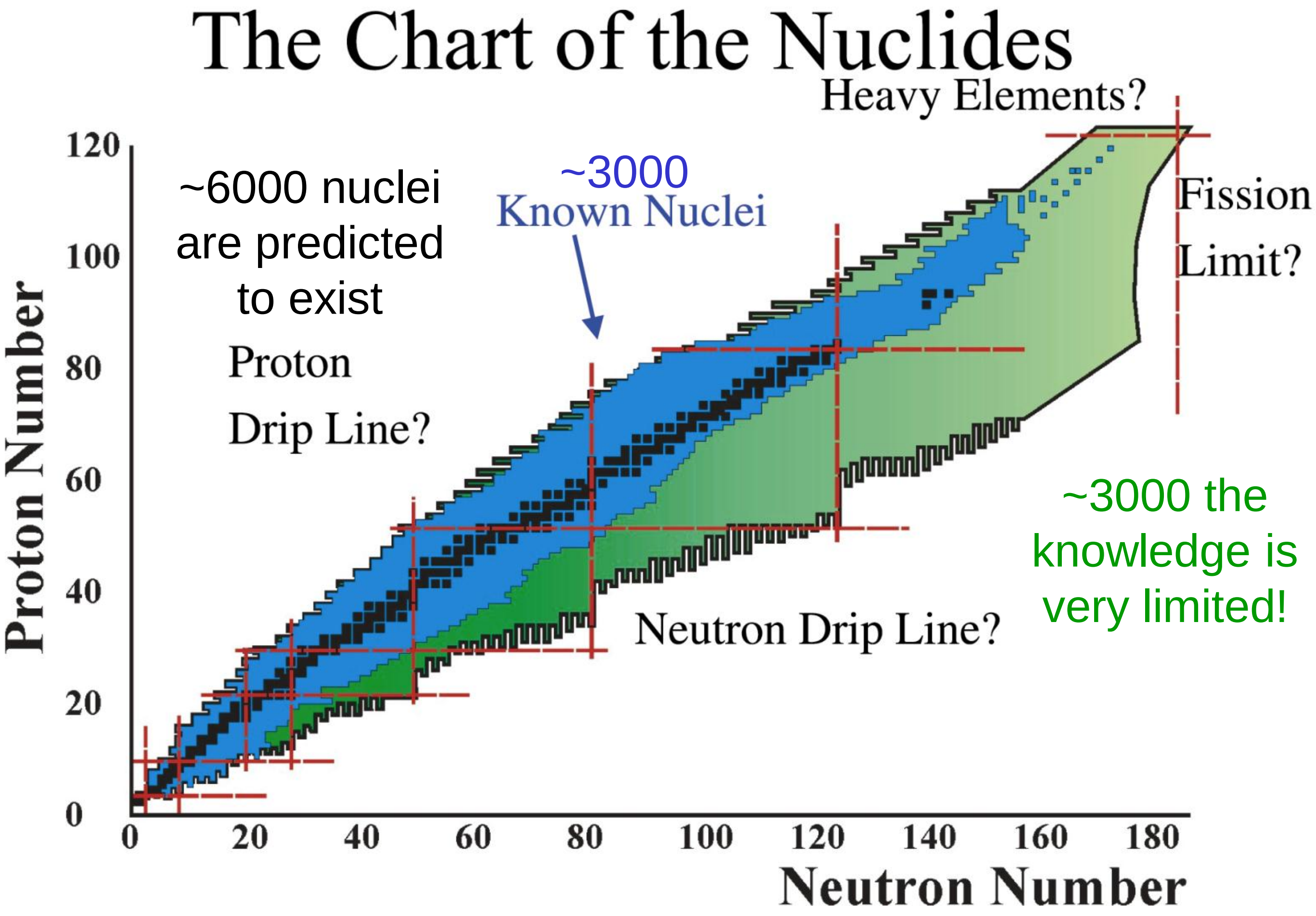
Study Of Nuclei at High Angular Momentum – Day 1

Outline

1) Introduction
2) Producing Nuclei at High Spin
3) Gamma-ray Spectrometers
4) Ancillary Detectors

Michael P. Carpenter
Nuclear Physics School, Goa, India
Nov. 9-17, 2011

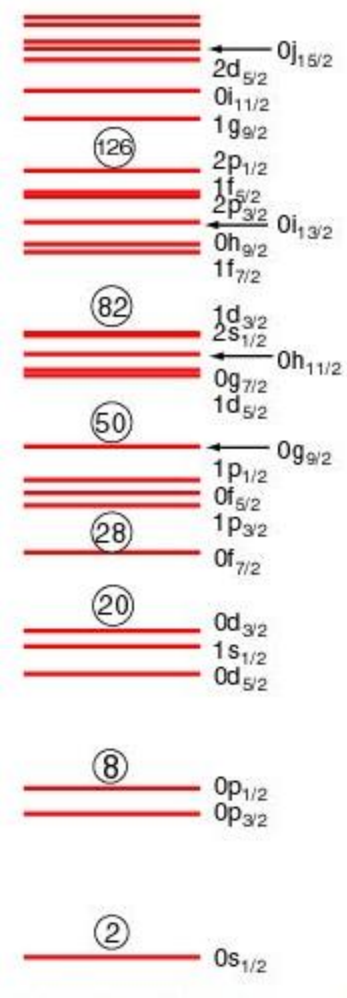
Nuclear Shell Model as function of N and Z



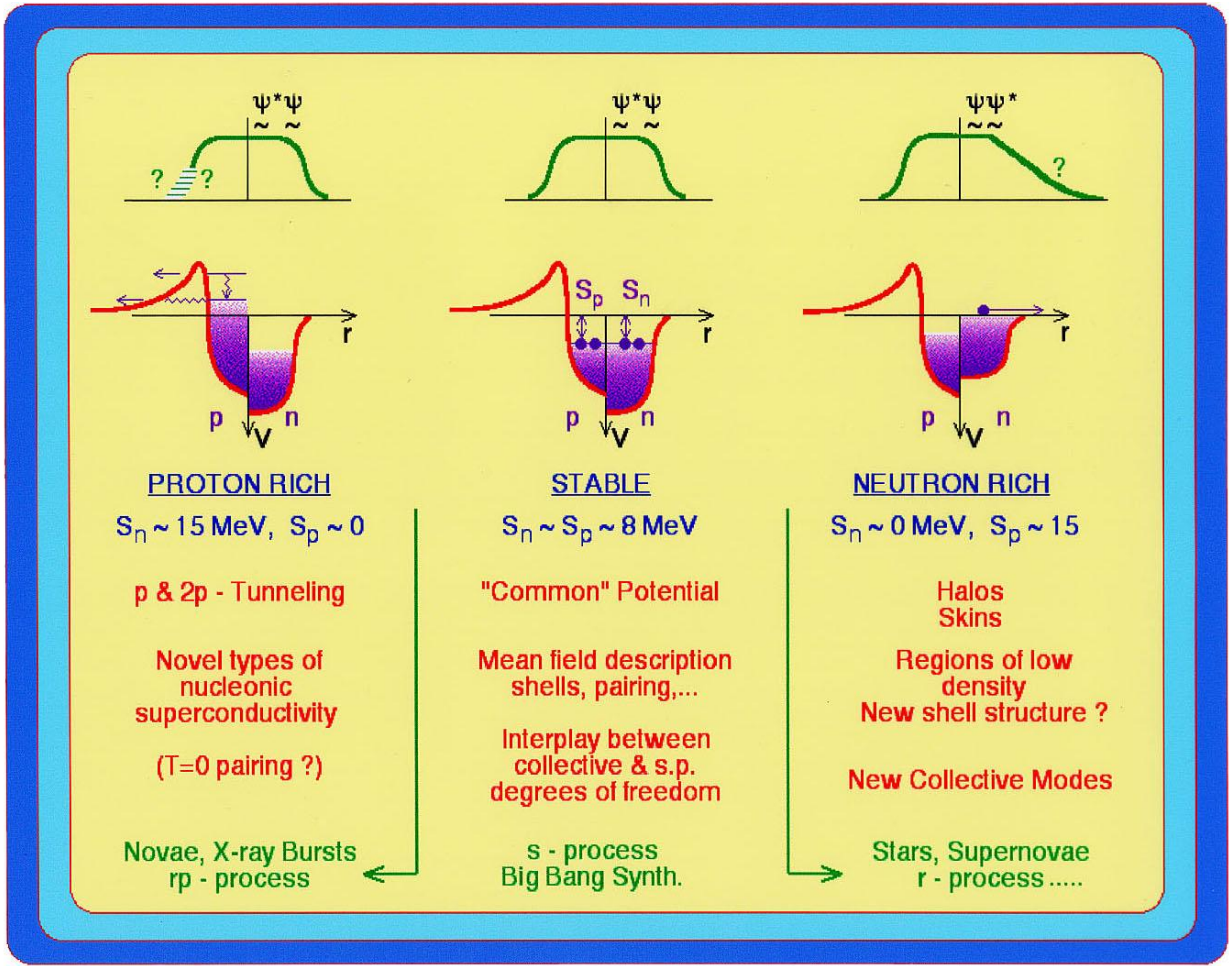
~6000 nuclei are predicted to exist

~3000 Known Nuclei

~3000 the knowledge is very limited!



Nuclear Structure



PROTON RICH

$S_n \sim 15$ MeV, $S_p \sim 0$

p & 2p - Tunneling

Novel types of nucleonic superconductivity

(T=0 pairing ?)

Novae, X-ray Bursts
rp - process

STABLE

$S_n \sim S_p \sim 8$ MeV

"Common" Potential

Mean field description
shells, pairing,...

Interplay between collective & s.p. degrees of freedom

s - process
Big Bang Synth.

NEUTRON RICH

$S_n \sim 0$ MeV, $S_p \sim 15$

Halos
Skins

Regions of low density
New shell structure ?

New Collective Modes

Stars, Supernovae
r - process .....

Some of the Physics Questions

How does the asymmetry in the proton and neutron Fermi surfaces impact the nucleus; *i.e.*

What is the impact on the mean field as reflected in:

the single particle energies

the shapes and spatial extensions

the modes of excitation

the binding energy, etc.

What is the impact on correlations in the medium as reflected in:

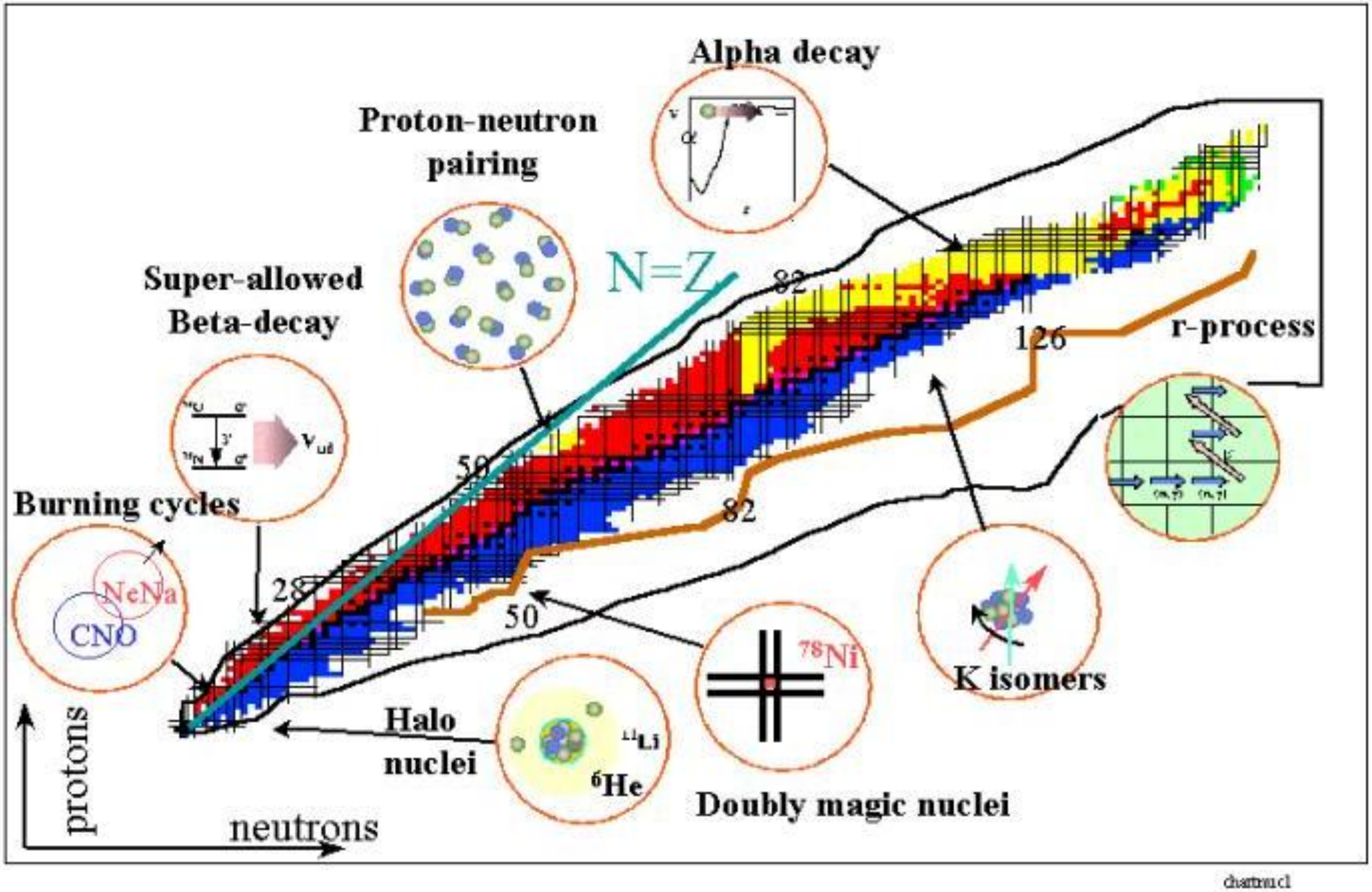
the effective interactions

the effective charges

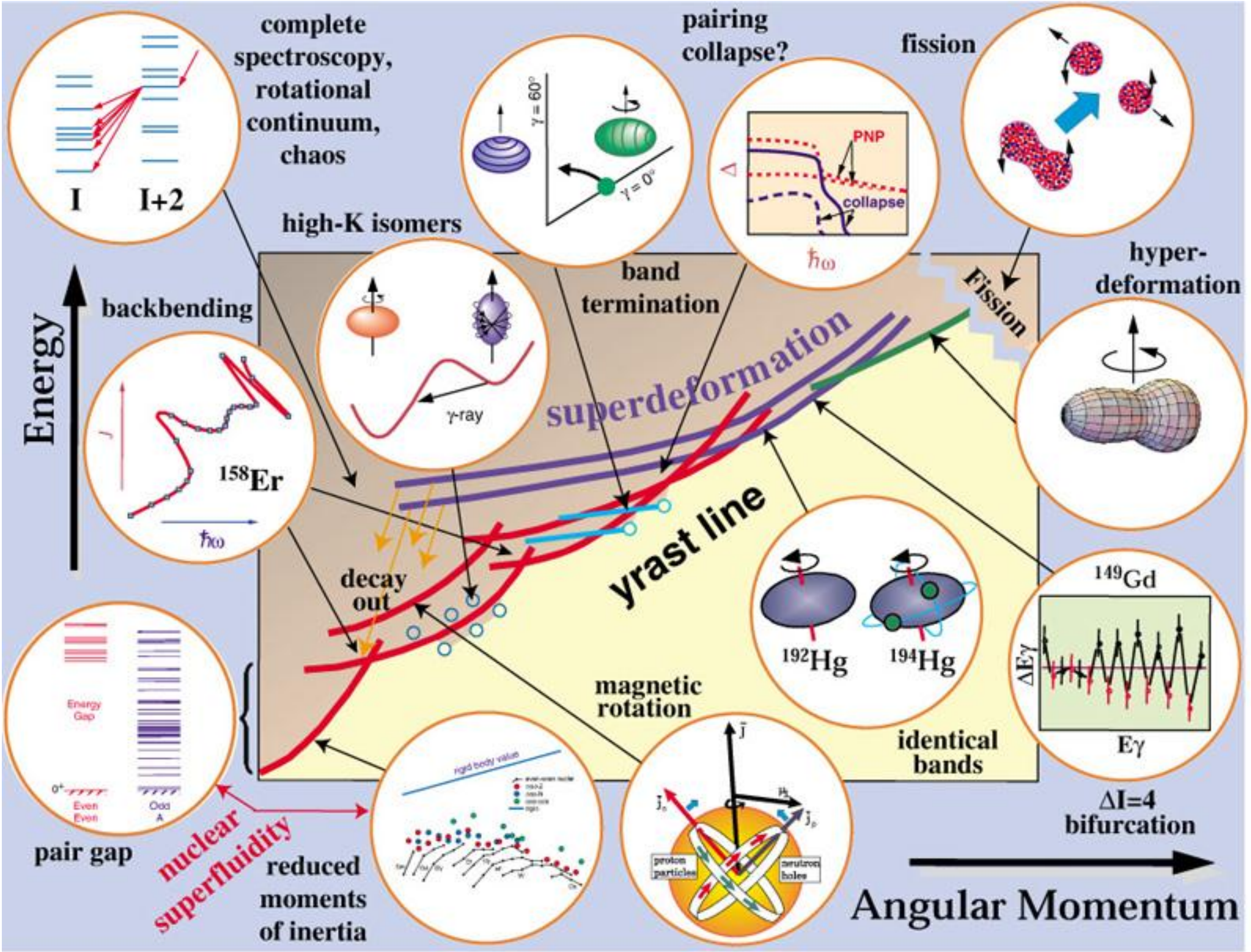
the transition rates, etc.

