Study of high-spin states by using stable and unstable nuclear beams

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- Introduction of high-spin studies
- Stable nuclear beam experiments

  Study of superdeformation and beyond

  = Limit of high-spin, deformation

  Gamma-ray spectroscopy near ^{100}Sn

  = Limit of proton-rich study
- Unstable nuclear beam experiments

  In-beam gamma-ray spectroscopy
- Future prospects

Introduction

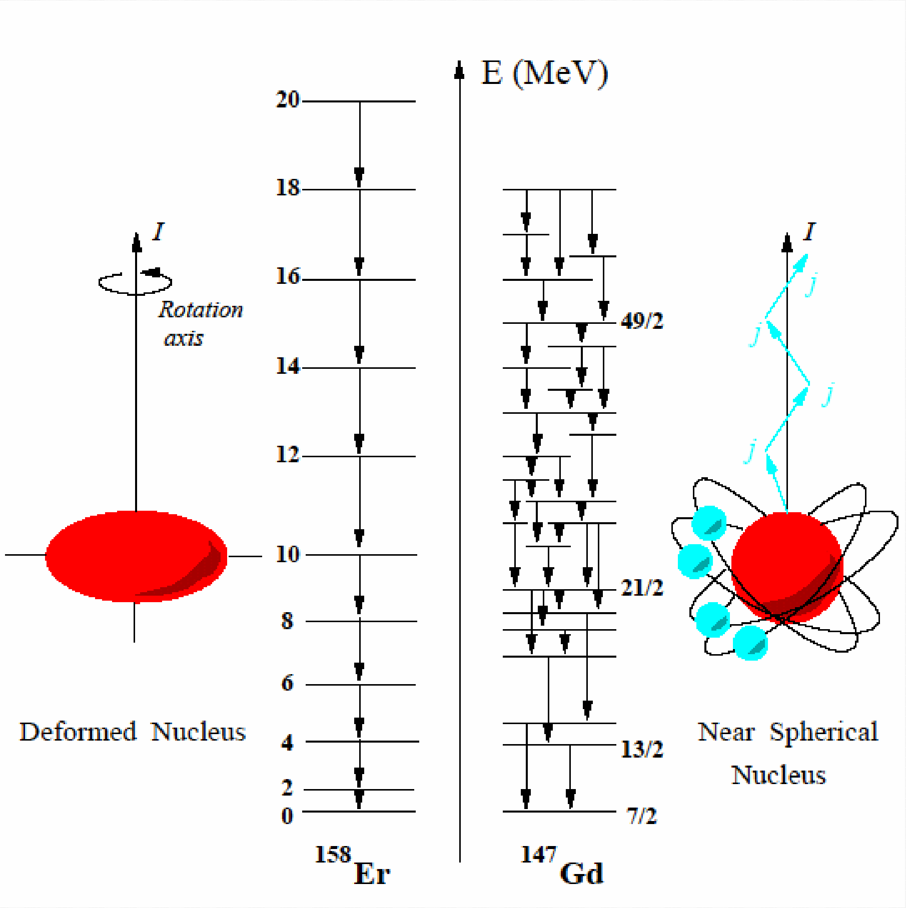
Change of nuclear structure in the excited state

as a function of angular momentum

High-spin states

Two basic aspects of nuclear motion

1. Single-particle motion
   → Shell model
2. Collective motion
   → Liquid drop model



Nuclei at the limits

- Limit of angular momentum

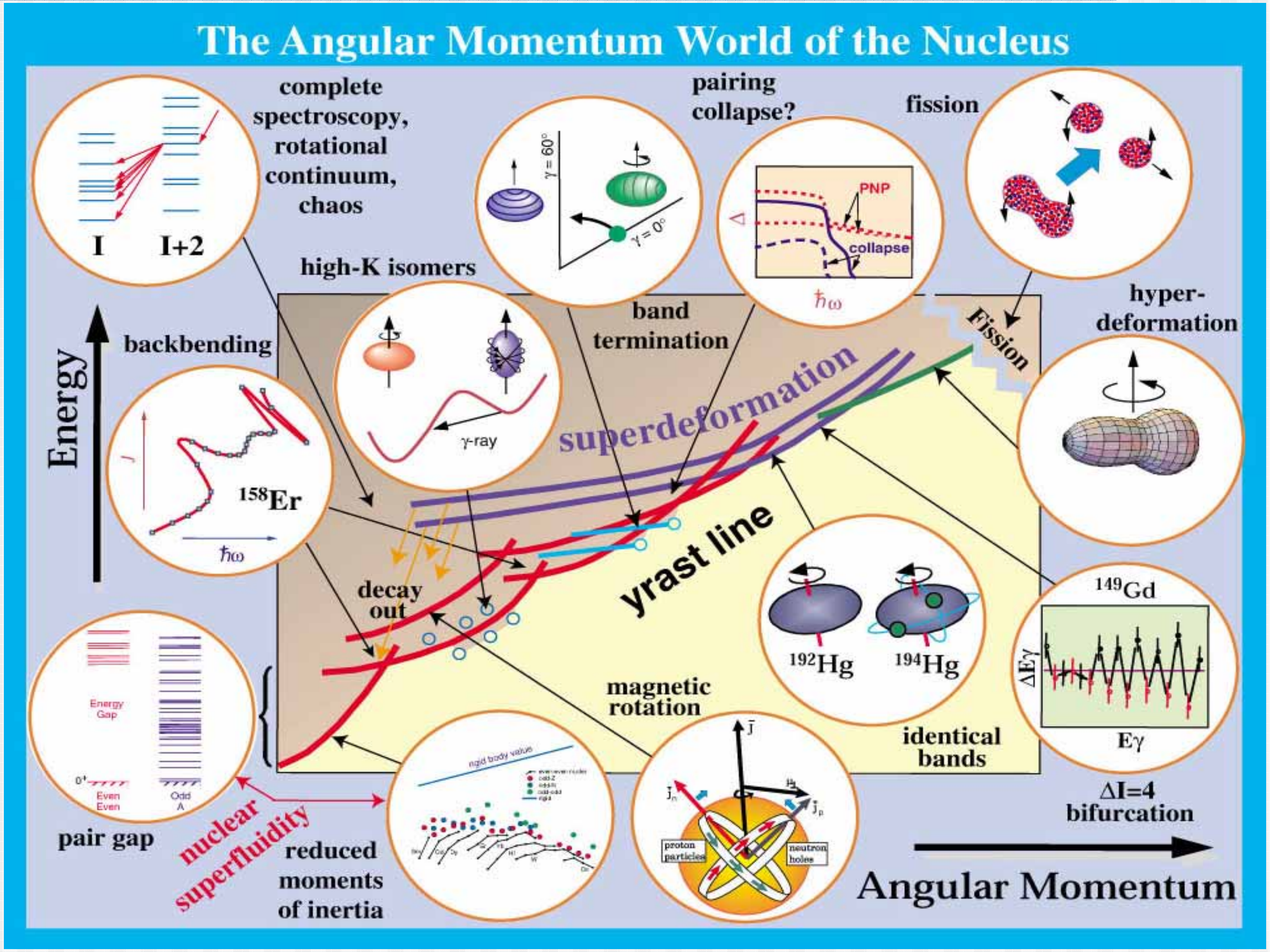
  The question of the maximal angular momentum that a nucleus is able to sustain against rotation is an old and still unsolved problem

- Limit of deformation

  superdeformation, hyperdeformation

- Limit of isospin (proton-rich)

Behavior of nucleus at high-spin



http://nucalf.physics.fsu.edu/~riley/gamma/

Limits of angular momentum and band termination

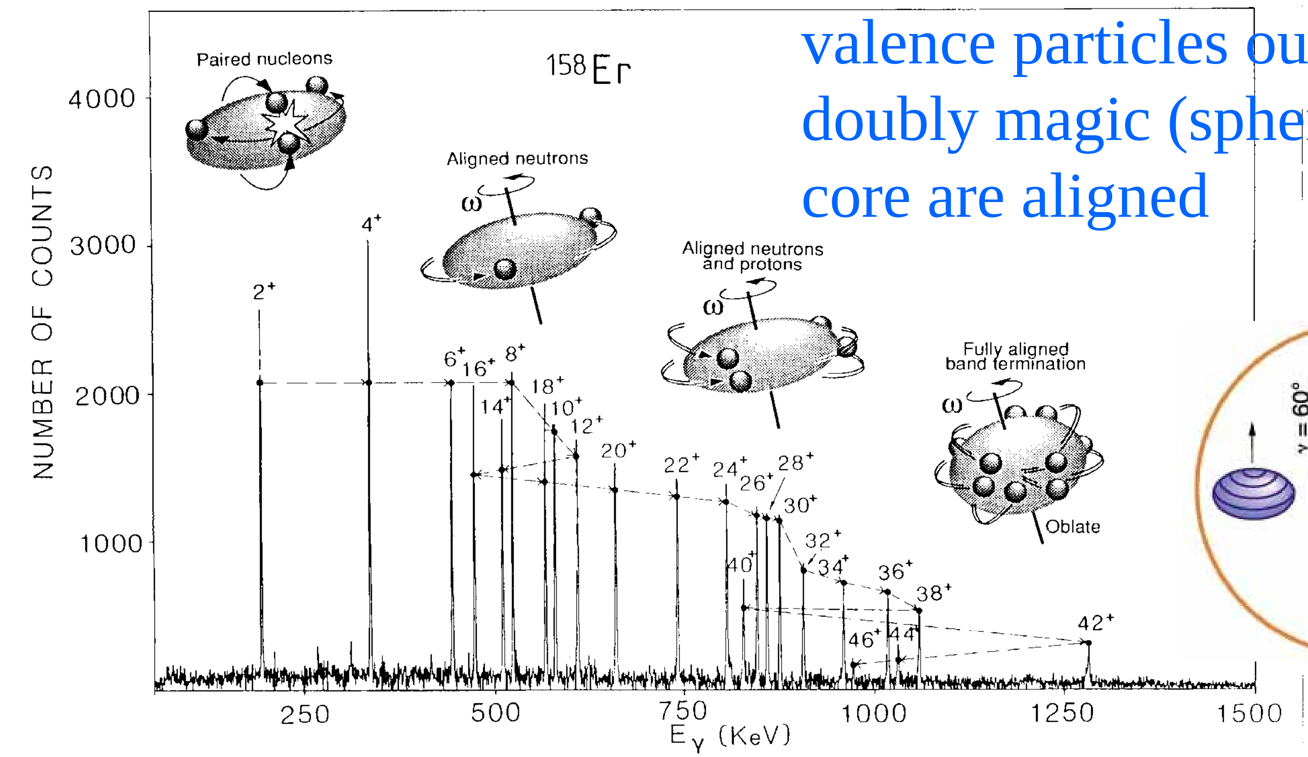
- Nuclear angular momentum is generated by the finite number of constituent nucleons
- Maximum number of angular momentum for a given nucleus with specific configuration
- This is seen as termination of a rotational band in nuclei when the nuclear angular momentum is generated entirely from constituent of nucleons rather than collective excitation

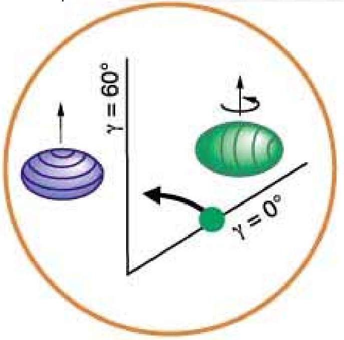
Yrast band of ^{158}Er

High-spin of deformed nucleus

Simpson et al., Phys. Rev. Lett. 53(1984)648

A band terminates when all valence particles outside a doubly magic (spherical) core are aligned





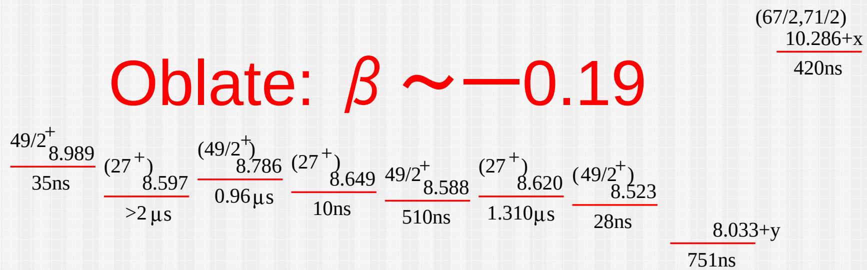
Prolate → Oblate

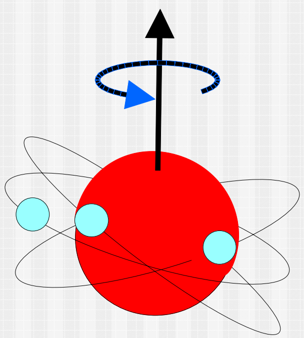
Yrast: lowest energy at given angular momentum

High-spin isomer (oblate shape)

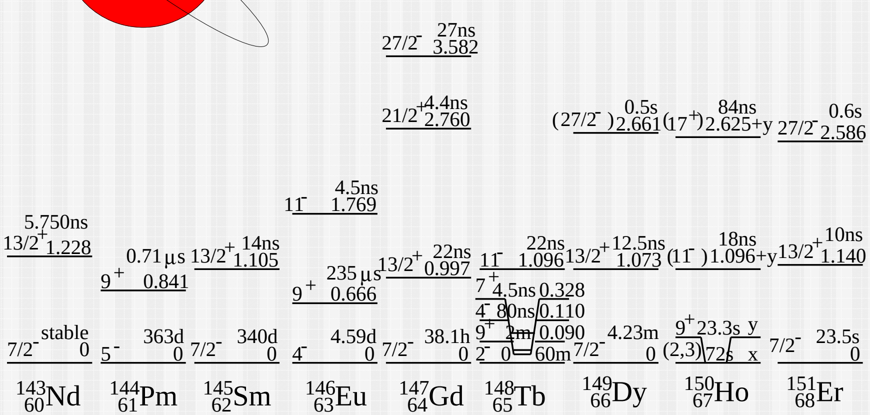
High-spin states of spherical nucleus

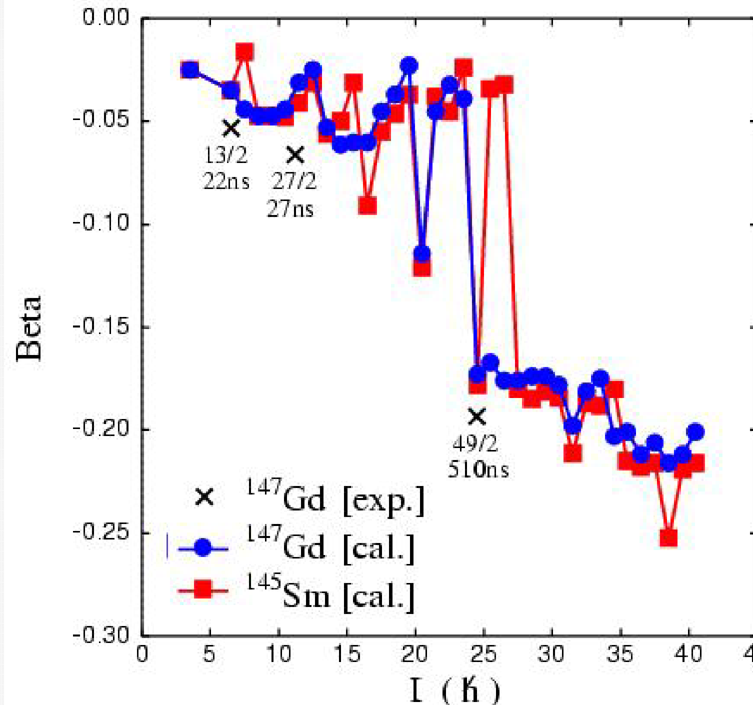
Oblate: $\beta \sim -0.19$





N=83 isotone





odd nuclei

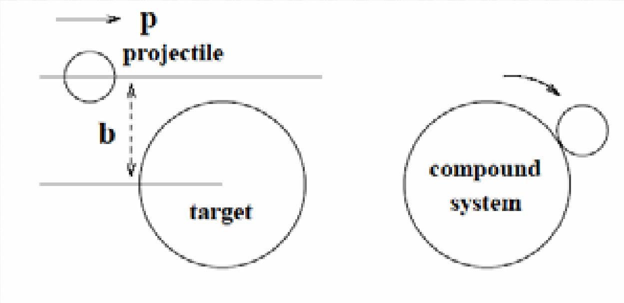
$[\nu (f_{7/2}h_{9/2}i_{13/2}) \pi h_{11/2}^{2}]_{49/2}+$

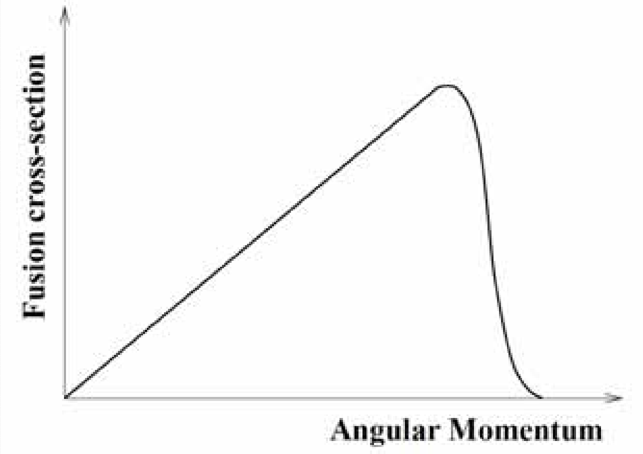
odd-odd nuclei

$[\nu (f_{7/2}h_{9/2}i_{13/2}) \pi (h_{11/2}^{2}d_{5/2})]_{27}+$

How to study high-spin states

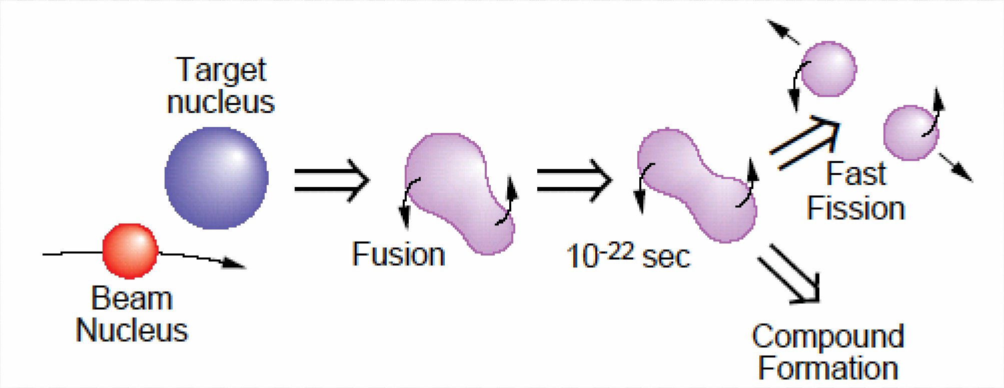
- Fusion-evaporation reaction
- Coulomb excitation
- Transfer reaction (^{18}O, ^{16}O)
- Fragmentation
- Fission
  Spontaneous: ^{238}U, $^{244,246,248}Cm$, $^{250,252}Cf$, ^{253}Es, $^{254,256}Fm$
  n-induced: $^{235}U(n,f)$
- β decay



