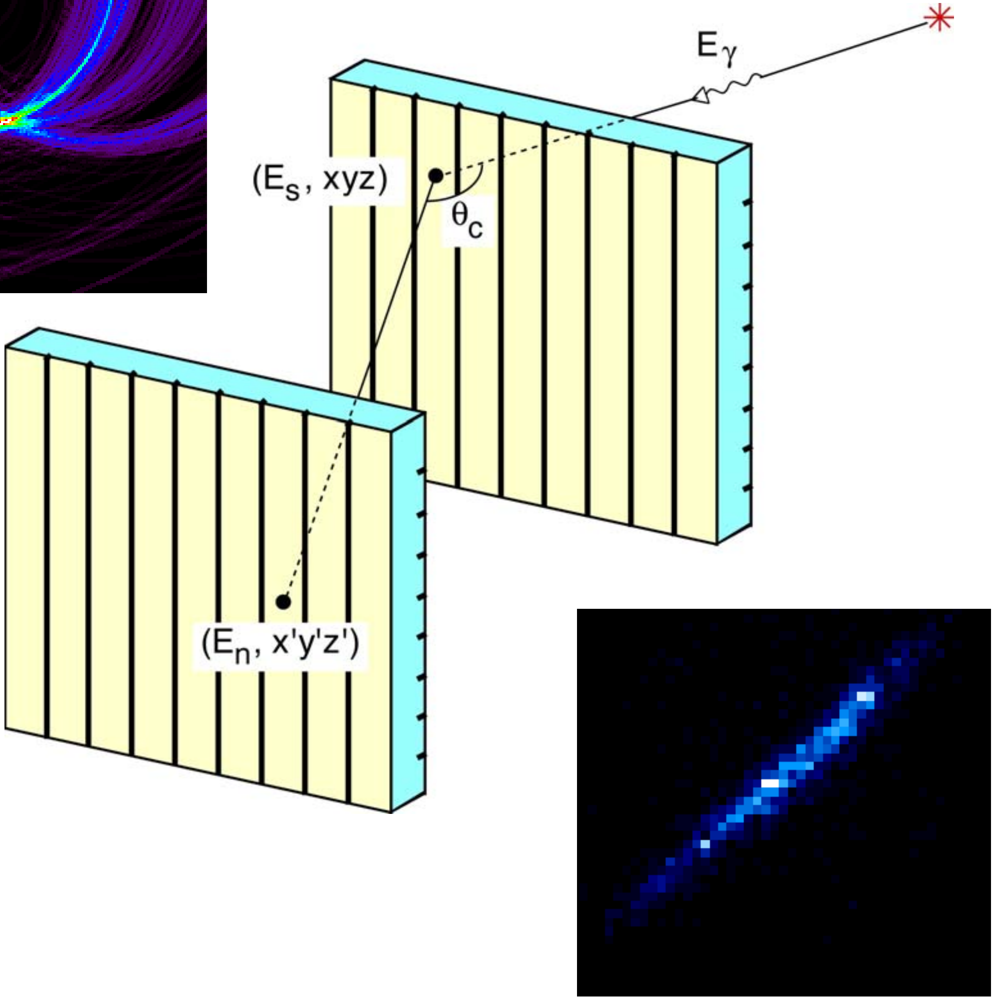
$$E_\gamma = E_{\gamma 1} + E_{\gamma 2}$$