Ultimate goal: A unified theory of the nucleus

Nuclear Structure Varies as a Function of N and Z



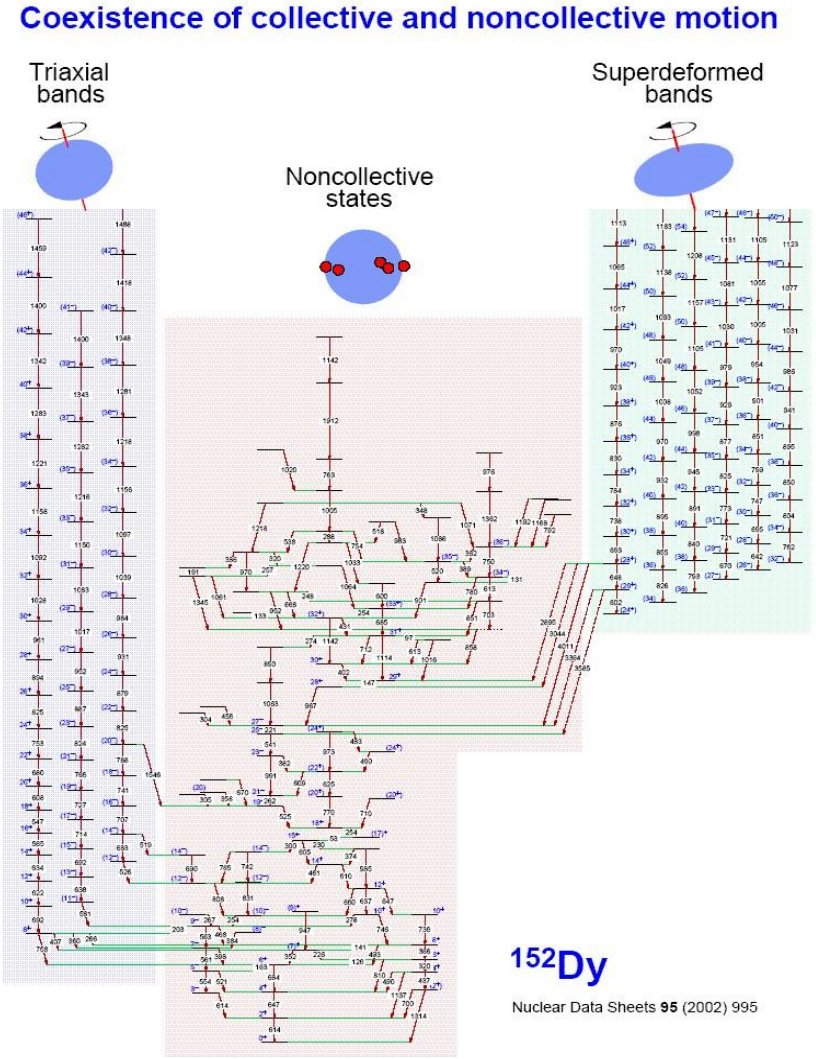
Angular Momentum World of the Nucleus



Why Study Nuclei at High Angular Momentum?

- A variety of nuclear properties can be described by the shell model, where nucleons move independently in their average potential, in close analogy with the atomic shell model.
- The nucleus often behaves collectively, like a fluid - even a superfluid, in fact the smallest superfluid object known in the nature and there are close analogies both to condensed matter physics and to familiar macroscopic systems, such as the liquid drop.
- A major thrust in the study of nuclei at high angular momentum is to understand how nucleon-nucleon interactions build to create the mean field and how single-particle motions build collective effects like pairing, vibrations and shapes
- The diversity of the nuclear structure landscape results n the fact that the the small number of nucleons leads to specific finite-system effects, where even a rearrangement of a few particles can change the “face” of the whole system.

Measure Nuclear Levels and Properties



Nuclear Data Sheets **95** (2002) 995

- Level sequences determined by measuring de-excitation γ rays.
- Only Ge detectors can offer the required efficiency and energy resolution
- Lifetime information is often crucial to characterize state.
- States that levels decay to are also important in characterizing states.
- Highest spins reached using fussion evaporation reactions.

Some Current Topics in Study of Nuclei at High Spins

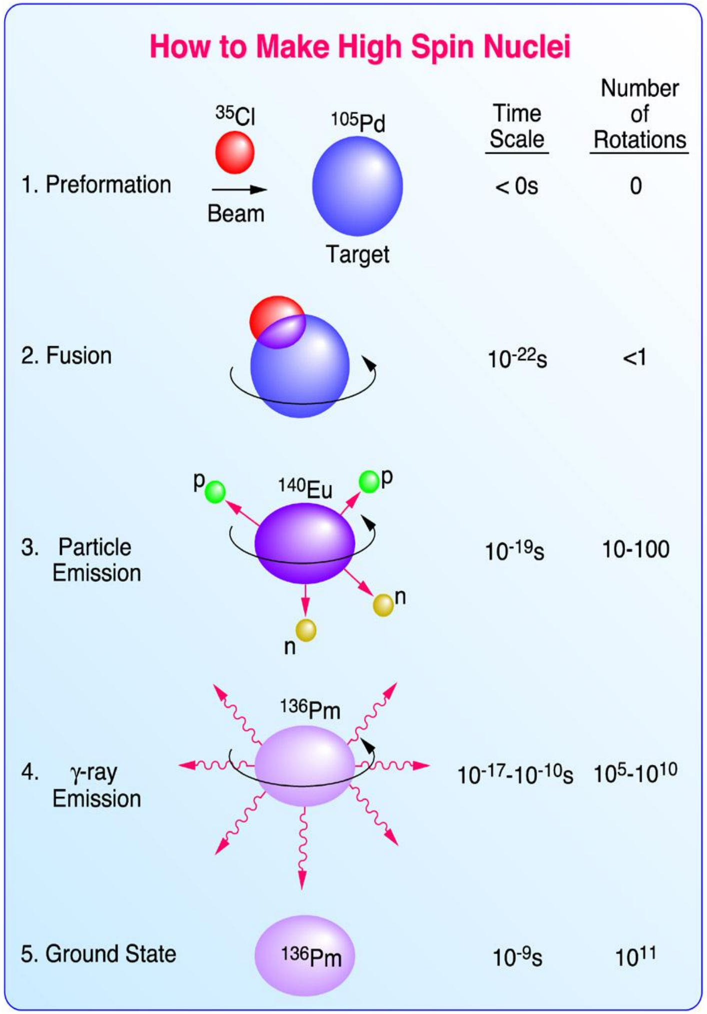
- Superdeformation
- Nuclear Chirality
- Shape Co-existence
- Magnetic Rotation
- Octupole Collectivity
- Tetrahedral Deformation
- Static Triaxiality
- Resumption of Collectivity at Ultra High Spins

Many of these topics were already discussed in the Workshop

How to Populate Nuclei at High Spin

Producing Nuclei at High Spins with HI Fusion

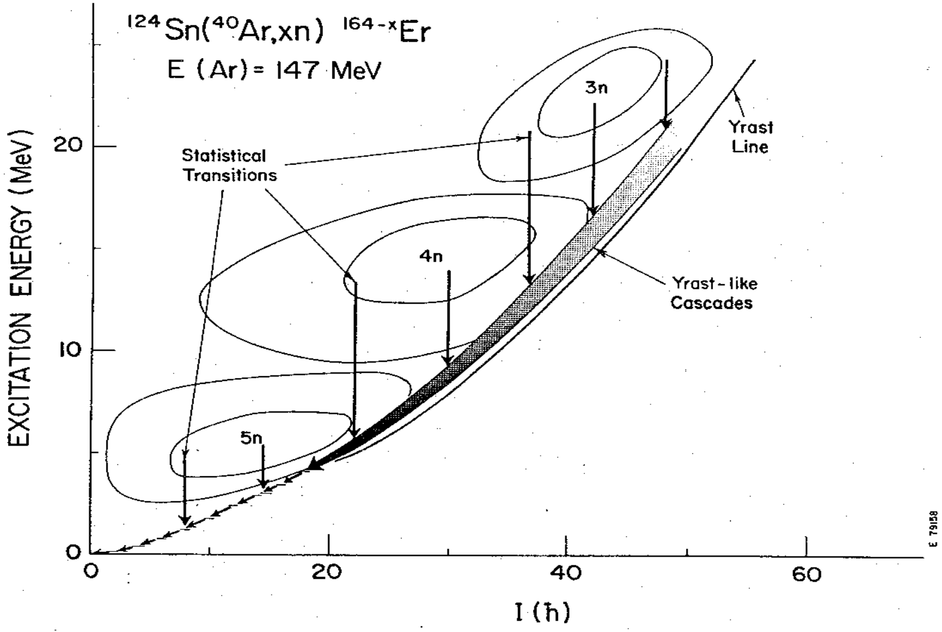
Heavy-Ion Fusion Evaporation is reaction of choice



How to Make High Spin Nuclei

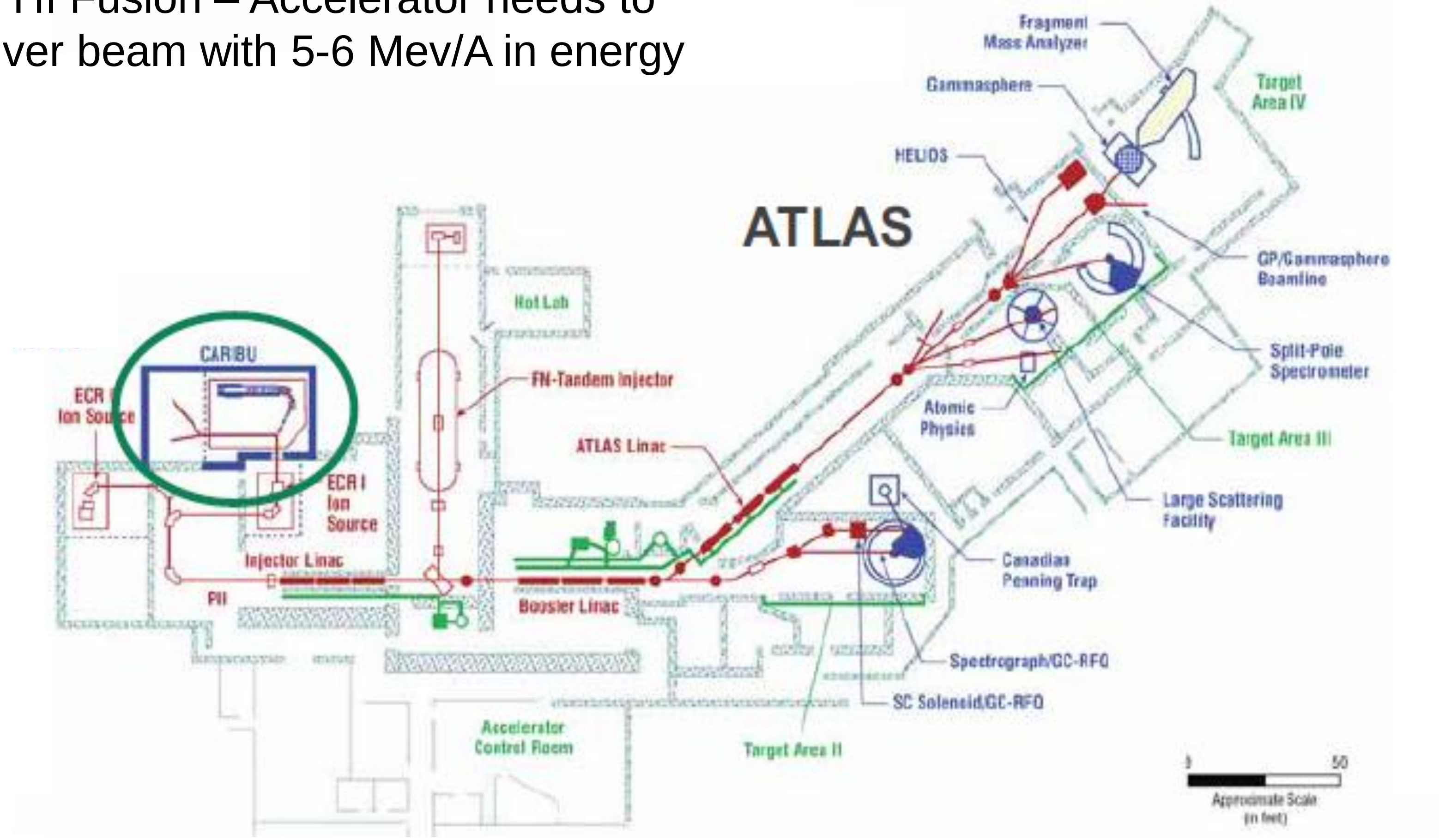
	Time Scale	Number of Rotations
1. Preformation	< 0s	0
2. Fusion	10^{-22}s	<1
3. Particle Emission	10^{-19}s	10-100
4. γ-ray Emission	10^{-17}-10^{-10}s	10^5-10^{10}
5. Ground State	10^{-9}s	10^{11}

Less particle evaporation corresponds to higher spins states for a particular bombarding energy.

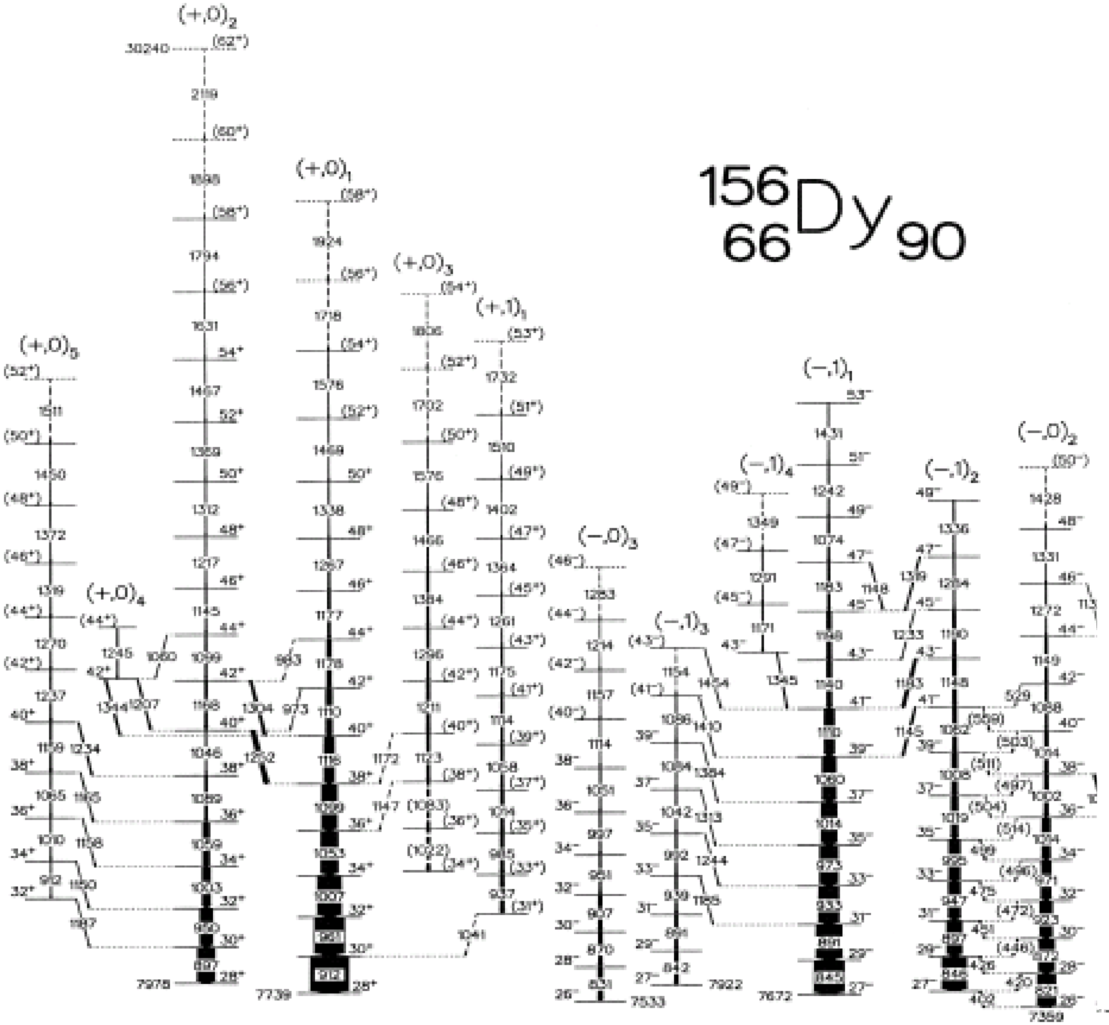


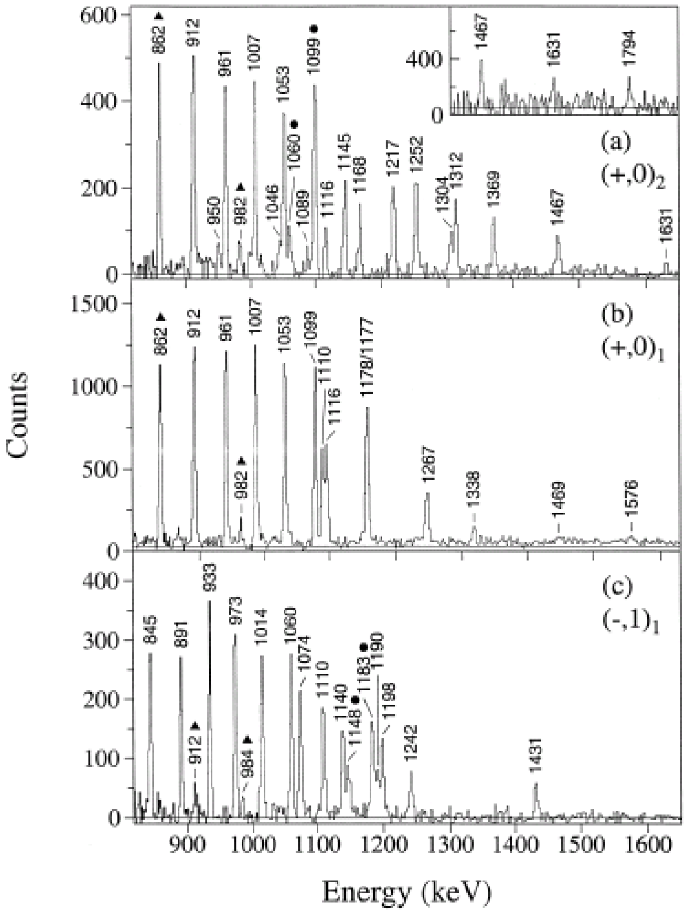
It Helps to have a Heavy-Ion Accelerator

