# Observation of a long regular band structure in $^{89}$Zr

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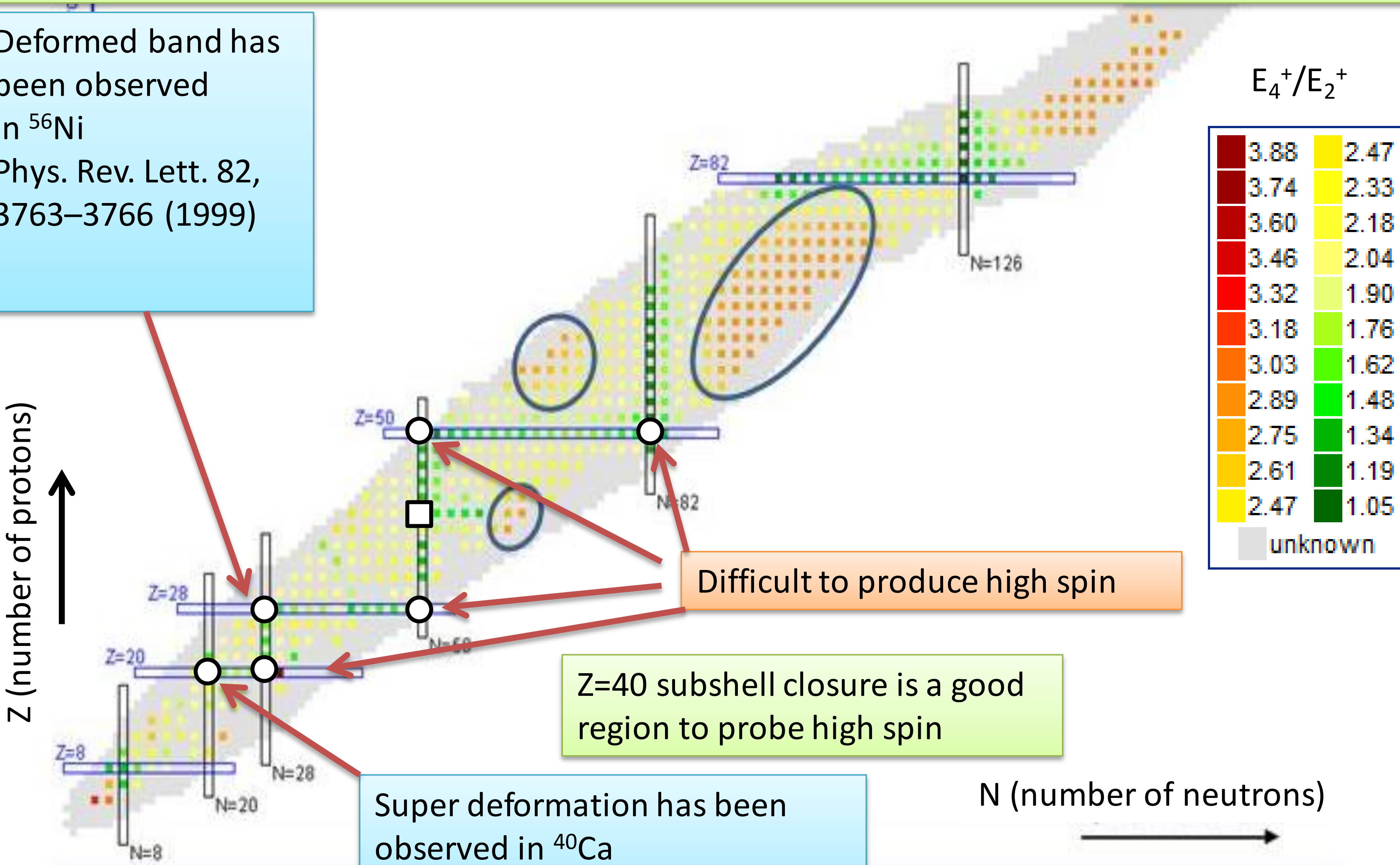
NUSPIN2017
26-29 June 2017
GSI

# Outline

- Motivation
- Experimental details
- Results
- Summary

# Ground state deformation of the nuclear landscape




Deformed band has been observed
In $^{56}$Ni
Phys. Rev. Lett. 82, 3763–3766 (1999)

Difficult to produce high spin

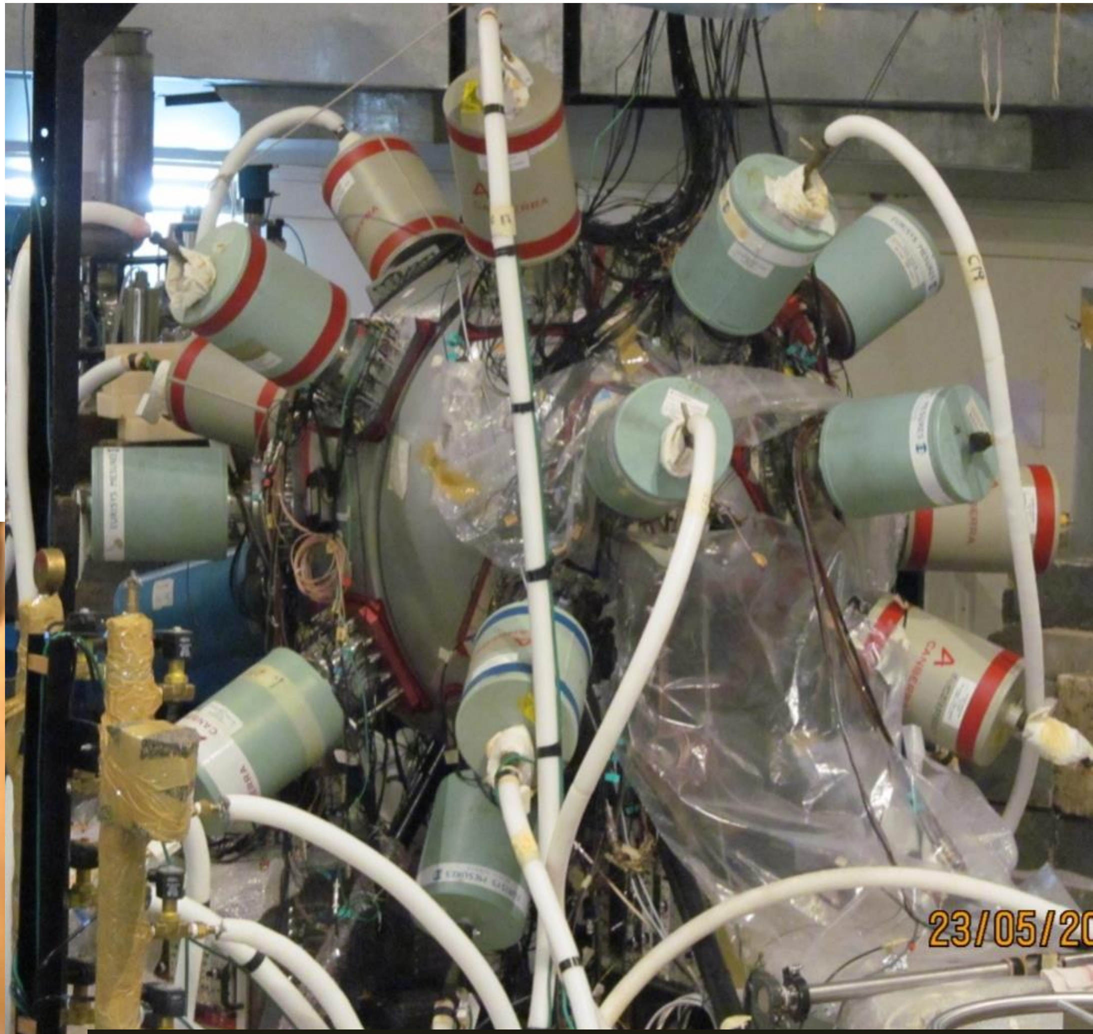
Z=40 subshell closure is a good region to probe high spin

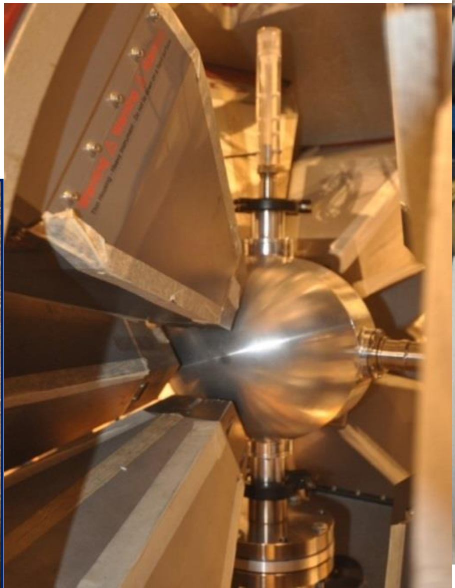
Super deformation has been observed in $^{40}$Ca
Phys Rev Lett. 87 (2001) 222501.