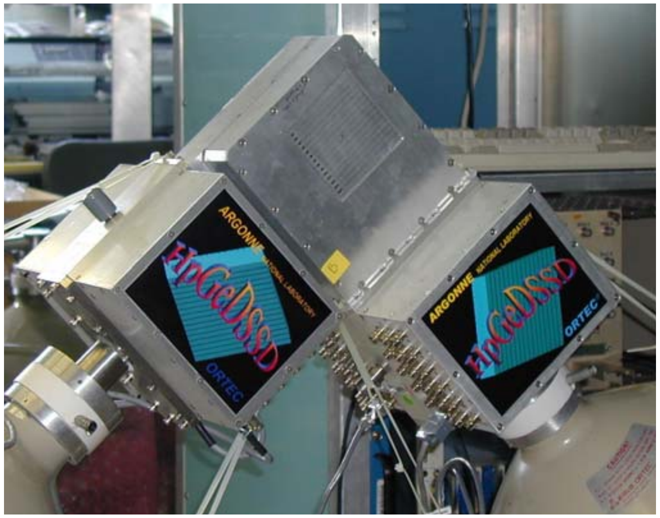
Concept

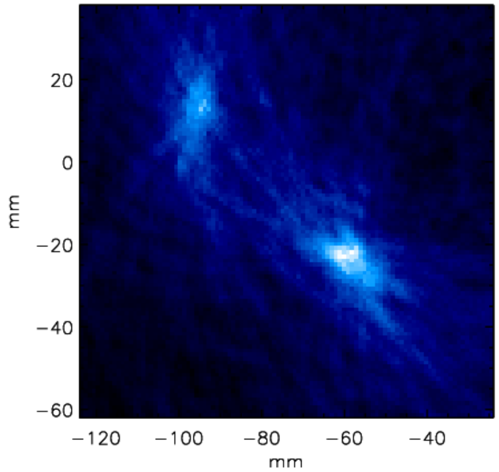
- Gamma ray Compton scatters in the first detector
- Positions and energies of individual interactions enables to determine pathway of gamma ray in the detector – *gamma-ray tracking*!
- Energies and positions define cone of incident angles (electron path is not measured)
- Cones are projected on a plane or a sphere (one circle per event) for 2D or into a cube (one cone per event) for 3D imaging