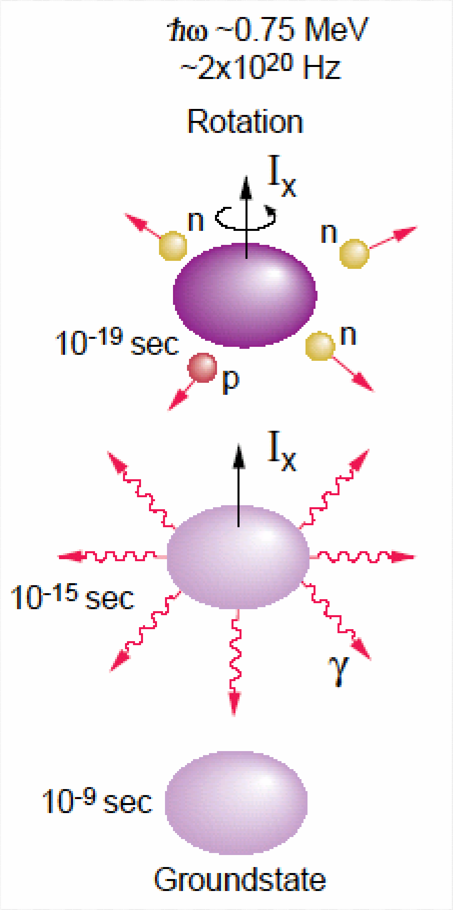


$$\ell = b \times p$$
$$d\sigma_{fus}(\ell) \propto \ell$$

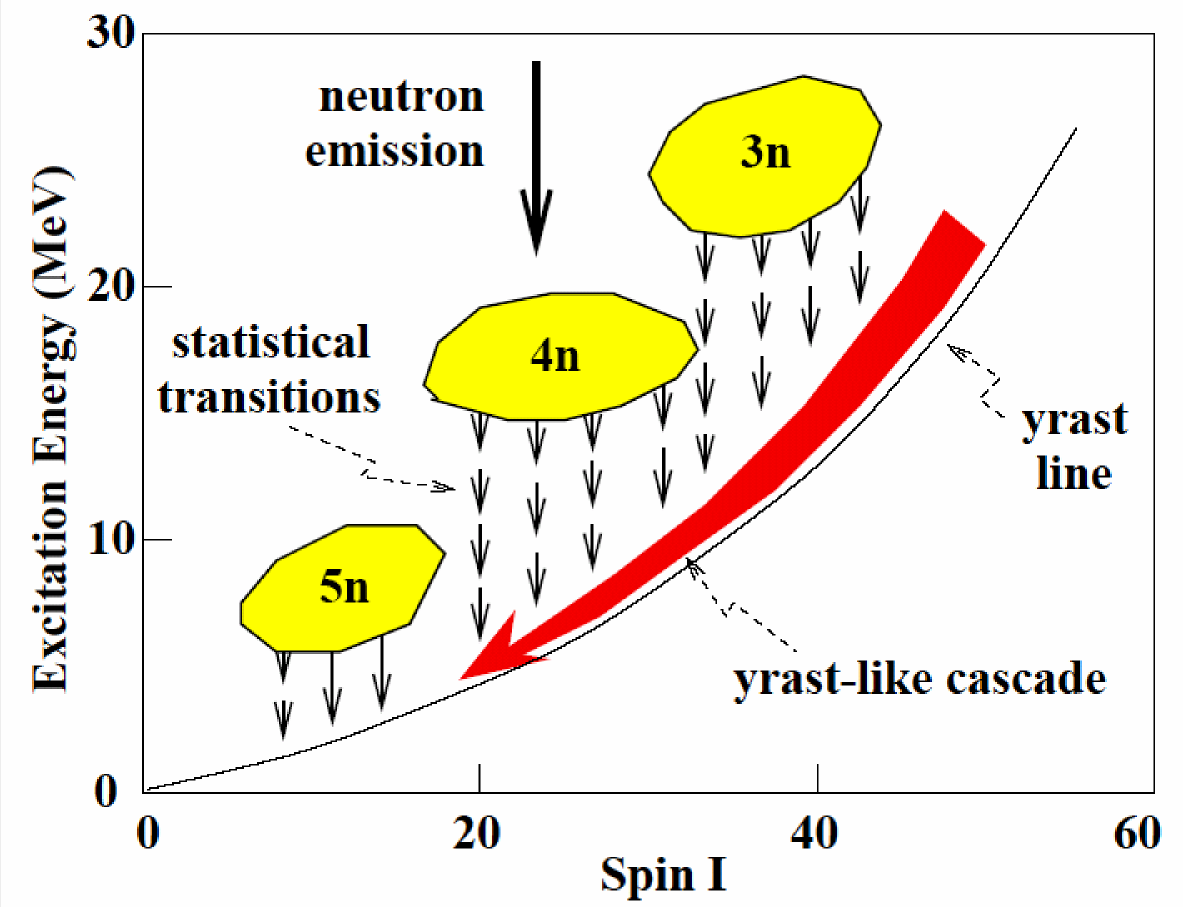
Fusion-evaporation reaction



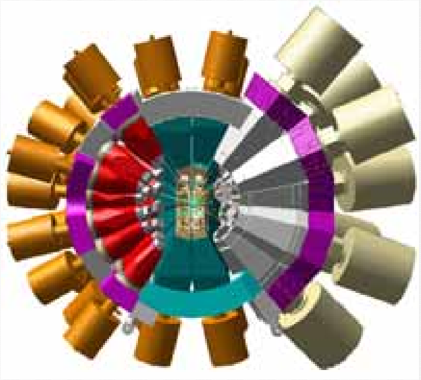
3-6MeV/A



Fusion evaporation and gamma decay



Measure Gamma decay To investigate High-spin excited states



Euroball

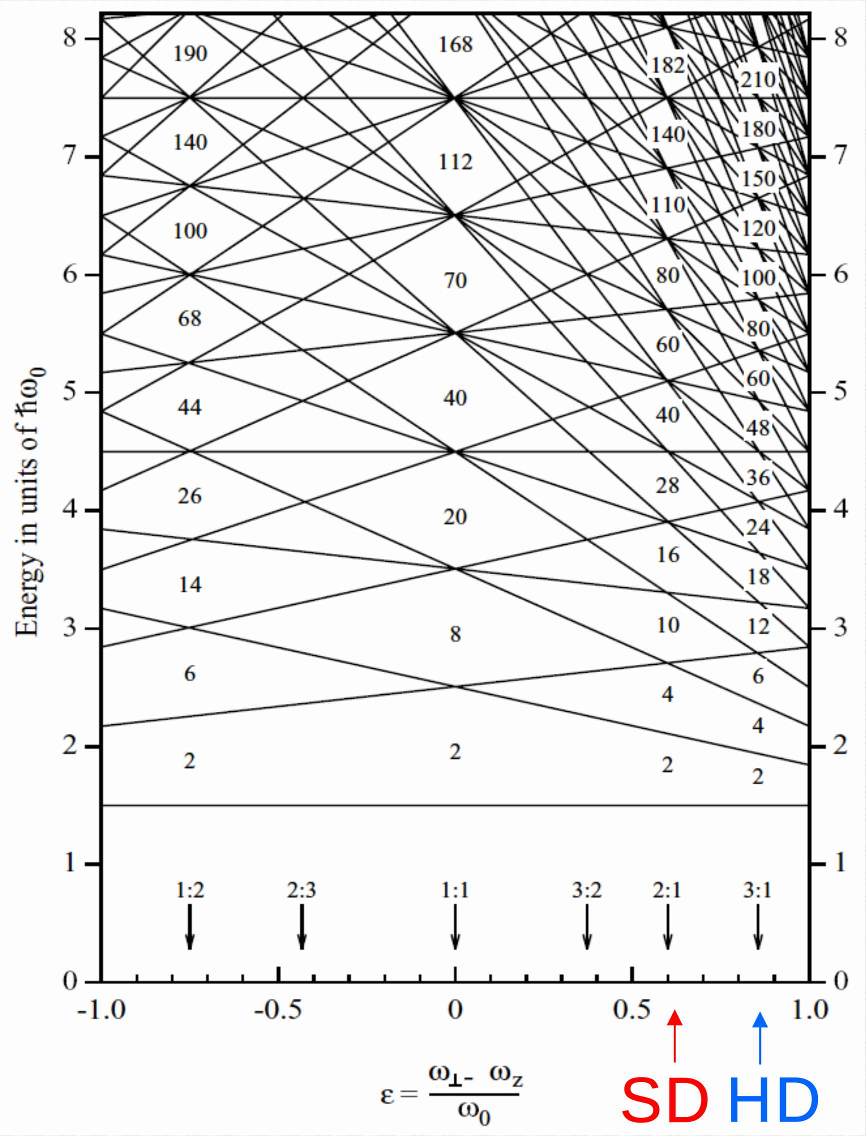
High-spin limit

- For small deformed nucleus, configurations will terminate into a non-collective oblate state where the spin is given by the sum of angular momenta of single particle configuration: I_{max}
- For large deformation (superdeformation), spin above I_{max} can be generated
- With increasing angular momentum, large deformed states (superdeformation, hyperdeformation) become yrast, and finally will decay by fission

Superdeformed shell gaps

H.O.		Realistic Potential	
140	⇔	∼146	fission isomer
110	⇔	112	A=190 (N)
80	⇔	80 ∼82	A=190 (Z)
60	⇔	∼64	A=150 (Z)
40	⇔	42	A=80
28	⇔	30	A=60
16	⇔	16	S

K.Matsuyanagi, RIKEN winter school 2002

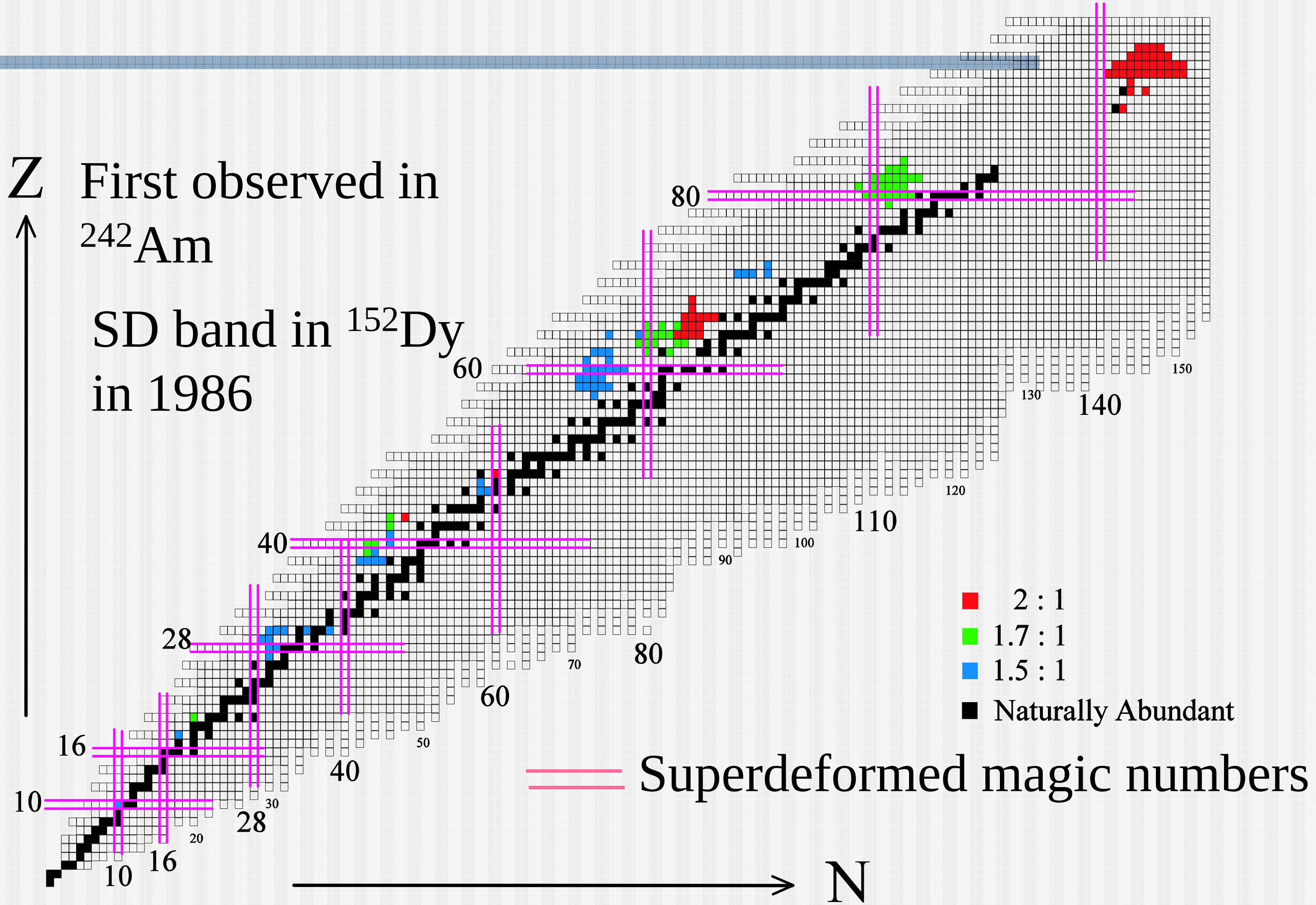


Superdeformation

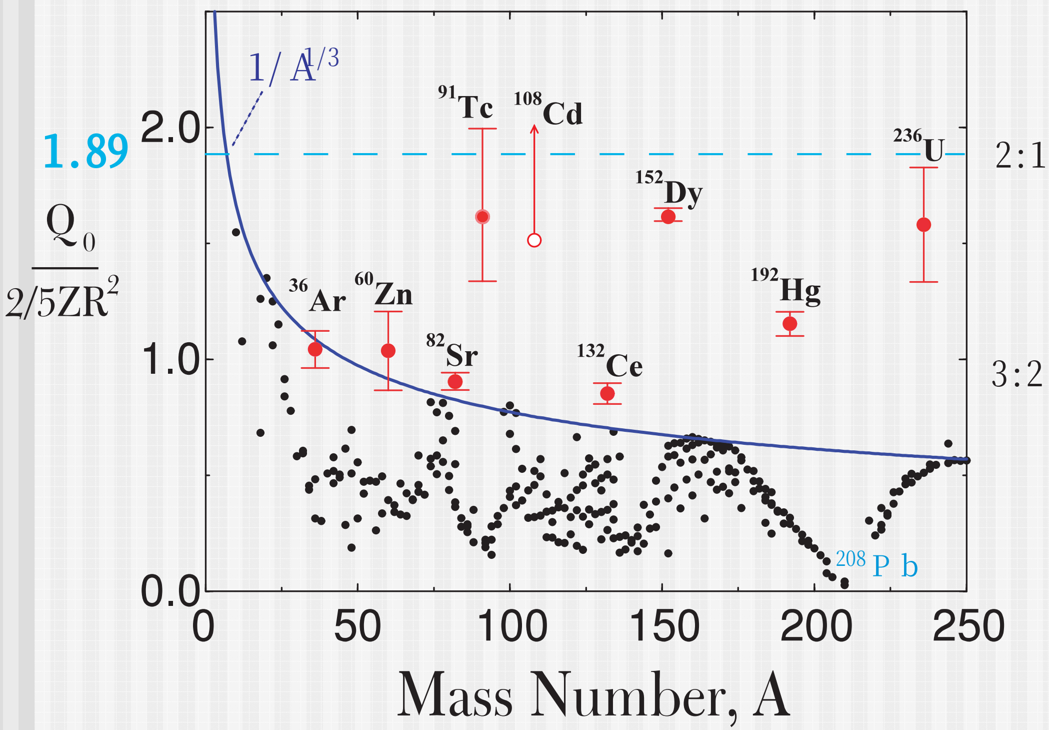
2:1

First observed in ^{242}Am

SD band in ^{152}Dy in 1986



Limit of deformation



$$Q_0 = \frac{2}{5} Z R^2 \frac{x^2 - 1}{x^{2/3}} \times 10^{-2}\, eb$$

x : major-to-minor axis ratio

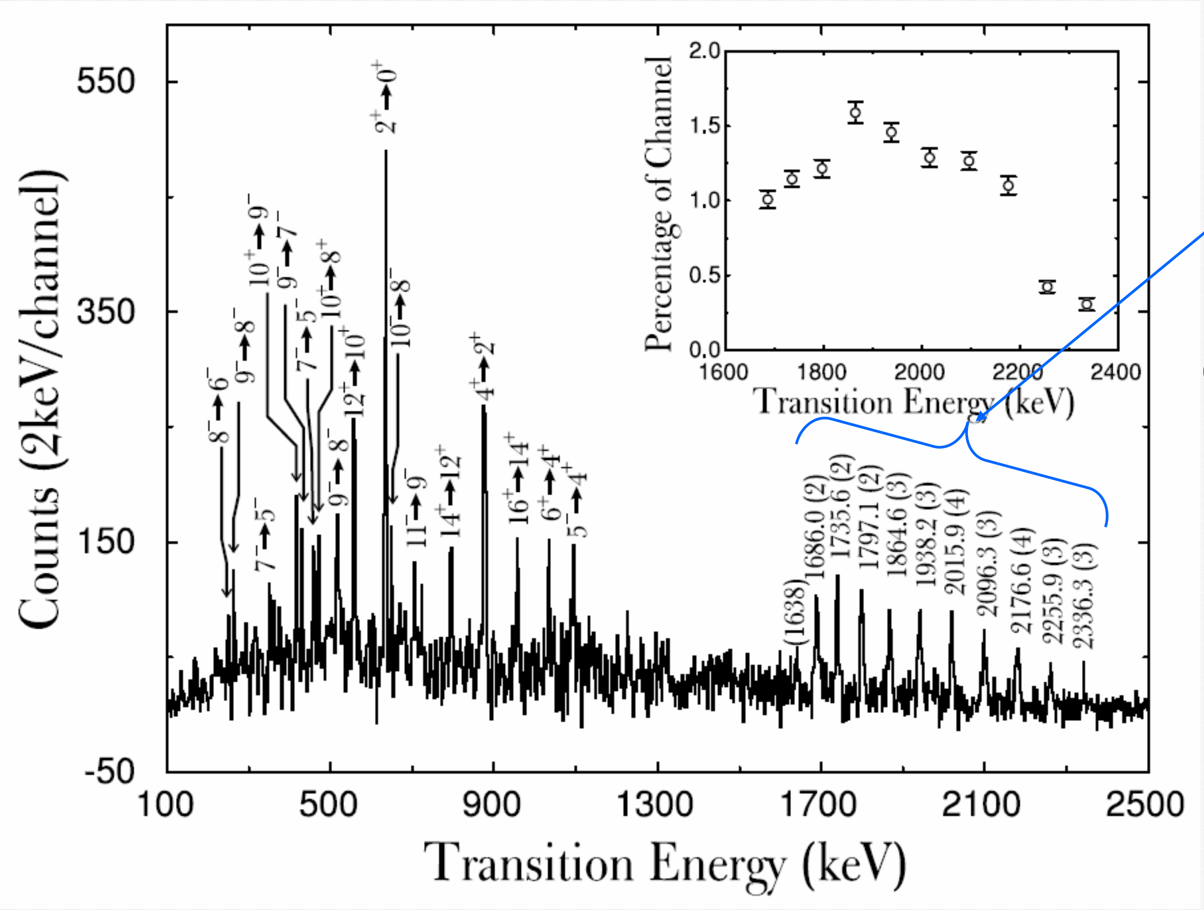
x = 2 ⟶ 2:1deformation

$$\frac{Q_0}{2/5 Z R^2} = 1.89$$

R = 1.2A$^{1/3}$ fm

R.M.Clark et al., Phys. Rev. Lett. 87, 202502 (2001)