# Experimental Details

- 24 CS clover HPGe Detectors
- Efficiency 5% @ 1MeV
- Detectors at $23^{o}$, $40^{o}$, $65^{o}$, $90^{o}$, $115^{o}$, $140^{o}$ and $157^{o}$: Angular distribution
- Polarisation and DCO

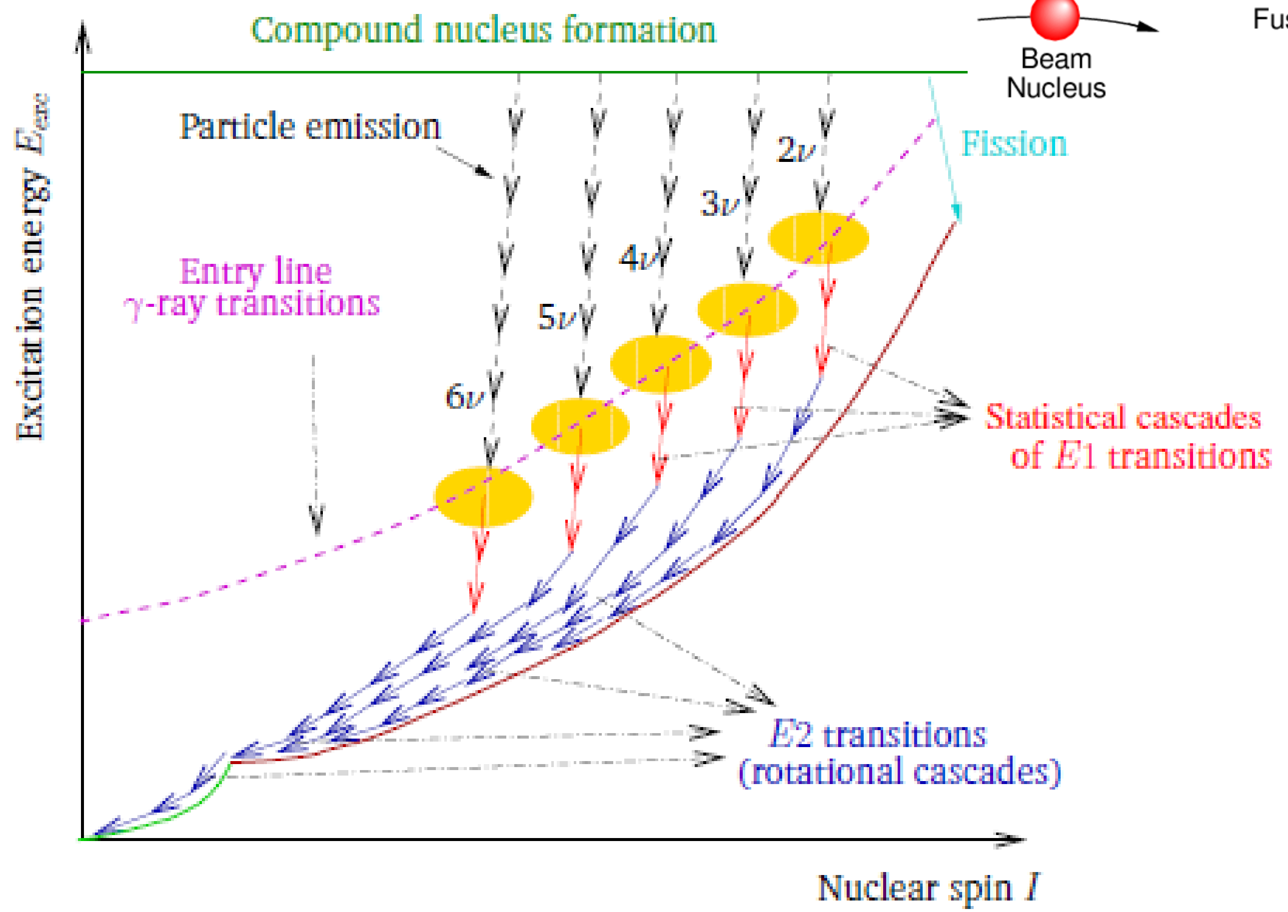
INGA@TIFR

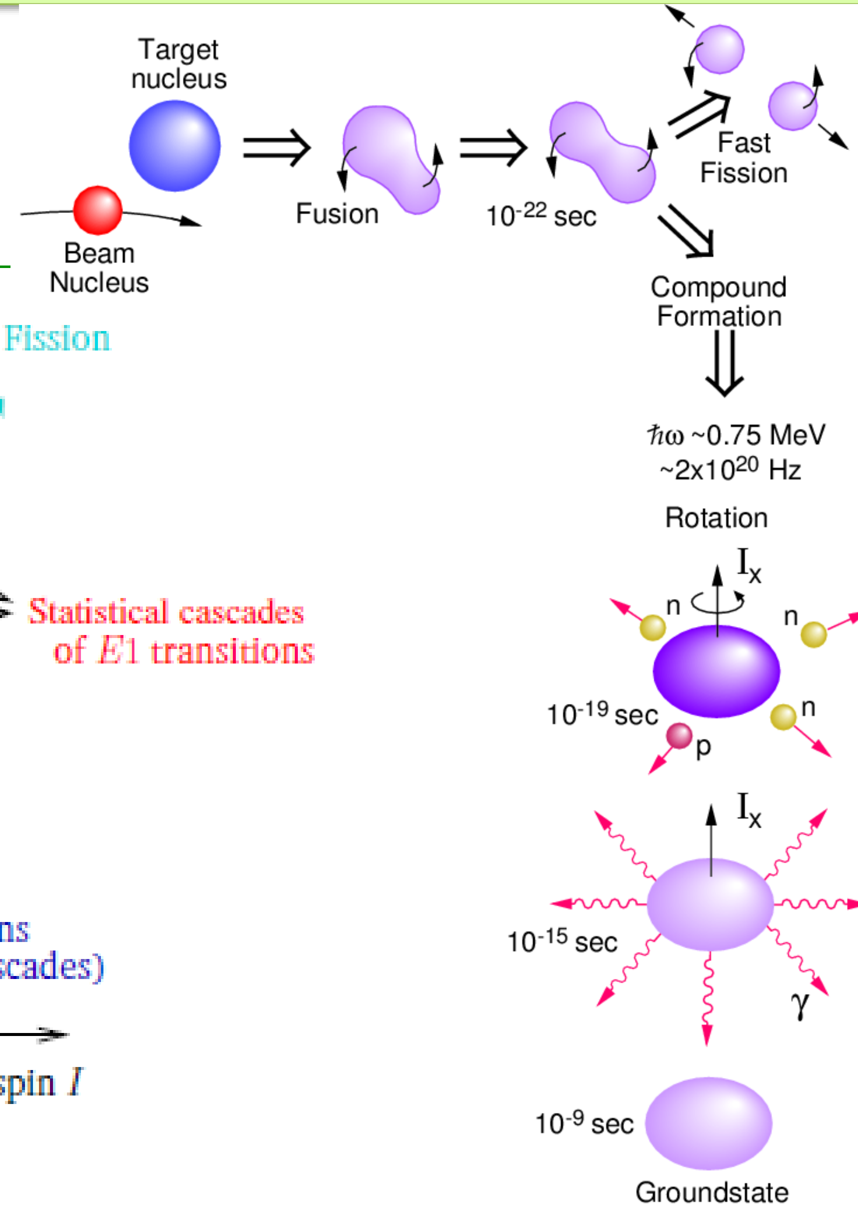


R. Palit *et. al*. Nucl. Inst. Meth. A **423,** 90 (2012)

# Reaction mechanism




Figs. taken from PhD. thesis of Ali Al-Khatib

# Fusion evaporation reaction to produce high spin states

Reaction: $^{13}C + {}^{80}Se$ @ 50, 60 MeV

Detectors: INGA with 18 clovers.

A total of $1 \times 10^9$ coincidence events with fold $f \geq 2$ were collected.