For HI Fusion – Accelerator needs to deliver beam with 5-6 Mev/A in energy



Heavy-Ion Fusion Evaporation Reaches Highest Spins





F.G. Kondev et al., Phys. Lett. **B** 437, 35 (1998)

Alternative Methods to Populate Nuclei at High Spin

Alternative reactions:

- Un-Safe Coulomb Excitation (stable beams or targets)

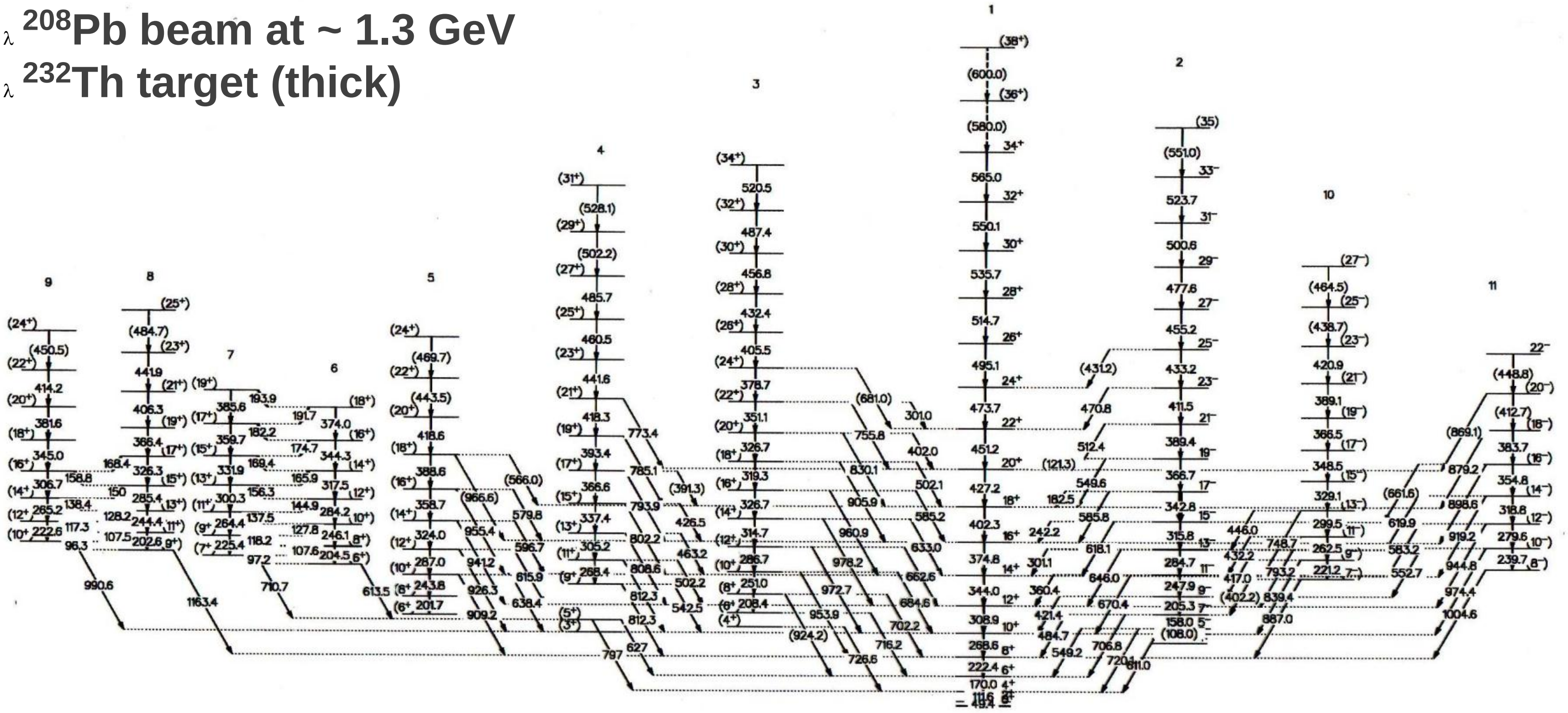
- Inelastic Collisions
  - Multi nucleon transfer (neutron rich)
  - Deep Inelastic Collisions (neutron rich)

- Spontaneous fission sources ^{252}Cf, ^{248}Cm (neutron rich)

- Induced fission of actinide targets (neutron rich)

Unsafe Coulex of Actinide Targets

- ^{208}Pb beam at ~ 1.3 GeV
- ^{232}Th target (thick)

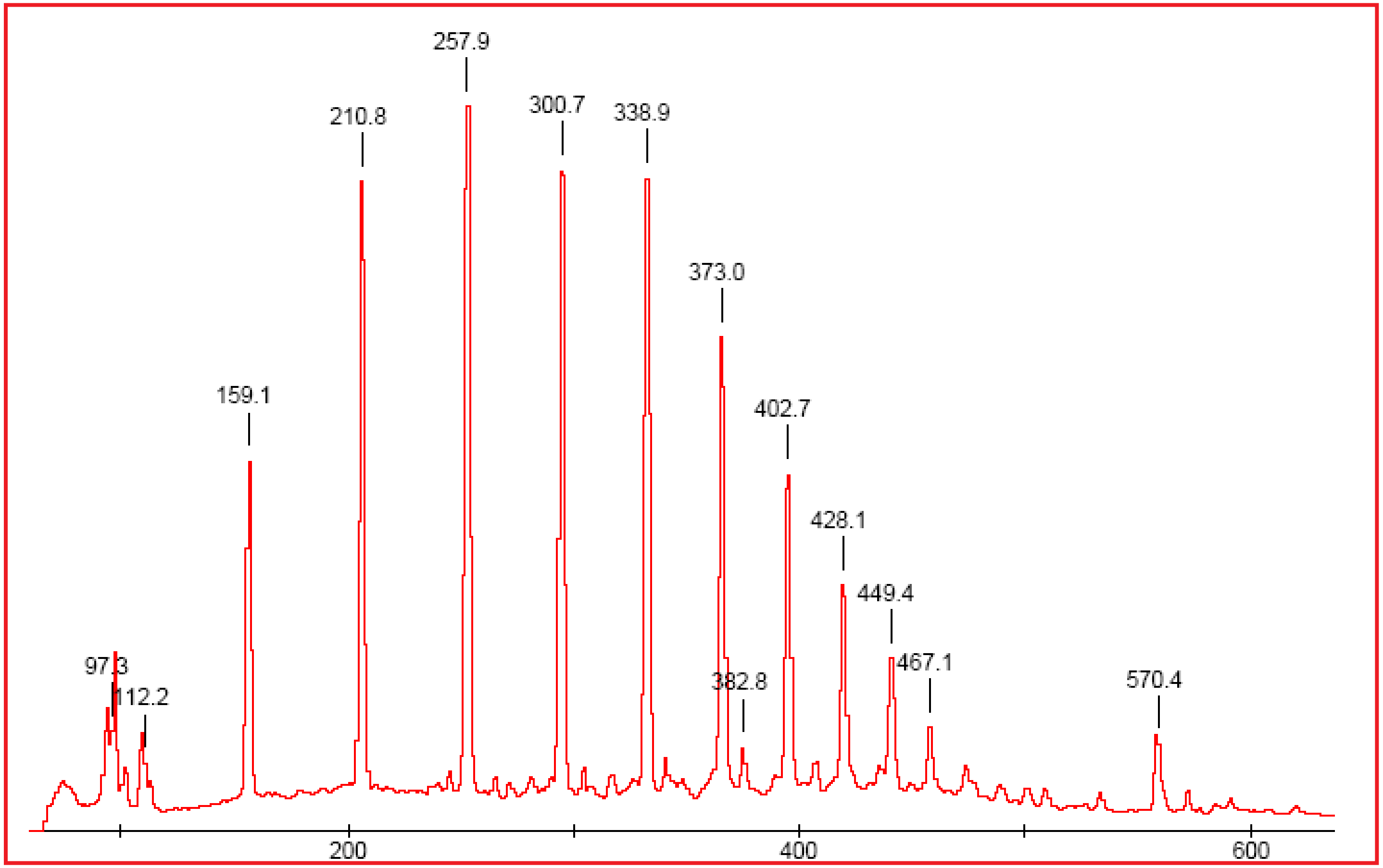


Double Gamma **Beta** **Gamma** **K=0$^-$ Octupole** **K=1$^-$ Octupole**

^{232}Th

K. Abu Saleem, Ph D. Thesis, Argonne Nat. Lab.

Gamma-Ray Spectrum of $^{238}U+^{207}Pb$ reaction

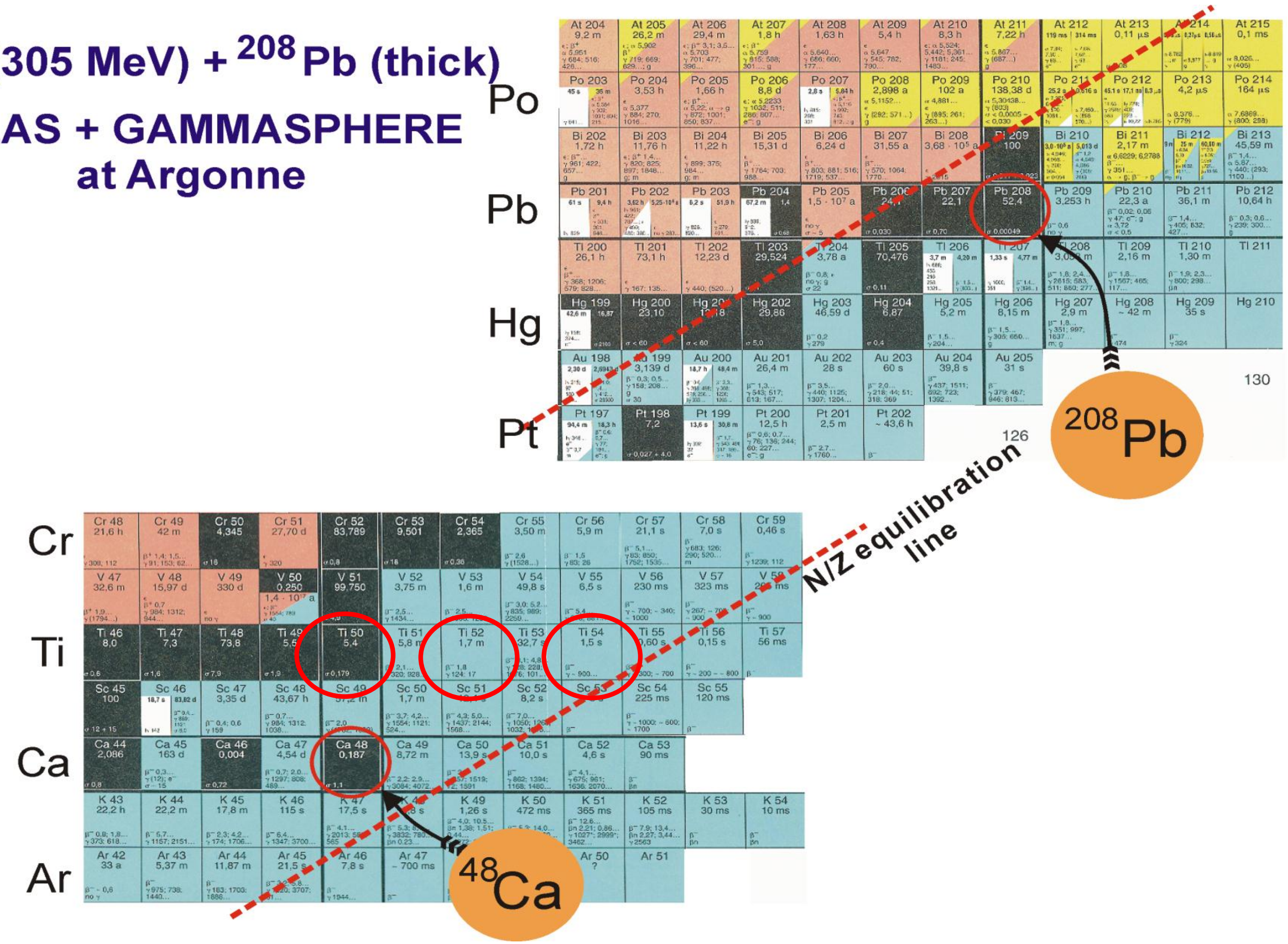


Lines are sharp when emitted after nucleus come to rest in target.