SD band in ^{108}Cd

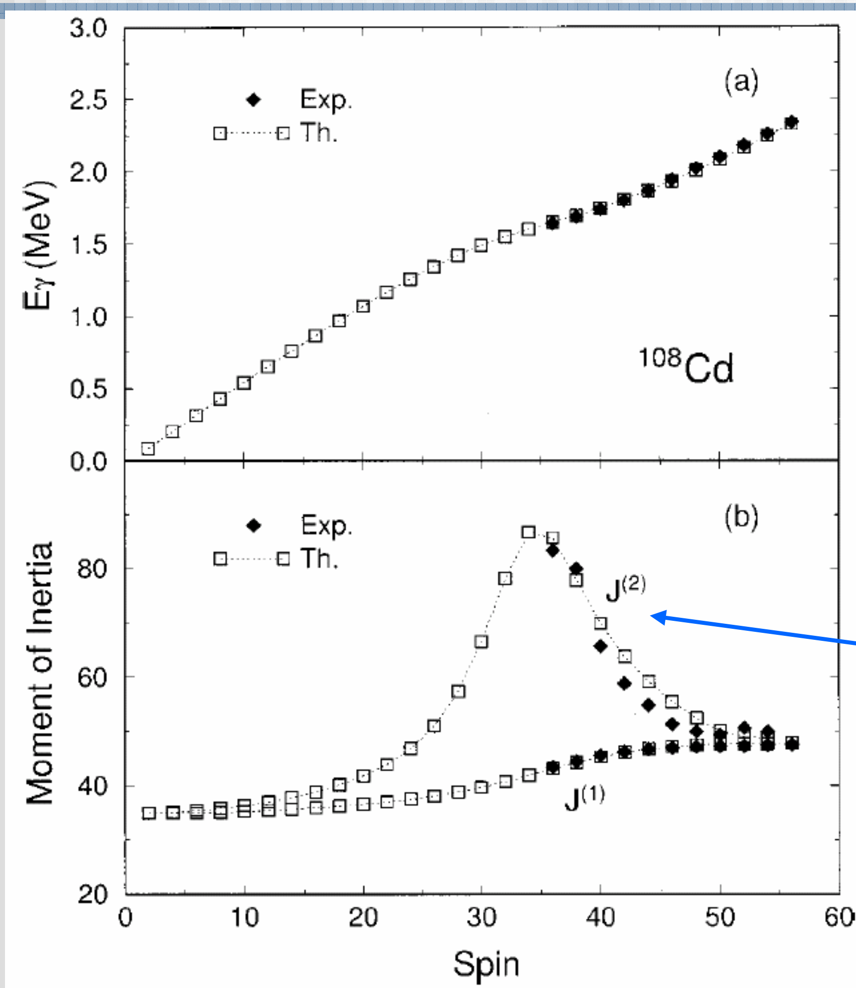


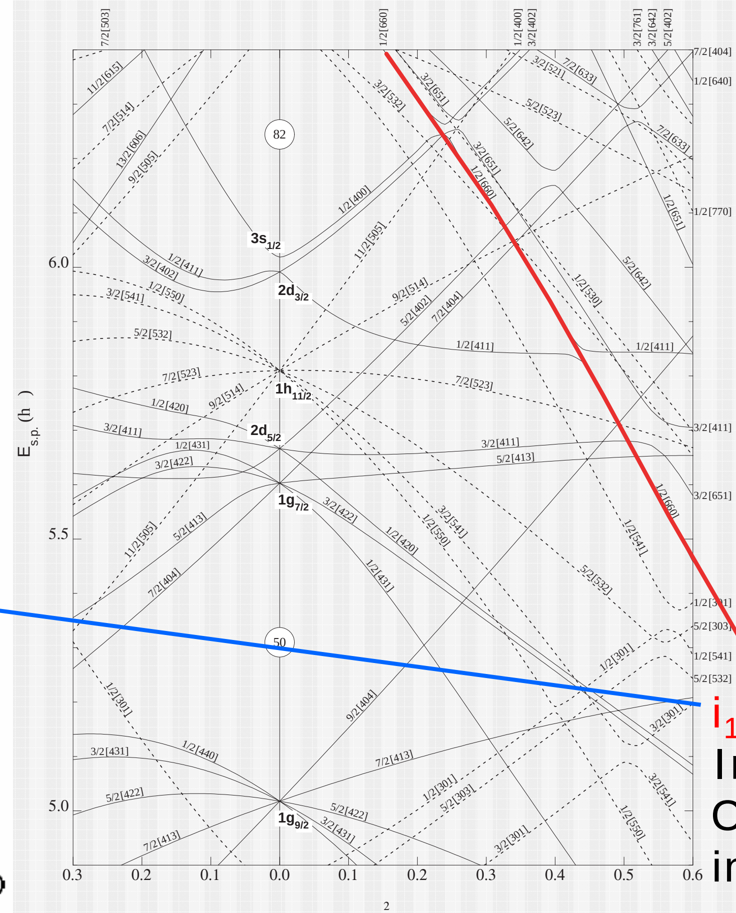
SD band
$I \geq 20\hbar$

^{64}Ni(^{48}Ca,4n)^{108}Cd
207MeV
@ ATLAS, GS
ANL

R.M.Clark et al., Phys. Rev. Lett. 87, 202502 (2001)

$i_{13/2}$ intruder orbital





$i_{13/2}$ proton Intruder Occupied in ^{108}Cd

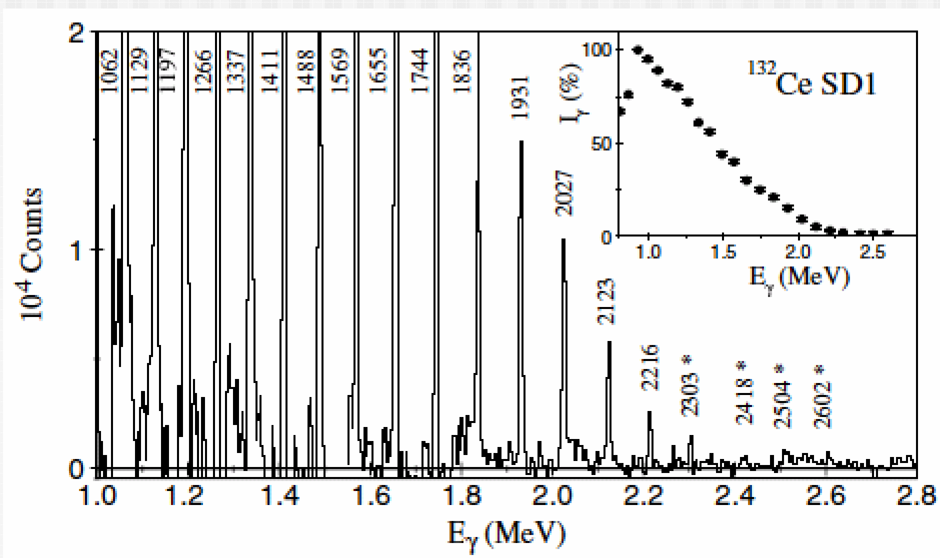
C-T. Lee et al., PRC 65, 041301 (2002)

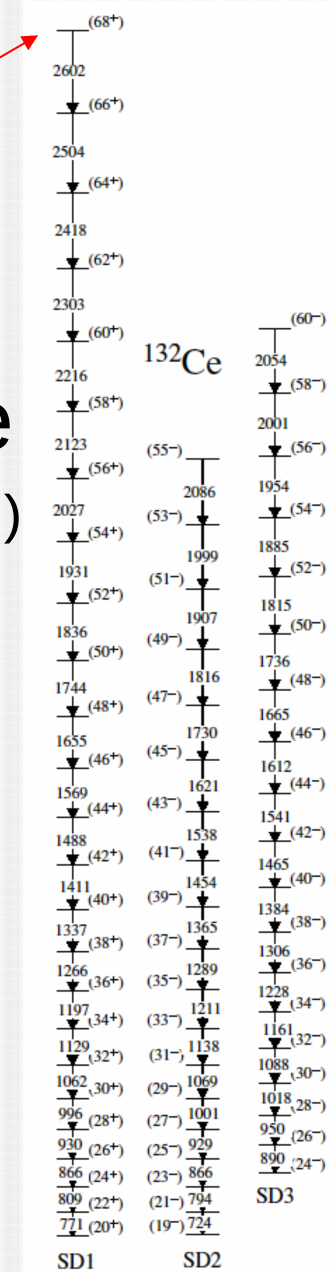
Highest spin observed

- Superdeformed band in ^{132}Ce

E.S.Paul et al., Phys. Rev. C71, 054309 (2005)

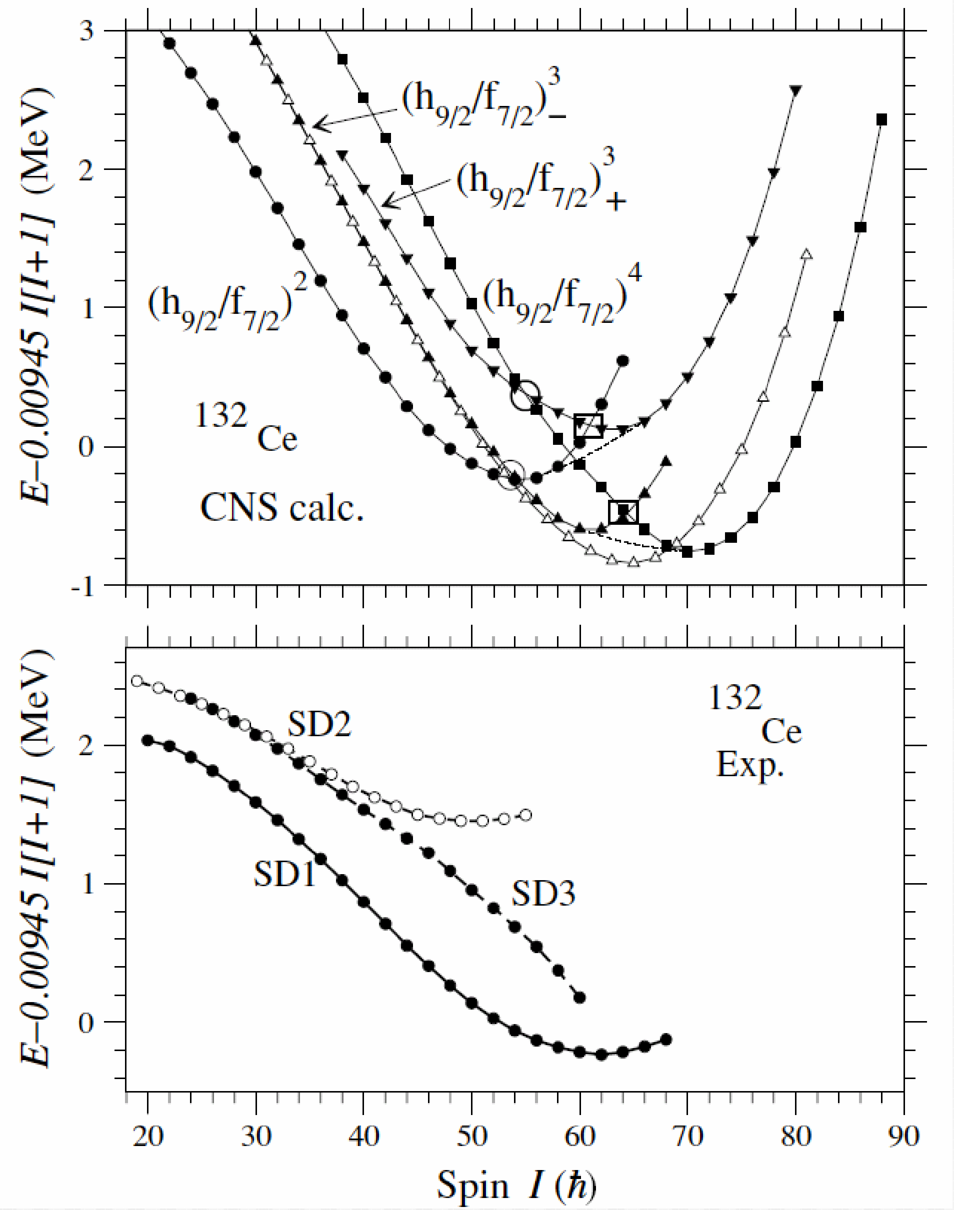
I_{max} = (68+)





Excitation energy

- Excitation energy Relative to a rigid Rotor reference
- Comparison with Cranked Nilsson Strutinsky calculation
- Similar behavior with smooth band termination in A≈110

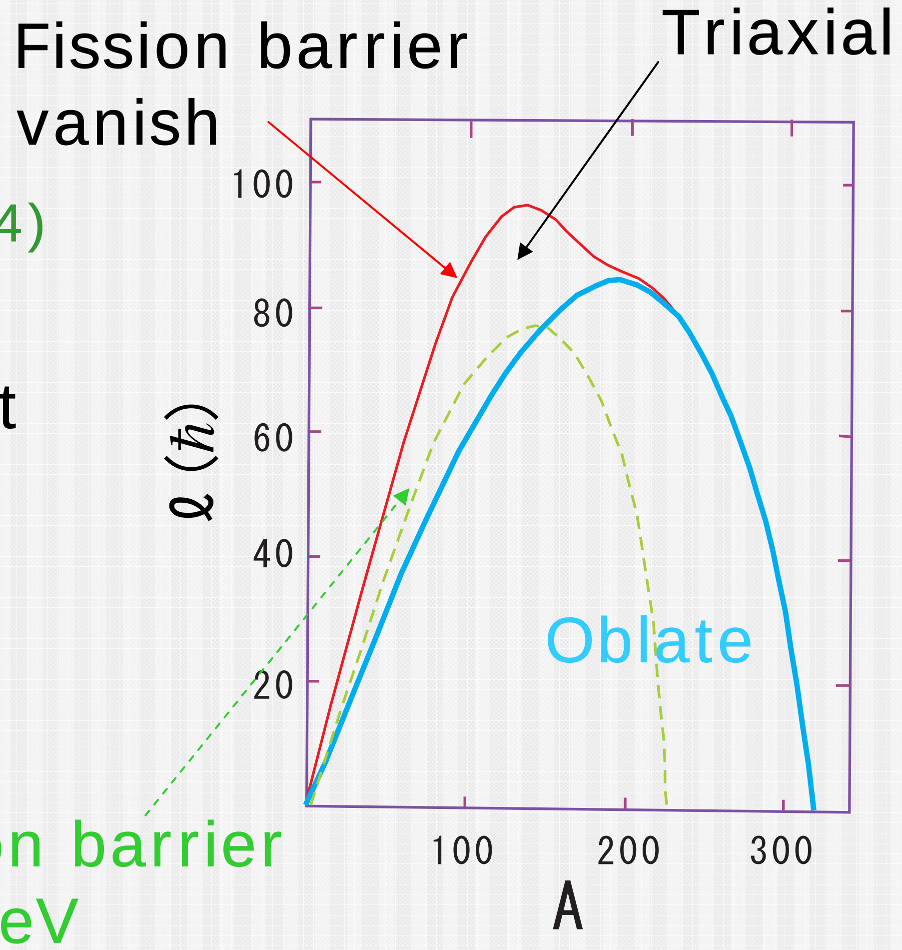


E.S.Paul et al., Phys. Rev. C71, 054309 (2005)

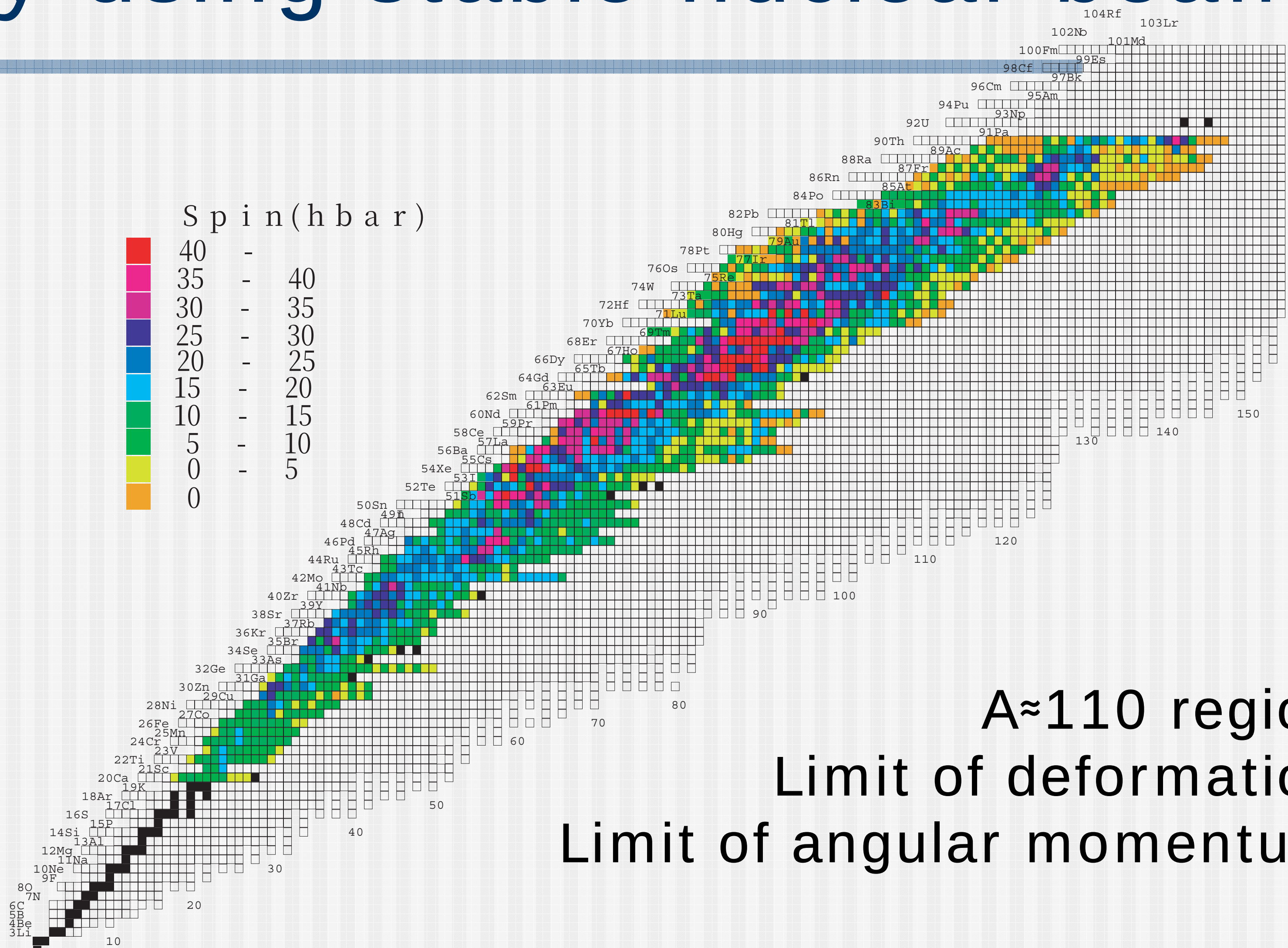
Limit of high-spin

Rotating Liquid Drop
S. Cohen et al.,
Ann. Phys. 82, 557 (1974)

- The nuclei able to support the highest angular momenta near A≈130
- Fission barrier vanishes at 97$\hbar$