Compton Camera

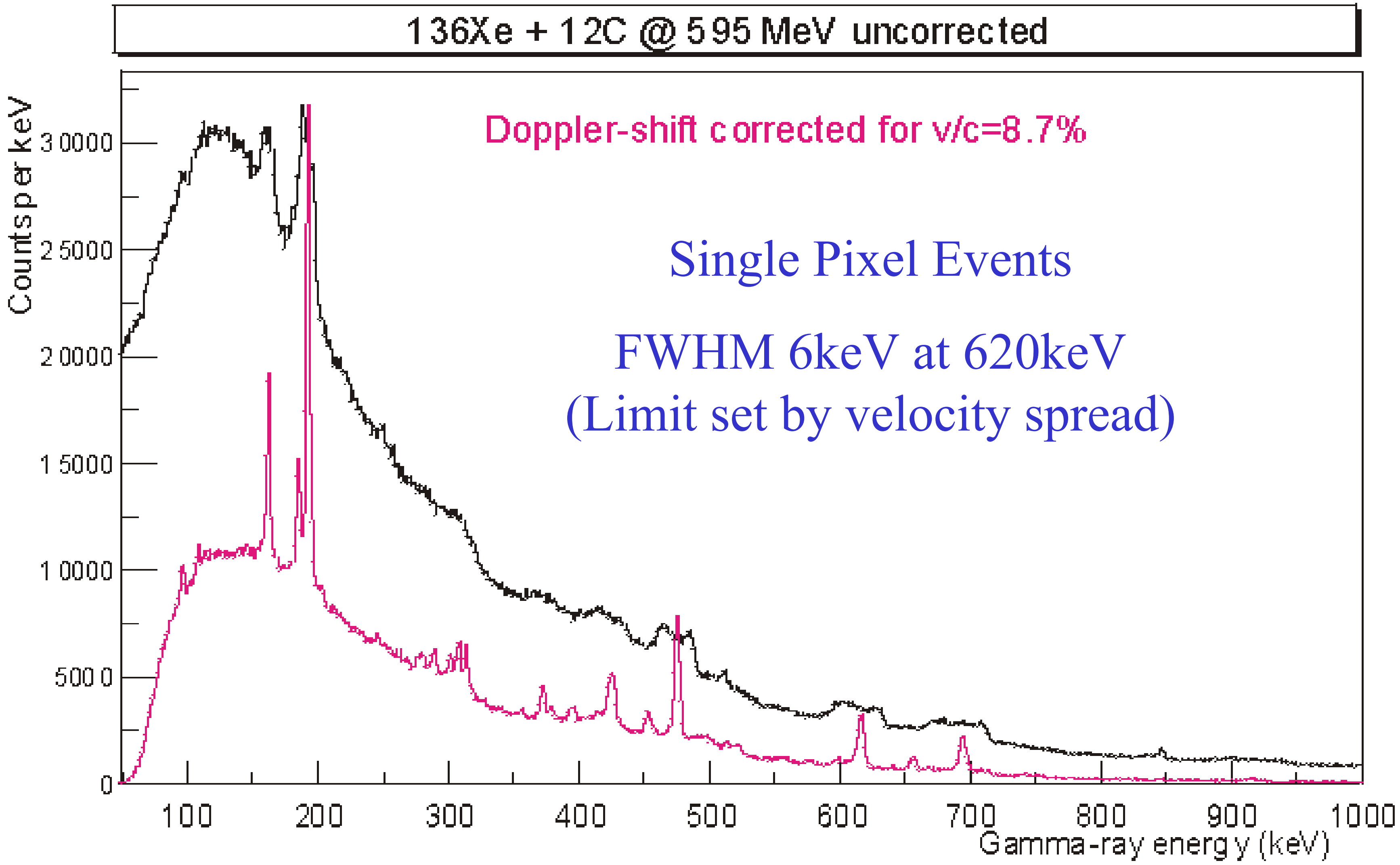








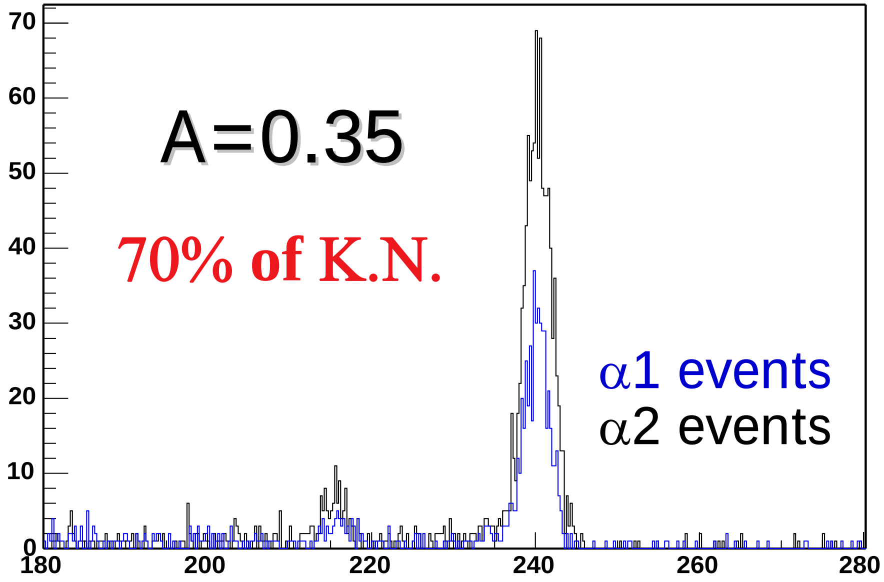
Doppler Correction



Single Pixel Events

FWHM 6keV at 620keV
(Limit set by velocity spread)