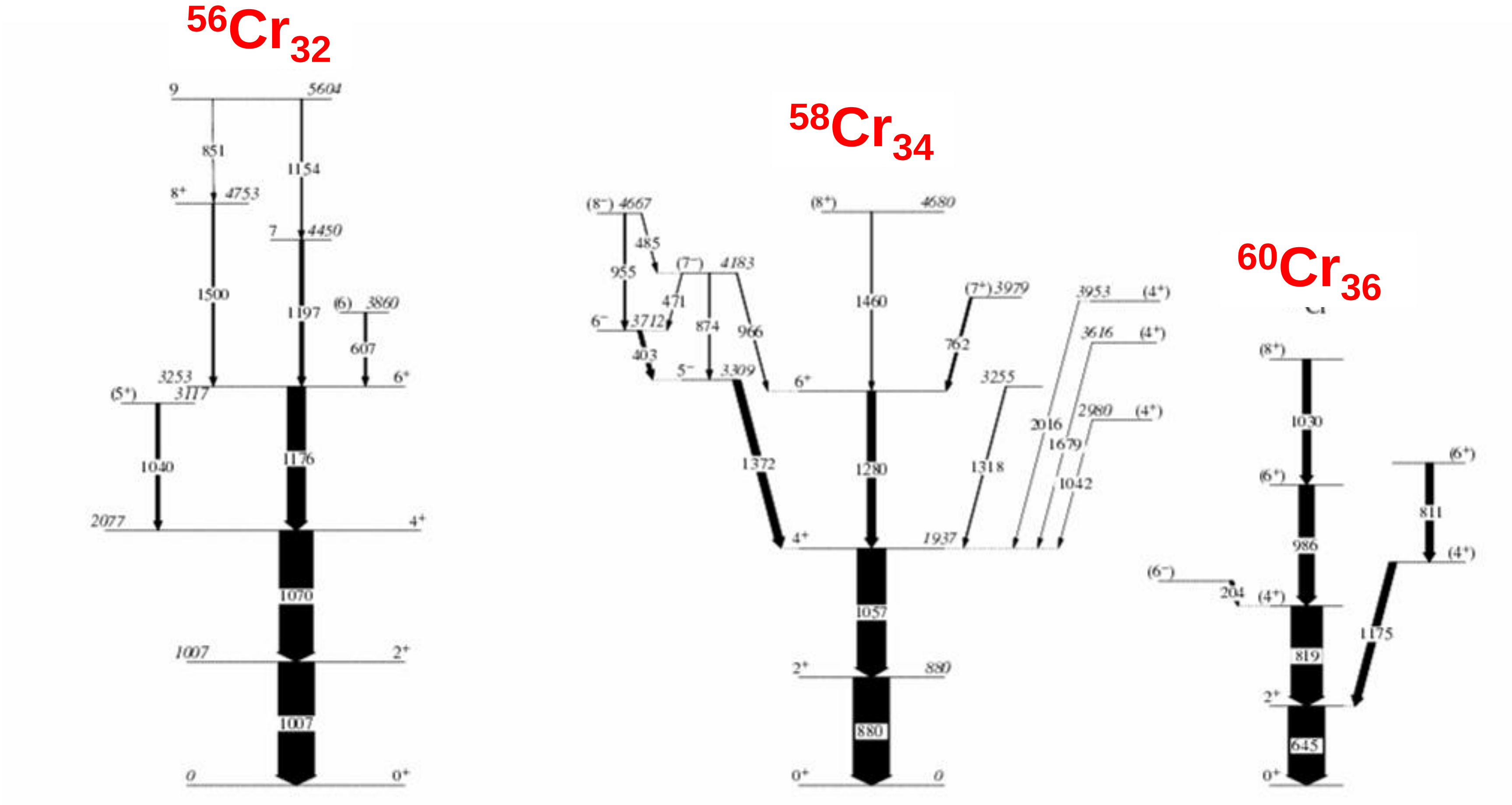
Deep Inelastic Reactions

^{48}Ca (305 MeV) + ^{208}Pb (thick)

ATLAS + GAMMASPHERE at Argonne



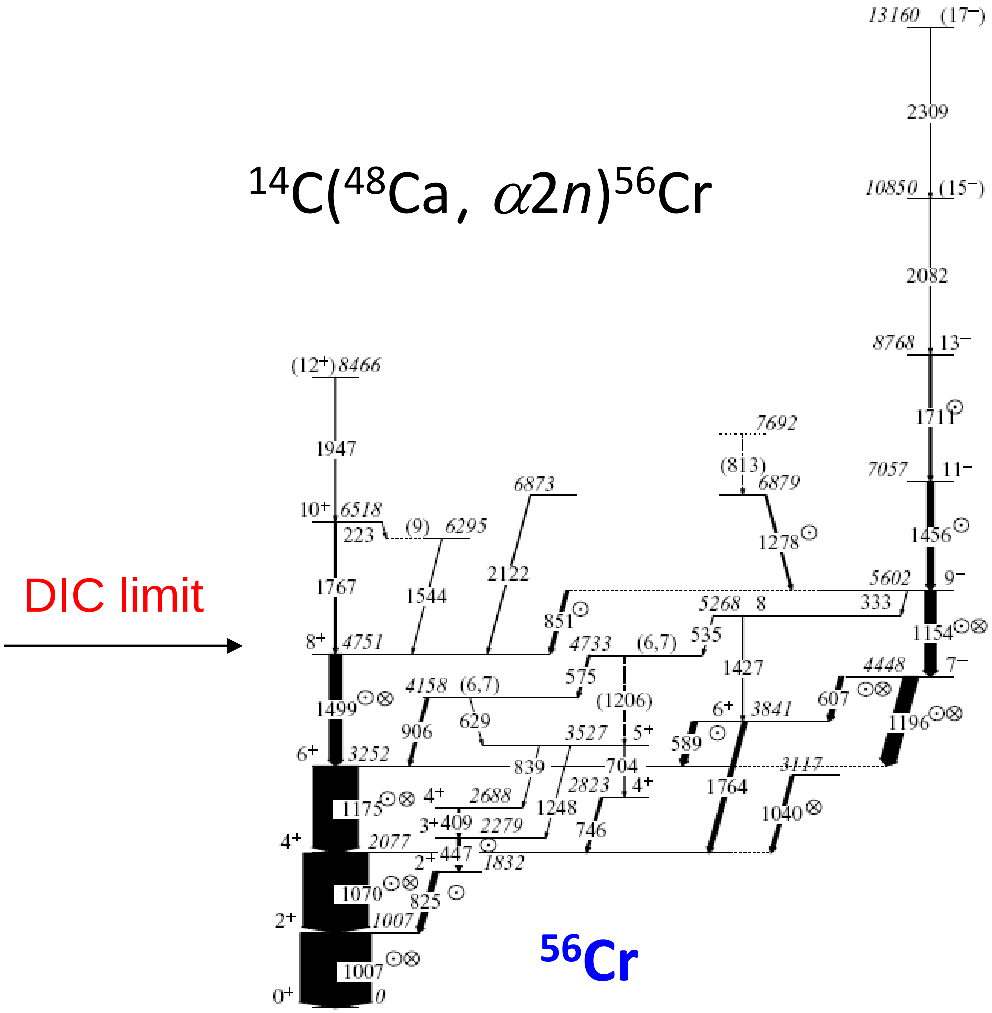
Level Structure of Neutron-Rich Cr Isotopes



S. Zhu *et al.*, Phys. Rev. C **74** (2006) 064351

DIC Limits in Angular Momentum

^{14}C(^{48}Ca, α2n)^{56}Cr



DIC limit

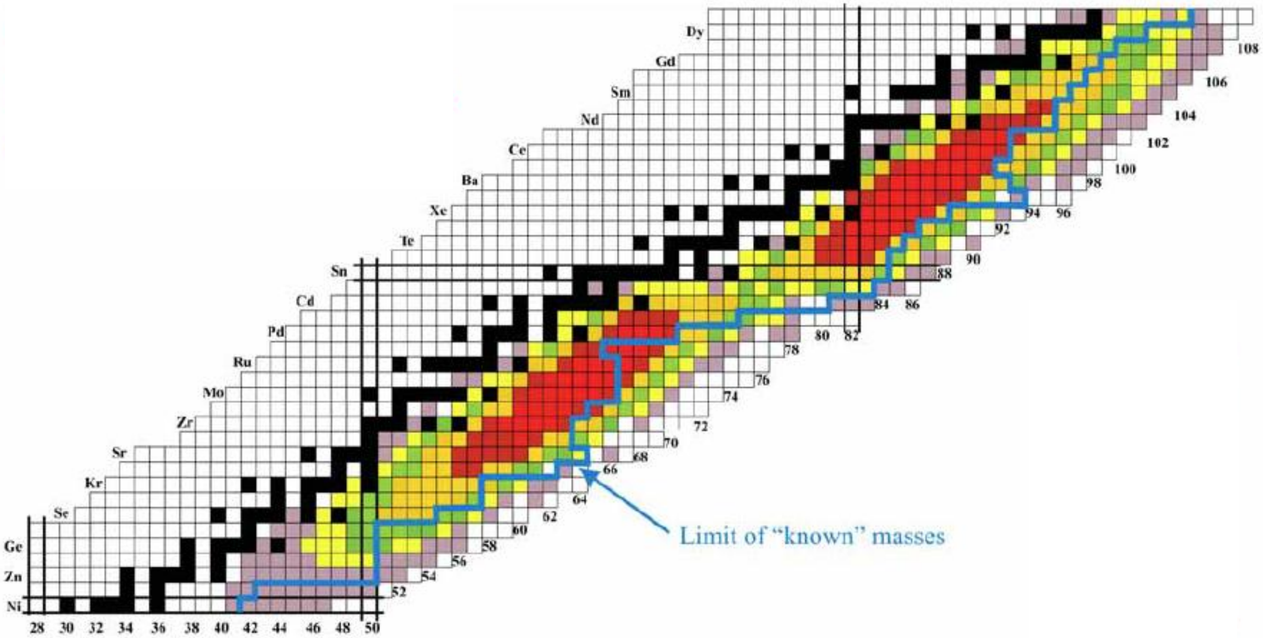
^{56}Cr

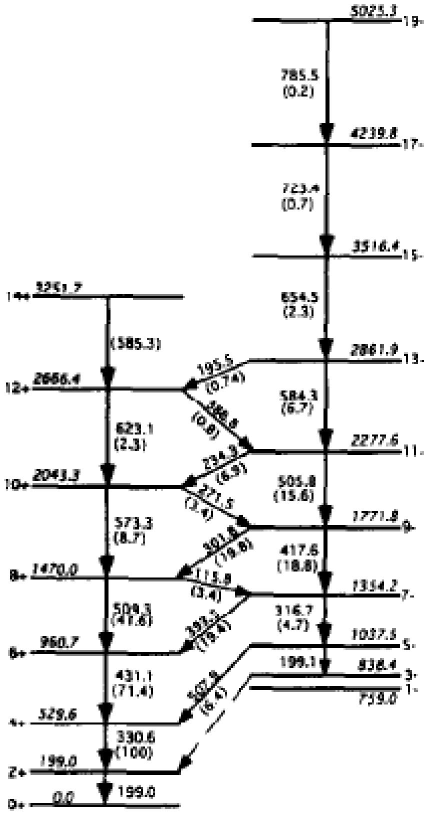
$\nu(g_{9/2} x f_{5/2})$

S. Zhu *et al.*, Phys. Rev. C **74** (2006) 064351

High Spin Studies with Spontaneous Fission Sources

Products from spontaneous fission of ^{252}Cf





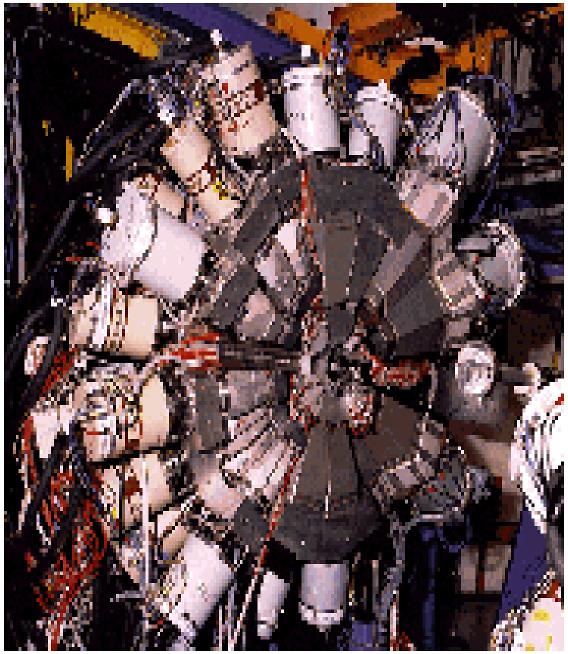
^{144}Ba

S.J. Zhu et al., PLB 357 (1995) 273.

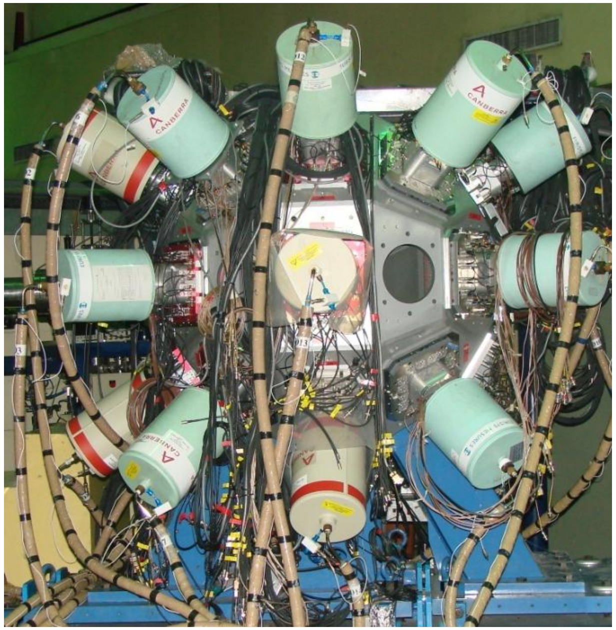
Gamma Ray Detector Arrays for Measuring High Spin States

Compton Suppressed Arrays

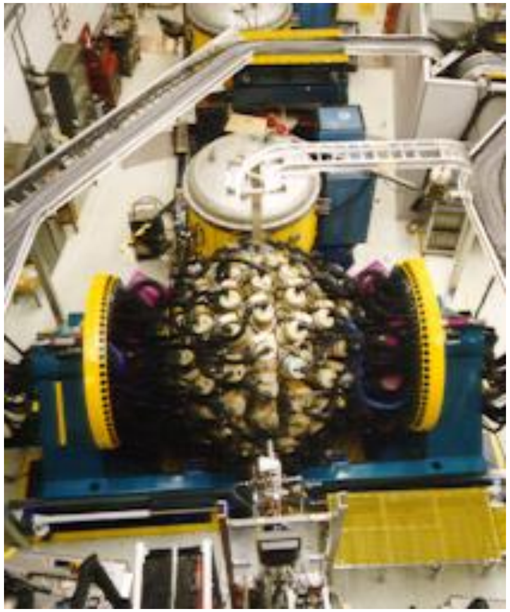
For the last ~ 15 - 20 years, large arrays of Compton-suppressed Ge detectors such as EuroBall, JUROBALL , GASP, EXOGAM, TIGRESS, INGA, Gammasphere and others have been the tools of choice for nuclear spectroscopy.