High-spin nuclei studied by using stable nuclear beams



A≈110 region

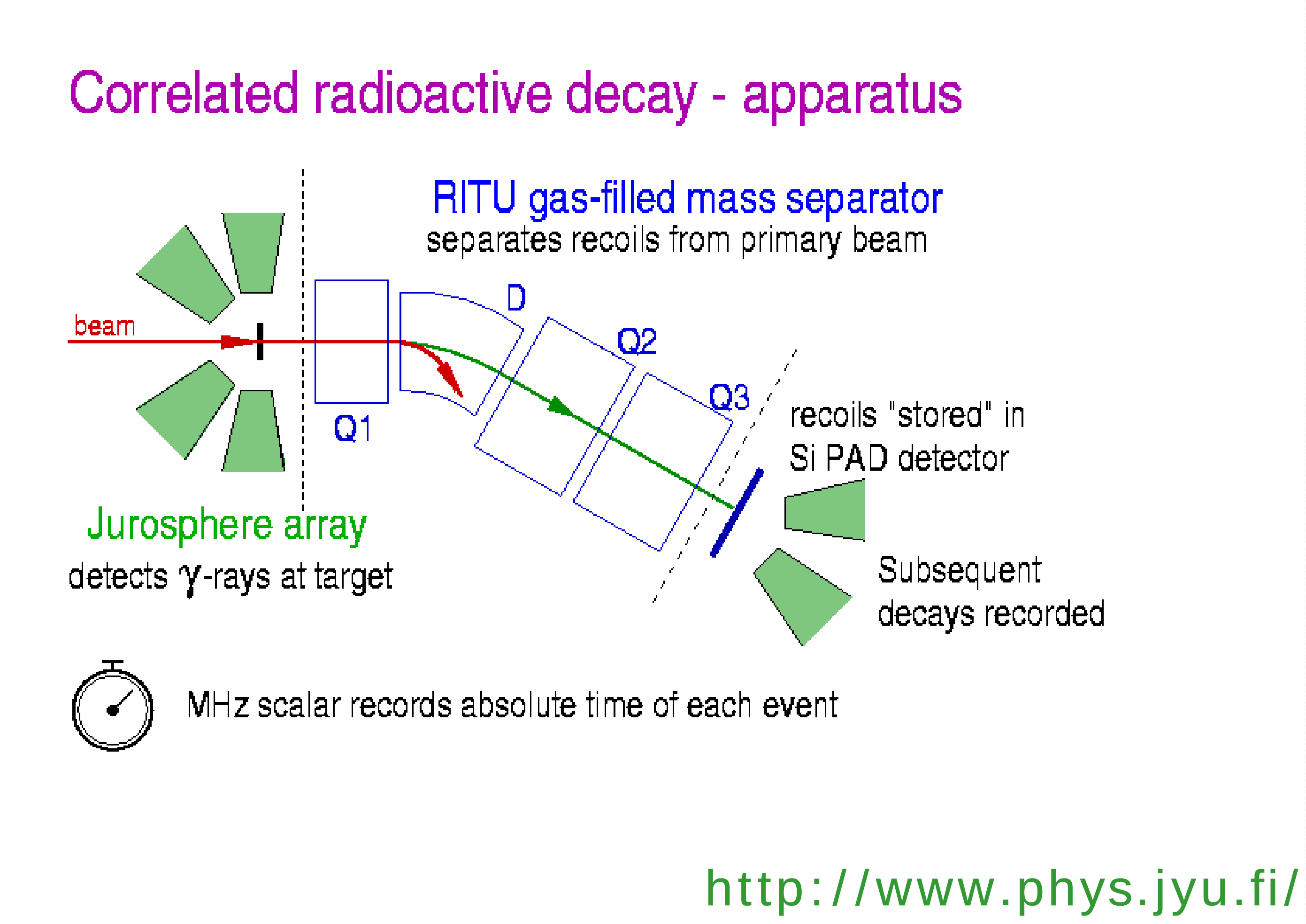
Limit of deformation

Limit of angular momentum

High-spin studies in proton-rich nuclei

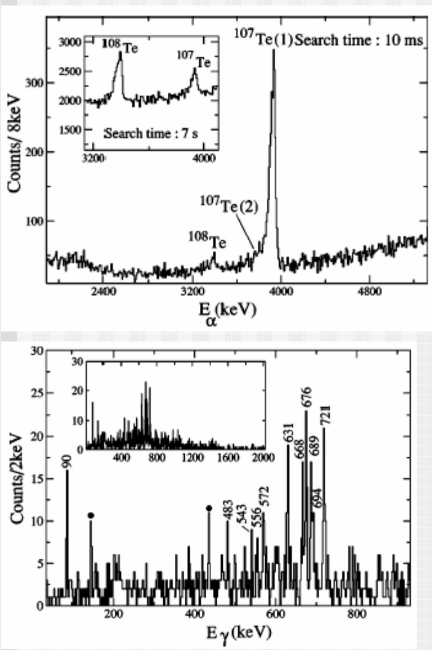
- Nuclei produced by fusion-evaporation reaction are in proton rich side relative to the line of β-stability
- By using most proton rich stable beam and target, we can access to the proton rich region
- Proton rich nuclei close to proton drip line often decay by α decay or proton decay
  → using tagging technique to access proton rich limit (Jyväskylä, ANL)
- Many proton rich nuclei can also be studied (^{107}In)

Recoil decay tagging

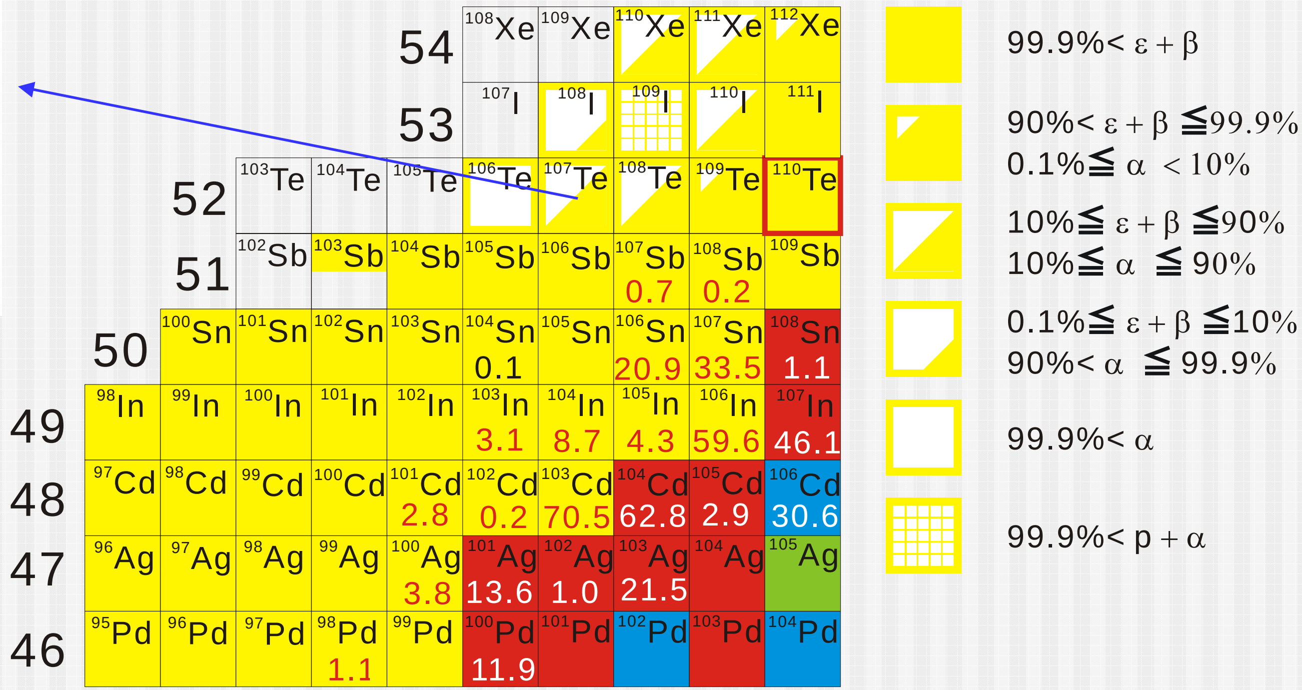


Study of ^{107}In (Z=49, N=58)

Reaction : ^{52}Cr(187MeV) + ^{58}Ni(580+640 μ g/cm^2)



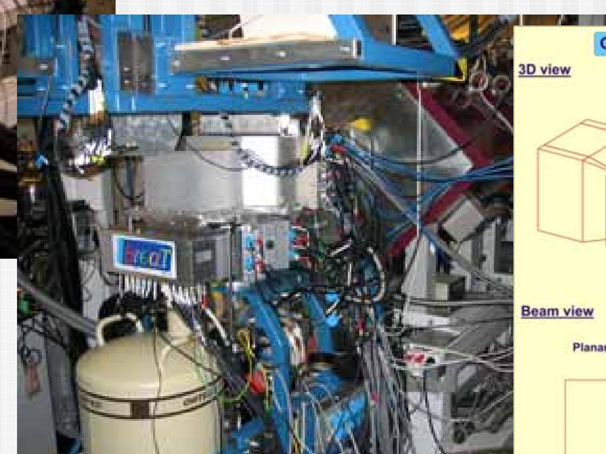
B. Hadinia et al.
PRC70, 064314(2004)

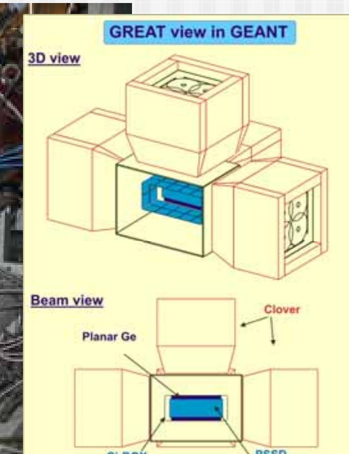


^{58}Ni(^{52}Cr, 3p)^{107}In

Experimental Setup

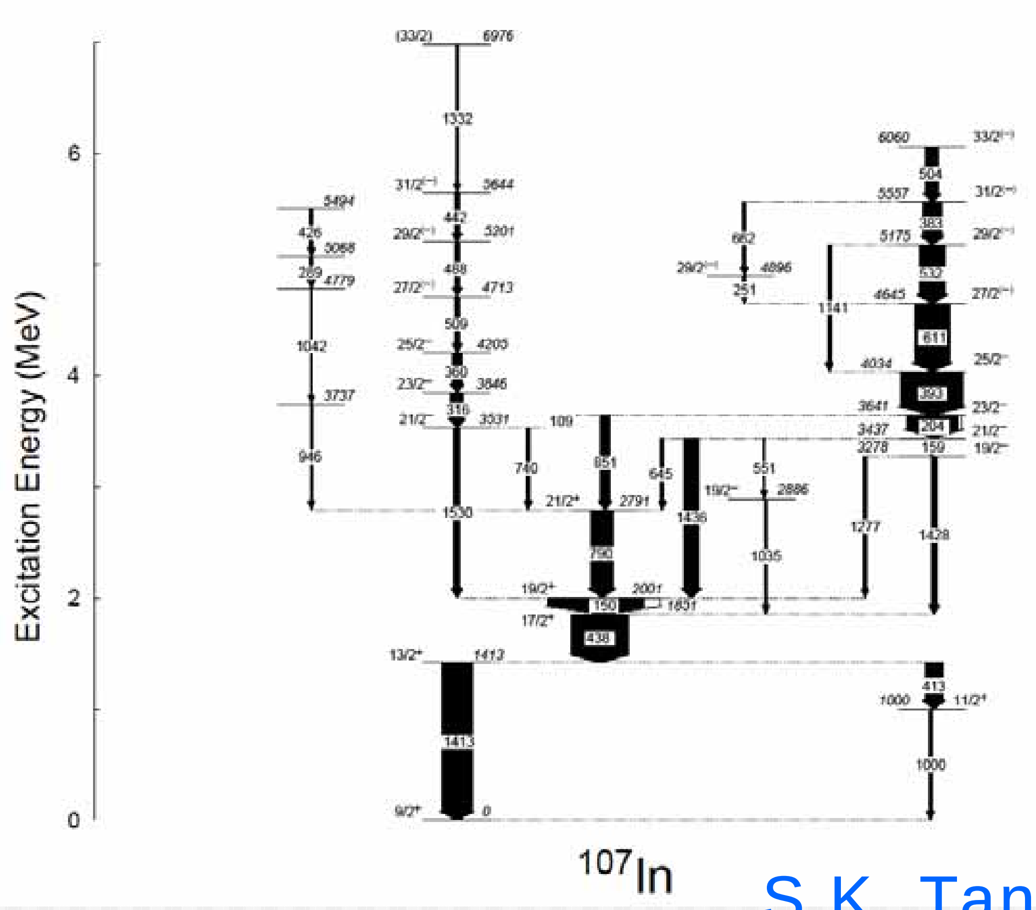
JUROGAM
43 Ge+BGO
+ RITU
Gas filled Ion Sep.
+GREAT spectrometer





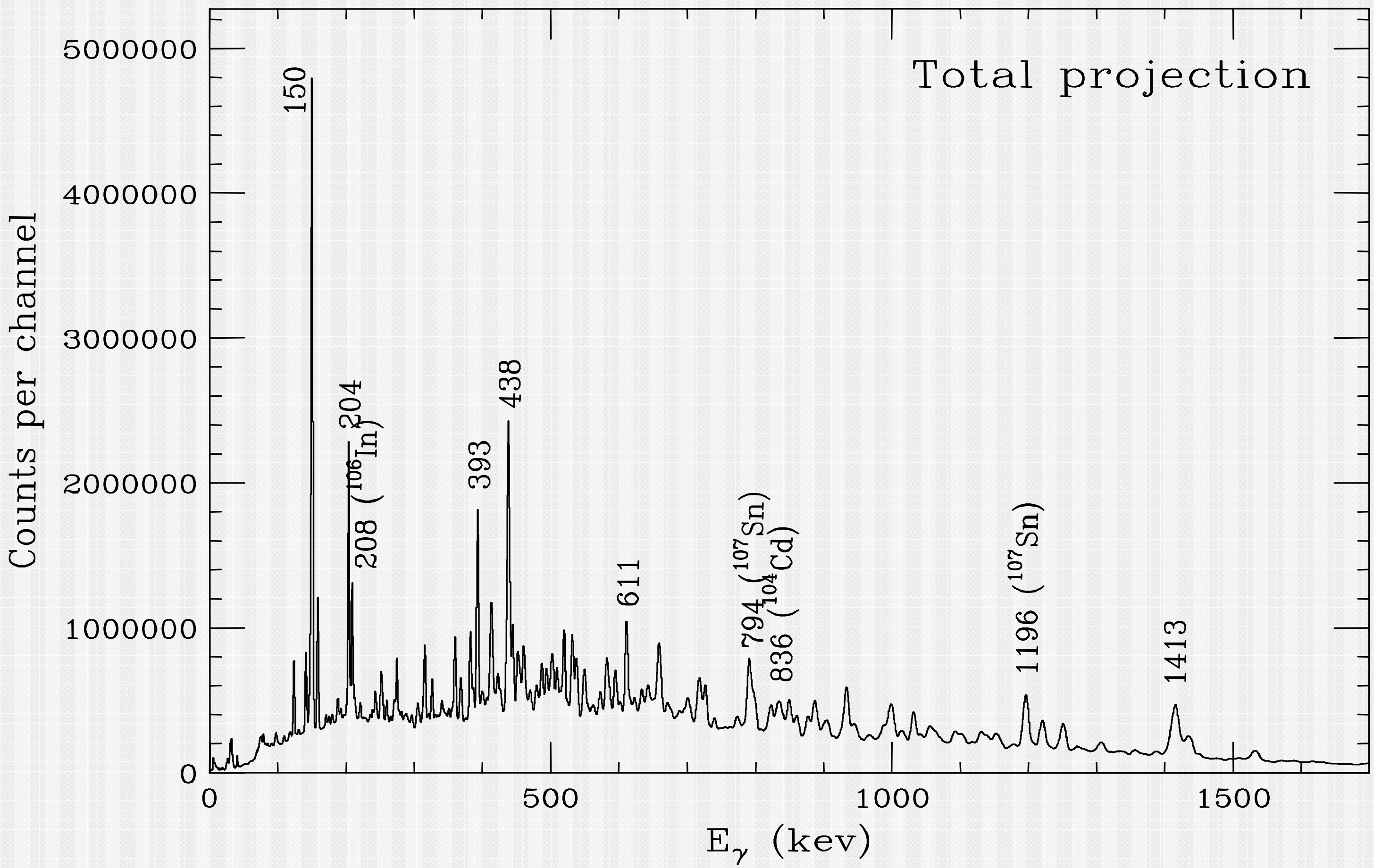
GREAT: Double sided Si strip
Si PIN photodiode array
Double sided planar Ge
Segmented Clover Ge

^{107}In level scheme

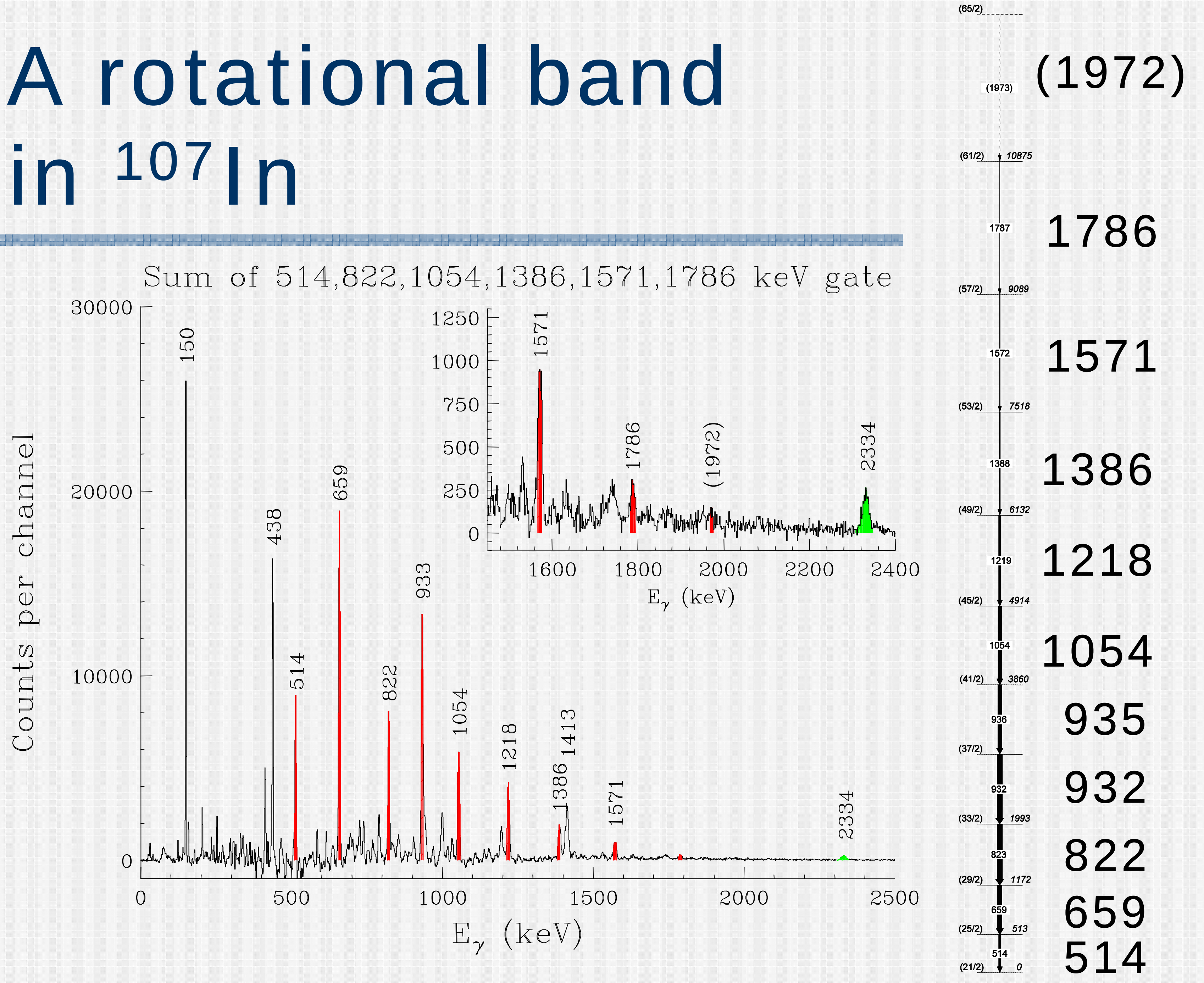


S.K. Tandel et al.
PRC58, 3738 (1998)

