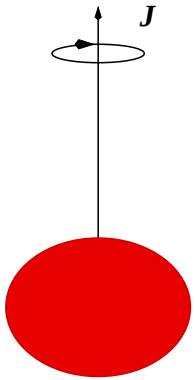
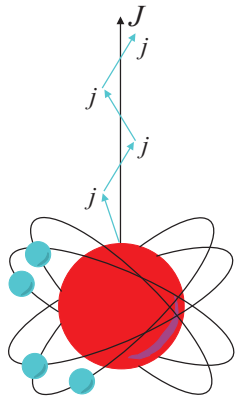
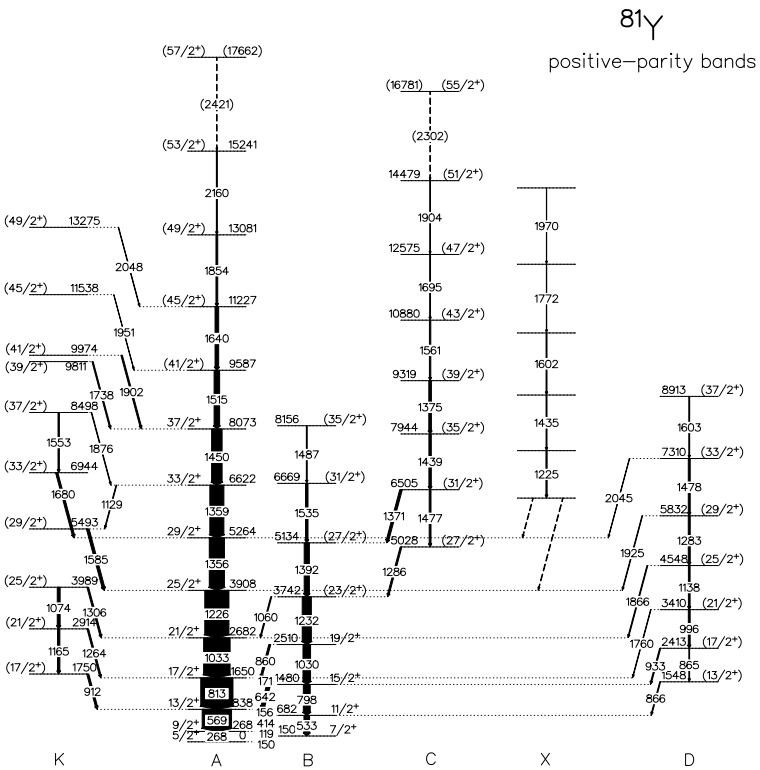
EXPERIMENTS ON NUCLEAR ROTATION

- Experiments with multidetector systems (EUROBALL, GASP)
- Collective rotation in deformed nuclei
- Signature inversion, band termination
- Magnetic rotation in weakly deformed nuclei
- Spin coupling in few-particle excitations in nearly spherical nuclei

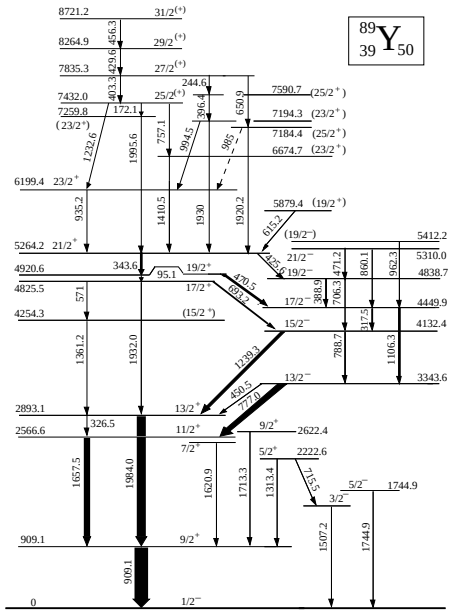
The two ways that a nucleus can generate angular momentum