EUROBALL

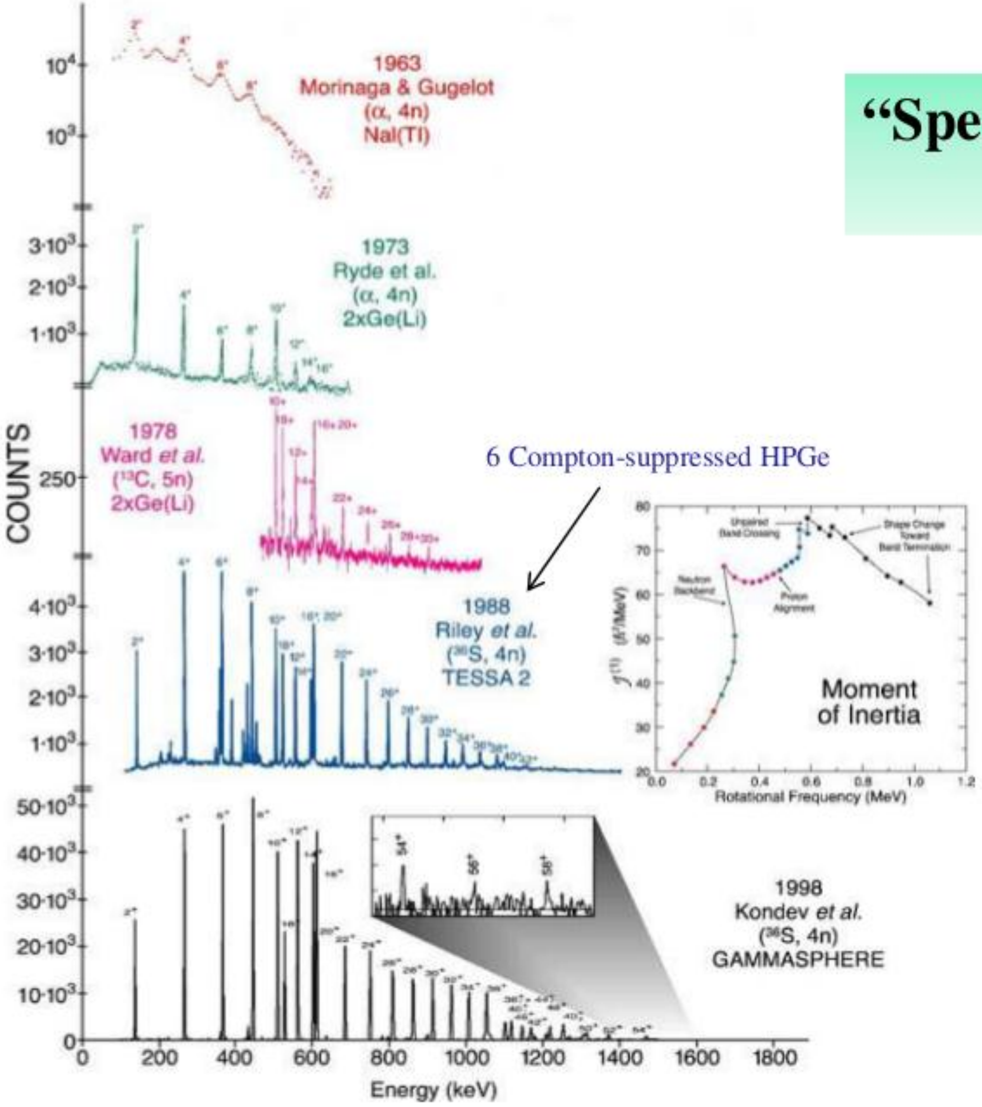


INGA



Gammasphere

Reaching Higher in Angular Momentum

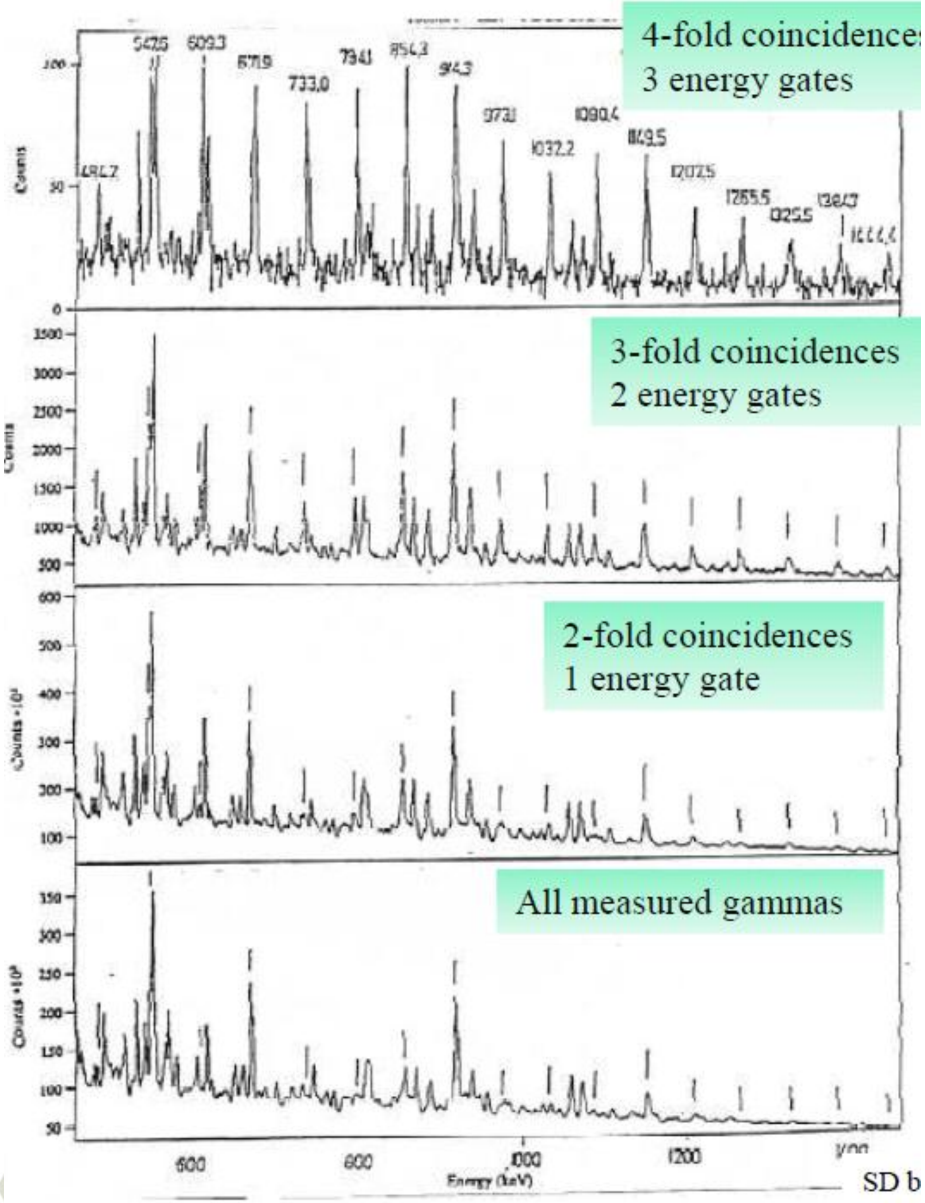


“Spectroscopic history” of ^{156}Dy

What Does this Slide tell Us

- Solid State detectors better than Scintillators (Resolution)
- Compton Suppression is important (Signal to Noise)
- Number of Detectors is Important (Efficiency and Multiplicity)

Identifying Weak Cascades

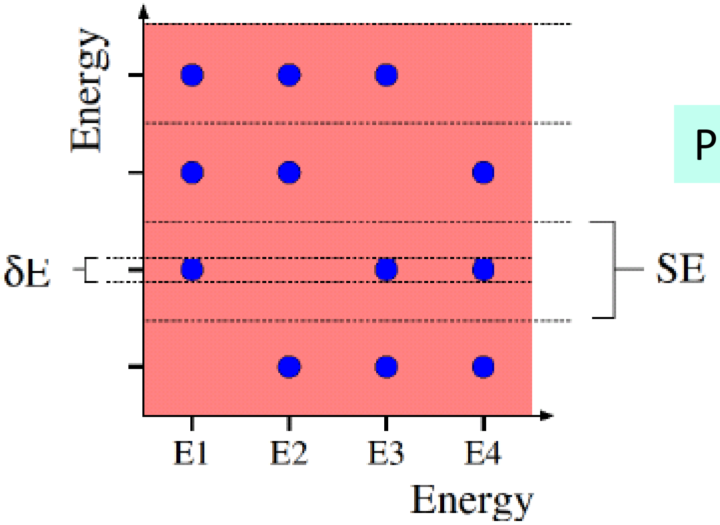


Multifold Gating: By applying F-1 coincidence gates, where F is measured gamma-ray multiplicity, the weaker intensity peaks associated with the superdeformed band are enhanced over everything else.

What are the important characteristics of the detector array which allow these weak cascades to be resolved?

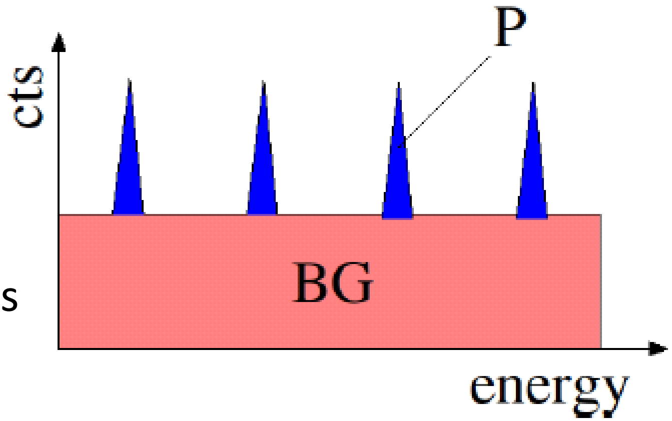
Simple Model to Illustrate Improvement in P/B

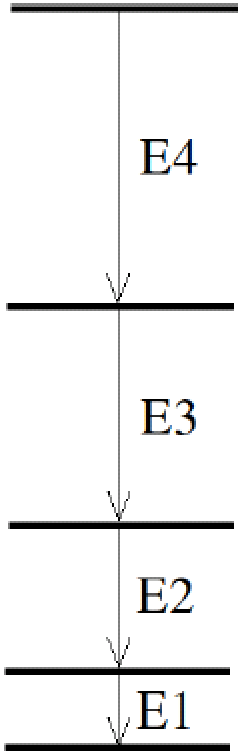
Two fold coincidences (F=2)



δE is measured energy resolution
SE is average energy spacing between γ rays

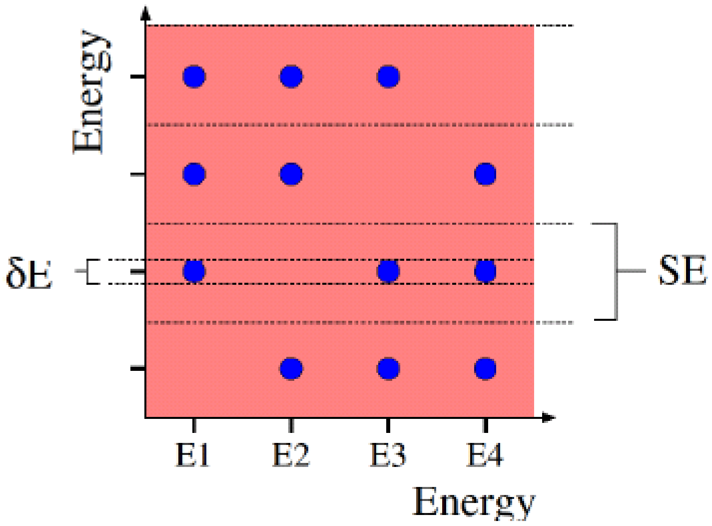
Project all gammas to 1D spectrum

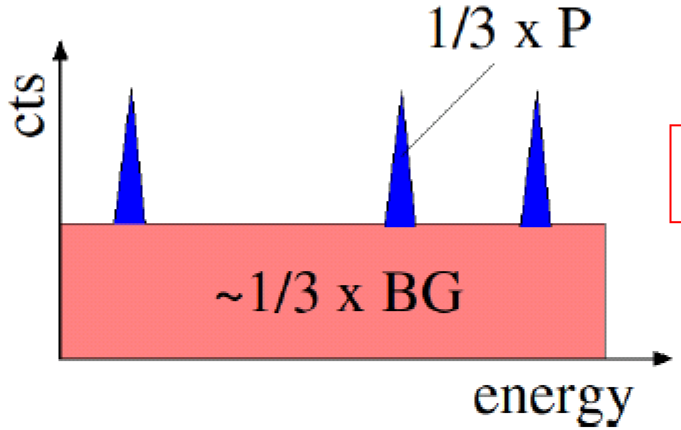




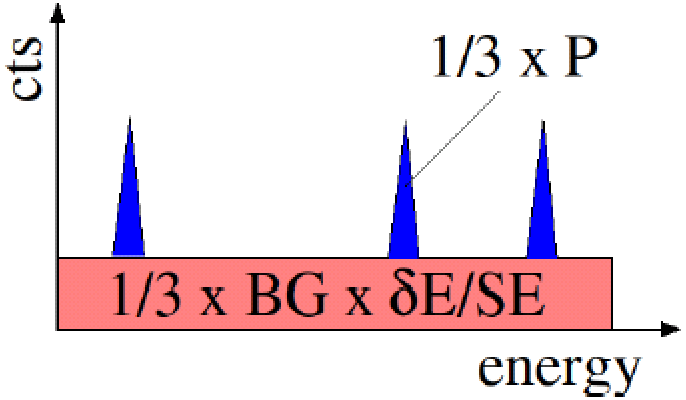
Applying Coincidence Gates

Two fold coincidences (F=2)





SE cut



δE cut

- Cut on SE gives no improvement in P/BG
- Cut on δE improves P/B by SE/δE

It is as we suspected

Background Reduction factor for an:

$$R = [0.76\times(SE/\delta E)\times(P/T)]^{F-1}$$

Where 0.76 corresponds to placing a gate on FWHM

This reduction factor is dependent on δE, P/T and F.

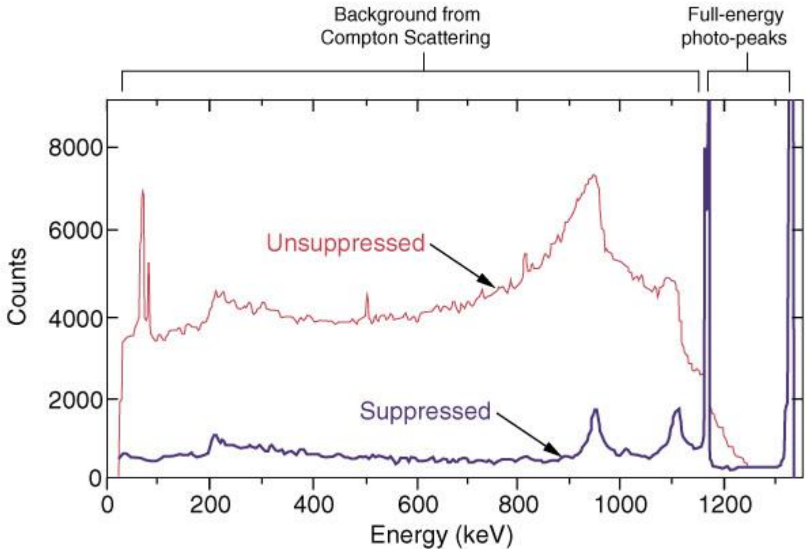
On the hand: The number of counts observed goes as

$$N = N_0\varepsilon^F$$

In conclusion, when building a gamma-ray spectrometer you must maximize P/T, efficiency and energy resolution.

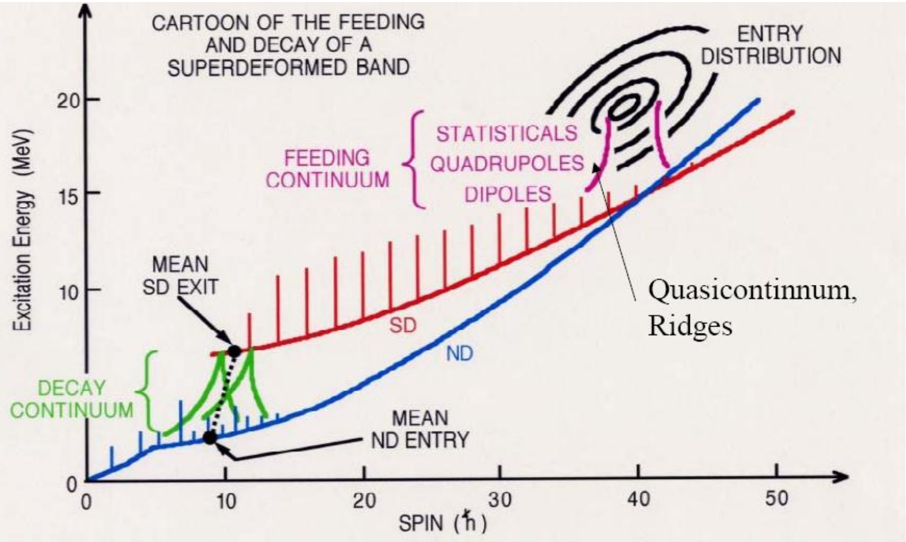
Compton Suppression

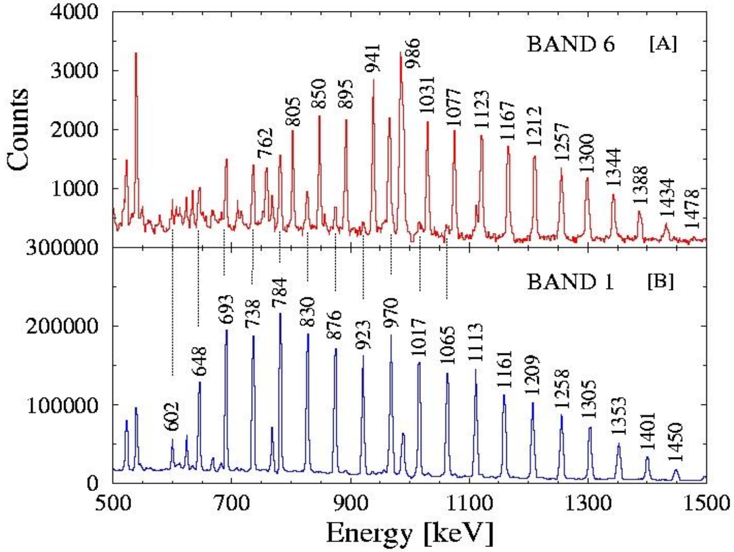
Gammasphere

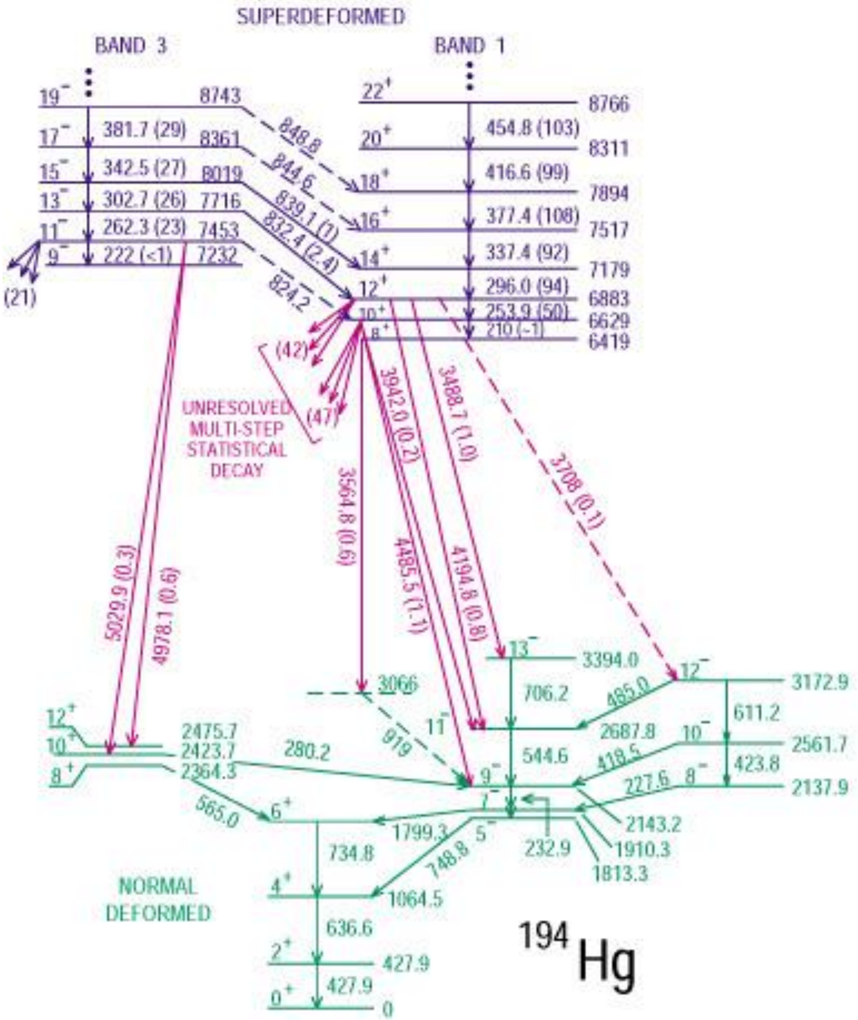


- Peak to Total (P/T) = Σ Photo Peaks/ Σ of all Counts
- P/T ~ 0.20 for 70% Co-axial Ge Detector
- P/T ~ 0.55 for Compton Suppressed Gammasphere Detector In Array
- Photopeak efficiency is ~10% for 1 MeV γ ray (110 Detectors)
- δE = 2.5 keV at 1MeV

First Sucesses for Large Compton Suppressed Arrays







Question:

If a gamma-ray is emitted while the nucleus is moving at 5% the speed of light, what characteristic of the Gammasphere array is compromised?

a) Peak/Total ?