Target details: 1) Thick Target 800 μg/cm$^2$ $^{80}Se$ on 9 mg/cm$^2$ Au foil

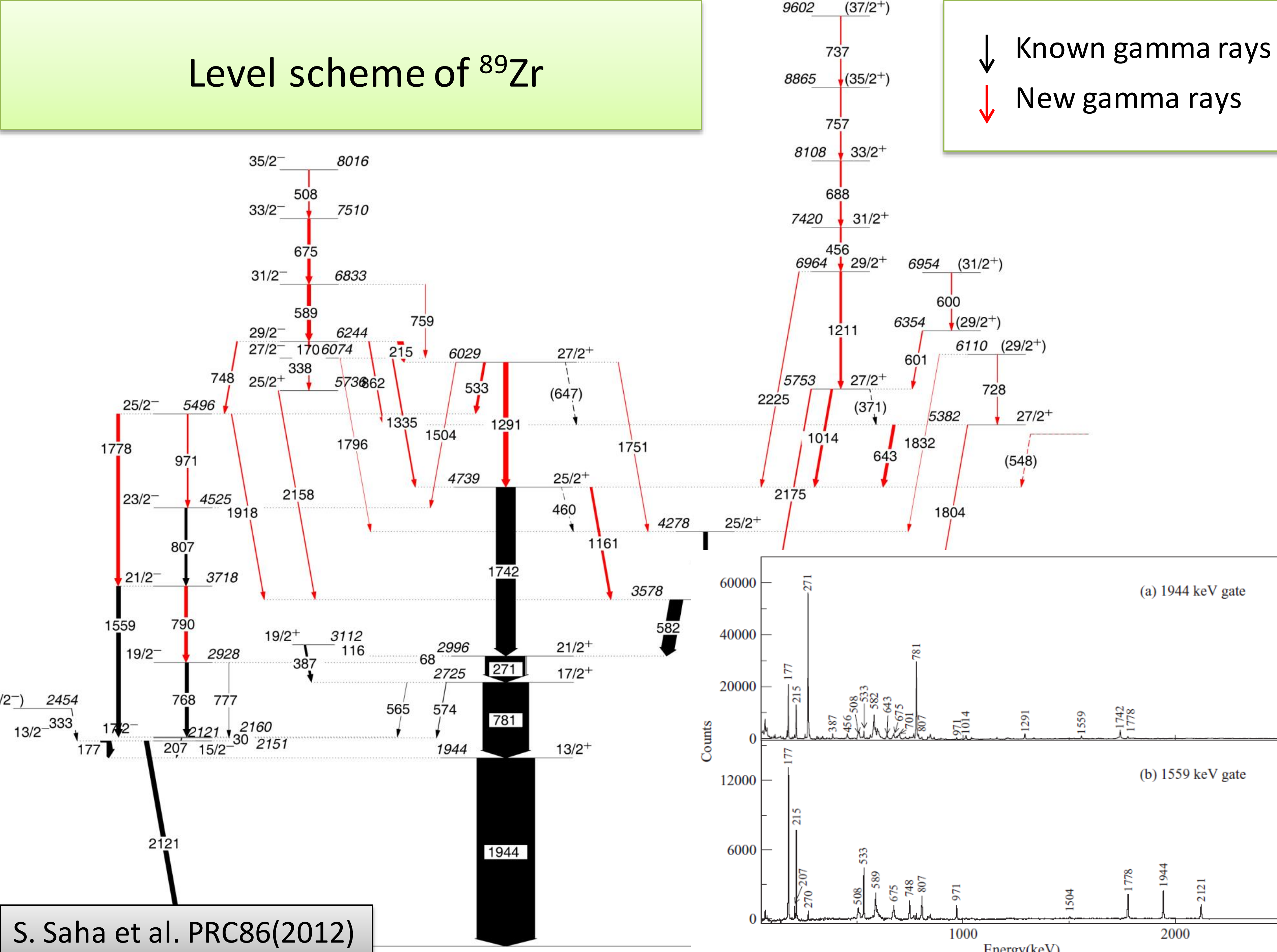
2) Thin Target 500 μg/cm$^2$ $^{80}Se$ on 80 μg/cm$^2$ Al foil

PHYSICAL REVIEW C 86, 034315 (2012)

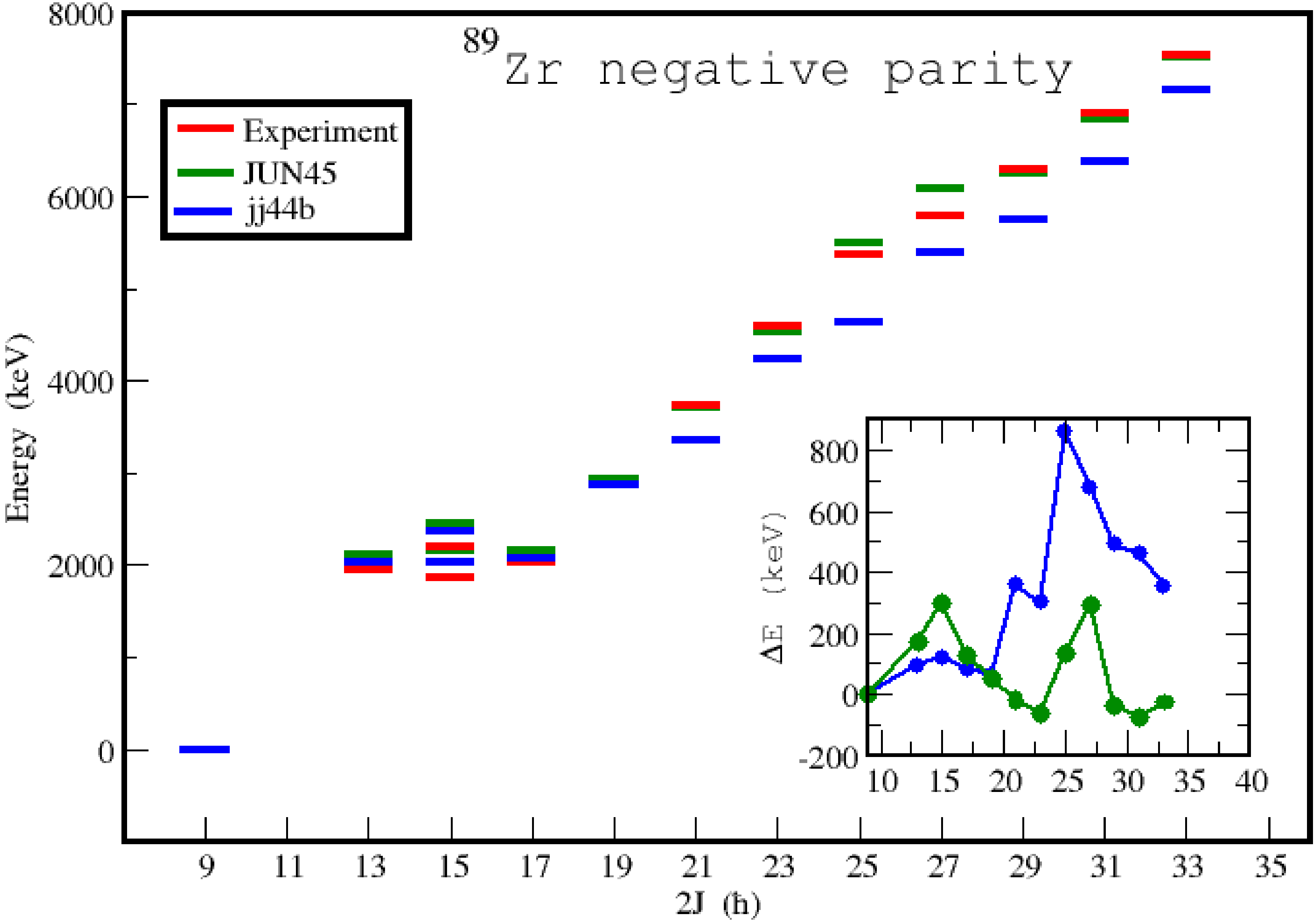
**Experimental investigation of shell-model excitations of $^{89}Zr$ up to high spin**

S. Saha,[1] R. Palit,[1,*] J. Sethi,[1] T. Trivedi,[1] P. C. Srivastava,[2] S. Kumar,[3] B. S. Naidu,[1] R. Donthi,[1] S. Jadhav,[1] D. C. Biswas,[4] U. Garg,[5] A. Goswami,[6] H. C. Jain,[1] P. K. Joshi,[1,†] G. Mukherjee,[7] Z. Naik,[8] S. Nag,[9] V. Nanal,[1] R. G. Pillay,[1] S. Saha,[6] and A. K. Singh[9]