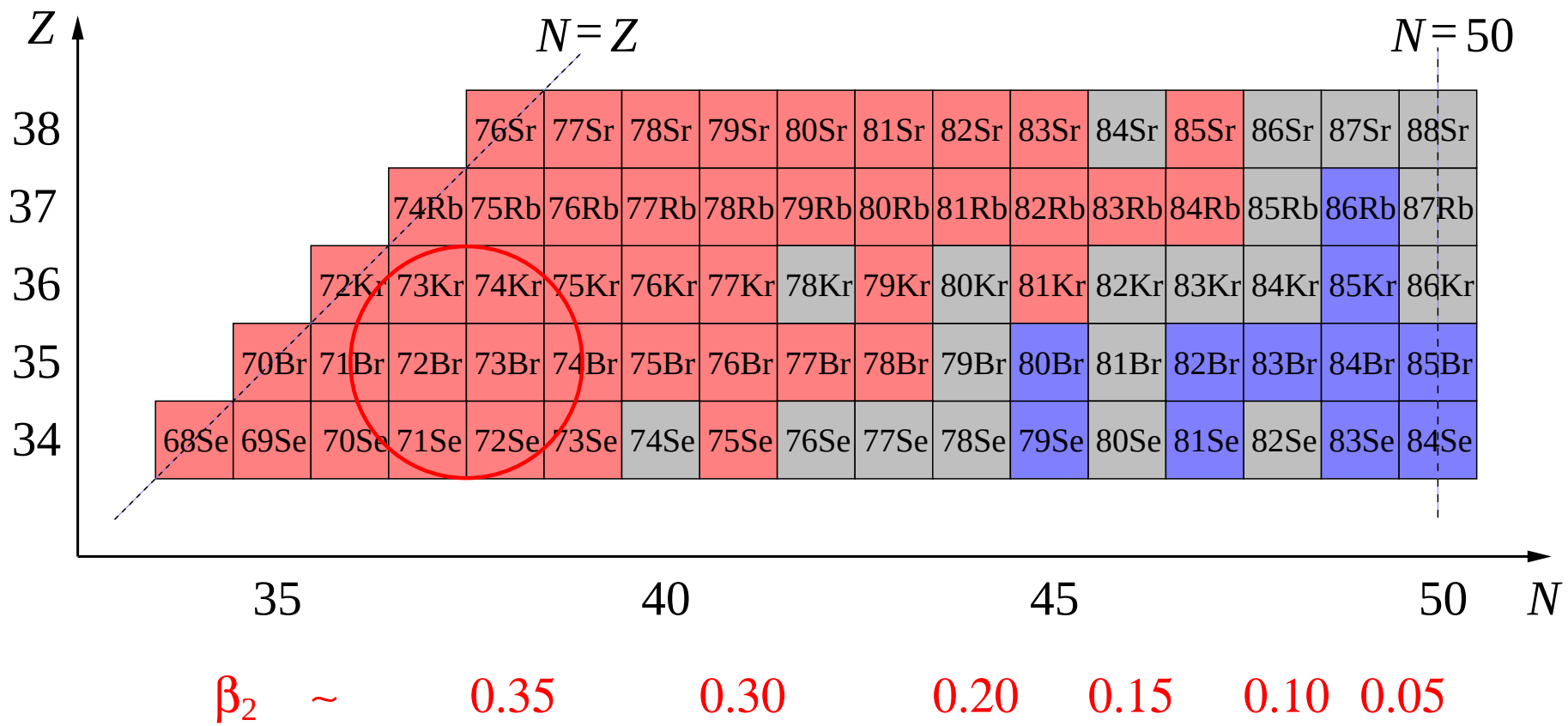


collective (classical) in deformed nuclei



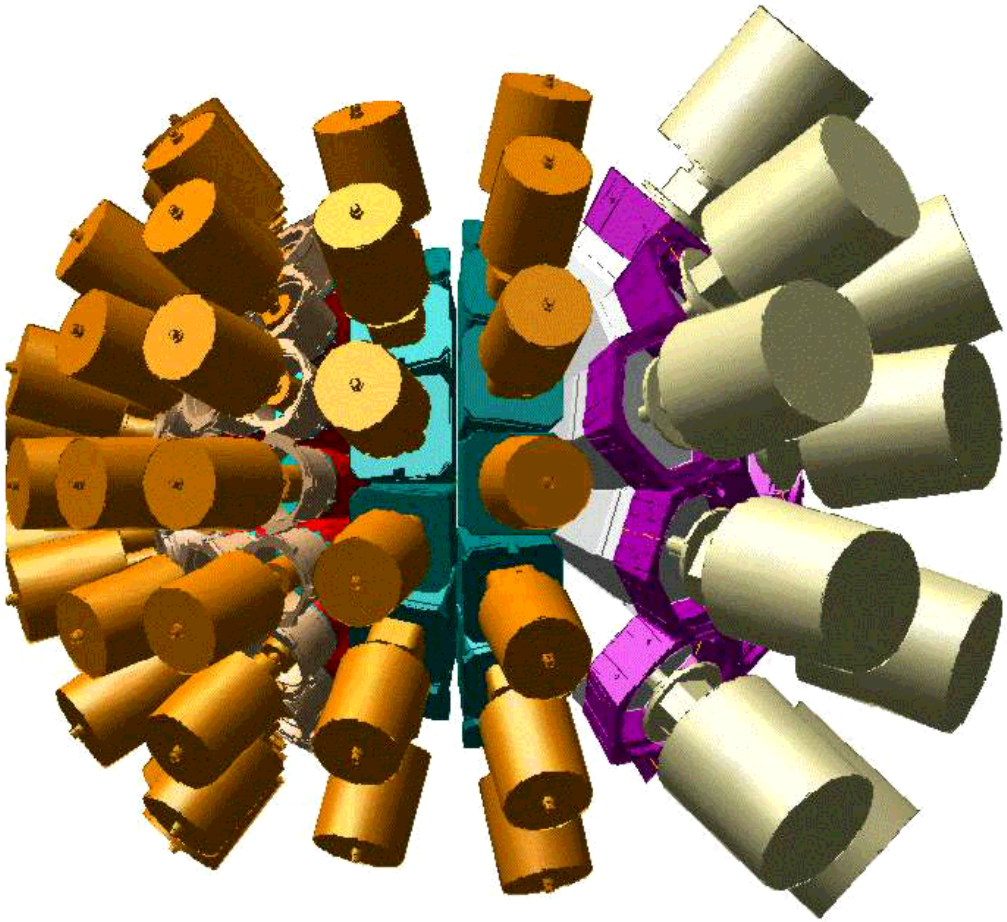
noncollective (quantal) in nearly spherical nuclei