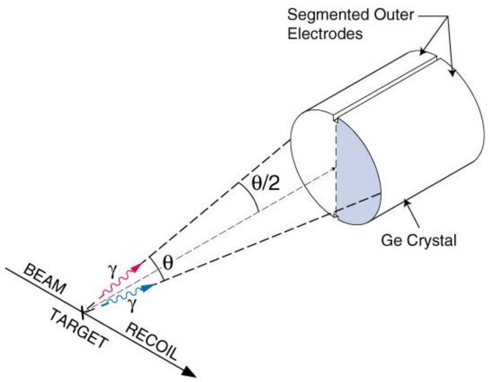
b) Energy Resolution?

c) Efficiency?

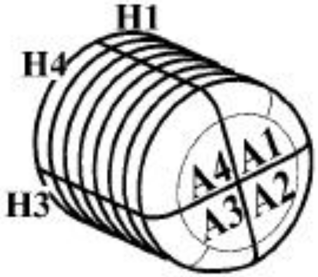
d) None of the above?

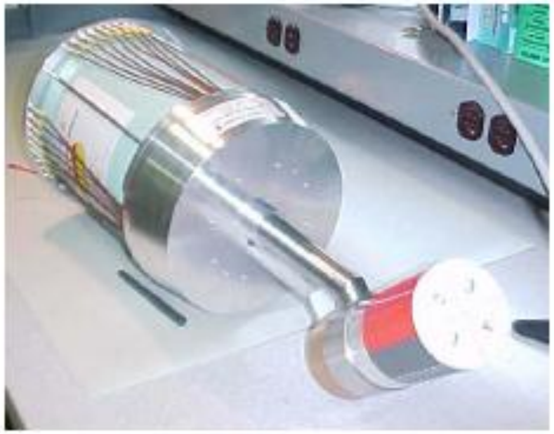
Answer:

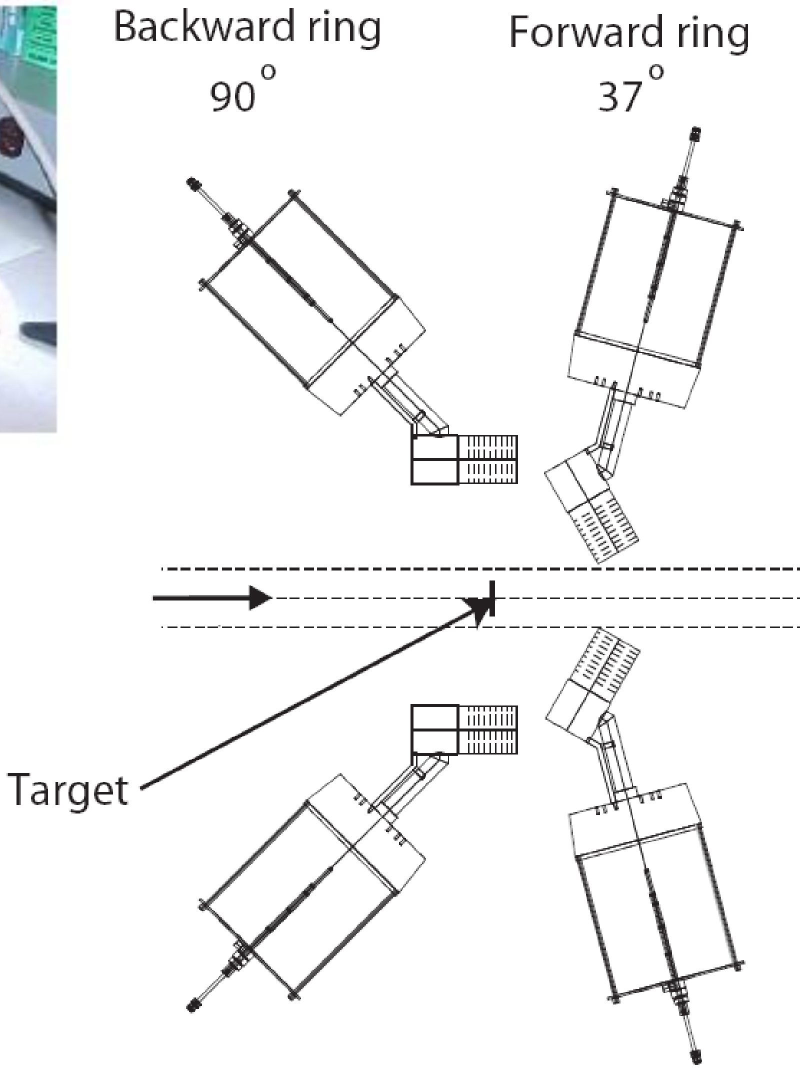
b) Energy Resolution



SEGA Array @ NSCL





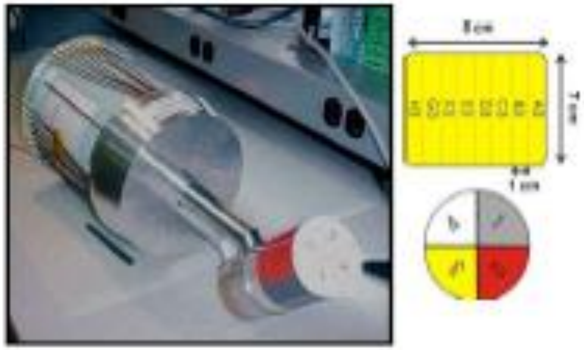


The 75% Ge Crystal has its outer electrode divided into 8 segments along the crystal axis and 4 segments perpendicular to the axis resulting in 32 fold segmentation

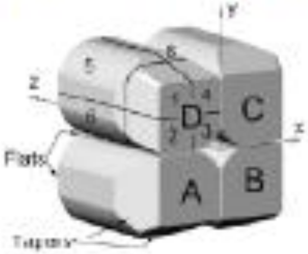
W. Mueller *et al.*, NIMA 466, 492 (2001)

Segmented Arrays:

SeGA (NSCL)

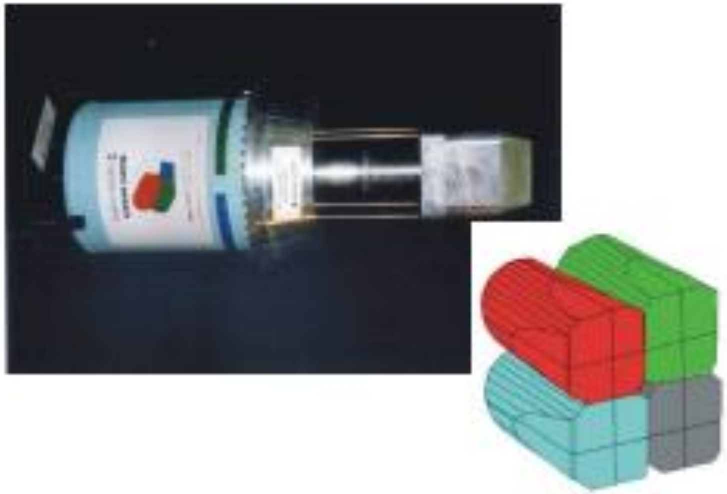


TIGRESS (TRIUMF)

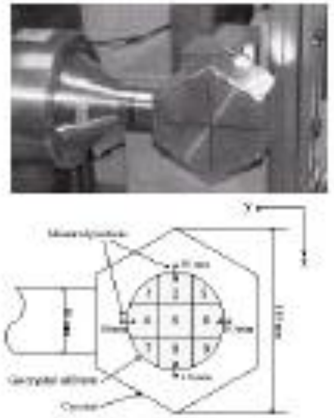


MINIBALL (CERN)

EXOGAM (GANIL)

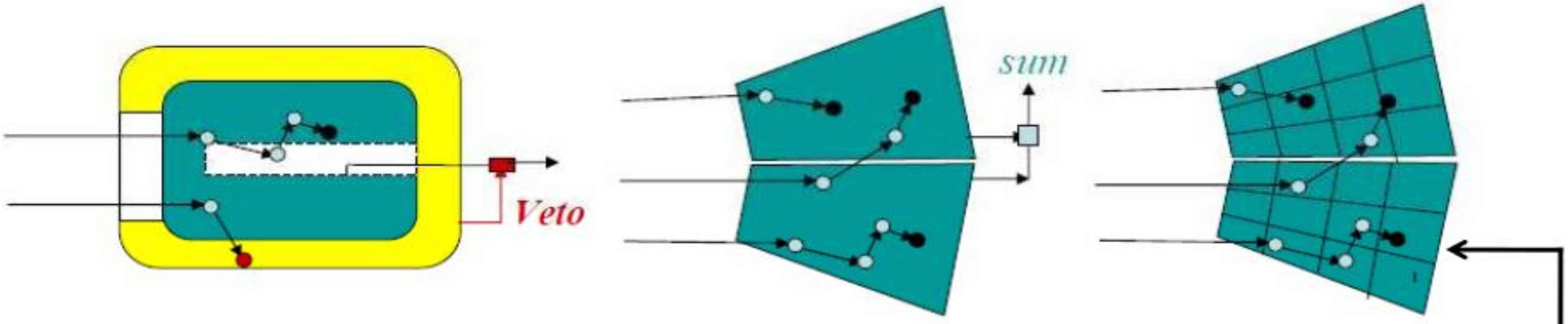


GRAPE (RIKEN)



Gamma-Ray Spectroscopy: The New Frontier

- Compton Suppressed Ge
- Ge Sphere
- Gamma Ray Tracking

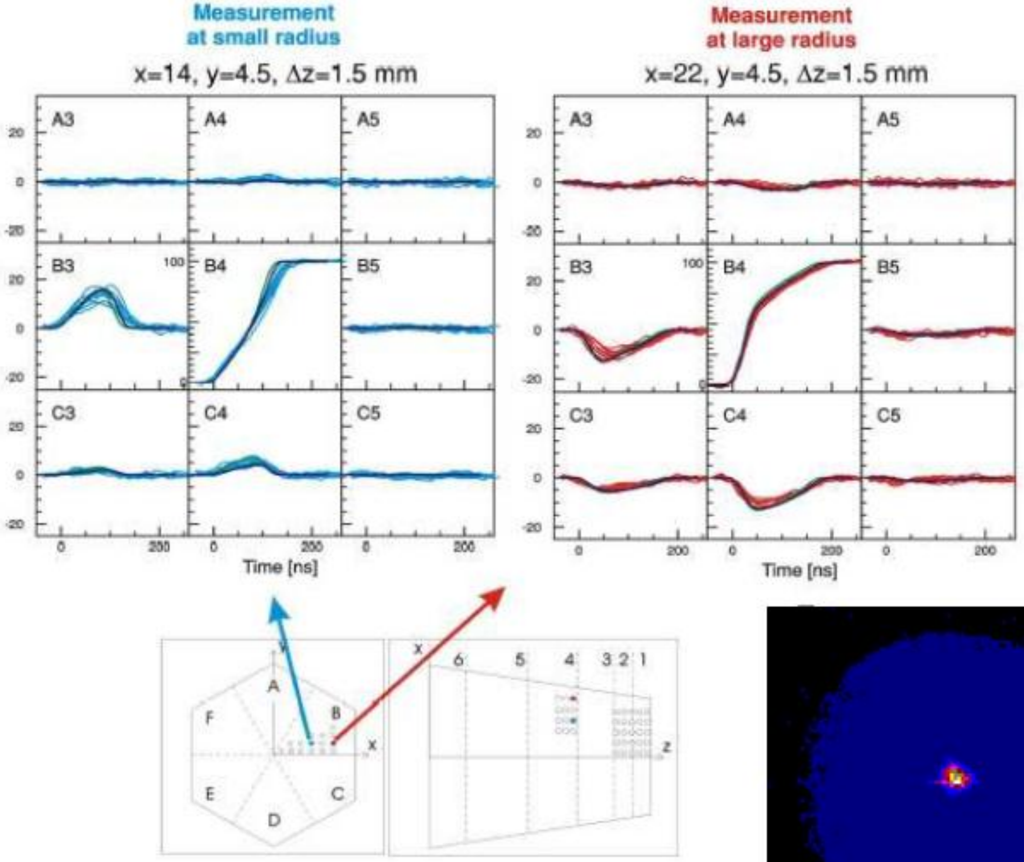


$N = 100$
$N\Omega\,\varepsilon = 0.1$
Efficiency limited

$N = 1000$ (summing)
$N\Omega\,\varepsilon = 0.6$
Too many detectors

$N = 100$
$N\Omega\,\varepsilon = 0.6$
Segmentation

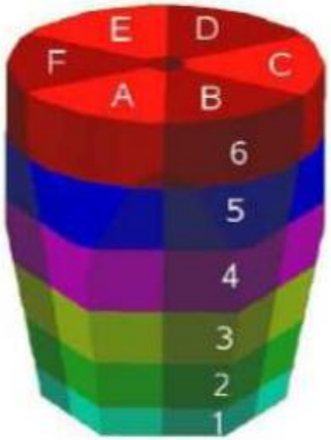
Beyond Segmentation: Gamma-Ray Tracking



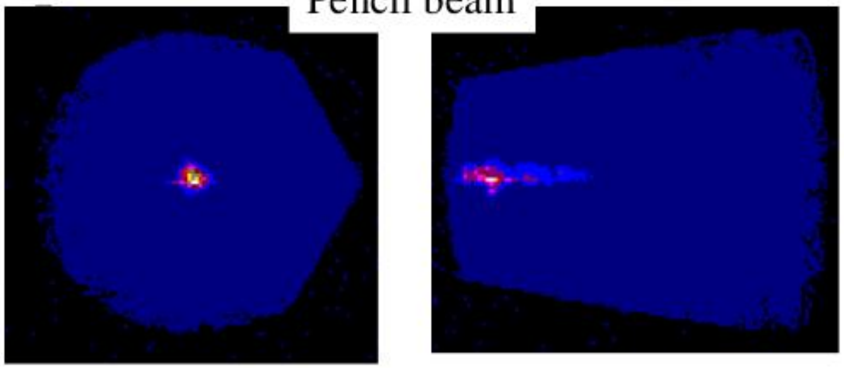
K. Vetter et al., NIM A452 (2000) 223-

Capable to resolve multiple interaction points (E_x,x_x,y_x,z_x) in crystal!!

36 segments



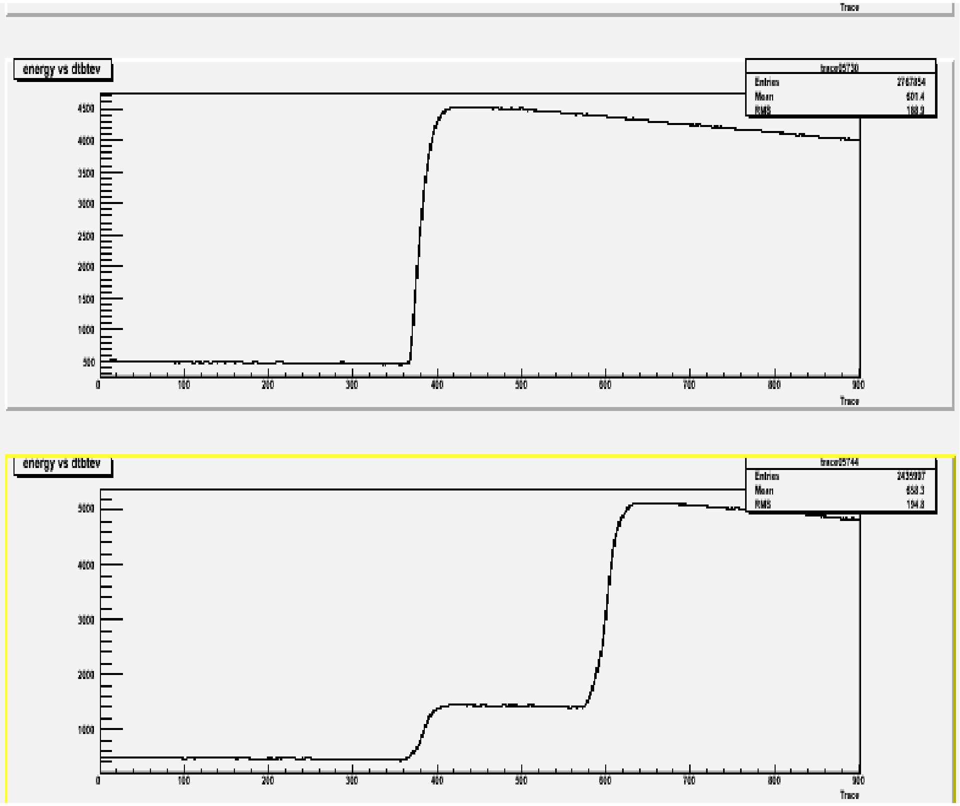
Pencil beam



Position resolution better then 2mm (rms)!