# Level scheme of $^{89}Zr$

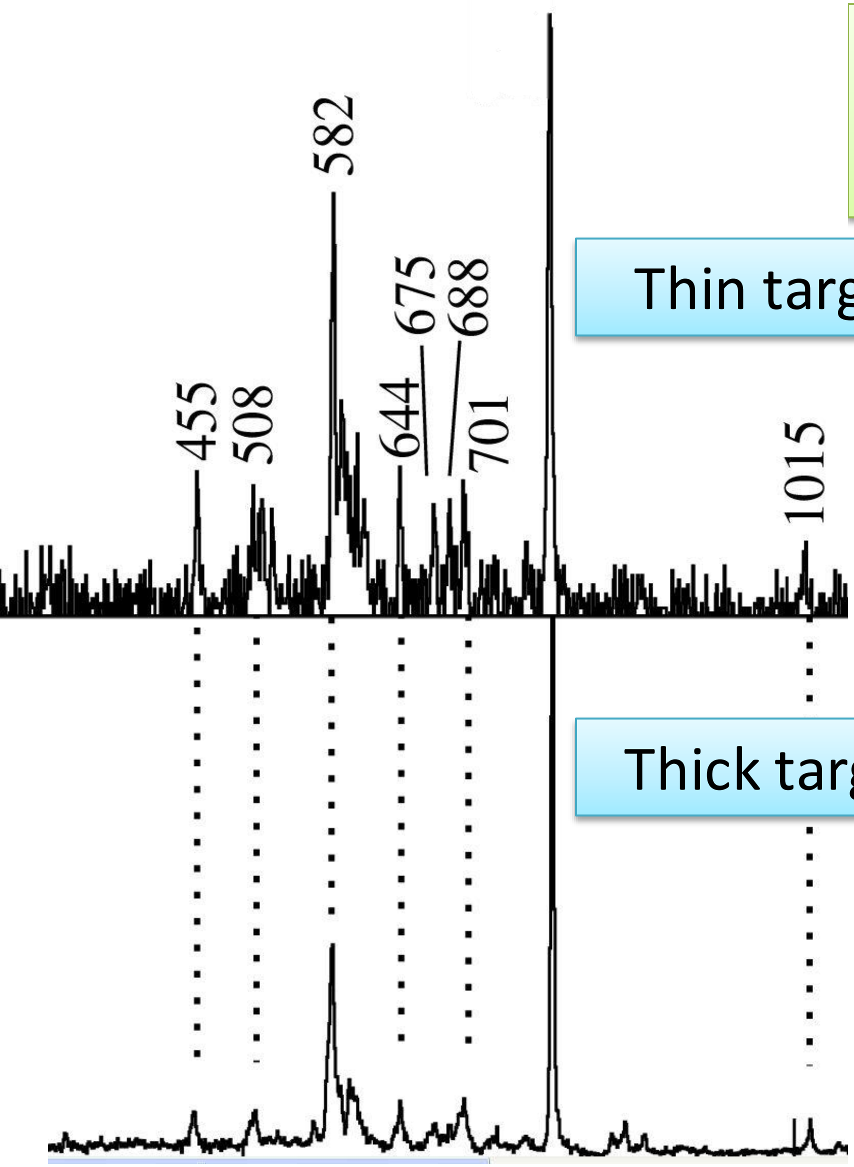



S. Saha et al. PRC86(2012)

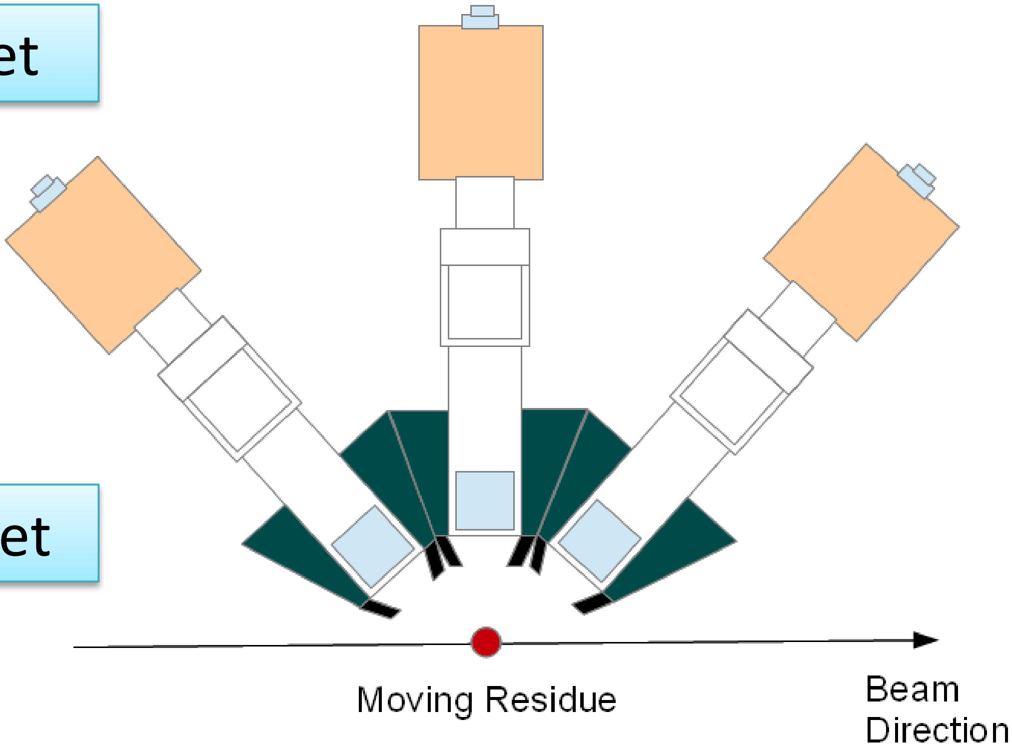


89Zr negative parity
Experiment
JUN45
jj44b
Energy (keV)
8000
6000
4000
2000
0
9
11
13
15
17
19
21
23
25
27
29
31
33
35
2J (h)
ΔE (keV)
800
600
400
200
0
-200
10
15
20
25
30
35
40

# Search for higher spin states: problem and solution



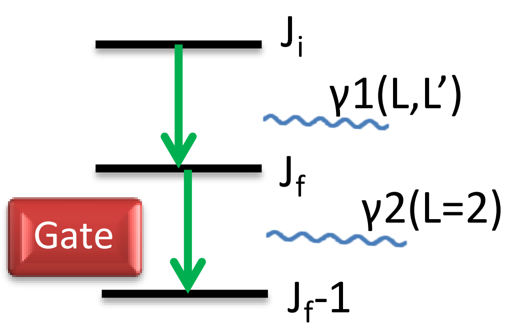

If the residue is allowed to escape the target Doppler shift of emitted ϒ-ray can be corrected. Resolution of fast transitions improves.




$$E_S = E_o\,(1 + v/c \cos\theta\ )$$

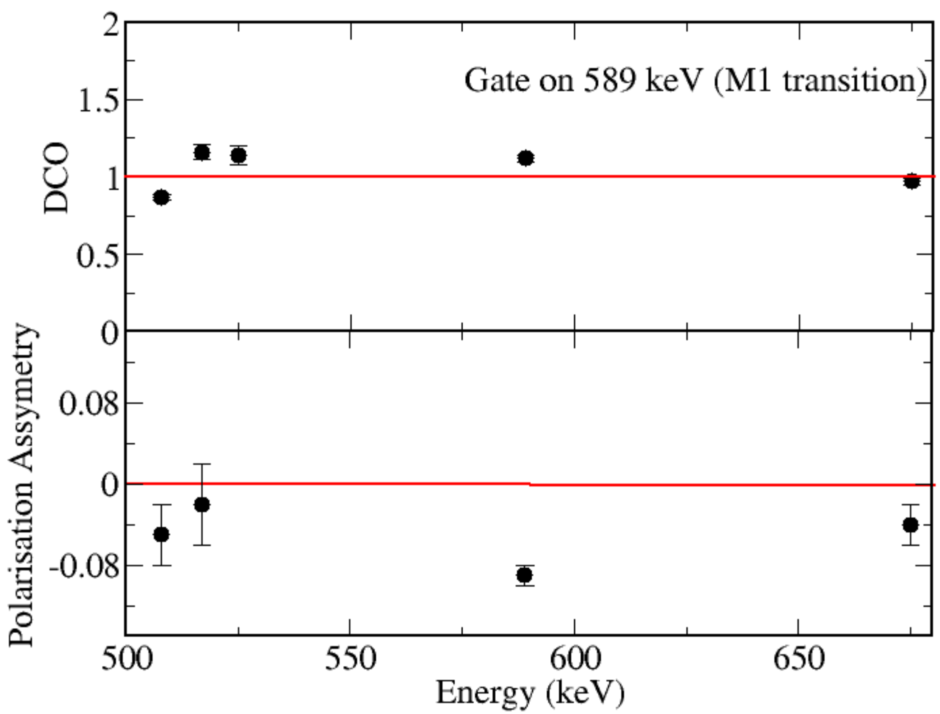
$$\Delta E_S = E_o\, v/c \sin\theta\, \Delta\theta$$

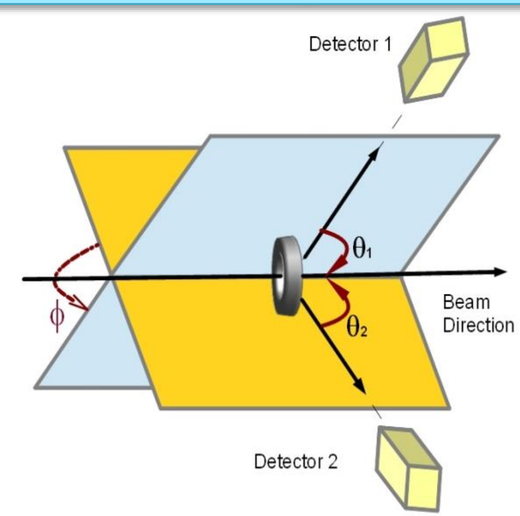
# DCO and polarisation asymmetry measurement



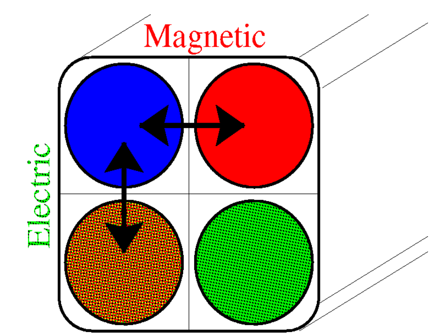

For INGA geometry

$$R_{DCO} = \frac{I(\gamma_1)\,observed\ at\ 157°\ gated\ on\ \gamma_2\ at\ 90°}{I(\gamma_1)\,observed\ at\ 90°\ gated\ on\ \gamma_2\ at\ 157°}$$