Polarization in α–γ coincidences



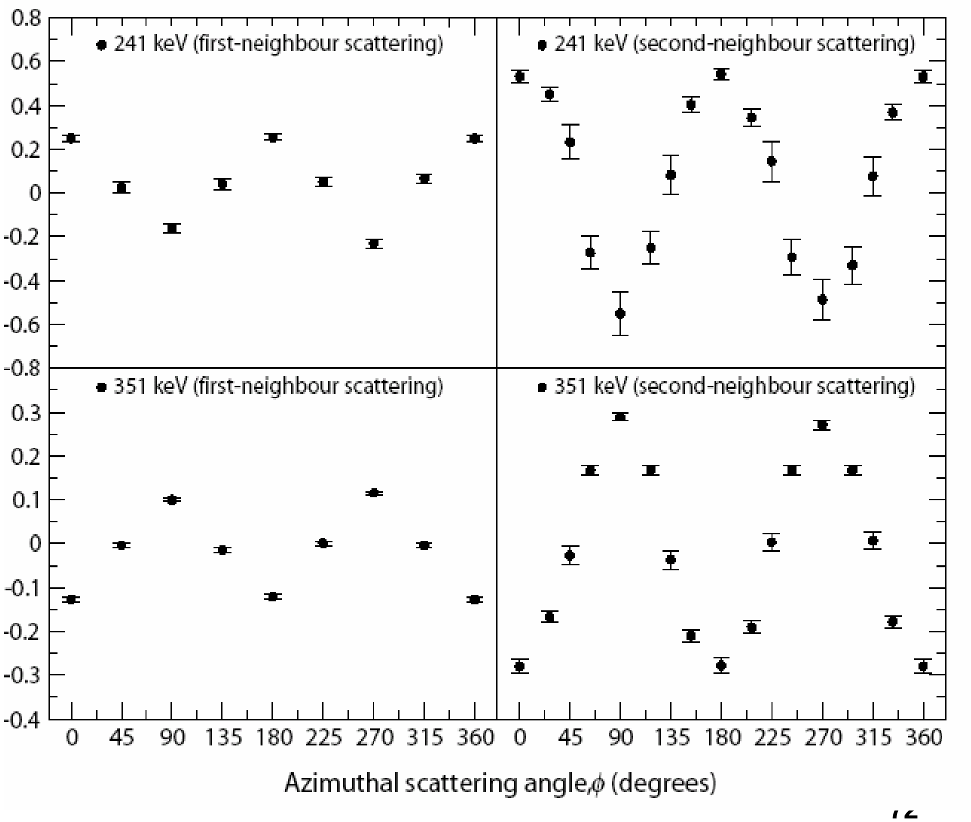
“Second Neighbor” analysis has even bigger asymmetry, and almost as much data.

16 pixels vs. 4.

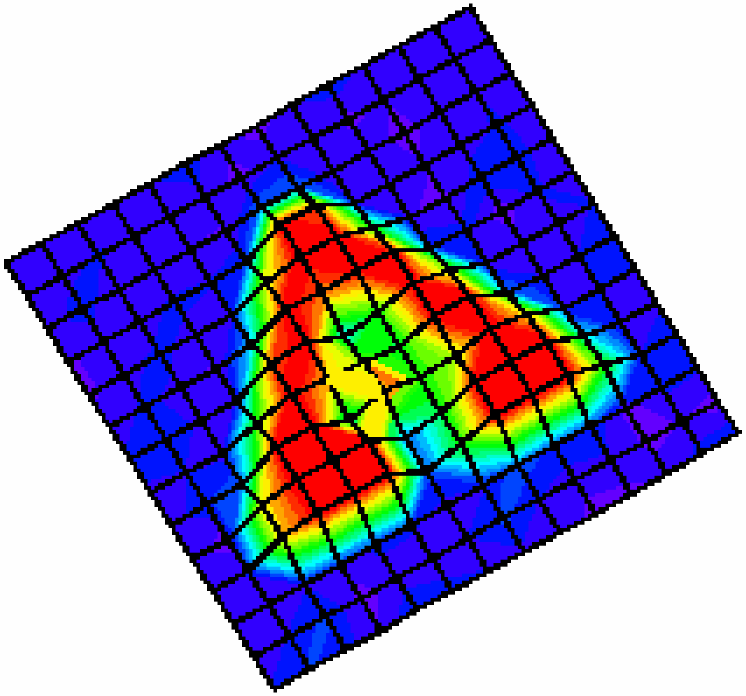
“Worlds Best” figure of merit

Vertical scatters in HpGeDSSD (Boron Side)