Gamma-ray spectrum

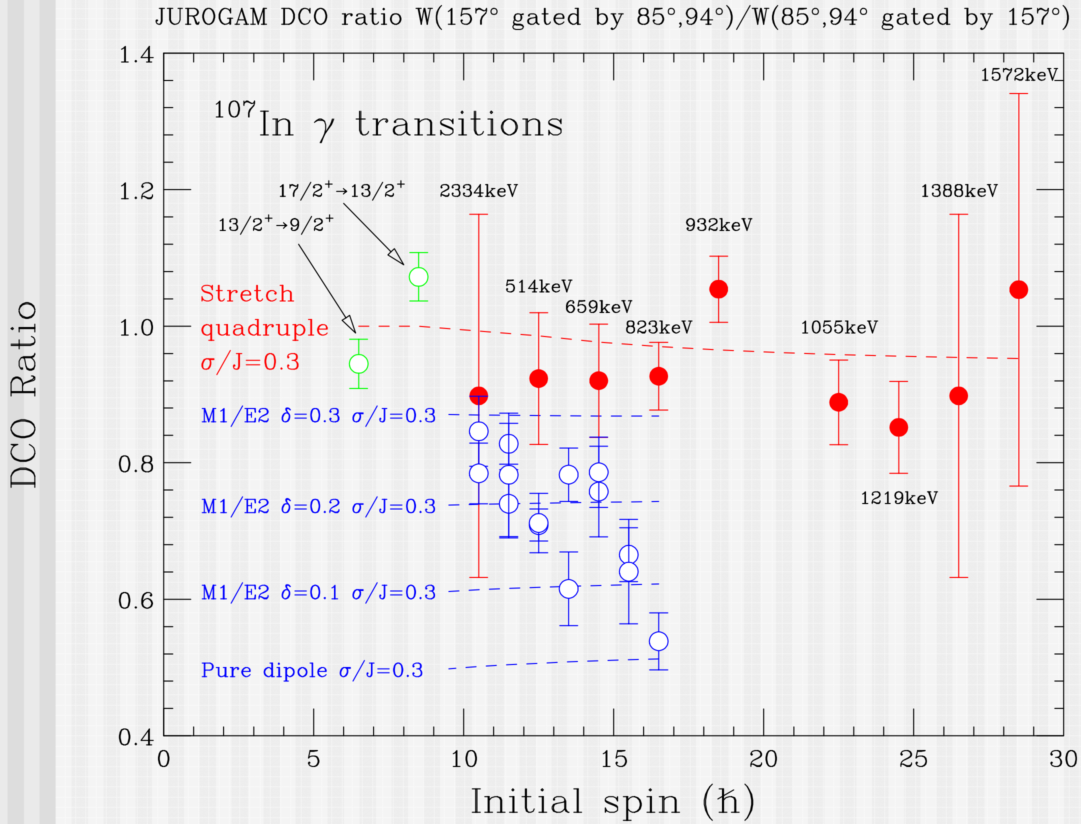


A rotational band in ^{107}In



DCO ratio analysis

(Directional Correlation from Oriented nuclei)



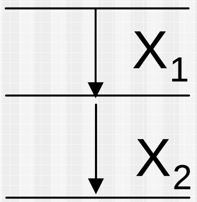
DCO Ratio:

$$R = \frac{W(\theta_1,\theta_2,\phi)}{W(\theta_2,\theta_1,\phi)}$$

Consistent with E2 of in-band transition

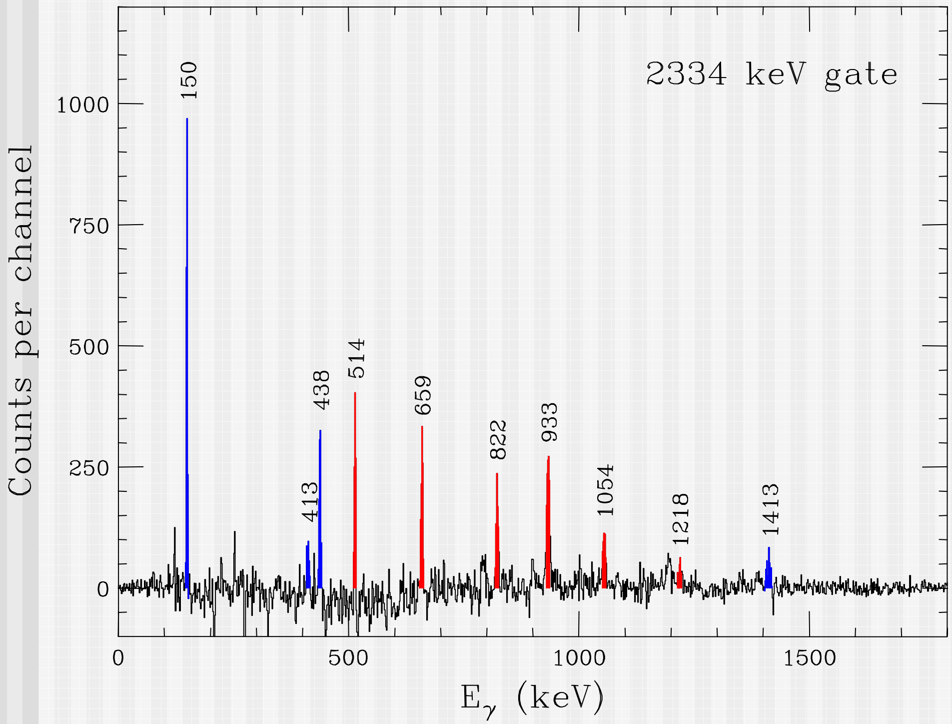
Most of known transitions are dipole | Mixed

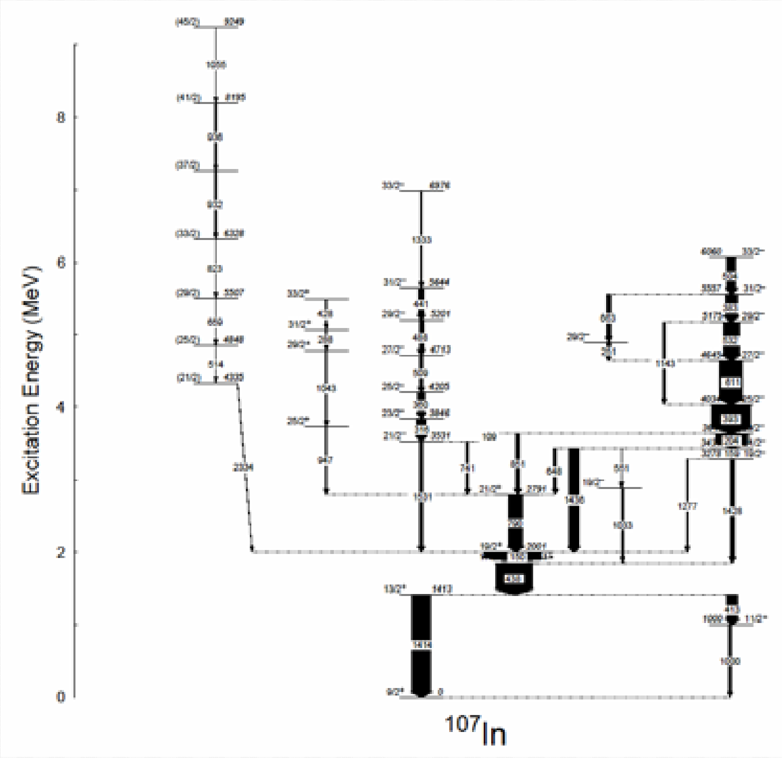
σ /J : alignment parameter
σ =0 : complete alignment
δ : mixing ratio



$$W(\theta_1,\theta_2,\phi) = N \sum_{\lambda\lambda_1\lambda_2} B_{\lambda_1}(I_1) A_{\lambda}^{\lambda_2\lambda_1}(X_1) A_{\lambda_2}(X_2) H_{\lambda_1\lambda\lambda_2}(\theta_1,\theta_2,\phi)$$

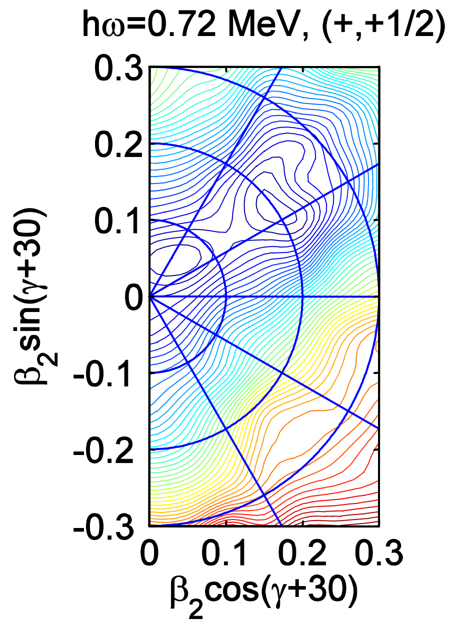
Linking transition

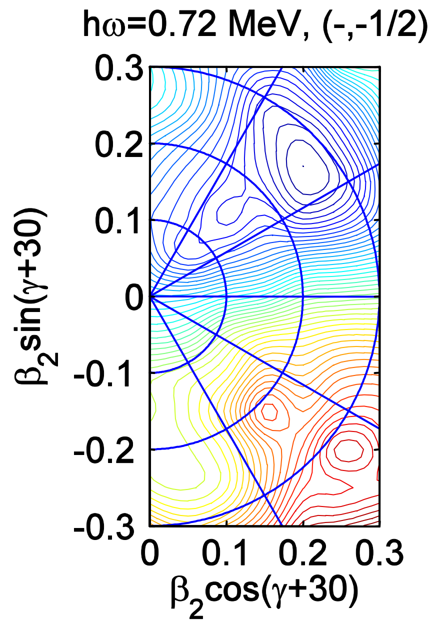




Total Routhian Surface (TRS) Calculation

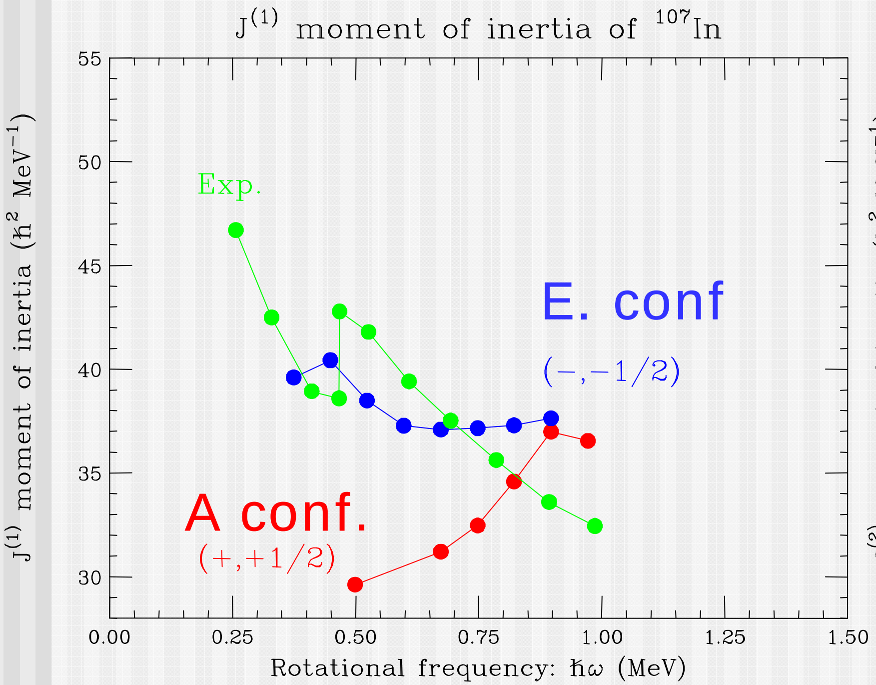
A conf. E. conf.

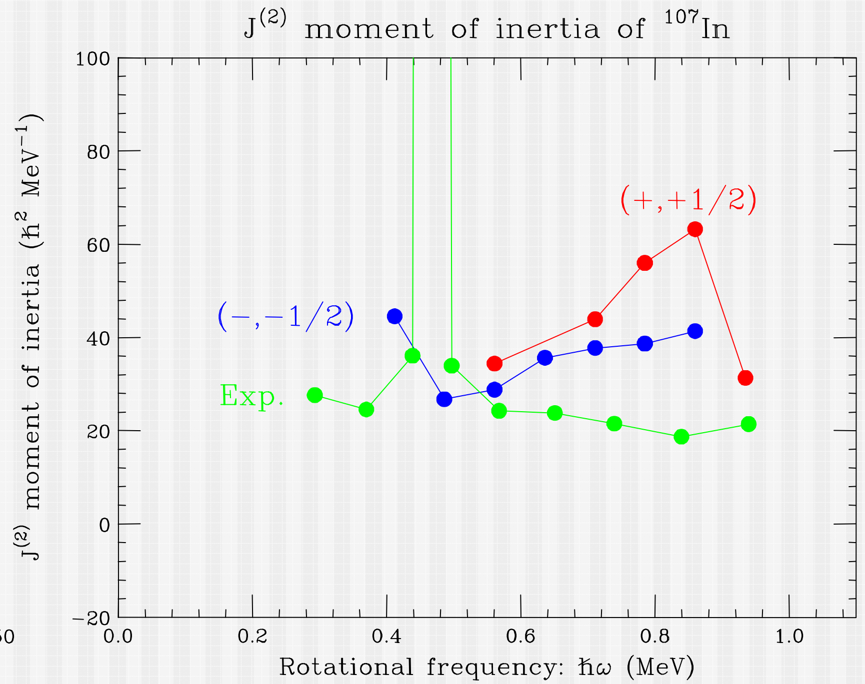




Deformed minima with $\beta_2 \sim 0.2-0.3$

$J^{(1)}$,$J^{(2)}$ moment of inertia Exp. and TRS calc.





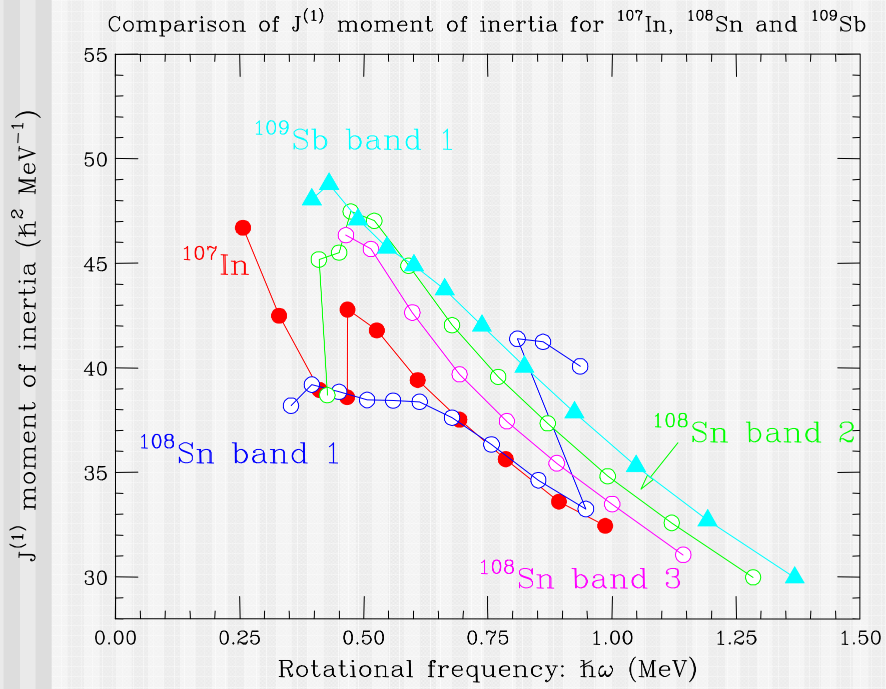
Kinematical

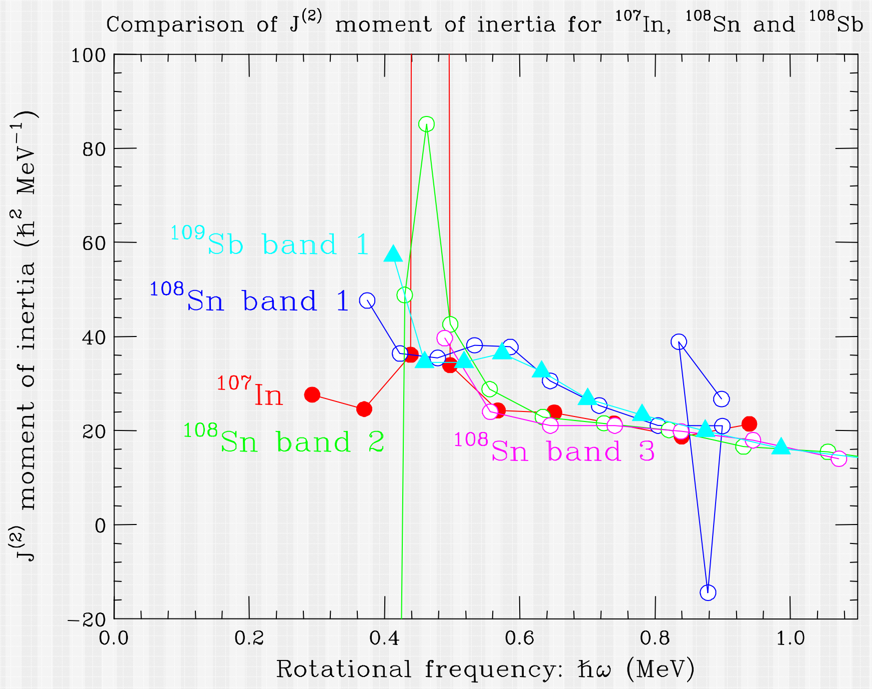
$$J^{(1)} = \left[\frac{2}{\hbar^2}\frac{dE(I)}{d(I^2)}\right]^{-1} = \hbar\frac{I}{\omega}$$

Dynamical

$$J^{(2)} = \left[\frac{1}{\hbar^2}\frac{d^2E(I)}{dI^2}\right]^{-1} = \hbar\frac{dI}{d\omega}$$