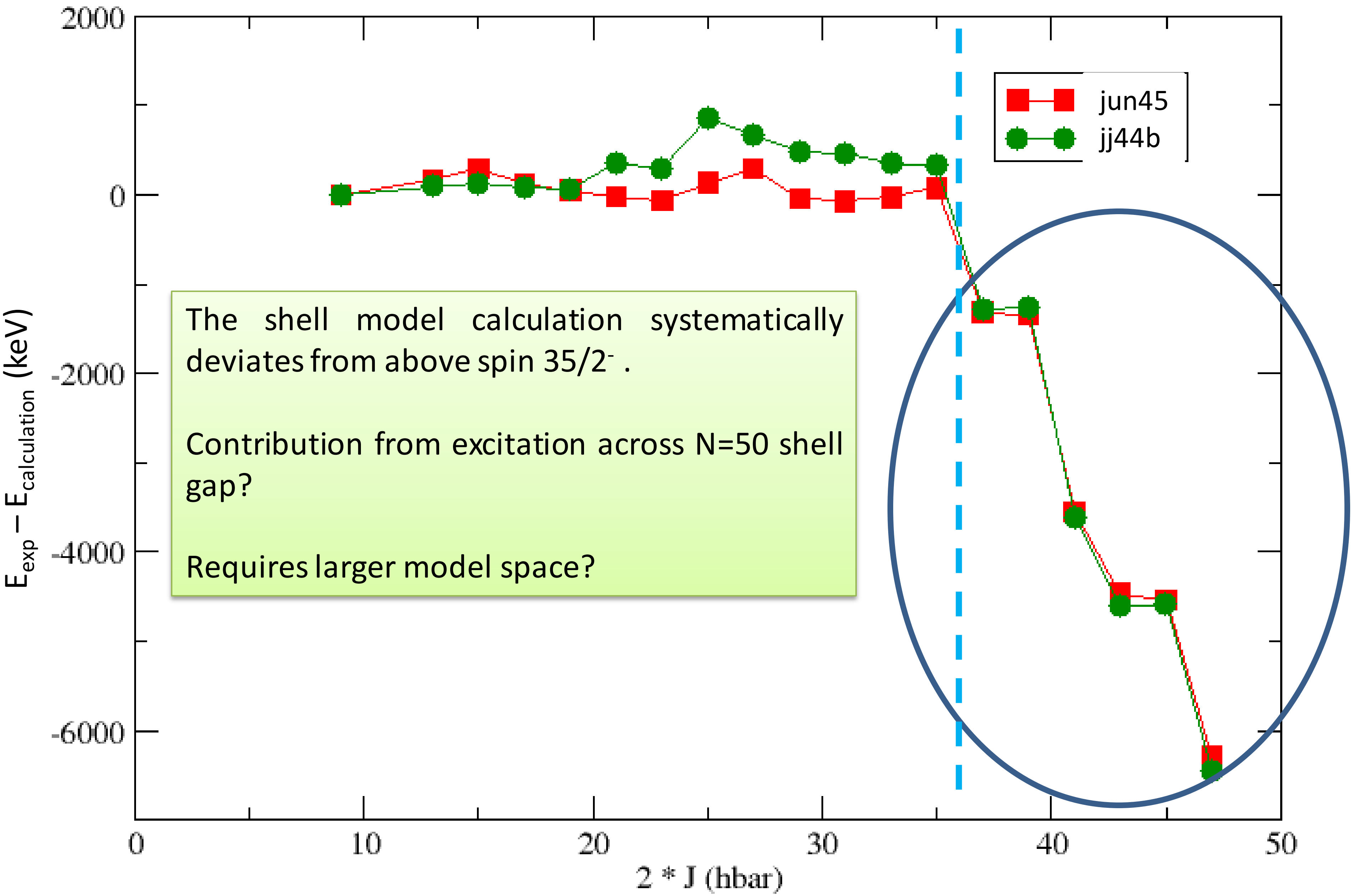



$$A = \frac{aN_{\perp} - N_{\parallel}}{aN_{\perp} + N_{\parallel}},$$




Transitions are M1 in nature



2000
0
-2000
-4000
-6000
0
10
20
30
40
50
2 * J (hbar)
$E_{exp} - E_{calculation}$ (keV)
jun45
jj44b
The shell model calculation systematically deviates from above spin 35/2⁻ .
Contribution from excitation across N=50 shell gap?
Requires larger model space?

# Configuration dependent Cranked Nilsson Strutinsky (CNS) approach

$$h_0^w = h_0 - \hbar w j_x$$

$h_0$ is the nucleon hamiltonian in the lab frame

$j_x$ is the component of total angular momentum of individual nucleon in the rotational axis

$$E_{tot}(\epsilon, J_0) = E_{RLD}(\epsilon, J_0) + E_{sh}(\epsilon, J_0)$$

$$E_{RLD}(Z,N,J,\epsilon) = E_{LD}(Z,N,J,\epsilon) + \frac{\hbar^2 J(J+1)}{2\Im_{rig}(Z,N,J,\epsilon)} \quad (2.27)$$

where, $E_{LD}$ is the static liquid drop energy and $\Im_{rig}$ is the rigid body moment of inertia. The static liquid drop energy of the nucleus can be given by the expression [51],

$$E_{LD} = -a_{vol}(1-k_{vol}T^2)A + \frac{3e^2Z^2}{5R_c}B_{Coul}(\epsilon) - C_4\frac{Z^2}{A} + a_{surf}(1-k_{surf}T^2)A^{2/3}B_{surf}(\epsilon) + b_{cur}(1-k_{cur}T^2)A^{1/3}B_{cur}(\epsilon) \quad (2.28)$$

where,

$$B_{Coul}(\epsilon) = E_{Coul}(\epsilon)/E_{Coul}(\epsilon=0)$$
$$B_{surf}(\epsilon) = E_{surf}(\epsilon)/E_{surf}(\epsilon=0)$$
$$B_{cur}(\epsilon) = E_{cur}(\epsilon)/E_{cur}(\epsilon=0)$$

are the Coulomb, surface, and curvature energies, respectively. The $T = \frac{N-Z}{A}$ denotes the isospin factor. The other terms are liquid drop model parameters obtained from fit to the experimental binding energies given by [51],

$$a_{vol} = -15.4920 \text{ MeV}, \quad k_{vol} = 1.8601,$$
$$a_{surf} = 16.9707 \text{ MeV}, \quad k_{surf} = 2.2938,$$
$$R_c = 1.21725\, A^{1/3} \text{ fm}, \quad C_4 = 0.9181 \text{ MeV},$$
$$b_{cur} = 3.8602 \text{ MeV}, \quad k_{cur} = -2.3764$$

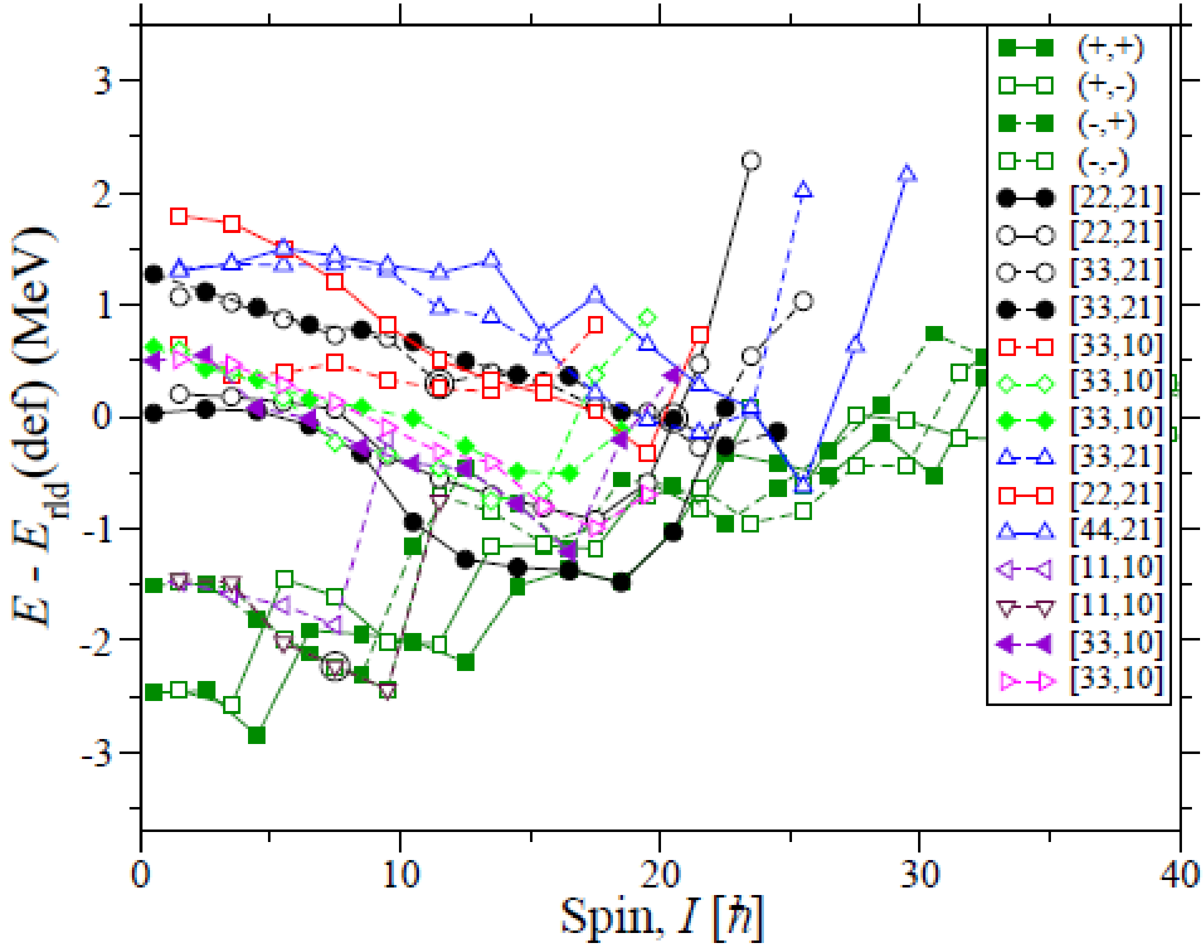
The shell energy term of Eq. 2.25 is the difference between the discrete and smooth single particle energy sums and can be written as,