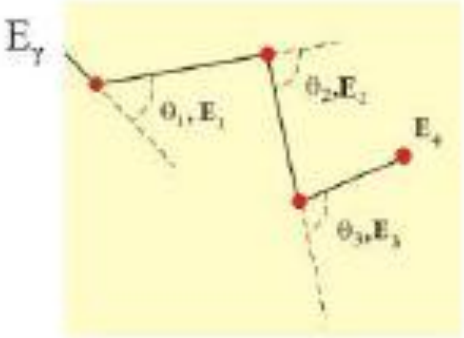
Waveforms Captured by Digitizers

GRETINA Digitizer



Measured Waveforms

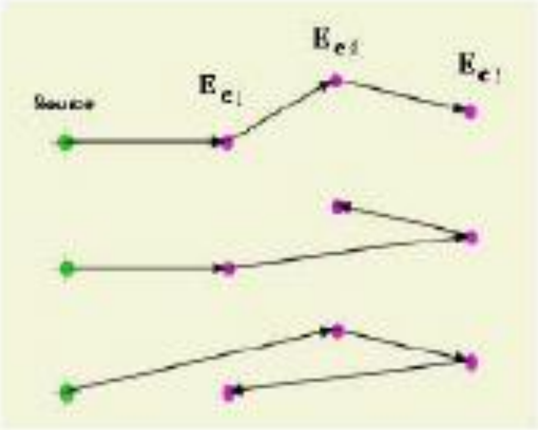
Reconstruct Gamma-rays via Tracking

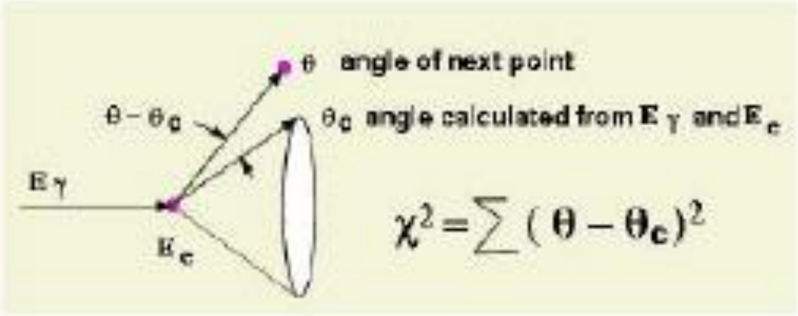


$$E_e = E_\gamma \left(1 - \frac{1}{1 + \frac{E_\gamma}{0.511}(1 - \cos\theta)} \right)$$

Problem: 3!=6 possible sequences

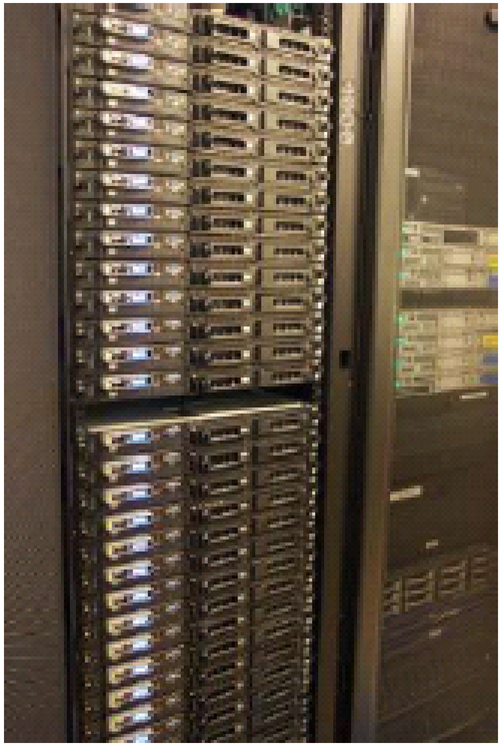
Assume: $E_\gamma = E_{e1} + E_{e2} + E_{e3}$: γ-ray from the source



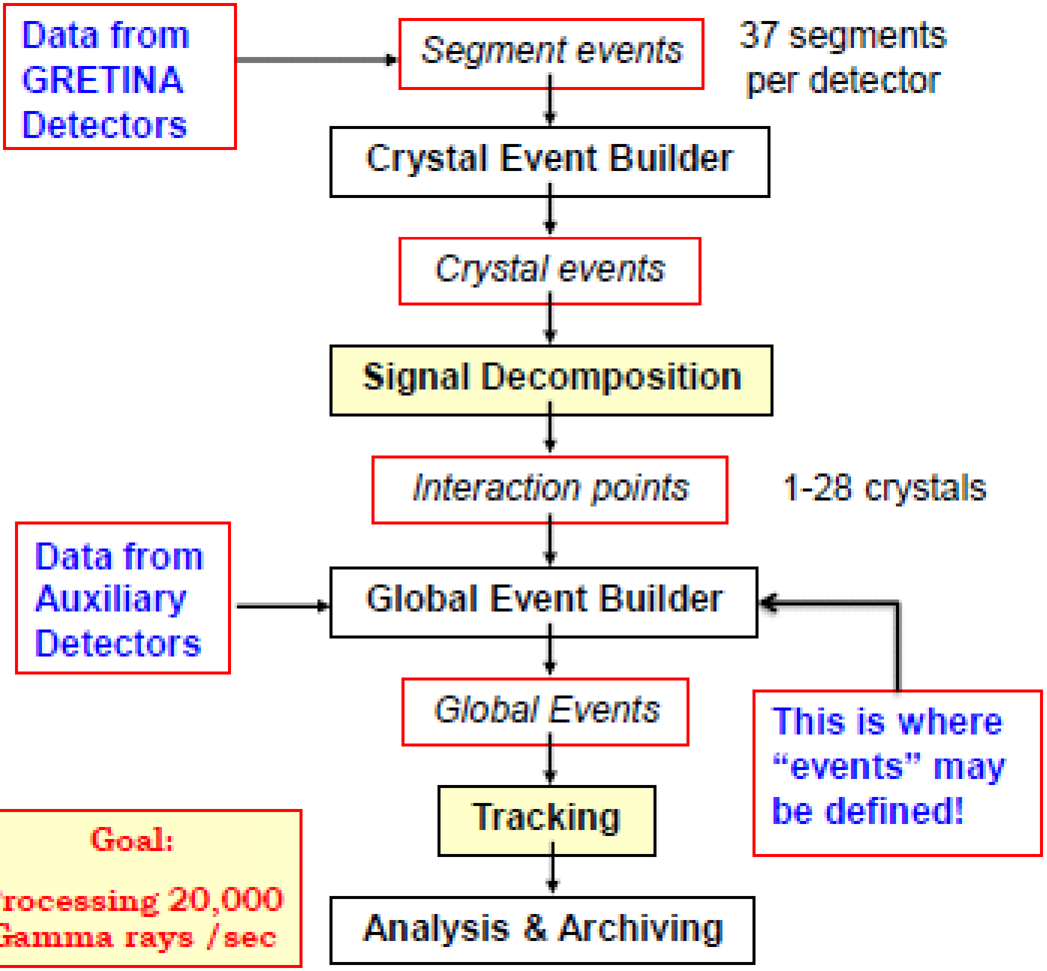


Sequence with the minimum $\chi^2 < \chi^2_{max}$
➔correct scattering sequence
➔rejects Compton and wrong direction

How this works in practice



70 nodes
2 cpu / node
4 core / cpu



Data from GRETINA Detectors

Segment events

37 segments per detector

Crystal Event Builder

Crystal events

Signal Decomposition

Interaction points

1-28 crystals

Data from Auxiliary Detectors

Global Event Builder

Global Events

This is where "events" may be defined!

Tracking

Analysis & Archiving

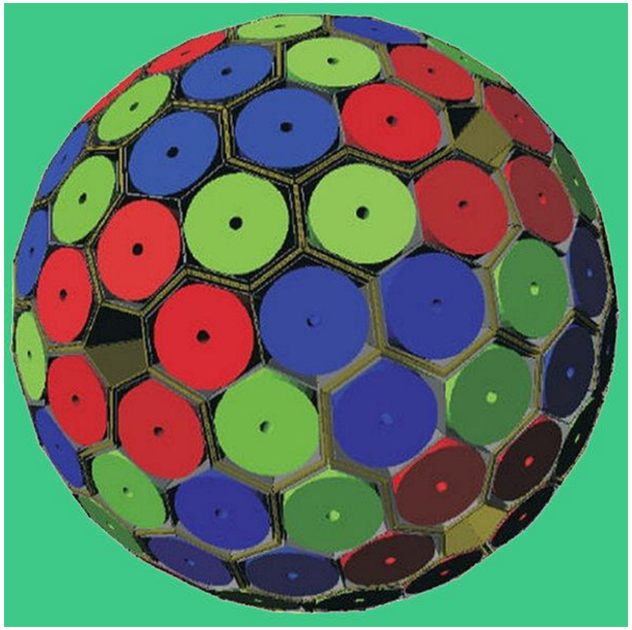
Goal:

Processing 20,000 Gamma rays / sec

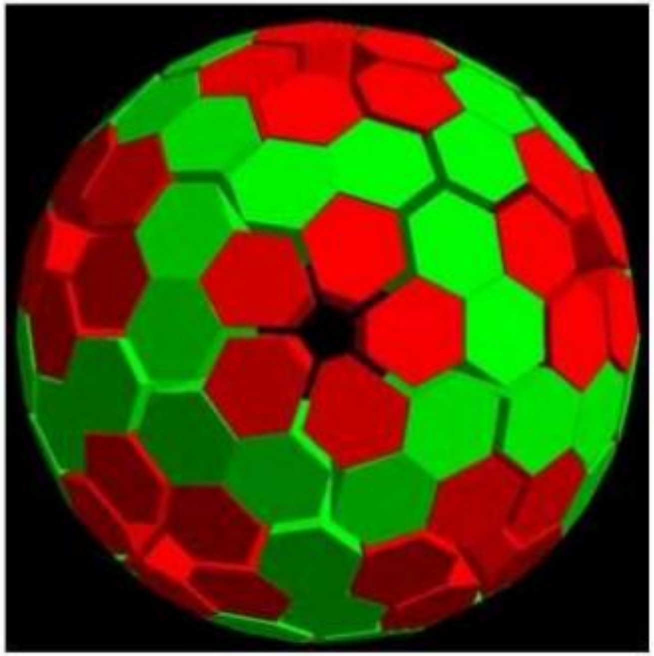
AGATA (Europe) and GRETA (US)

These tracking detectors

- Increase Ge efficiency by eliminating Compton shields
- Recover good P/T utilizing gamma-ray tracking
- Use position sensitivity for better Doppler reconstruction

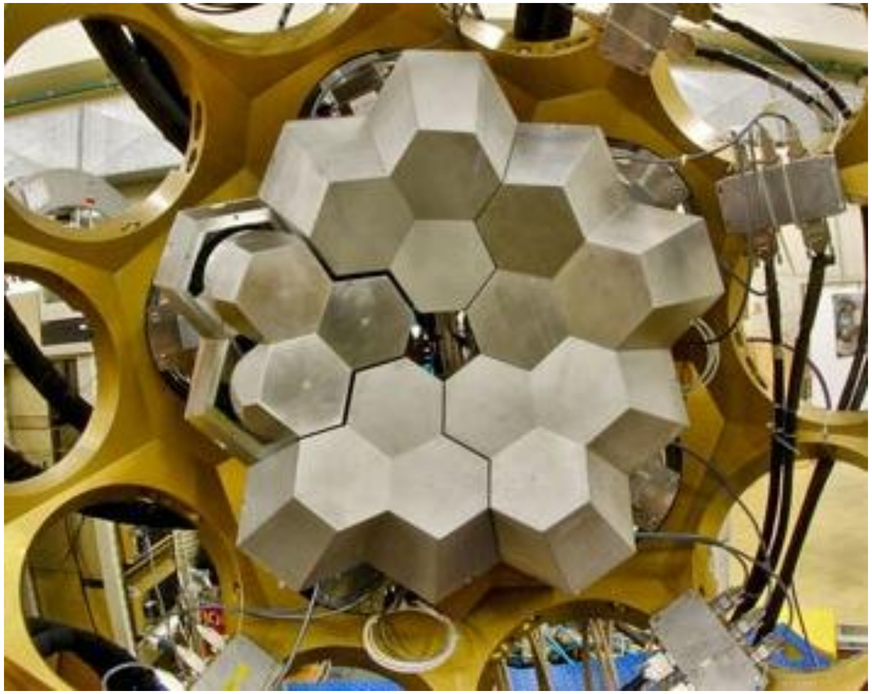


- 180 hexagonal Ge crystals
- 3 different shapes
- 3 crystals/cryostat

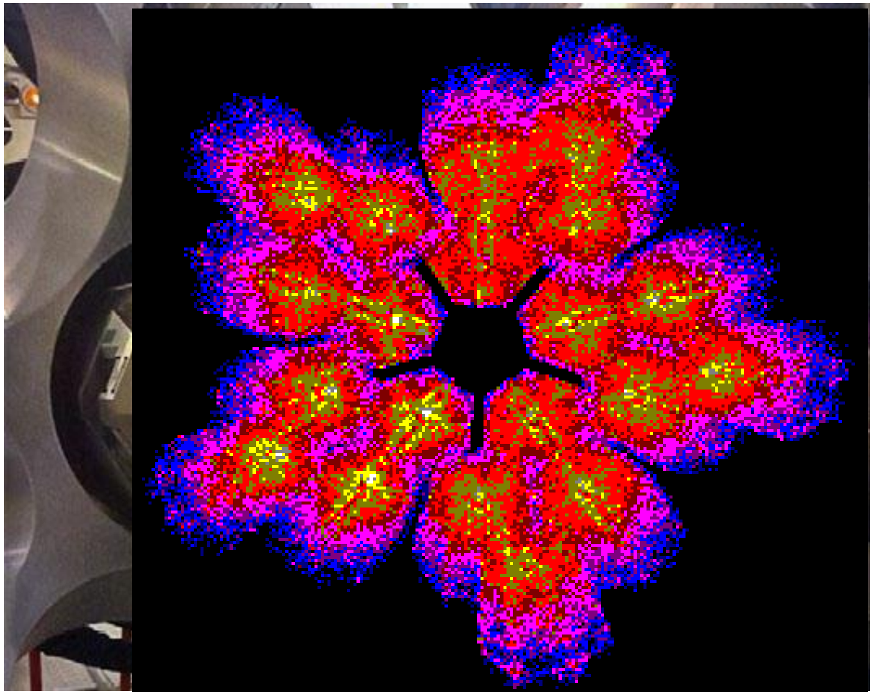


- 120 hexagonal Ge crystals
- 2 different shapes
- 4 crystals/cryostat

The First Steps to AGATA and GRETA

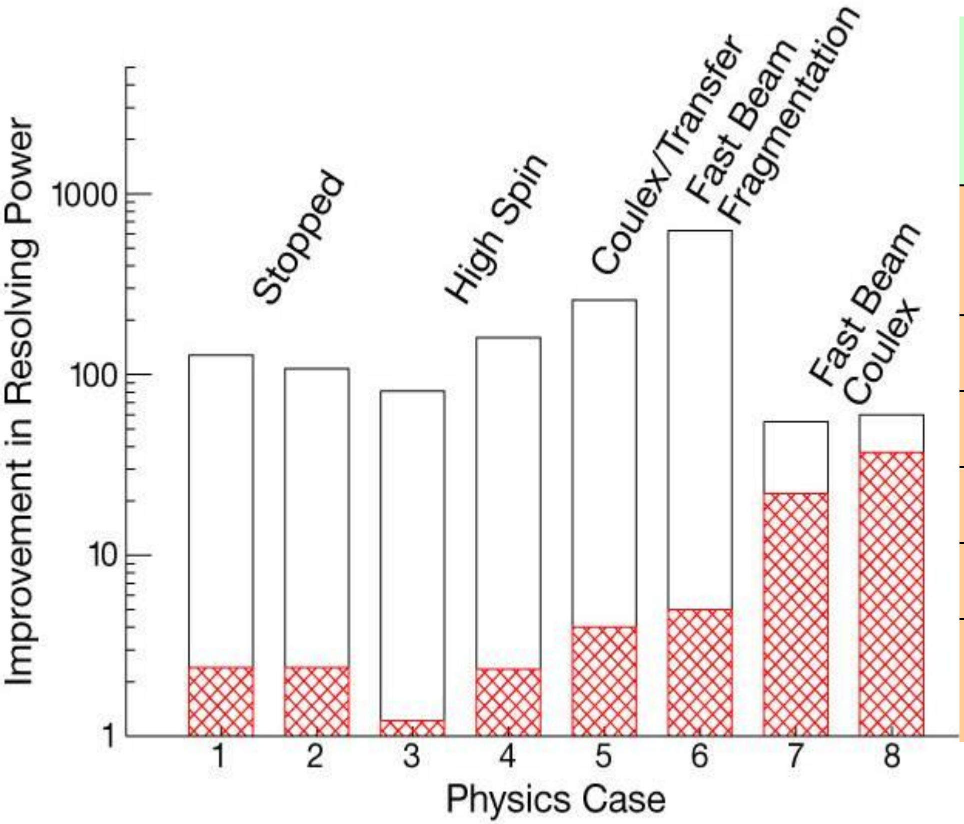


AGATA Demonstrator



GRETINA

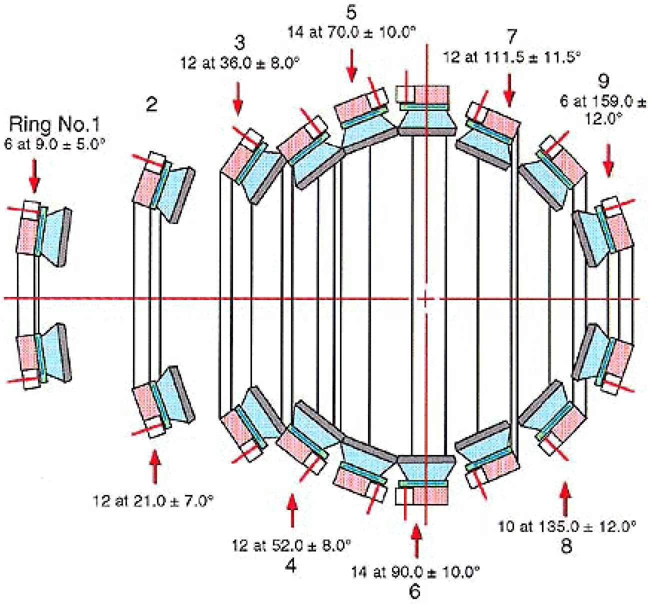
Performance: Gretina/Greta vs Gammasphere or SeGA