^{228}Th 240keV (0-2-0) correlation

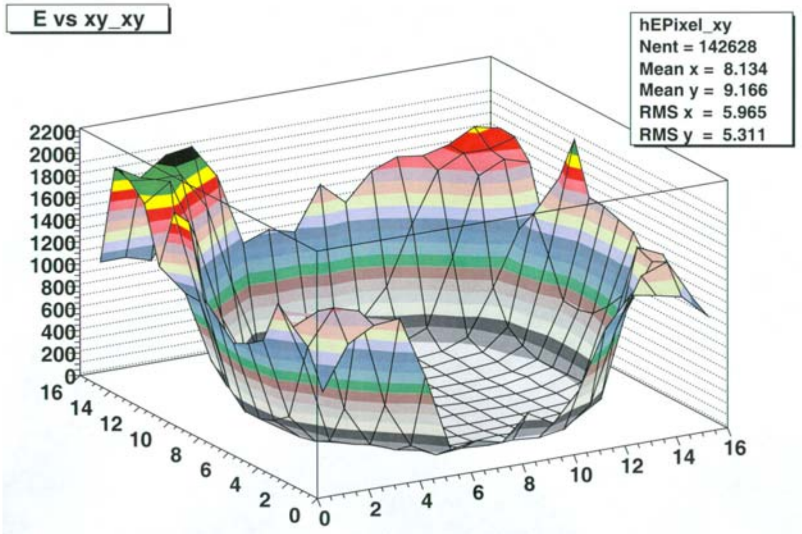


Imaging



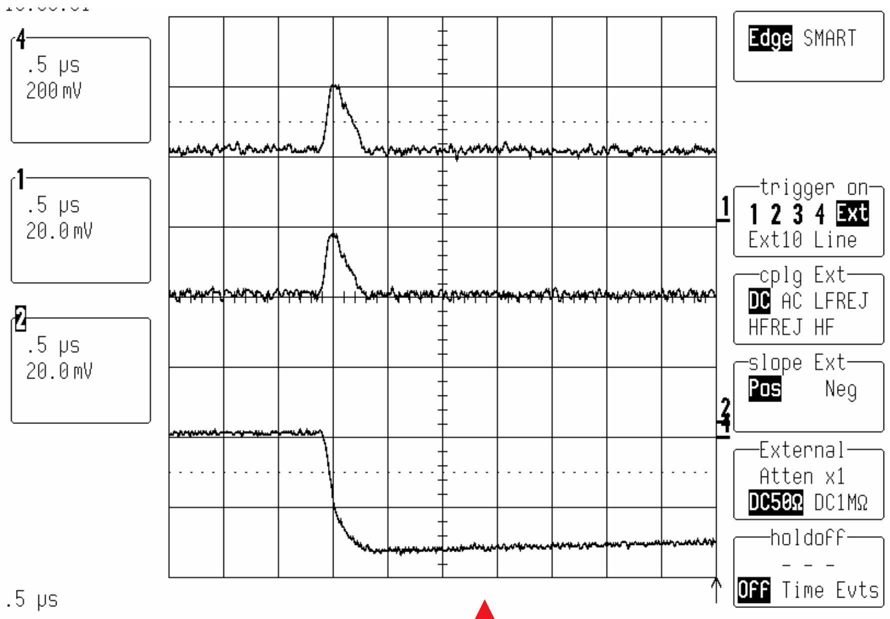
Direct Determination of materials by differential absorption

Varying source-object-detector baseline can give large magnification
This image 5mm steel ball bearing