$J^{(1)}$ and $J^{(2)}$ moment of inertia

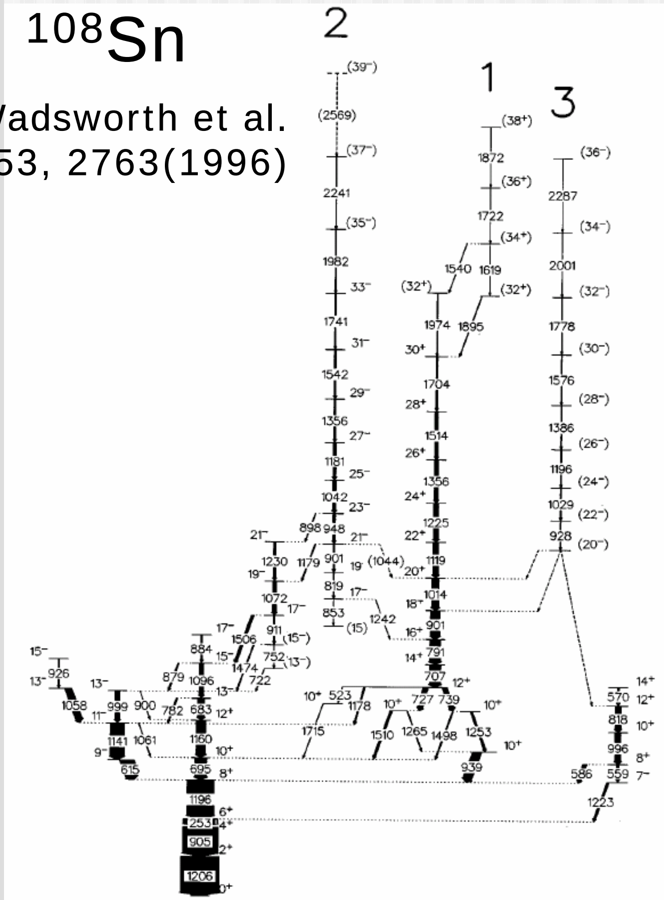




Smooth band termination in A~110 region

^{108}Sn

R. Wadsworth et al.
PRC53, 2763(1996)

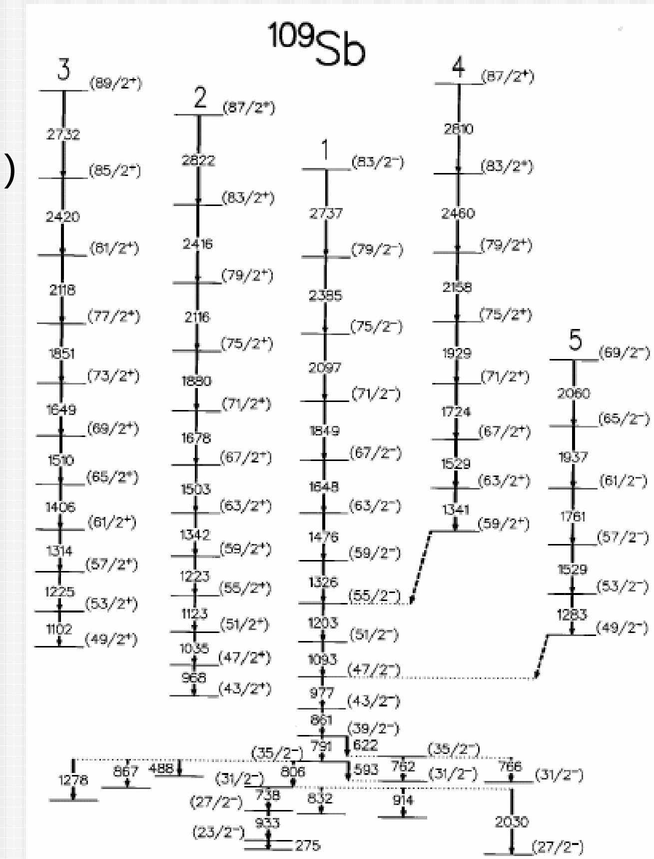


$\pi[g_{9/2}^{-2}(g_{7/2}h_{11/2})]\otimes\nu[(d_{5/2}g_{7/2})^6h_{11/2}^2]$

terminate@39^-

^{109}Sb

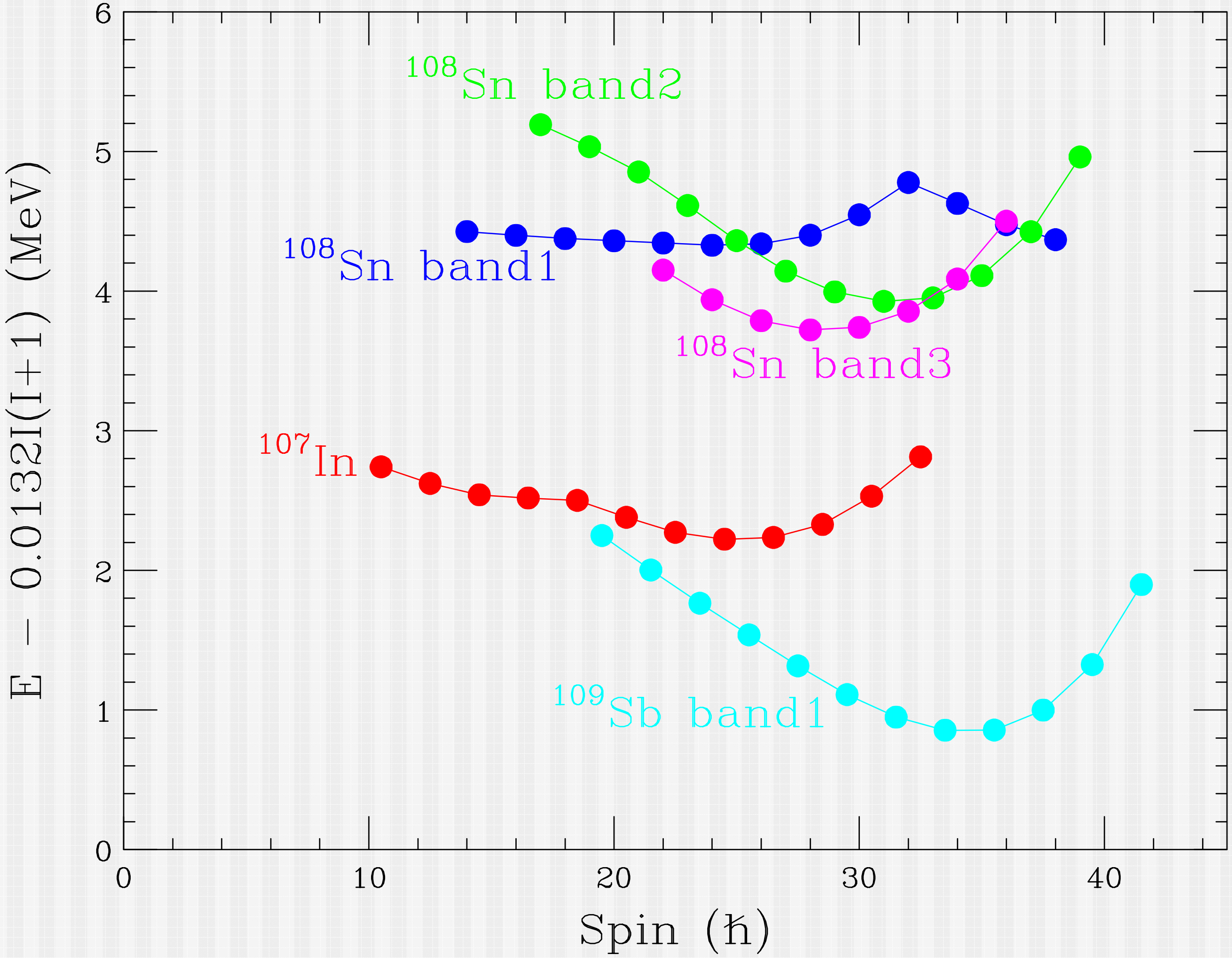
H. Schnare et al.
PRC54, 1598(1996)



$\pi[g_{9/2}^{-2}(g_{7/2}d_{5/2})h_{11/2}]\otimes\nu[(d_{5/2}g_{7/2})^6h_{11/2}^2]$

terminate@$83/2^-$

Excitation energy relative to rigid rotor reference



High-spin study in neutron rich nuclei

Fusion reaction:
Stable isotope beam + Stable isotope target

→ High-spin states in proton-rich nuclei

High-spin study induced by RI beam

Fusion reaction:
RI beam + Stable isotope target

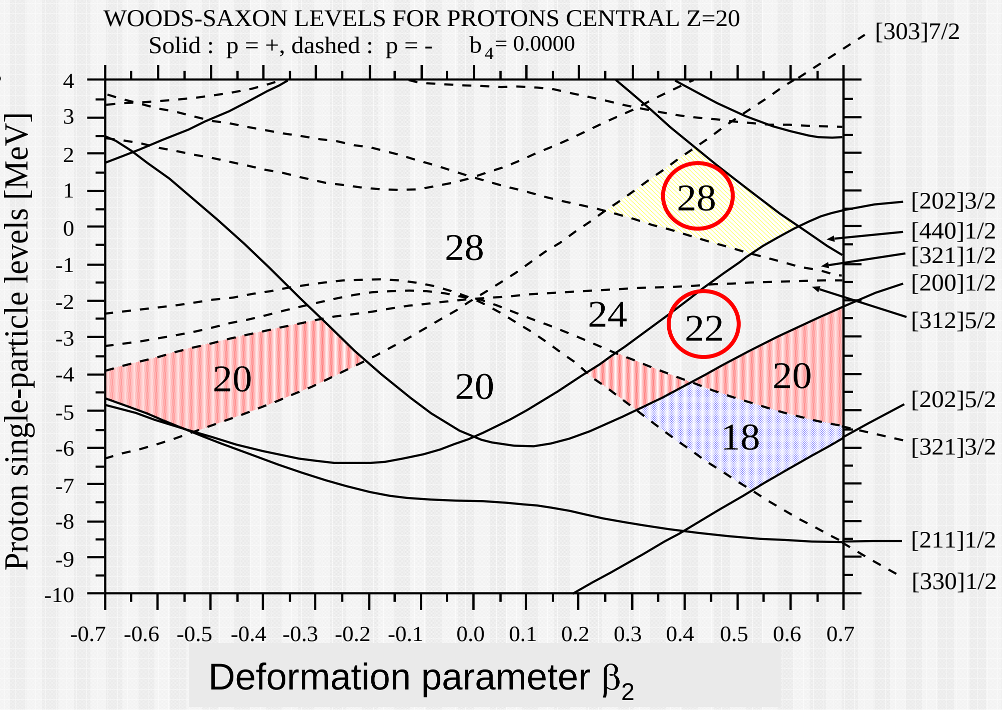
→ High-spin states in Stable | Neutron-rich nuclei

Study of $^{49-52}$Ti (Z=22,N=27-30)

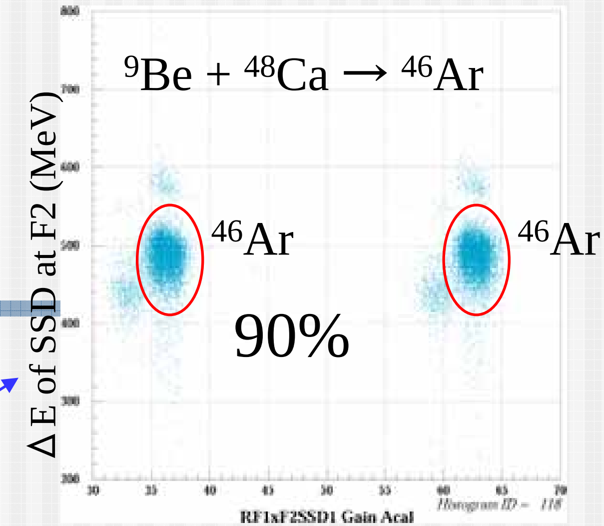
High-spin study of
most neutron-rich stable nuclei.
→ ^{48}Ca and neighbors
deformed states at high spin

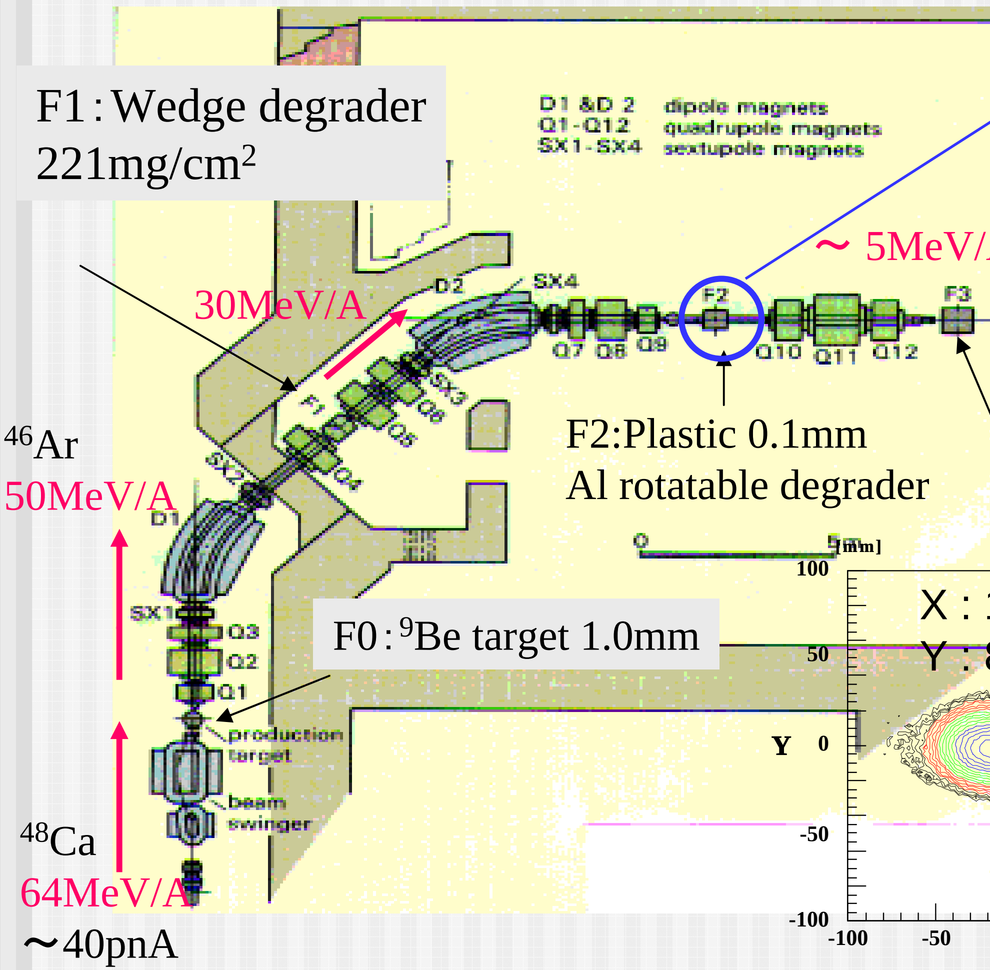
^{50}Ti (Z=22, N=28)

→ Deformed collective band
at high-spin

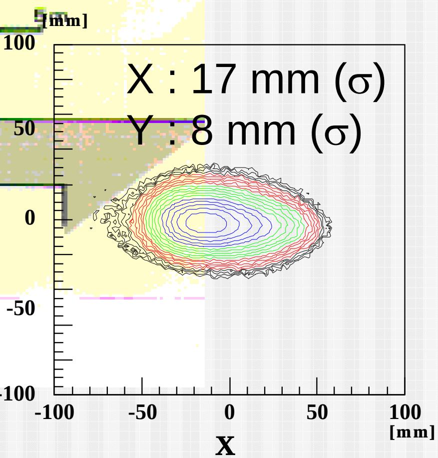


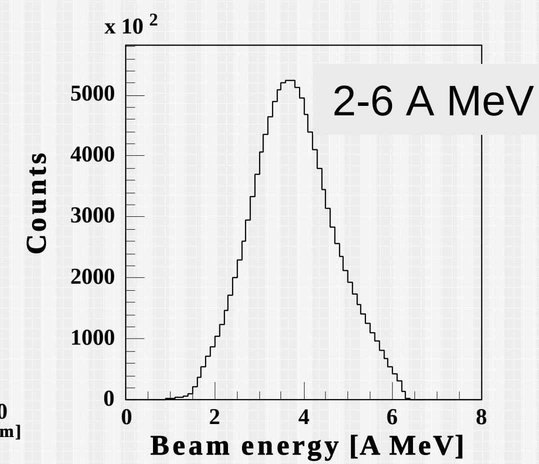
Low-energy 2ndary beams using RIPS





^{46}Ar beam intensity
F2 : 7.3×10^{5} cps
F3 : 3.2×10^{5} cps
Purity : 90 %





Setup around 2ndary target

Secondary target：^{9}Be 10μm (1.8mg/cm^{2}) thick、10cmϕ

Doppler correction:

2 PPACs before 2ndary target

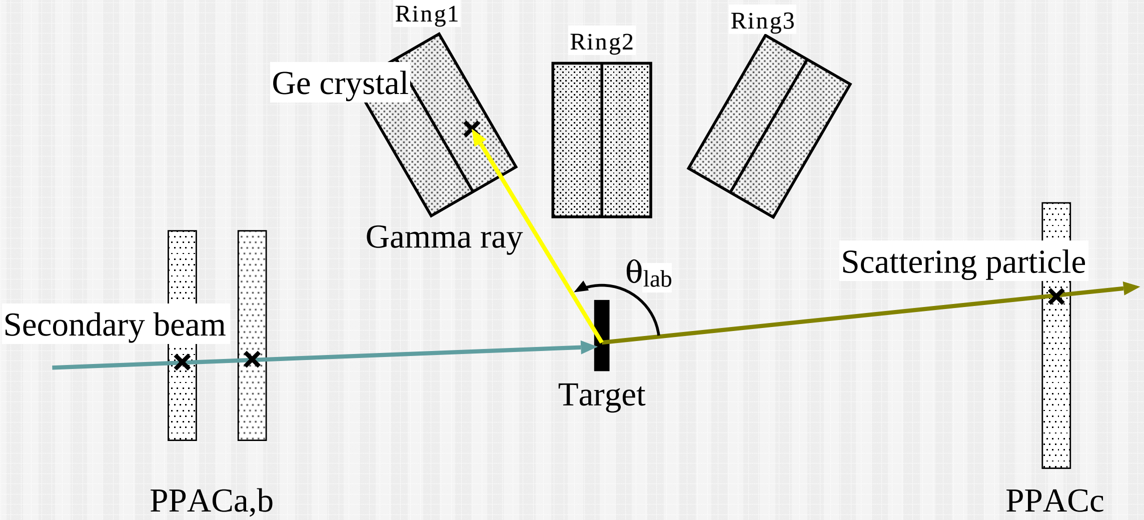
→ Beam Image, incident angle on target

F2 Plastic－F3PPAC TOF

→ Beam Energy

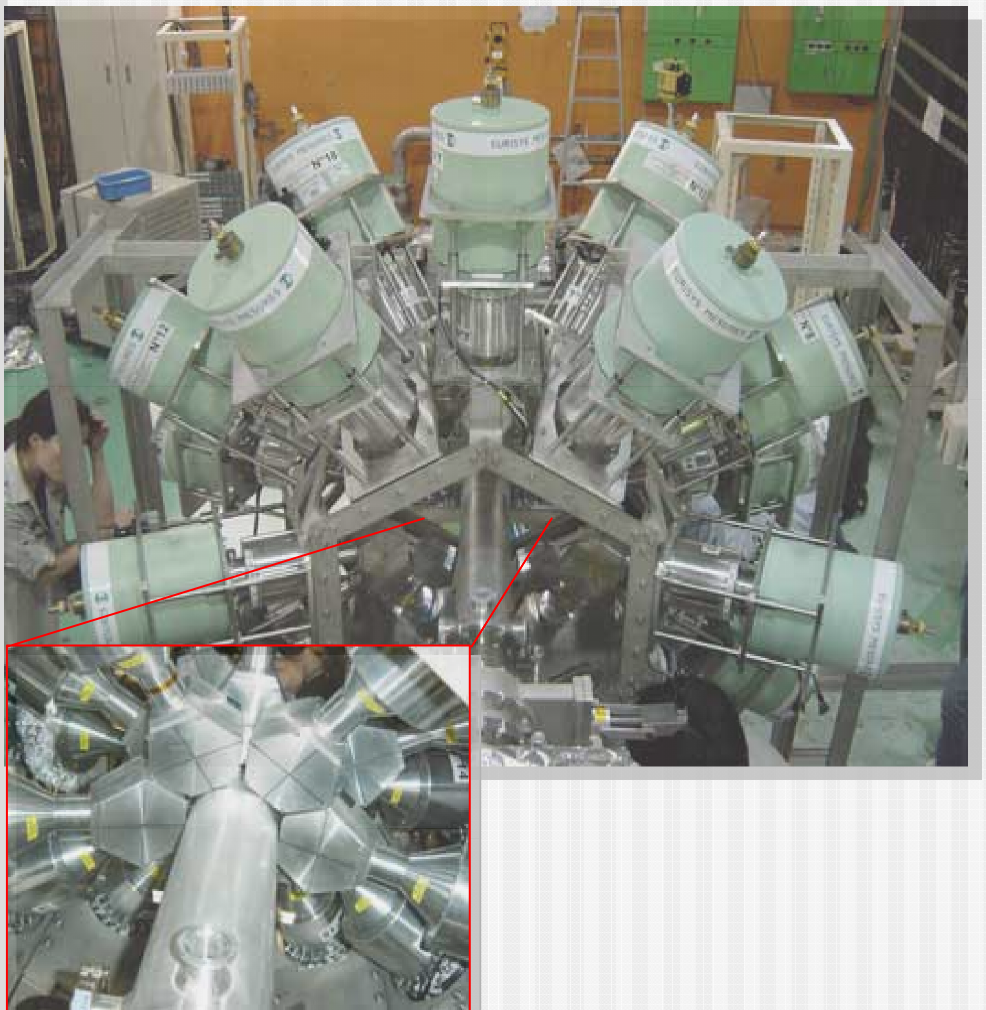
GRAPE(CNS Ge Array, position sensitive)