$$E_{sh}(\epsilon, J_0) = \sum e_i(w,\epsilon)|_{J=J_0} - \sum \widetilde{e_i(\tilde{w},\epsilon)}|_{J=J_0} \quad (2.29)$$

The smooth sum is calculated using Strutinsky procedure [49], which can be parameterized as,

$$e_i(\tilde{w},\epsilon)|_{J=J_0} = E_0 + \frac{1}{2\Im_{str}(\epsilon)}J_0^2 + bJ_0^4 \quad (2.30)$$

where, $\Im_{str}(\epsilon)$ is the (Strutinsky) smoothed moment of inertia and $E_0 = e_i(\tilde{w},\epsilon)|_{J=0}$. The constants, $E_0$, $\Im_{str}$ and b are determined by calculating the smoothed sum at different frequencies. The CNS formalism does not consider pairing hence it should be ideal for high spin states where the pairing interaction is quenched.




Nomenclature: [p1p2, n1n2]

p1 -> proton holes in fp

p2 -> proton particles in $g_{9/2}$

n1 -> neutron holes in $g_{9/2}$

n2 -> neutron particle in gd

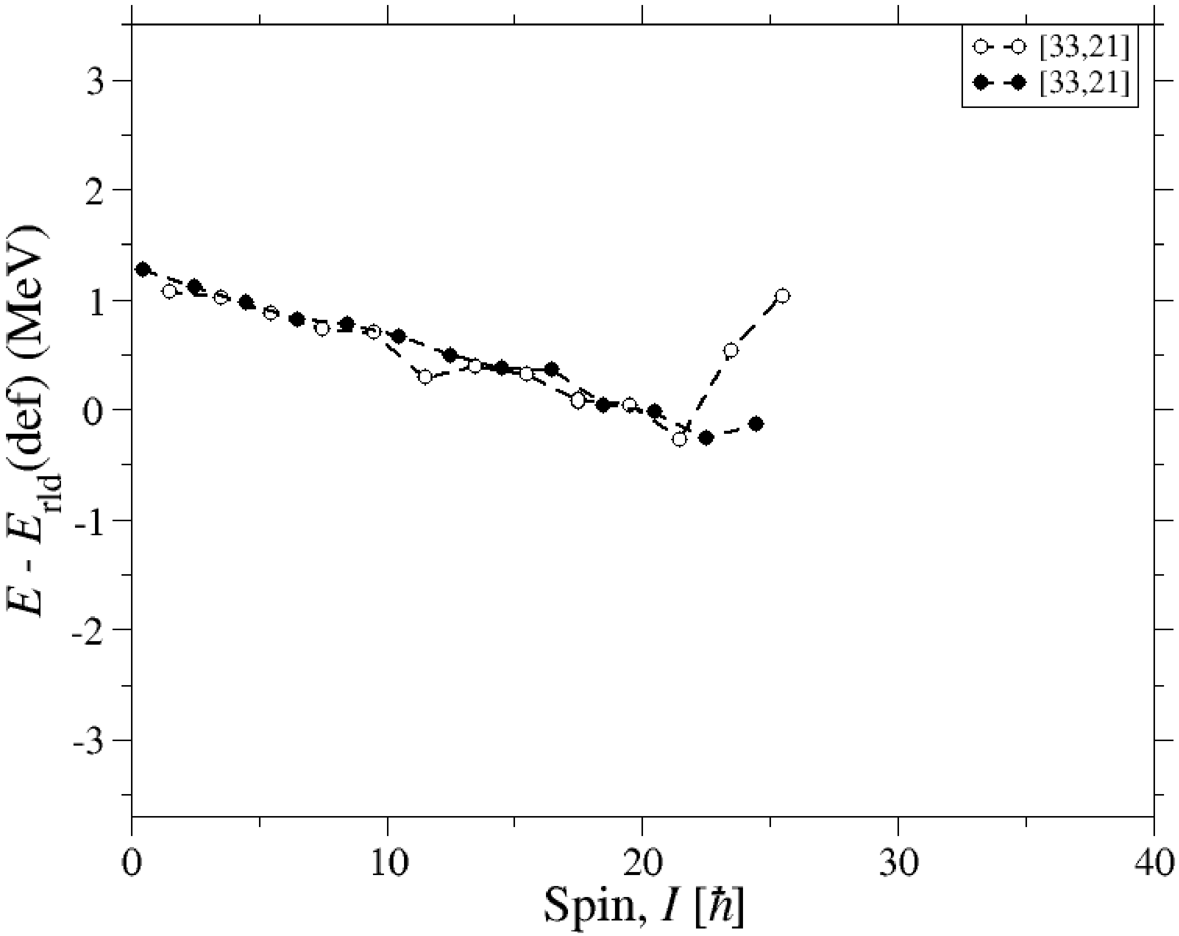
Filled markers rep. $\alpha = 0$

Open markers rep. $\alpha = 1$

Solid line rep. $\pi = +1$

Dashed line rep. $\pi = -1$

FIG. 4: (Color online) Calculated excitation energy relative to a rotating liquid drop energy as a function of spin in $^{89}$Zr. The closed and the open circles represents the ($\alpha = 1$ ) and the ($\alpha$=0) states respectively. The dashed lines are for negative parity states whereas the solid lines represent configurations with positive parity. The various cominbation of signature and parity for the yrast energies in $^{89}$Zr is shown by +, + and so on. Aligned states are encircled.