Nuclear chart around A ≈ 70 - 90

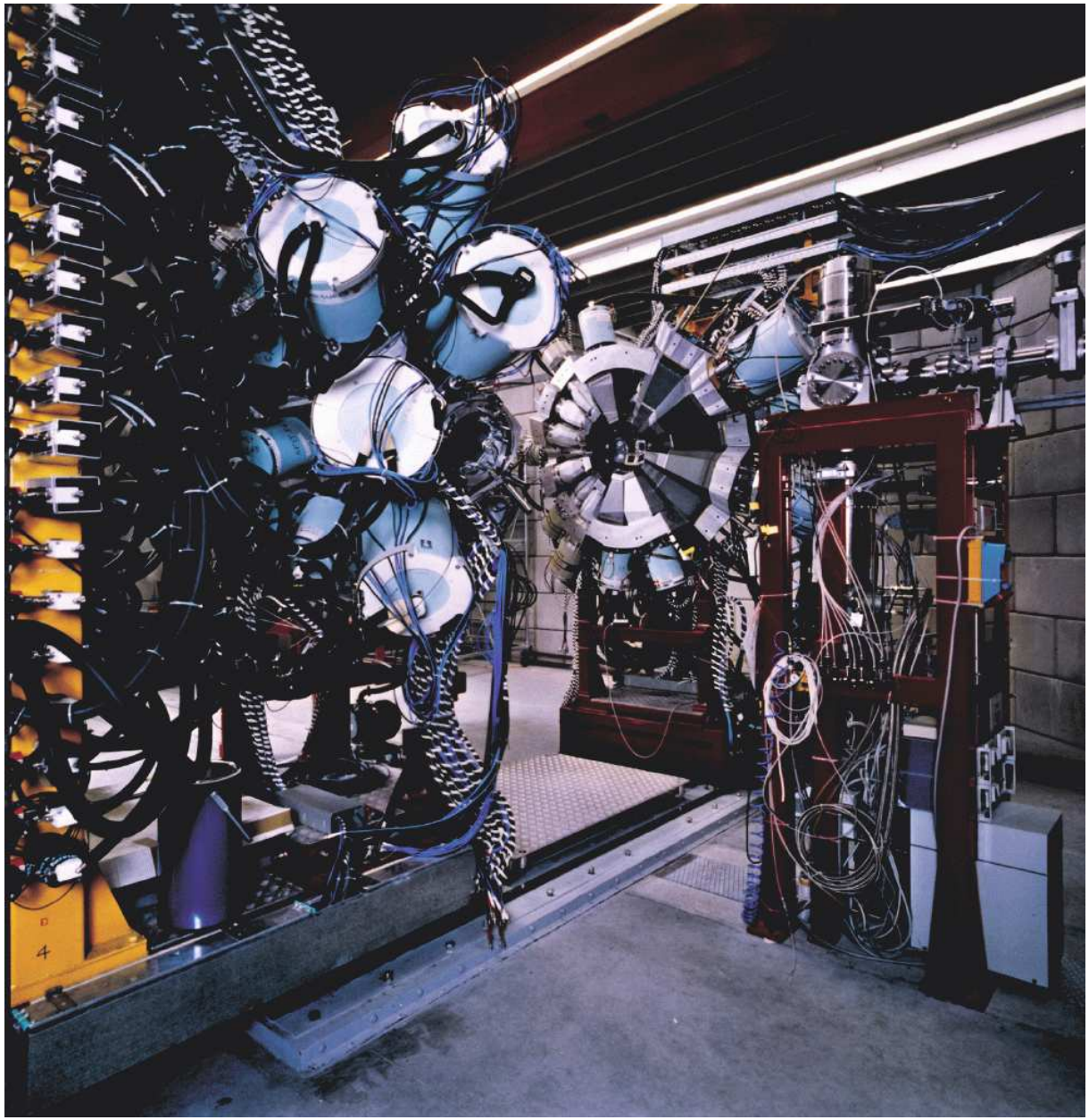


β_2 ~ 0.35 0.30 0.20 0.15 0.10 0.05

Multidetector array EUROBALL



Multidetector array EUROBALL at INFN-LNL (Legnaro)



EUROBALL III experiment

- Detectors:

  15 CLUSTER and 26 CLOVER detectors (total of 209 detectors)

  ISIS Si ball (40 Δ E - E telescopes)

  Neutron wall (50 liquid scintillation detectors)

- Reaction:

  ^{40}Ca + ^{40}Ca; $E = 185$ MeV; $\sigma_T \approx 1060$ mb

- Reaction channels:

  ^{40}Ca(^{40}Ca,1α3p1n)^{72}Br ($\approx$ 4 % $\cdot$ σ_T)

  ^{40}Ca(^{40}Ca,1α3p)^{73}Br ($\approx$ 4 % $\cdot$ σ_T)

- Target:

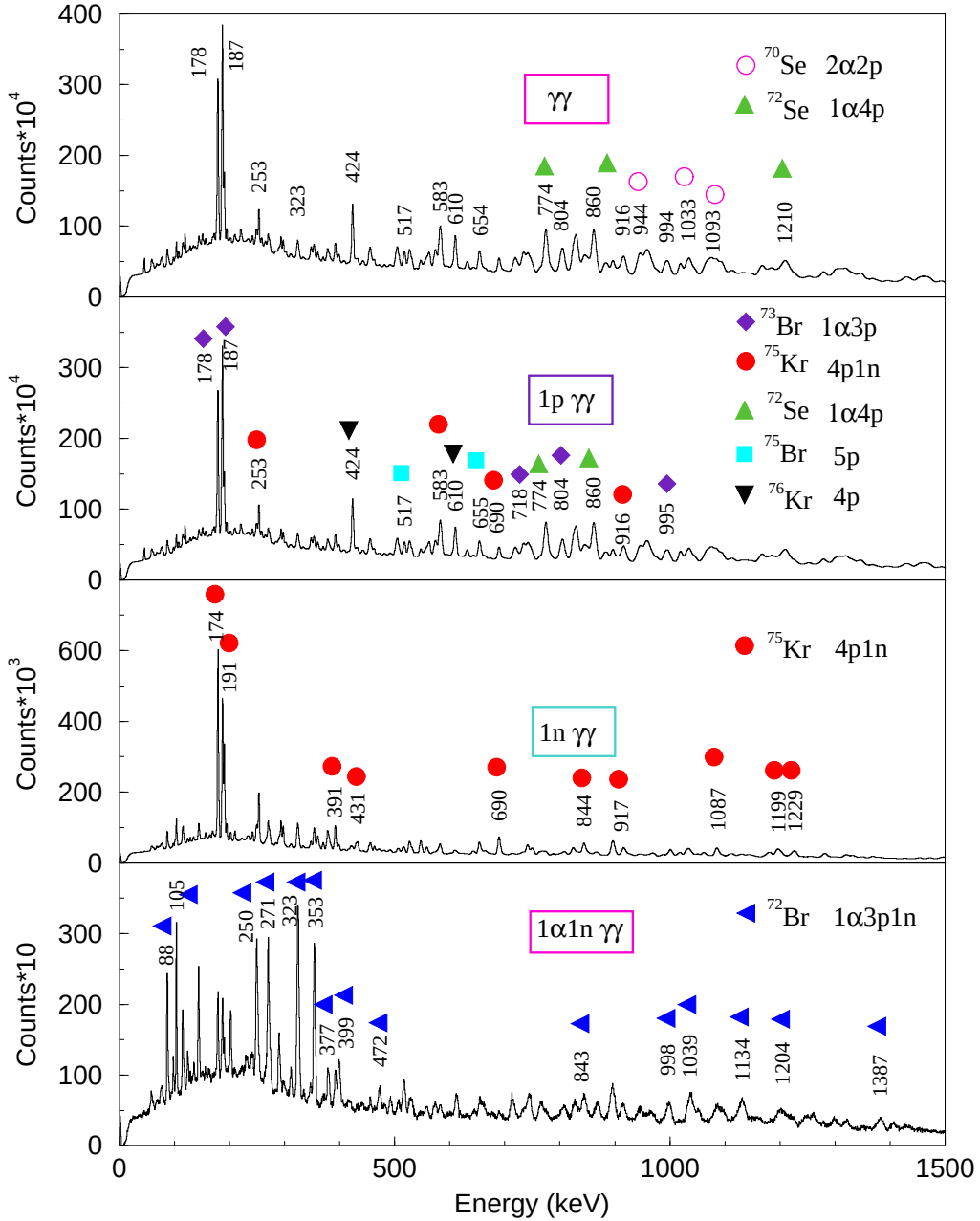
  0.9 mg/cm^2 self-supporting (enrichment 99.96 %)

- Total number of recorded events:

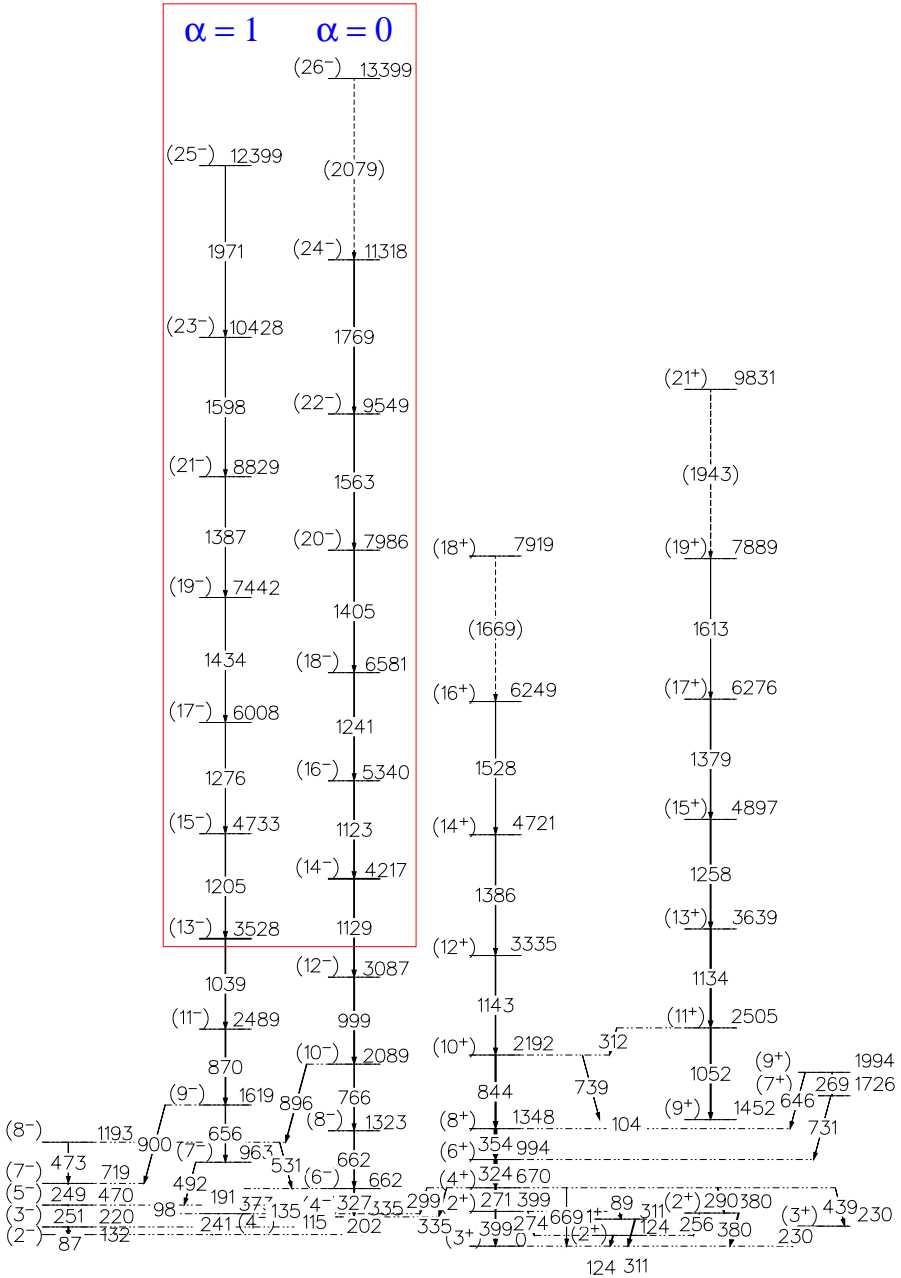
  $2 \cdot 10^9$ of fold three or higher

EUROBALL III experiment

Channel selection:

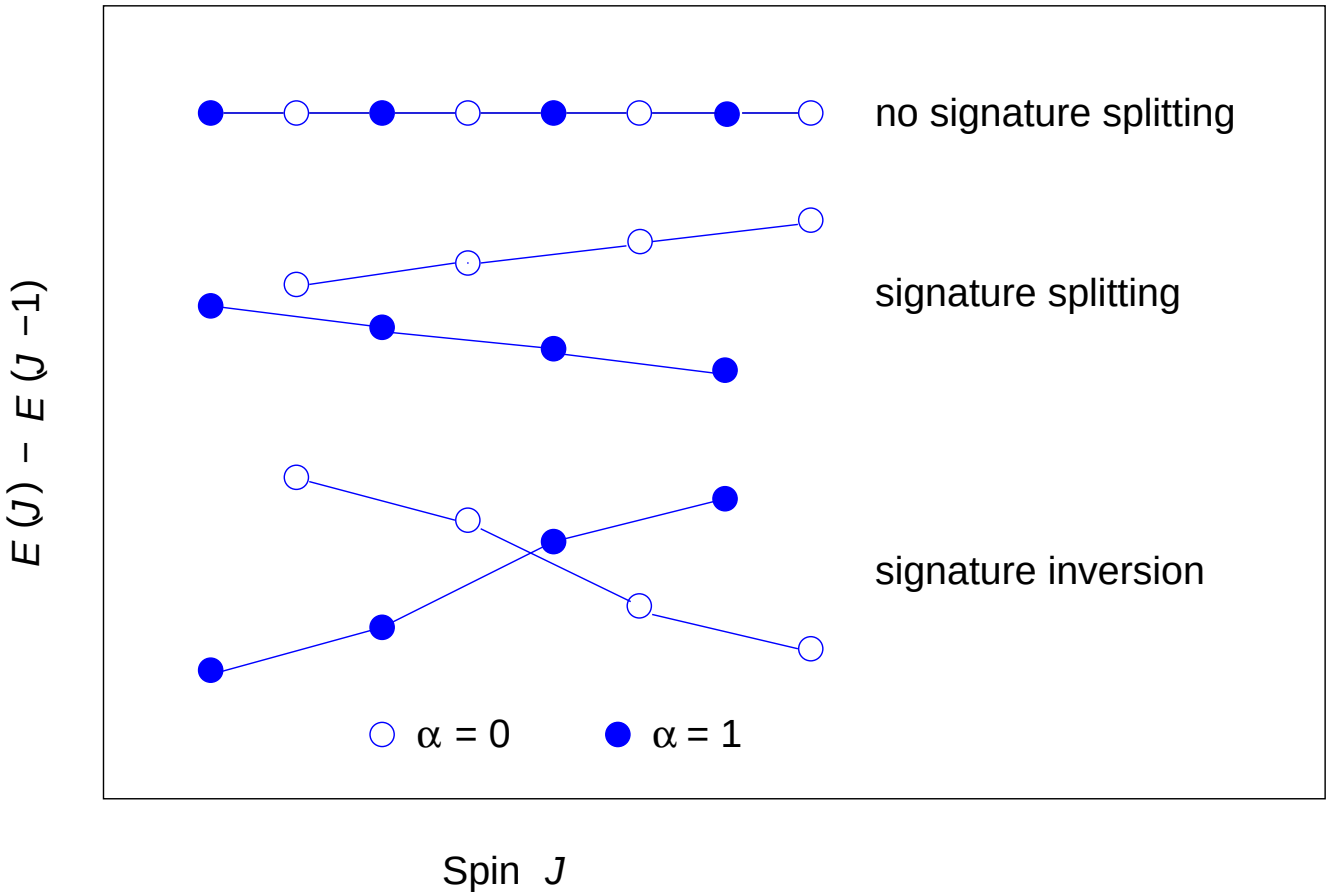


Level scheme of ^{72}Br

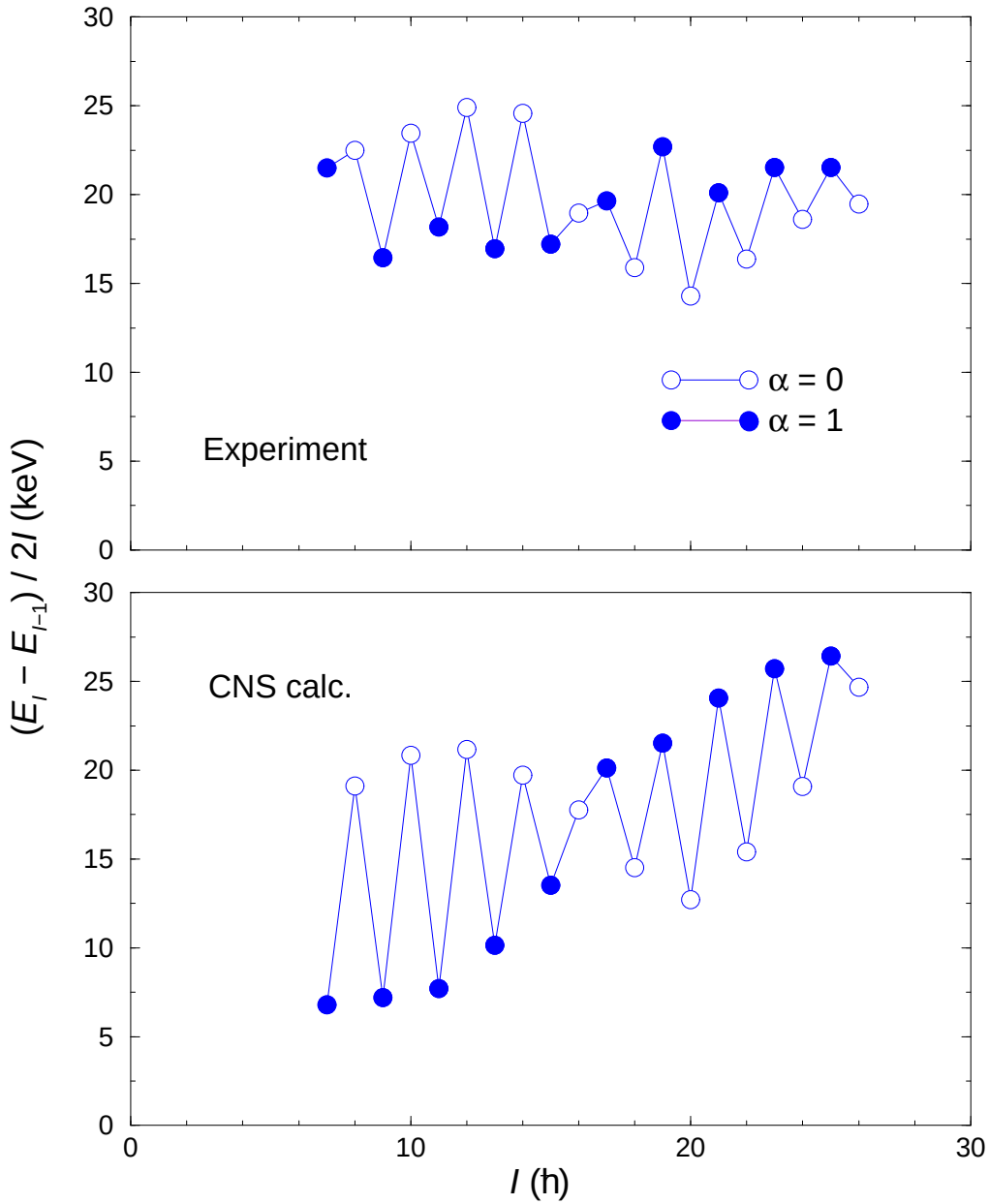


Signature in rotational bands

- The signature quantum number defines the admissible spins via the relation:
  $J = \alpha + 2n$ ($n = 0, 1, 2, ...$)
- Signature partners formed in odd-odd nuclei are:
  $\alpha = 0$ - even spins
  $\alpha = 1$ - odd spins