Experimental Technique or Reaction Type	$\langle E_\gamma \rangle$ MeV	v/c	M_γ
1. Stopped - Hi E_γ	5.0	0.0	4
2. Stopped - Low E_γ	1.5	0.0	4
3. Hi-spin - Normal Kinematics	1.0	0.04	20
4. Hi-spin - Inverse Kinematics	1.0	0.07	20
5. Coulex/Transfer	1.5	0.1	15
6. Fast Beam Fragmentation	1.5	0.5	6
7. Fast Beam Coulex - Hi E_γ	5.0	0.5	2
8. Fast Beam Coulex - Low E_γ	1.5	0.5	2

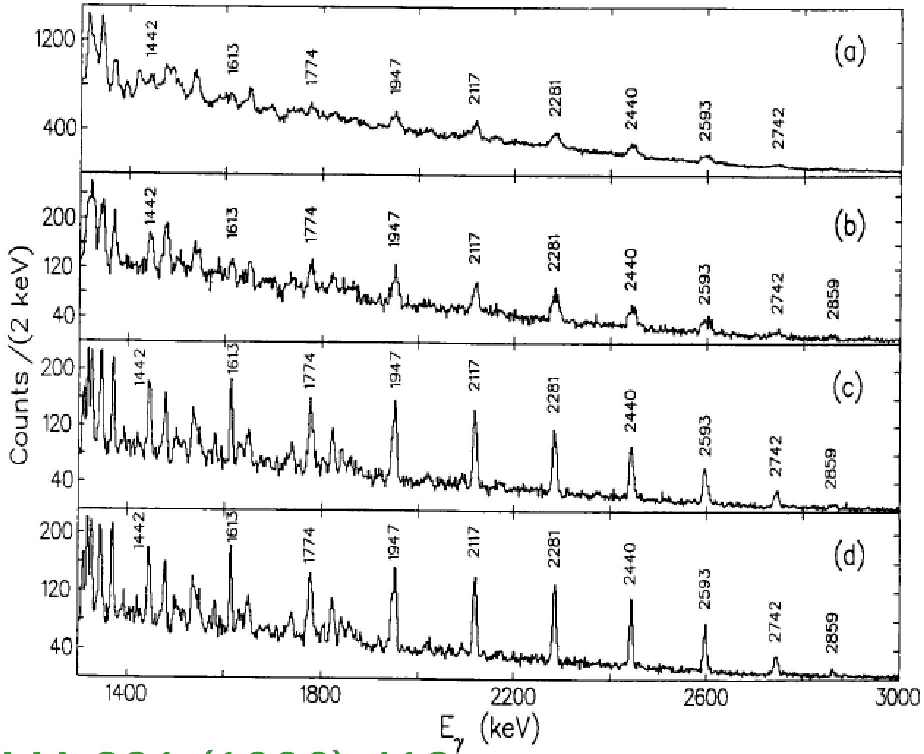
Ancillary Devices with Gamma-Ray Arrays

Gammasphere + microball (Washington U.)



The *microball* is a 96 element CsI(Tl) array for the detection of charged particles evaporated heavy-ion fusion reactions.

^{58}Ni(^{28}Si,α2p)^{80}Sr @ 130 MeV



a) Gammasphere alone
b) 2p,α gated with microball
c) Doppler corrected by recoil direction.
d) Dopper corrected by state lifetime

D. G. Sarantites *et al.*, NIMA 381 (1996) 418.

Recoil (Mass) Separators

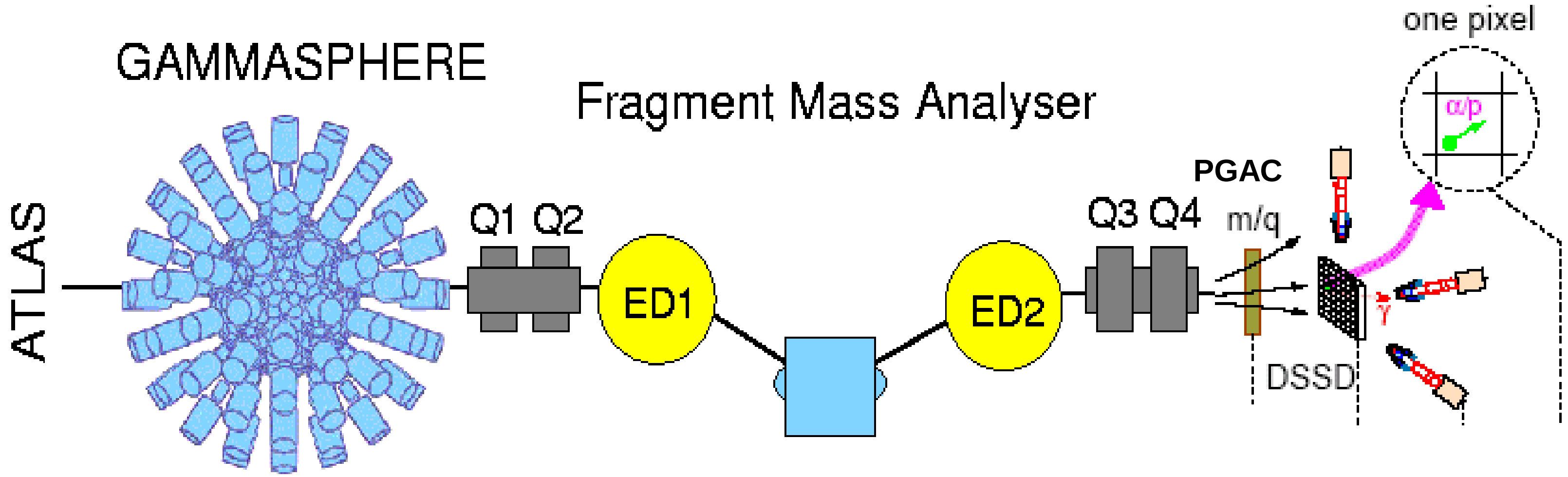
Gas Filled

- Pros: High Efficiency
- Cons: No Mass Resolution
- Examples: RITU (Jyvaskyla), BGS (Berkeley)

Vacuum

- Pros: Mass Resolution
- Conn: Low Efficiency
- Examples: FMA (Argonne), RMS (Oak Ridge)

Using Fragment Mass Analyzer (FMA) for High Spin Studies



- Separates ions produced at the target position as a function of M/q at the focal plane.
- 8.9 meters long with a +/- 20% energy acceptance.
- Mass resolution is ~ 350:1.
- Multiple detector configurations at focal plane.

High Spin Studies of Heavy Nuclei with Z>100

Reaction:

^{48}Ca + ^{208}Pb

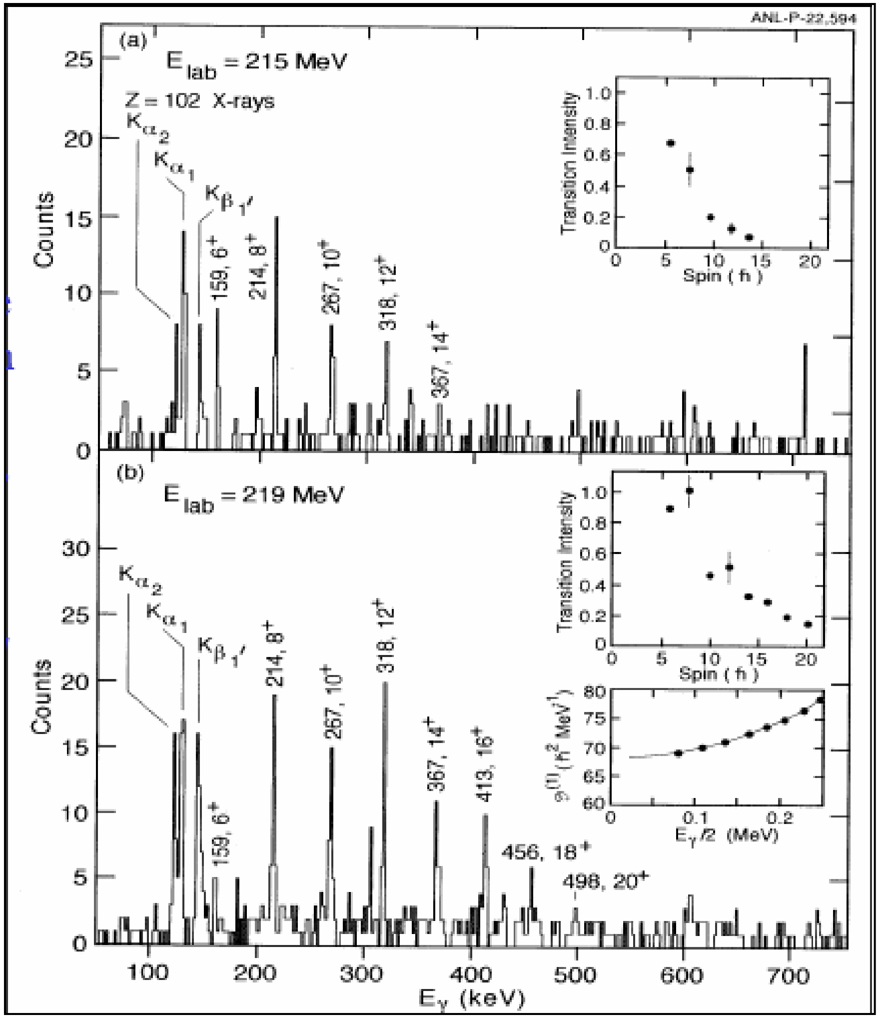
^{254}No σ ~ 3μb

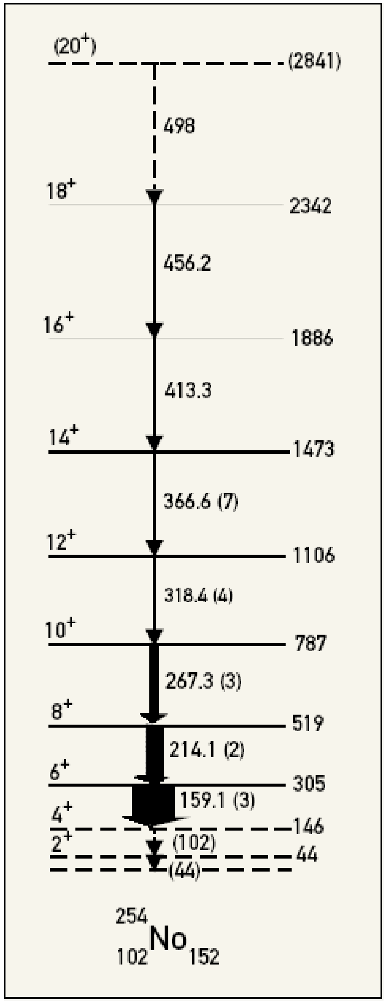
Gammasphere

+

FMA

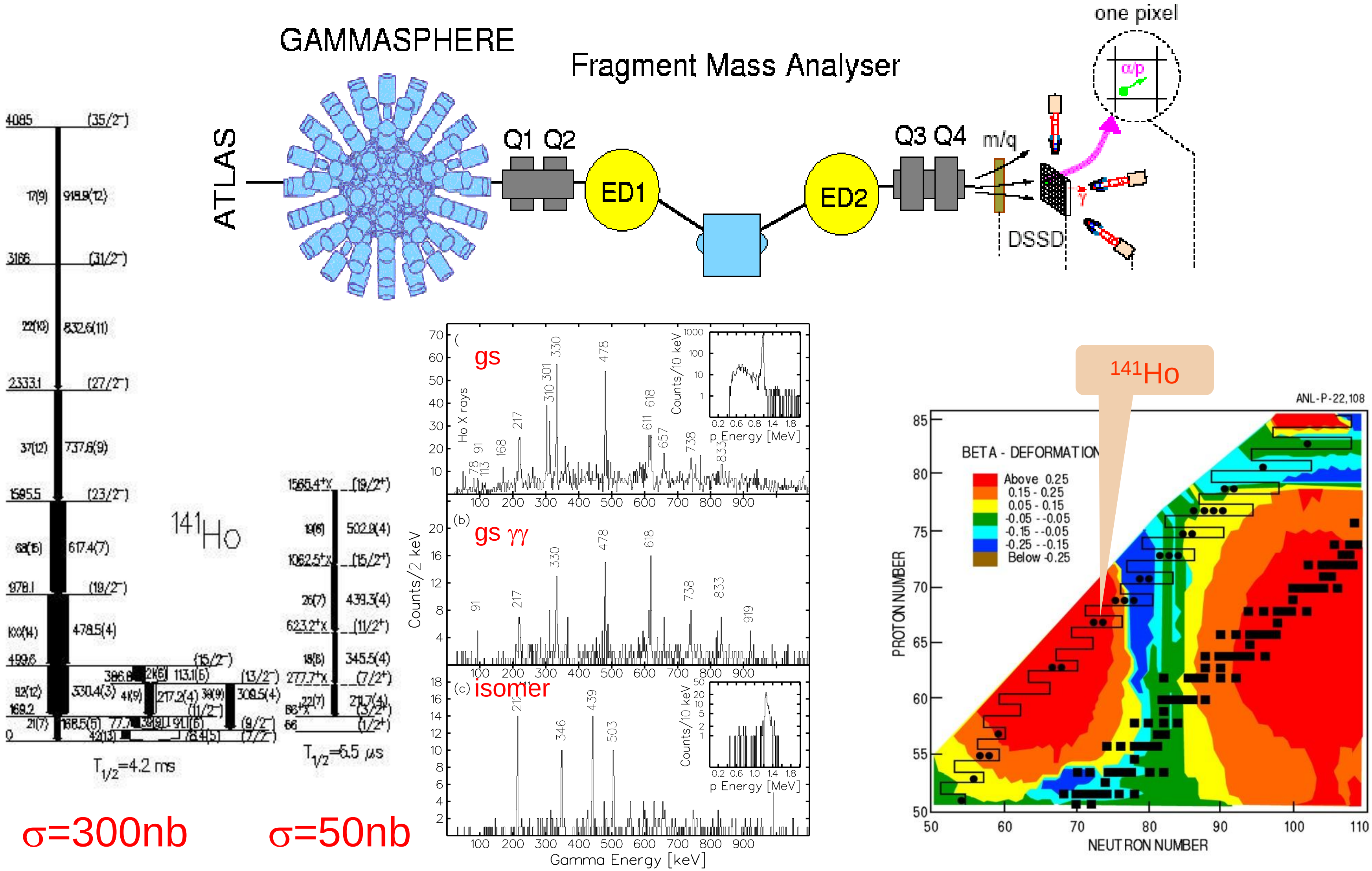
These studies are better suited with a Gas-Filled Separator with larger efficiency (RITU, BGS)





. Reiter *et al*., Phys. Rev. Lett. 82 (1999) 509

Recoil Decay Tagging (Isotopic Identification)



D. Seweryniak *et al*., PRL 86 (2001) 1458.

End of Day 1