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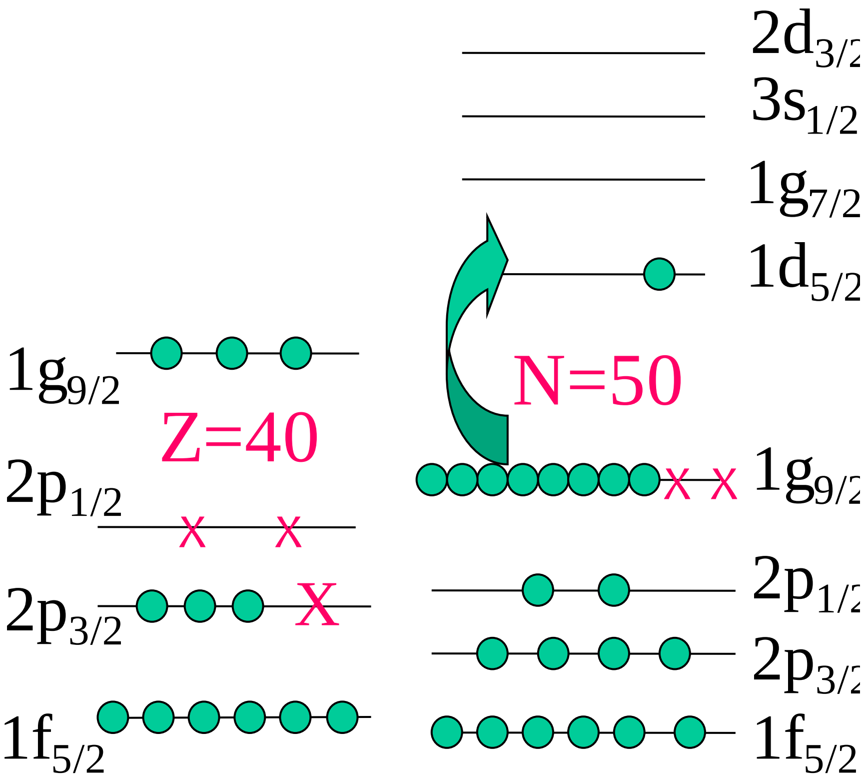
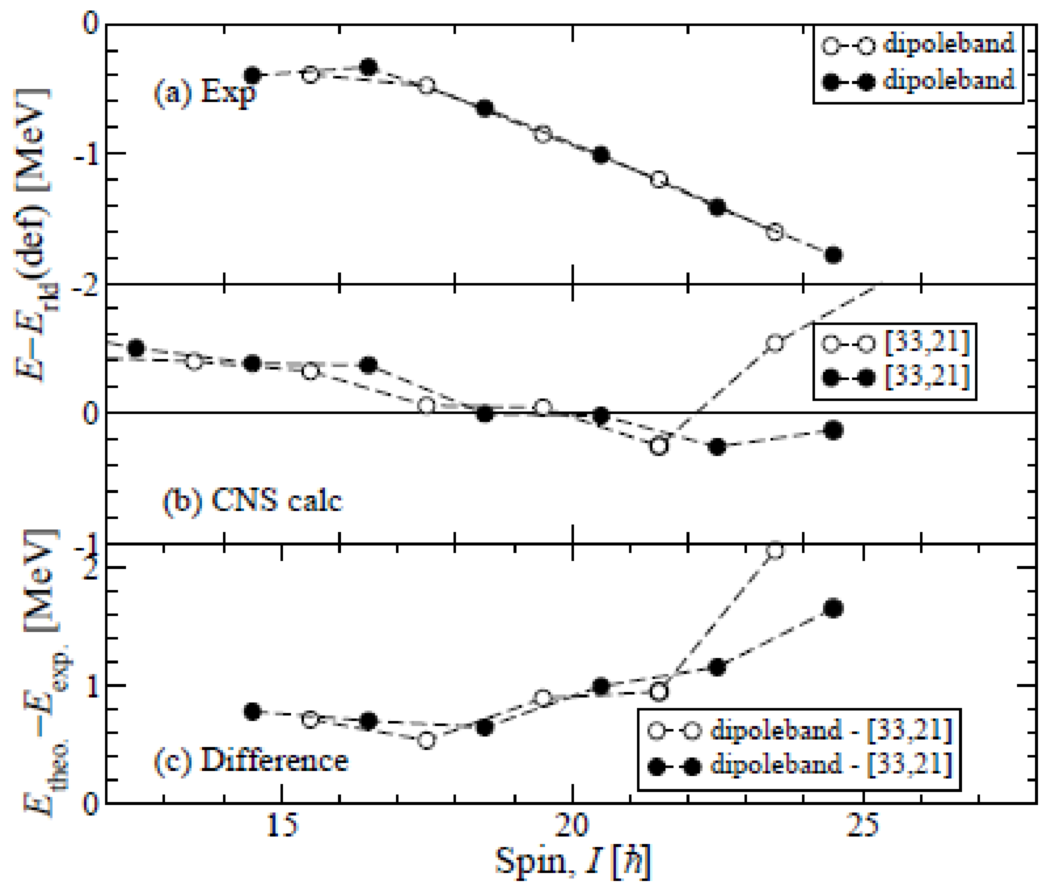
Solid line rep. $\pi = +1$

Dashed line rep. $\pi = -1$

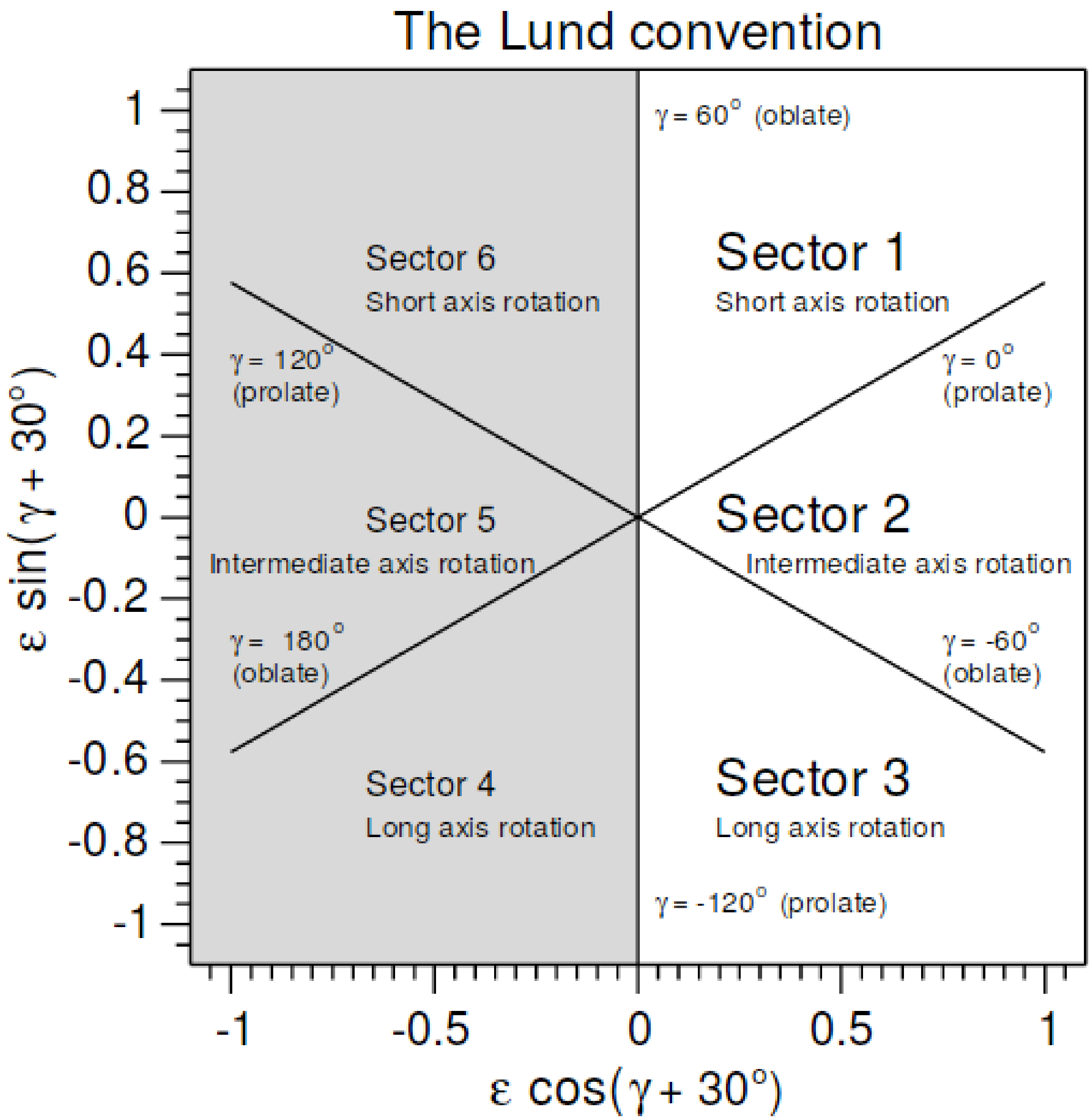
# Cranking calculations using Multi-quasi-particle configurations