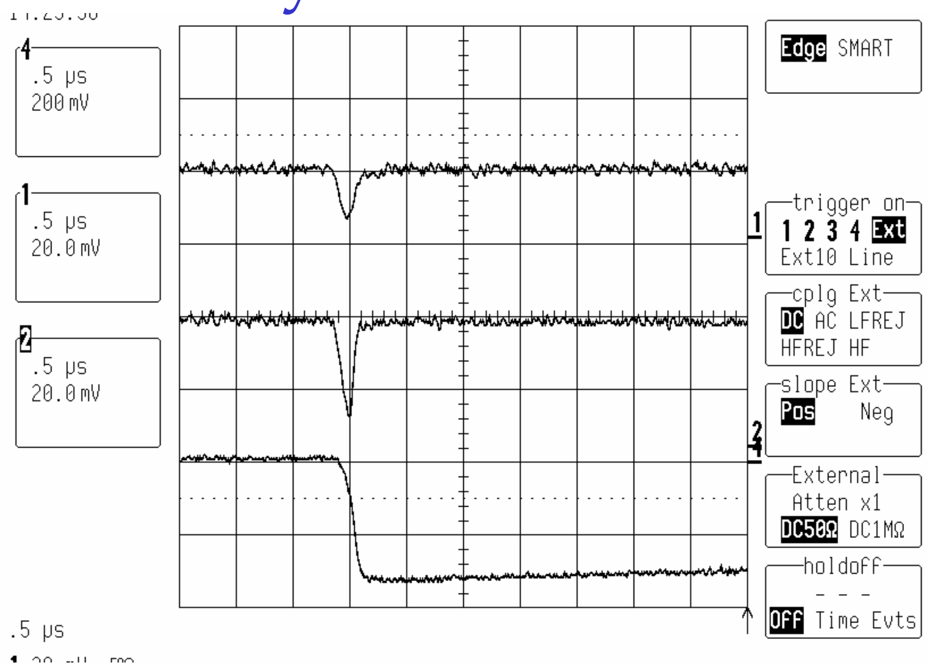
Digital Signal Processing

Here lies the most exciting prospect. The drifting charge created by the gamma rays induces images that allows the interaction points to be accurately located.

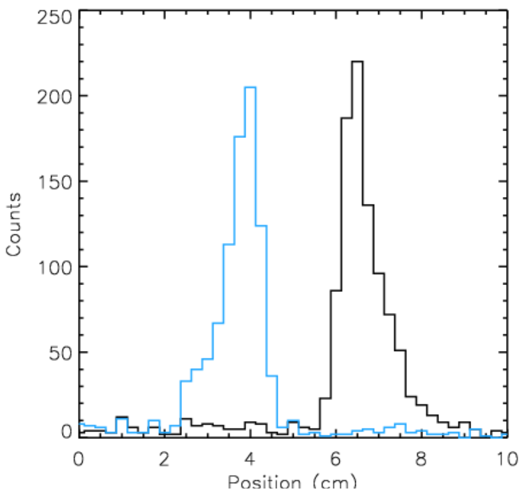


Shallow (Close to Electrode)
Central

Deep (Far from Electrode)
Right Side

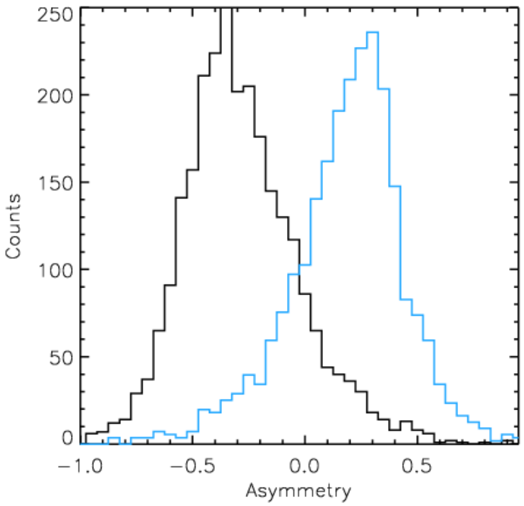


Digital pulse processing



DEPTH
From front-back time difference of charge pulse arrival

1-2 mm
but depends on position



LATERAL
From asymmetry of induced transient signals