Signature inversion in the negative-parity bands of ^{72}Br



C. Plettner et al., PRL 85 (2000) 2454

Cranked Nilsson-Strutinsky calculations for ^{72}Br

I. Ragnarsson and A.V. Afanasjev, NPA 608 (1996) 176

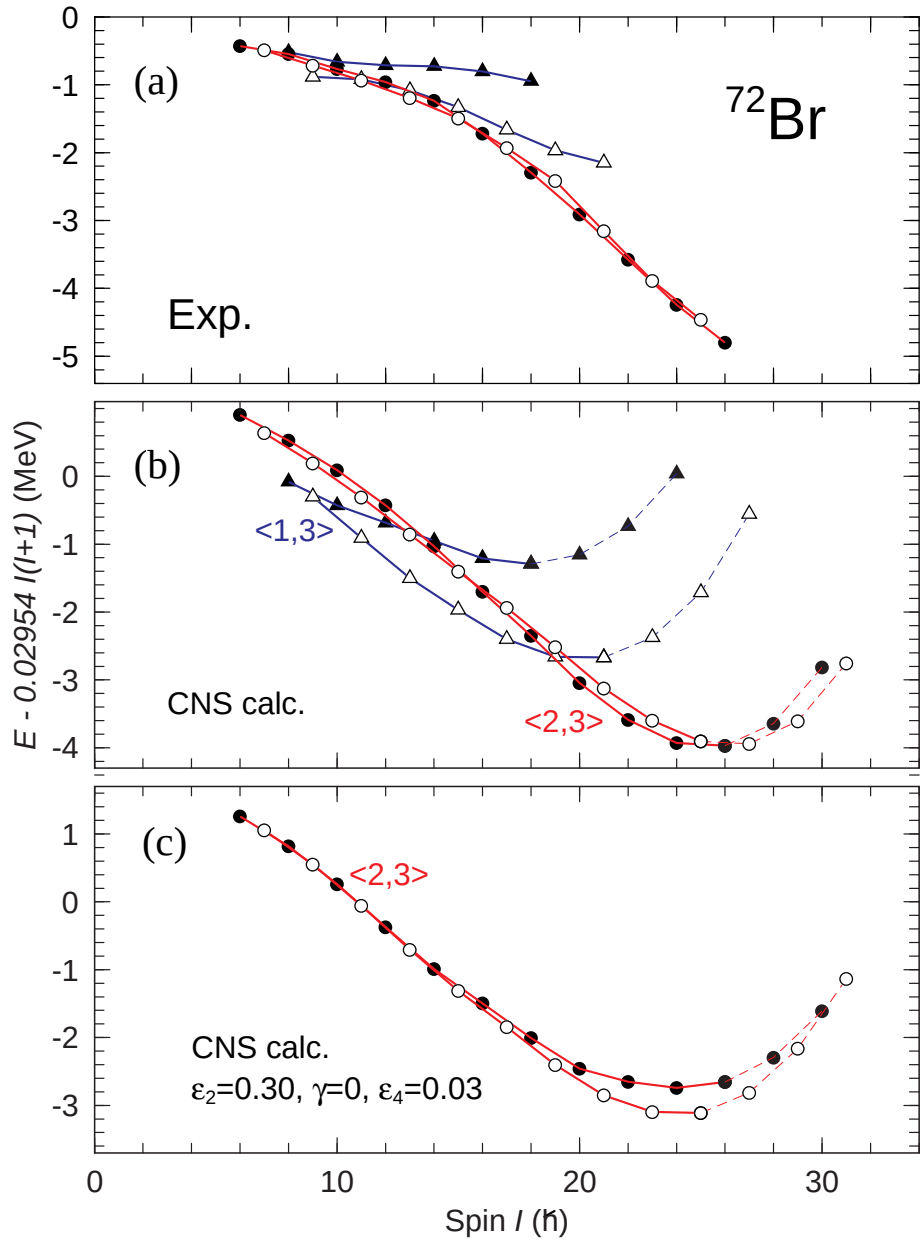
Assumed configurations of the bands:

$\pi(f_{5/2}\ p_{3/2})^6\ \pi(g_{9/2})^1\ \ \nu(f_{5/2}\ p_{3/2})^6\ \nu(g_{9/2})^3\ \equiv$ <1,3>

$\pi(f_{5/2}\ p_{3/2})^5\ \pi(g_{9/2})^2\ \ \nu(f_{5/2}\ p_{3/2})^6\ \nu(g_{9/2})^3\ \equiv$ <2,3>

$\pi = +$

$\pi = -$

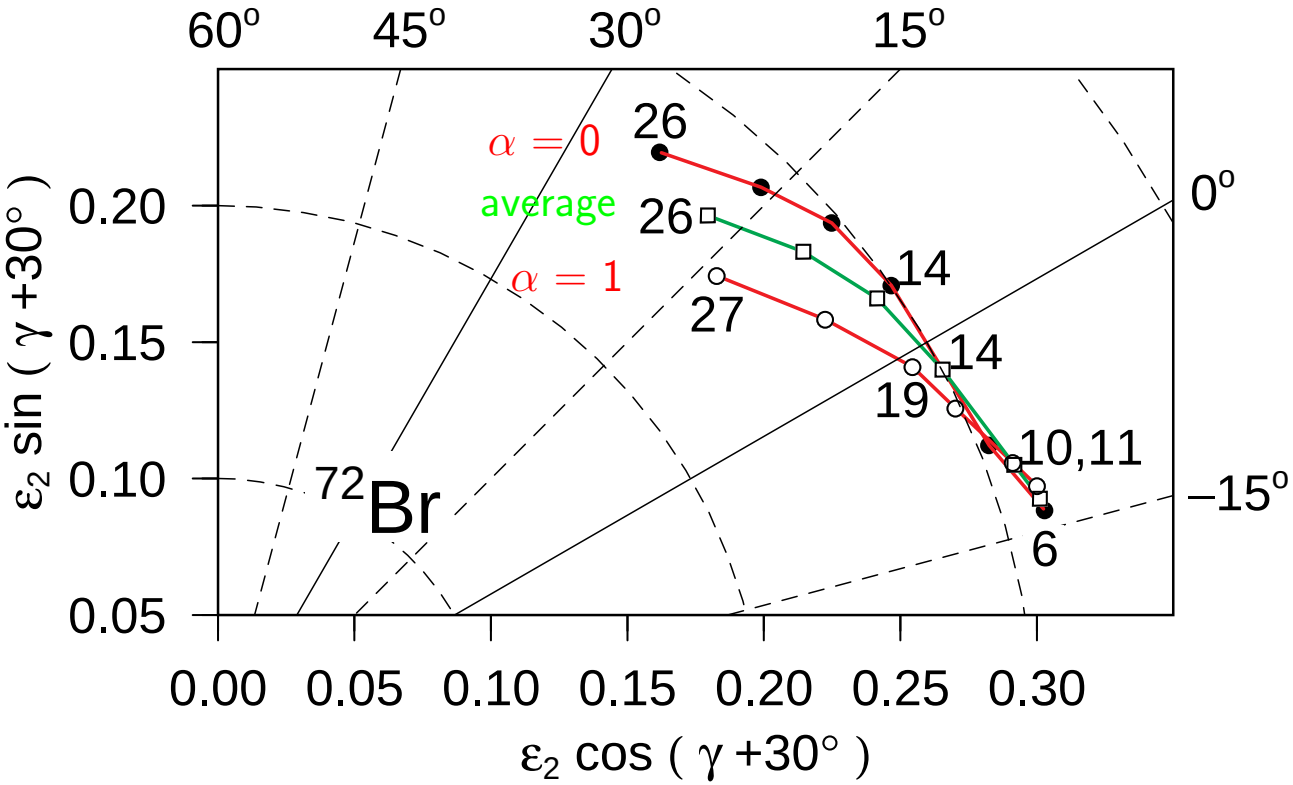


Cranked Nilsson-Strutinsky calculations for ^{72}Br

I. Ragnarsson and A.V. Afanasjev, NPA 608 (1996) 176

Shape trajectories for the negative-parity configurations:

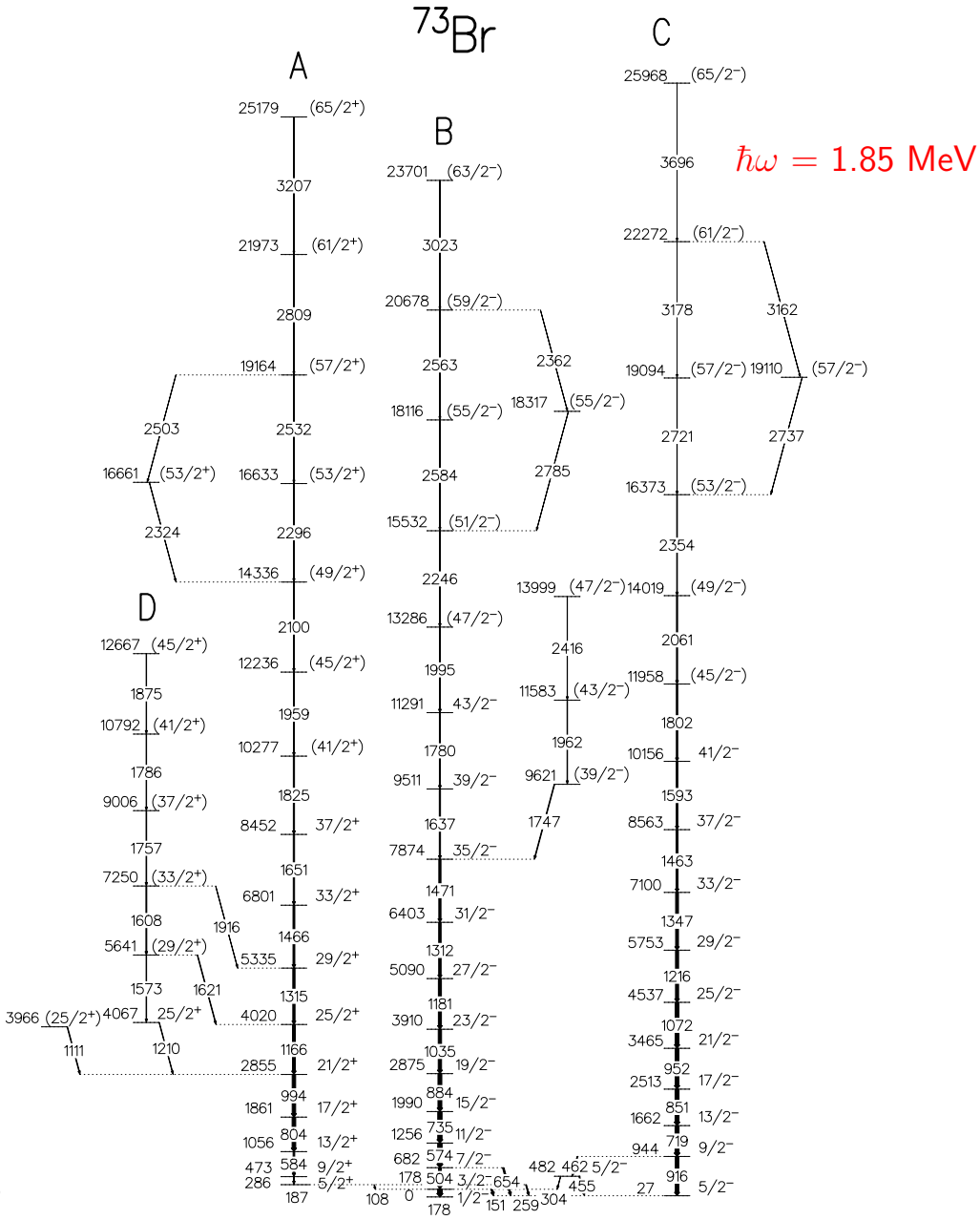
$\pi(f_{5/2}\ p_{3/2})^5\ \pi(g_{9/2})^2\ \ \nu(f_{5/2}\ p_{3/2})^6\ \nu(g_{9/2})^3\ \equiv\ <2,3>$



Signature inversion in ^{72}Br

- Negative-parity bands in ^{72}Br observed up to spin 26 with the EUROBALL spectrometer.
- A signature inversion occurs in the negative-parity bands around spin 16 in contrast to observations in neighbouring odd-odd Br isotopes.
- Fully consistent Cranked Nilsson-Strutinsky calculations describe the signature splitting as a consequence of an evolution of the nuclear shape from a triaxial shape with rotation about the intermediate axis at low spin through a collective prolate shape at medium spin to a triaxial shape with rotation about the shortest axis at high spin.
- The calculations show that the low-j orbits of the fp shell mainly determine the properties of the negative-parity bands.
- First case where signature inversion is clearly related with triaxiality.

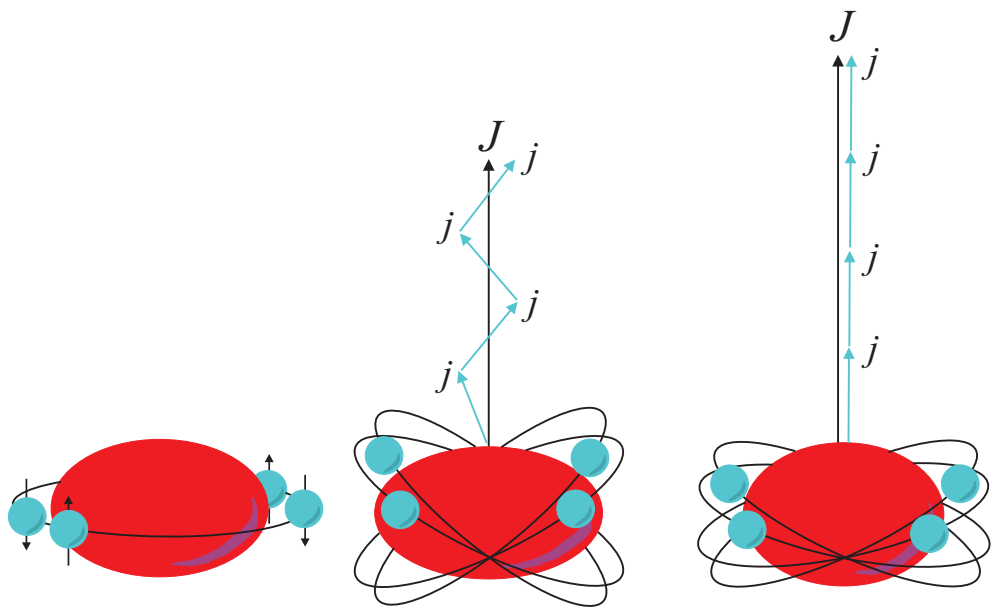
Level scheme of ^{73}Br



C. Plettner et al., PRC 62 (2000) 014313

Band termination

- The spin in a band is the sum of collective spin and the total angular momentum of unpaired nucleons.
- With increasing spin, the shape of the nucleus and the orientation of the rotational axis may change such that collective rotation is no longer possible. Consequently, spin can be generated only by aligning the angular momenta of the unpaired particles.
- In this case, the band terminates at the maximum spin of the multi-particle configuration, where the particle spins are fully aligned.