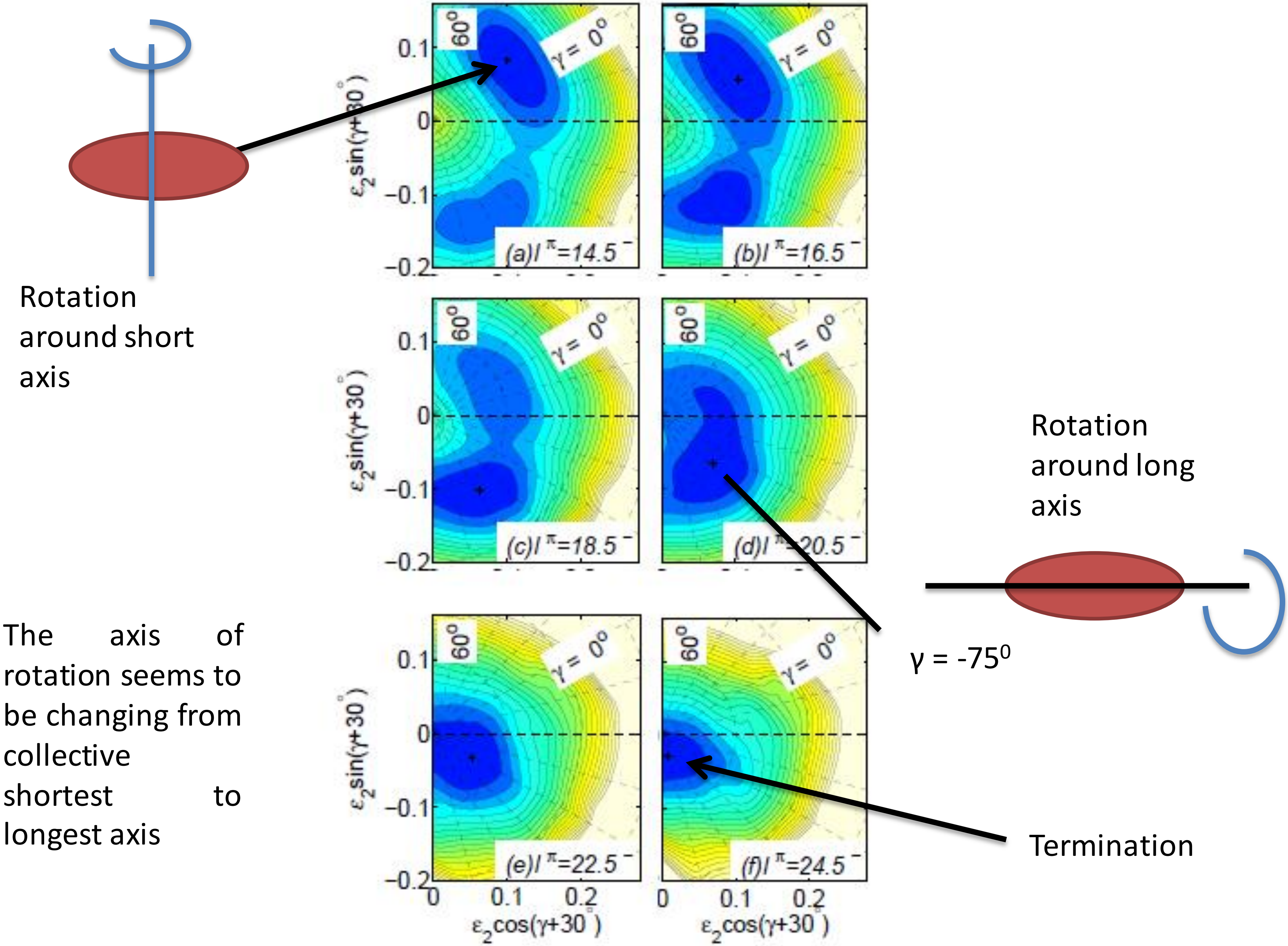
Excitation energy relative to a rotating liquid Drop w.r.t. spin for the observed negative parity Dipole band.



# Potential Energy Surface –The Lund Convention





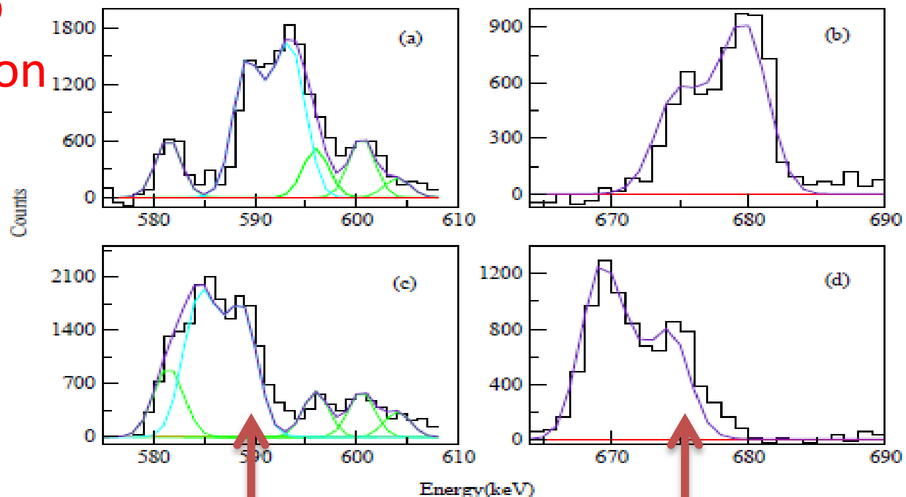
Rotation around short axis
The axis of rotation seems to be changing from collective shortest to longest axis
60°
γ = 0°
(a) $I^\pi$=14.5⁻
(b) $I^\pi$=16.5⁻
(c) $I^\pi$=18.5⁻
(d) $I^\pi$=20.5⁻
(e) $I^\pi$=22.5⁻
(f) $I^\pi$=24.5⁻
$\varepsilon_2\sin(\gamma+30^\circ)$
$\varepsilon_2\cos(\gamma+30^\circ)$
0.1
0
−0.1
−0.2
0.2
Rotation around long axis
γ = -75⁰
Termination

# Lifetime measurement using Doppler Shift Attenuation Method

Angle w.r.to Beam direction

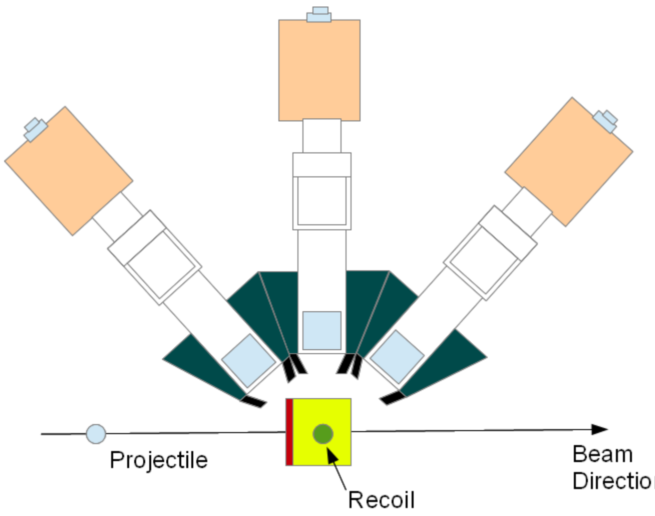
40°

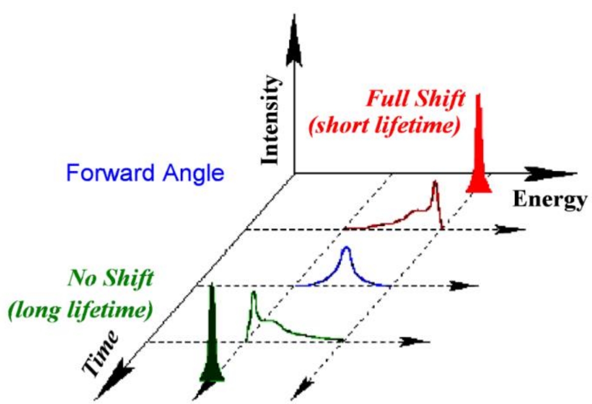
140°

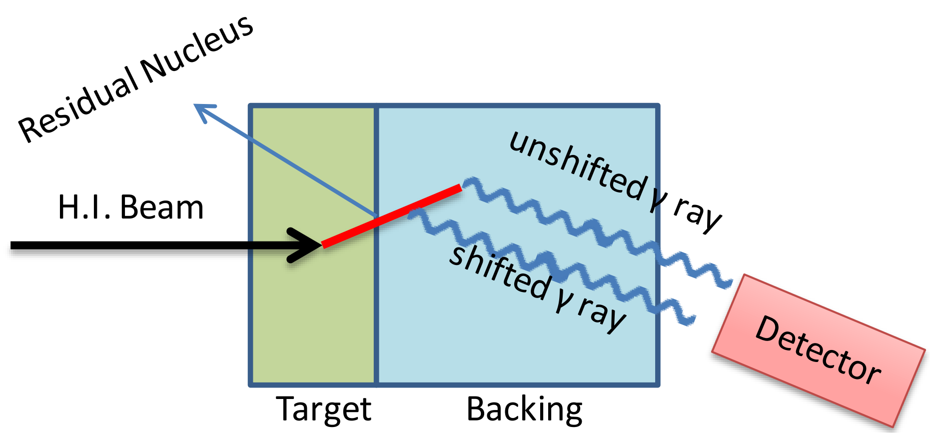



589 keV

675 keV



# Summary

- The excited levels of $^{89}Zr$ have been observed up to ~ 12 MeV excitation energy.
- Shell model calculation provide good agreement up to $35/2^{-}$ ħ.
- Evidence of cross shell excitation is observed at higher spin.
- Lifetime measurement has been performed for 5 levels.
- A regular band with 10 transition is observed at high spin – outside the scope of $f_5pg_9$ model space.
- CNS calculation gives good agreement to the observation.
- Particle excitation across N=50 shell gap is expected.
- The Potential energy surface (PES) plot indicates axis of rotation changing from shortest to longest axis of rotation before termination.

# Collaboration
# and
# Acknowledgement

| | | |
|---|---|---|
| R.Palit, J.Sethi, S. Biswas | ---TIFR, Mumbai, India | |
| A. K. Singh | ---IIT Kharagpur, India | CNS Calculation |
| S. Nag | ---NIT Raipur, India | |
| Z. Naik | ---Sambalpur University, India | HFB Calculation |
| P.C. Srivastava | ---IIT Roorkee, India | Shell Model Calculation |
| INGA Collaboration | | |

The authors are highly indebted to Prof. I. Ragnarsson for his advices and suggestions regarding cranked Nilsson Strutinsky calculations as well as theoretical interpretations of the observed phenomenon.

Thanks to Pelletron Linac Facility at TIFR for good quality beam.

**Thank You**