GRAPE



GRAPE

(Gamma-Ray detector Array with Position and Energy sensitivity)



18 segmented Ge detectors

ε ~ 4% for 1MeV

~ 5mm position sensitivity for depth direction

6cm 2cm

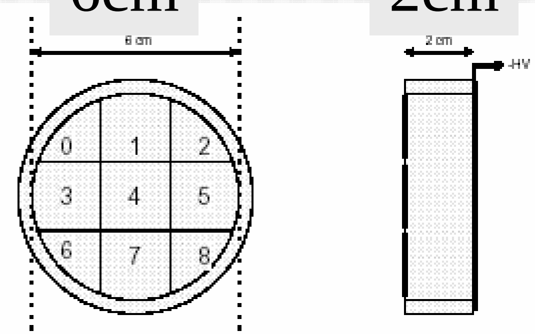
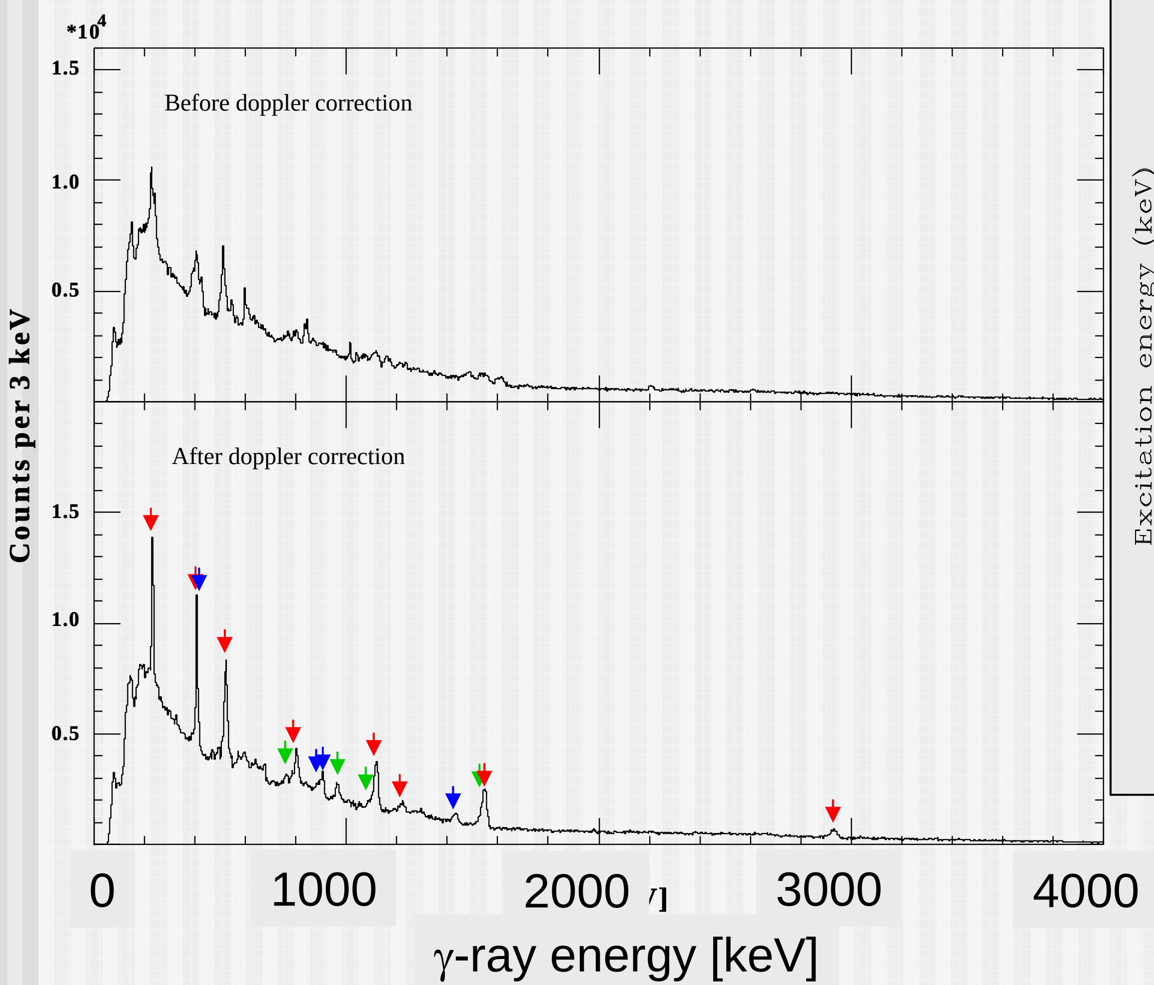
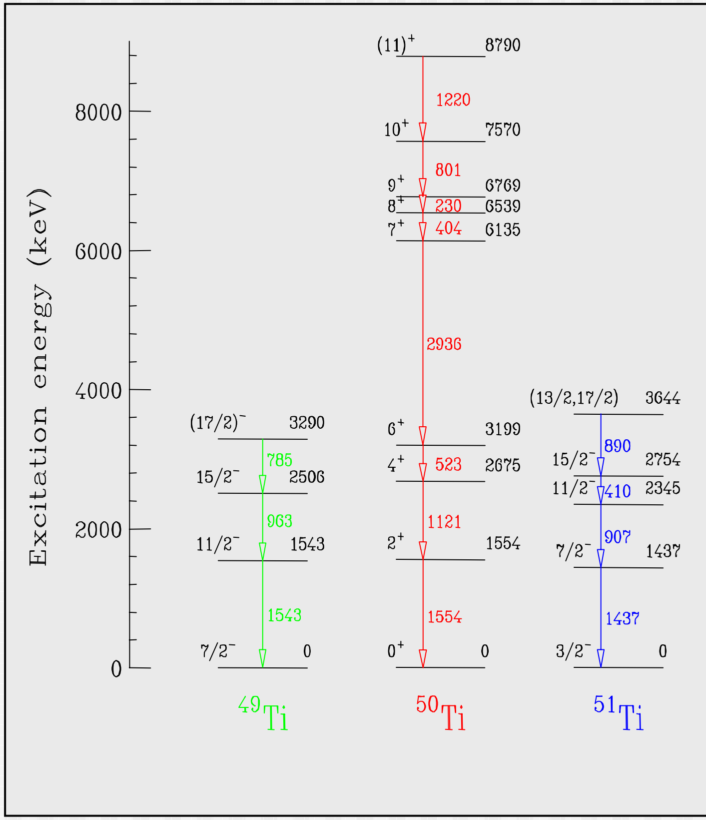


Figure 1: Illustration of a Ge detector.

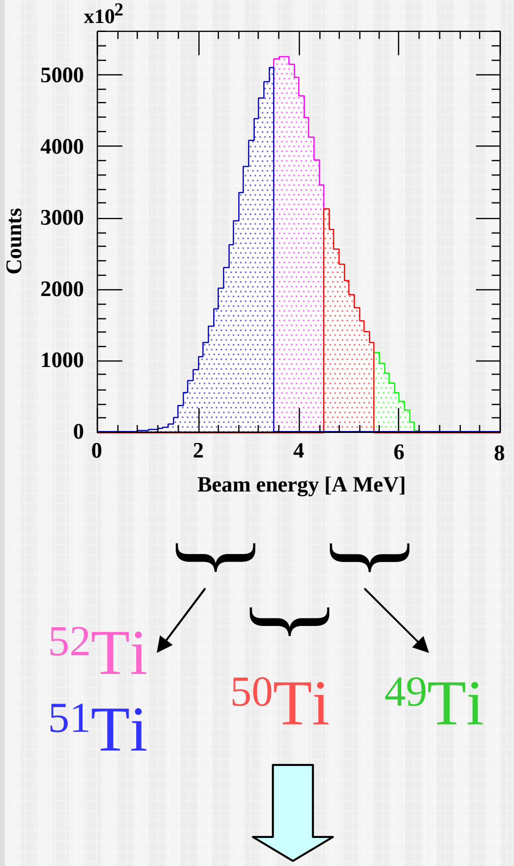
type	d	ρ (cm^{-3})
p^+ (segmented)	0.2 μm	10^{14}
p	2.0 cm	0.8×10^{10}
n^+ (high voltaged)	300 μm	10^{14}

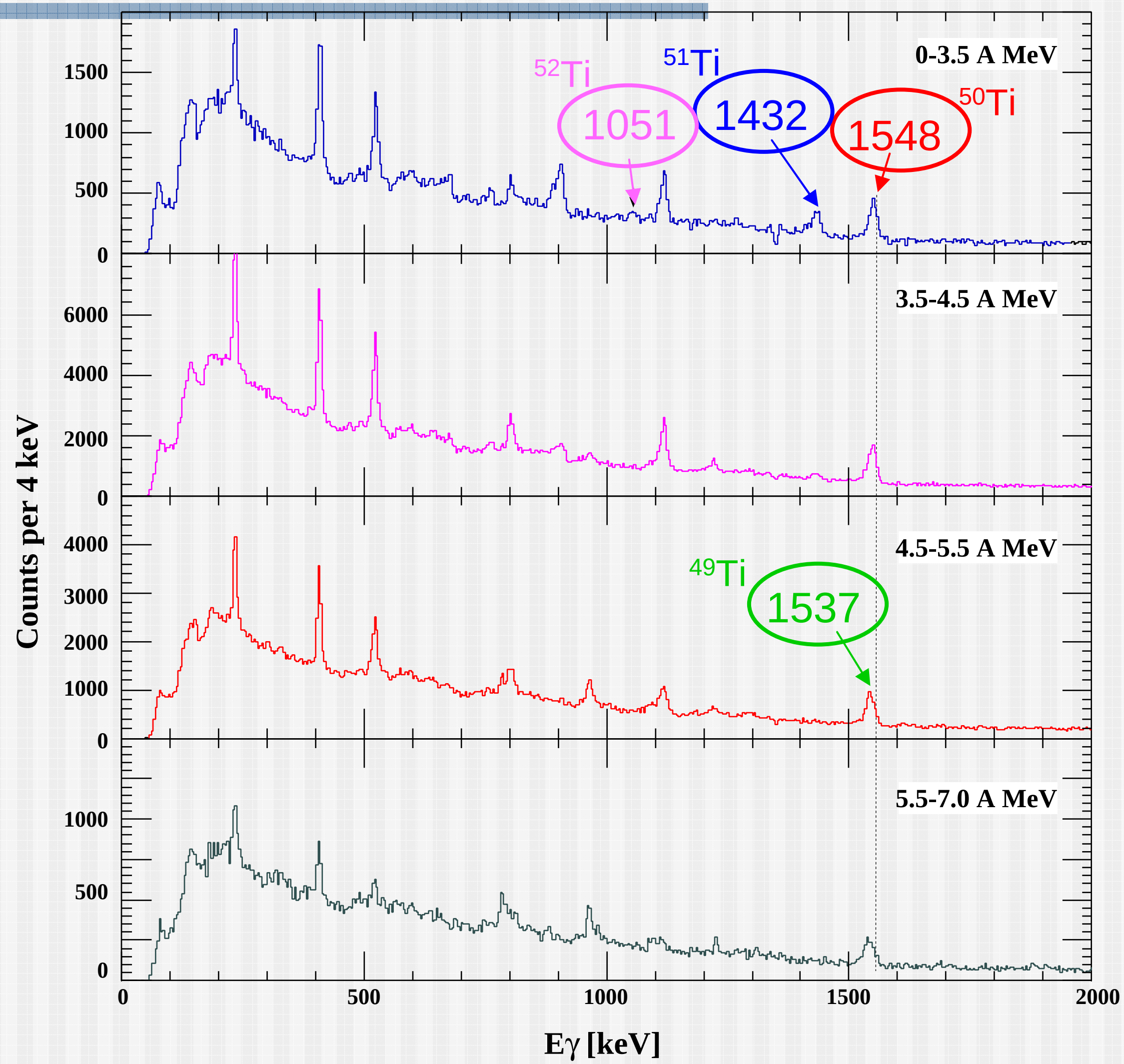
Gamma-ray spectra in $^{9}Be(^{46}Ar, xn)^{55-x}Ti$ reaction





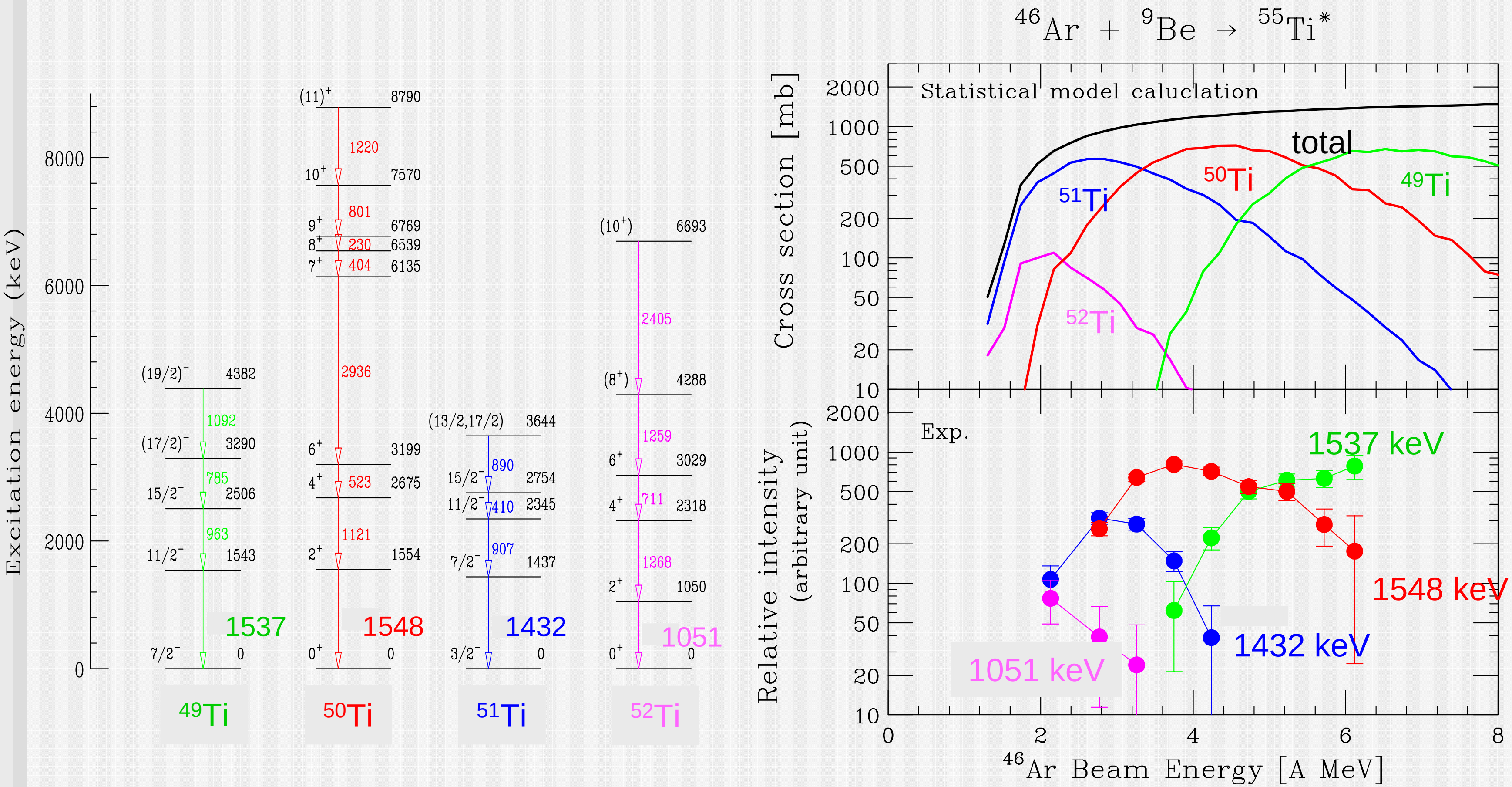
Excitation function measurements





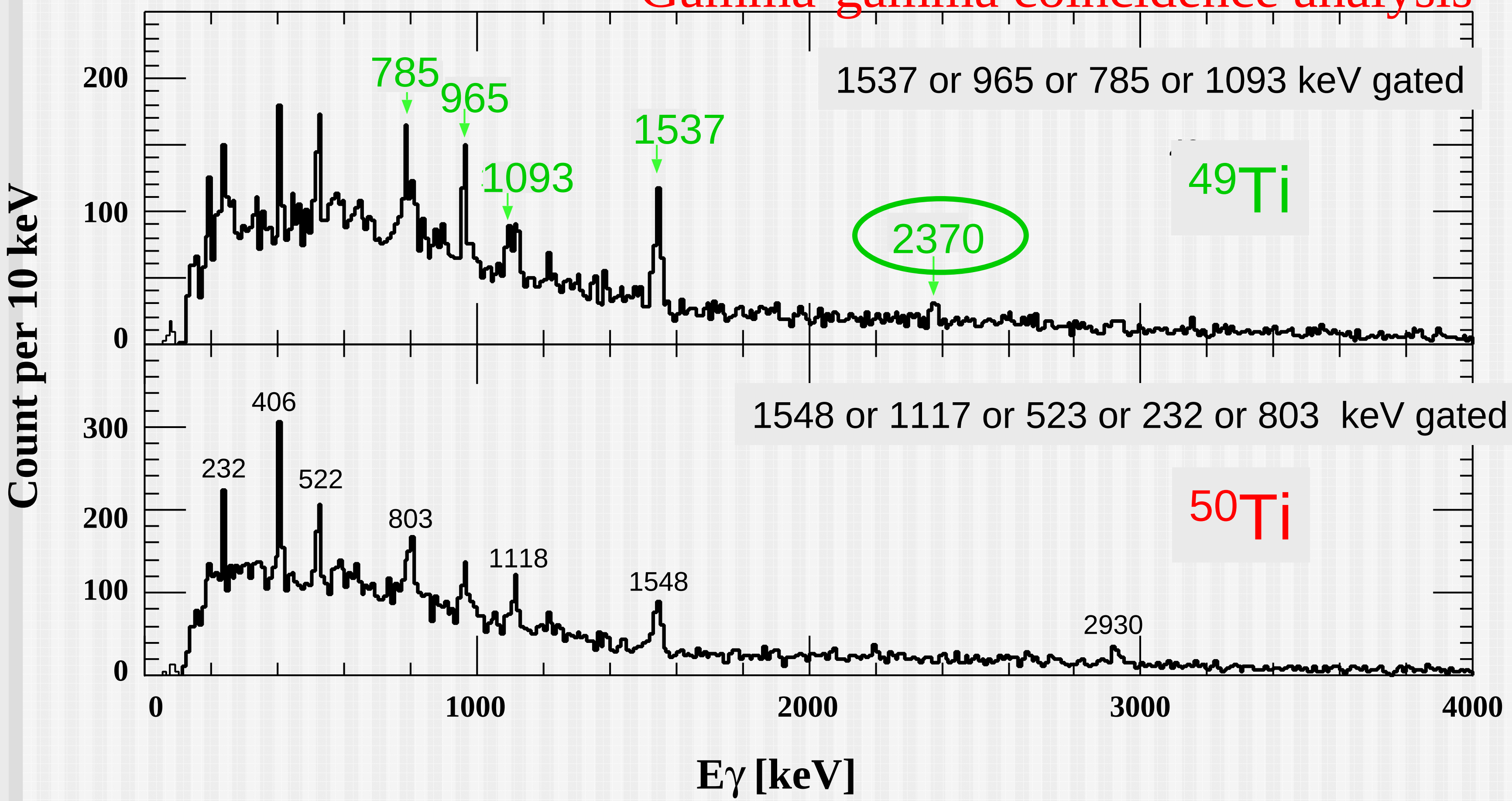
Gamma-ray assignment

Excitation function



New transition in ^{49}Ti

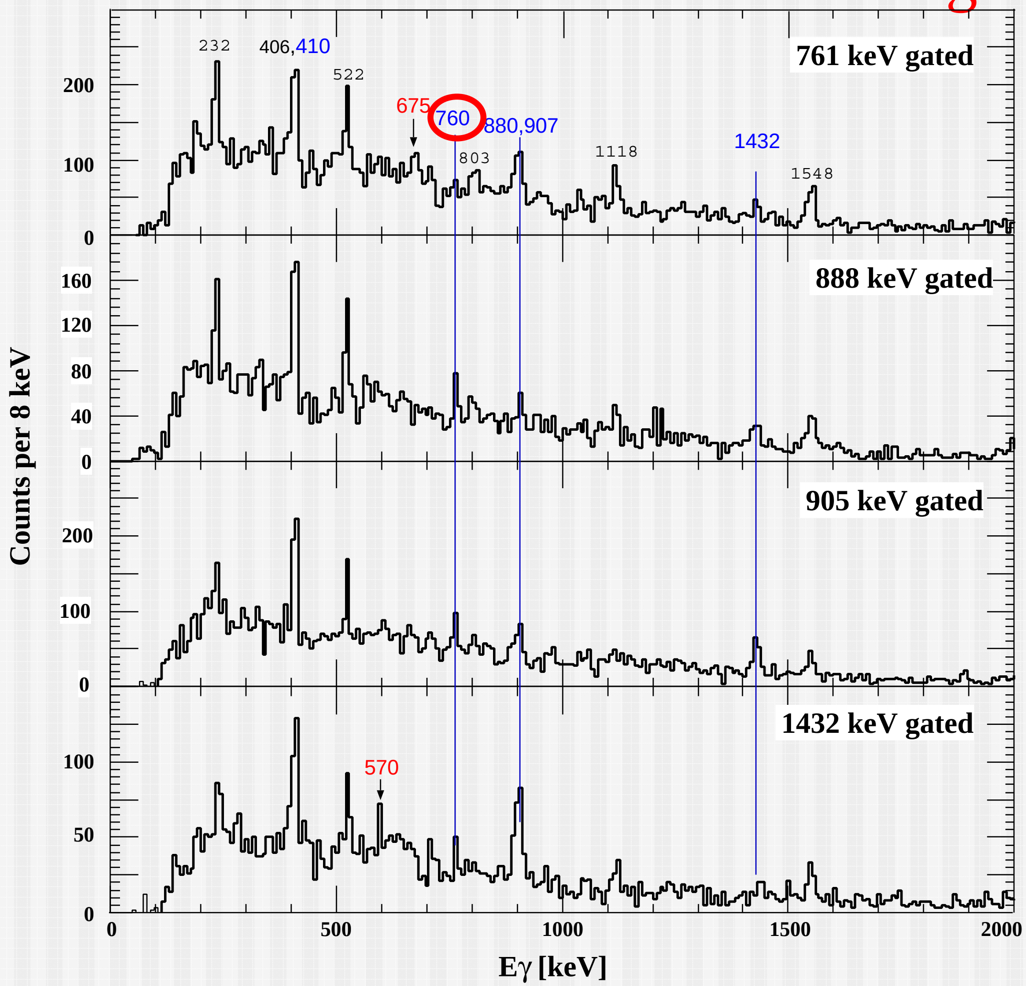
Gamma-gamma coincidence analysis

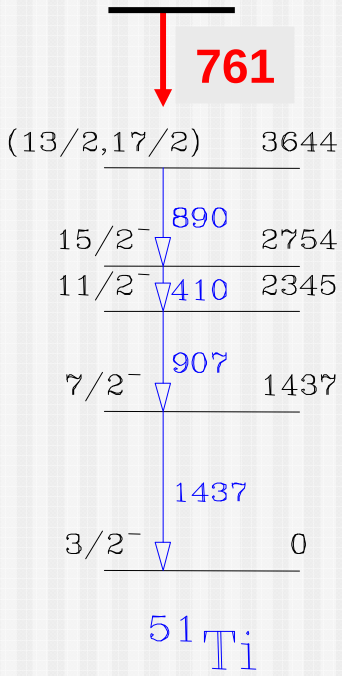


→ 2370 keV transition above $(19/2)^{-}$ state

New transition in ^{51}Ti

Gamma-gamma coincidence analysis





761keV transition above (13/2,17/2) state

Future prospects

At present facility with RI-beam

- Fusion reaction of RI beams for high-spin study

^{44}S beam $\longrightarrow$ ^{9}Be(^{44}S, xn) $^{53\text{-}x}$Ca

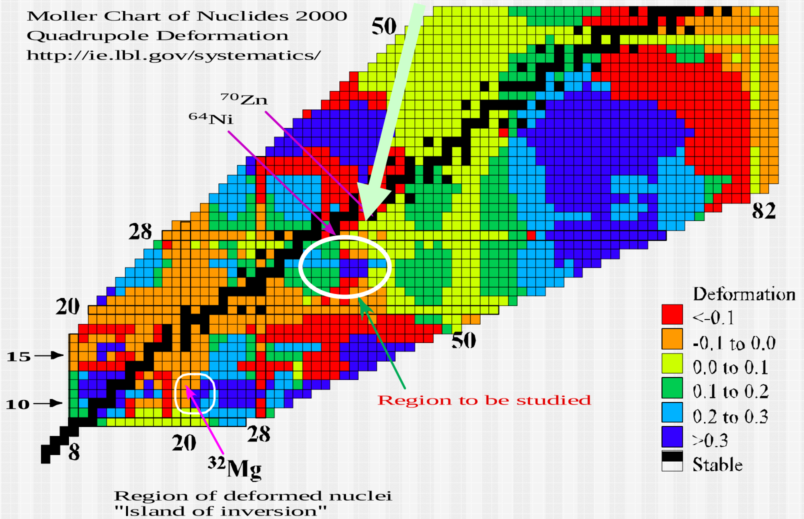
^{45}Cl beam $\longrightarrow$ ^{9}Be(^{45}Cl, xn) $^{54\text{-}x}$Sc

^{67}Co beam $\longrightarrow$ ^{9}Be(^{67}Co, xn) $^{76\text{-}x}$Ga

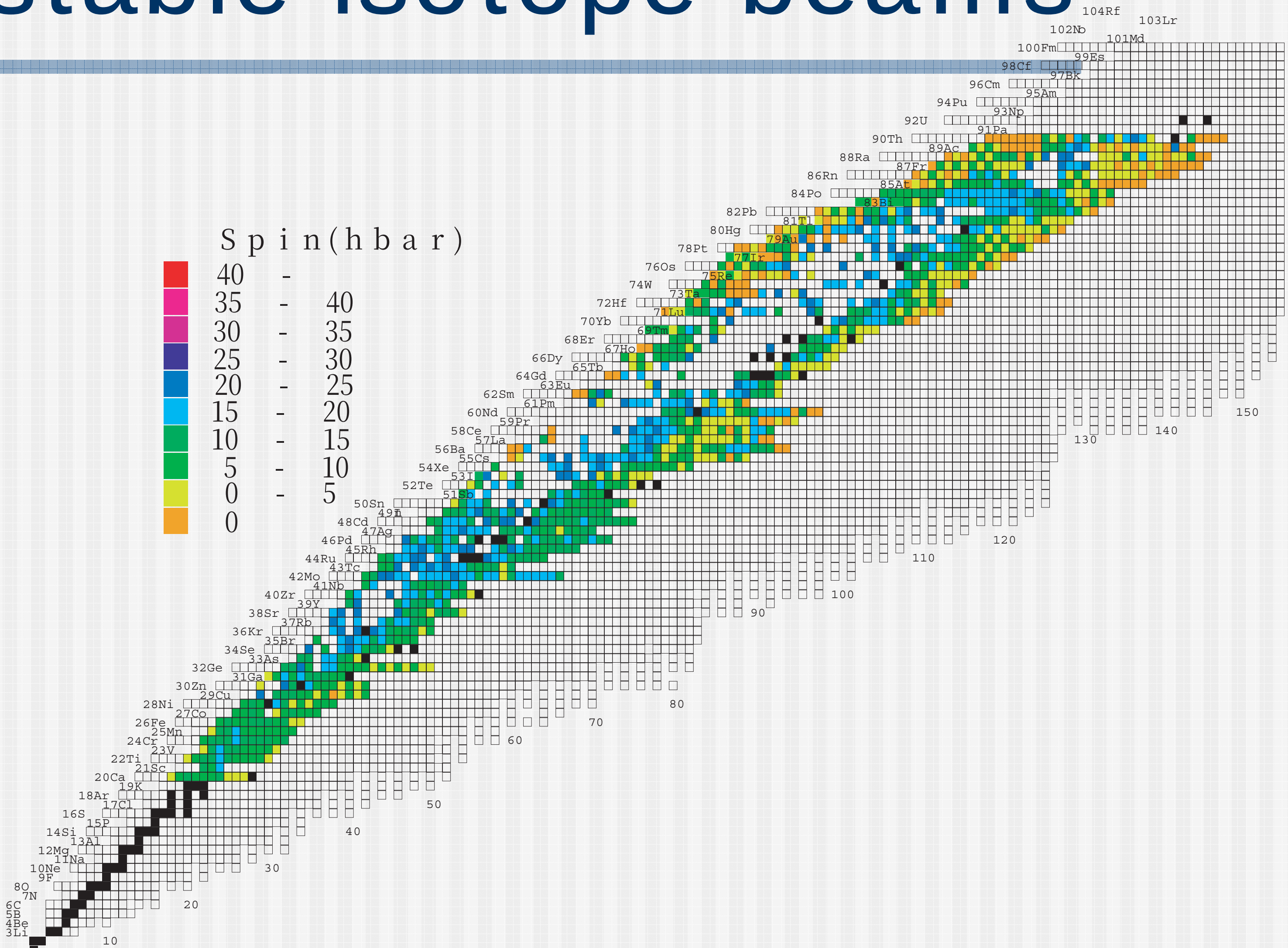
- Multiple Coulomb excitation of low-energy RI beam

Neutron-rich deformed nuclei

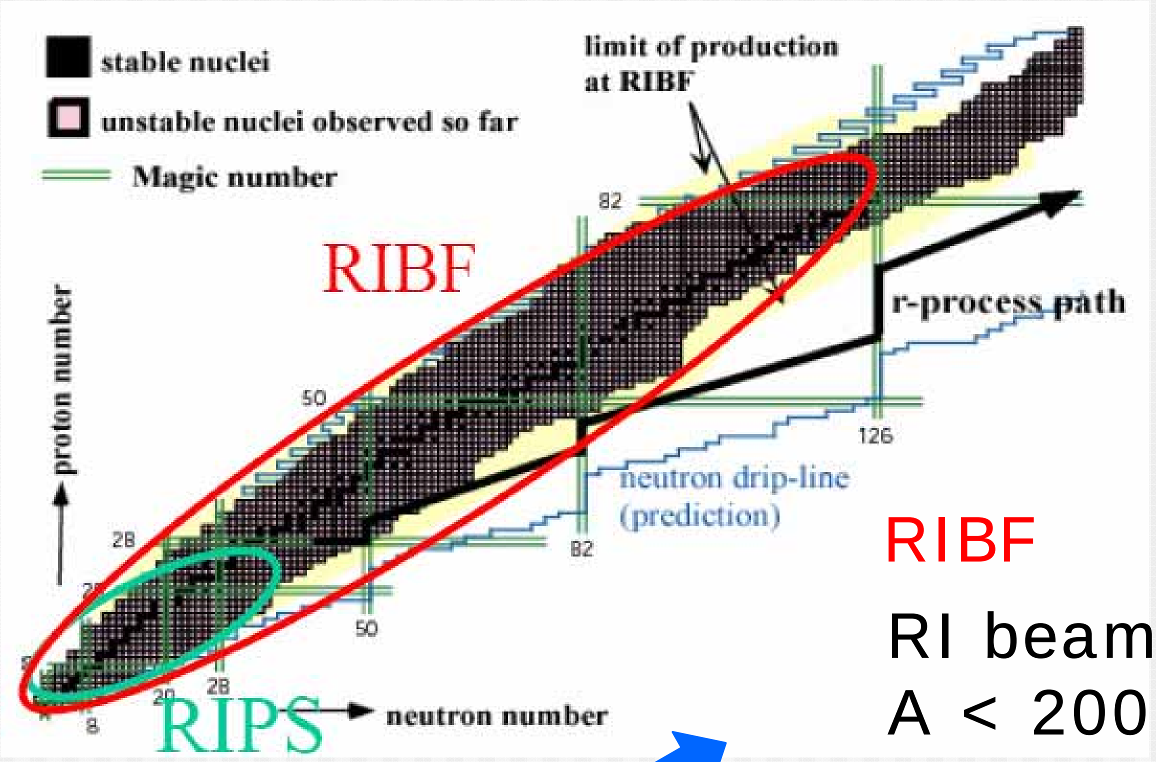
Region to be studied



High-spin study using stable isotope beams



RI Beam Factory

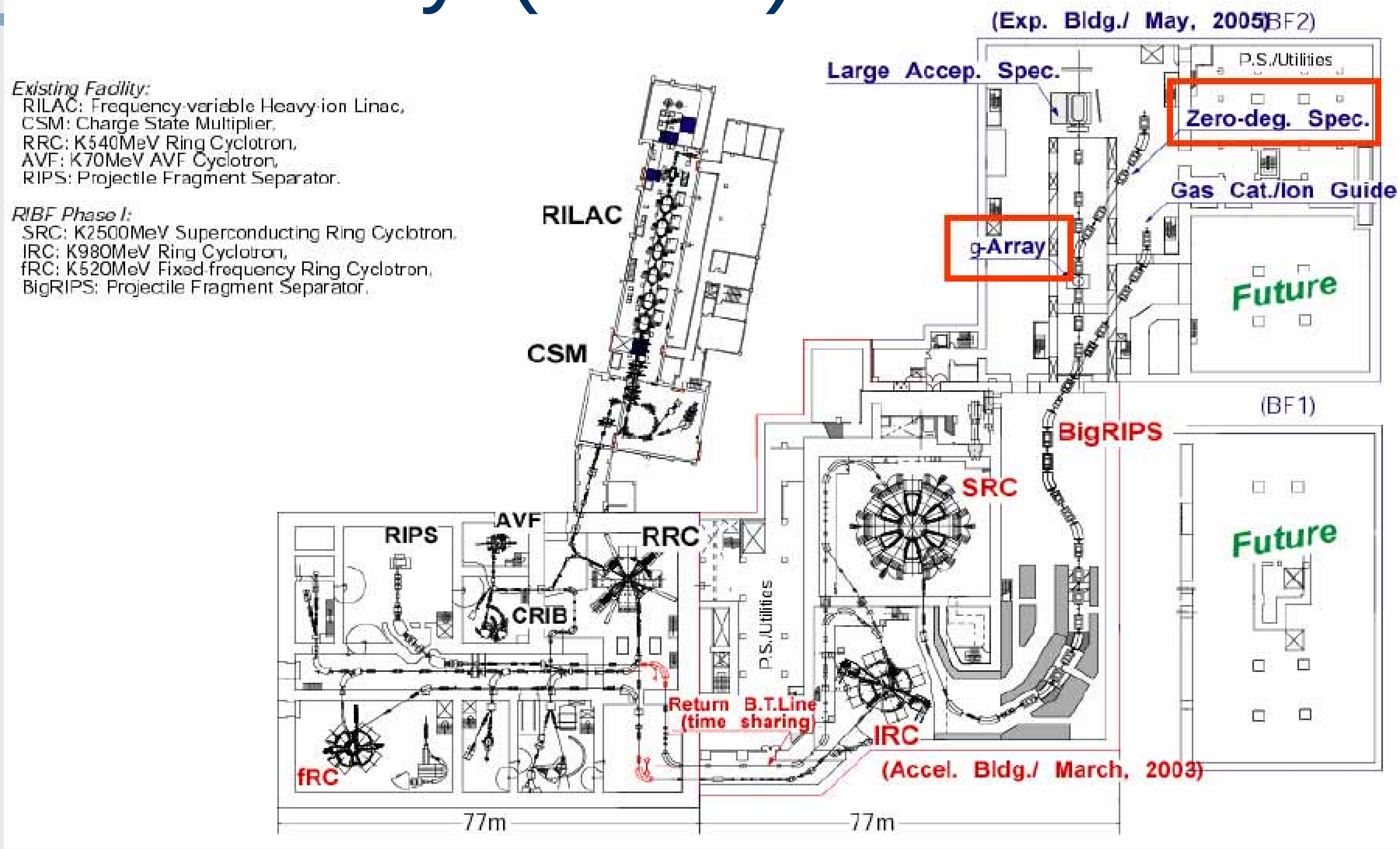


RI beams
A < 50
E ～ 50 MeV/A

RIBF

RI beams
A < 200
E ～ 250 MeV/A

Layout of the RI Beam Factory (RIBF)



Reactions for in-beam γ-ray spectroscopy at RIBF

- Intermediate energy RI-beams (～250MeV/A)
  → Coulomb excitation,
  Proton inelastic scattering,
  Fragmentation
  Knock-out reaction

- Deceleration with materials (5 ～ 30 MeV/A)
  → Transfer reactions
  Deep inelastic reactions
  Multiple Coulomb excitation
  Fusion reaction

End