Cranked Nilsson-Strutinsky calculations for ^{73}Br

I. Ragnarsson and A.V. Afanasjev, NPA 608 (1996) 176

Possible configurations include excitations in the orbits: $f_{5/2}$,$p_{3/2}$, $p_{1/2}$ and $g_{9/2}$

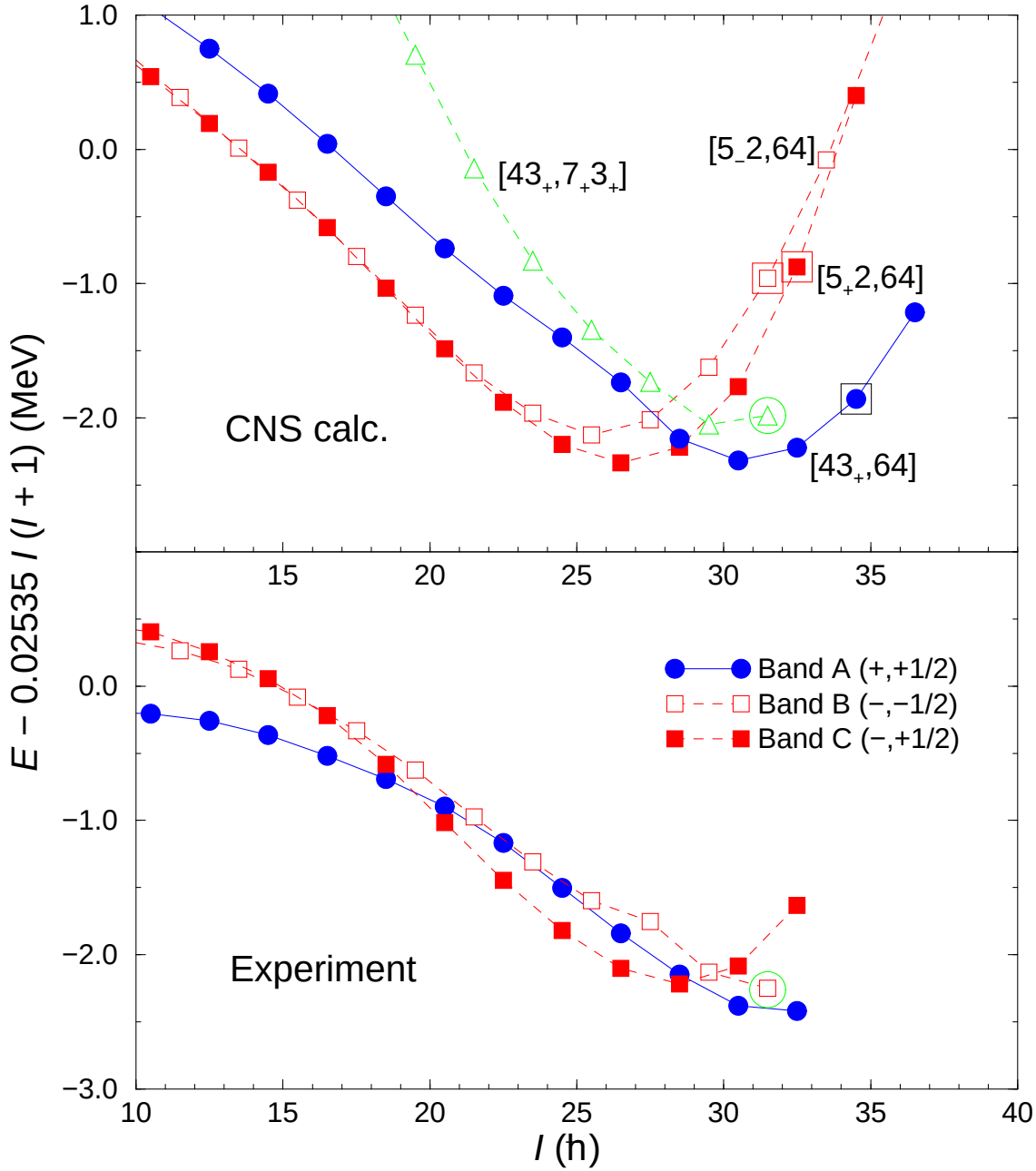
- Protons
  - $(f_{5/2}\ p_{3/2})^4\ \ (g_{9/2})^3\ \Rightarrow\ J_{\mathrm{max}} = 33/2,\ \pi = +$
  - $(f_{5/2}\ p_{3/2})^5\ \ (g_{9/2})^2\ \Rightarrow\ J_{\mathrm{max}} = 27/2,\ 29/2,\ \pi = -$
- Neutrons
  - $(f_{5/2}\ p_{3/2})^6\ \ (g_{9/2})^4\ \Rightarrow\ J_{\mathrm{max}} = 18,\ \pi = +$
  - $(f_{5/2}\ p_{3/2})^7\ \ (g_{9/2})^3\ \Rightarrow\ J_{\mathrm{max}} = 15,\ 16,\ \pi = -$

Possible configurations of the bands:
Notation [$\pi(f_{5/2}\ p_{3/2})^{p'}\ \pi(g_{9/2})^{p}$, $\nu(f_{5/2}\ p_{3/2})^{n'}\ \nu(g_{9/2})^{n}$]

- Band A: [43,64] $\Rightarrow J^{\pi}_{\mathrm{max}} = 69/2^{+}$
- Band B: [43,73] $\Rightarrow J^{\pi}_{\mathrm{max}} = 63/2^{-}$
- Band C: [52,64] $\Rightarrow J^{\pi}_{\mathrm{max}} = 63/2^{-}$

Cranked Nilsson-Strutinsky calculations for ^{73}Br

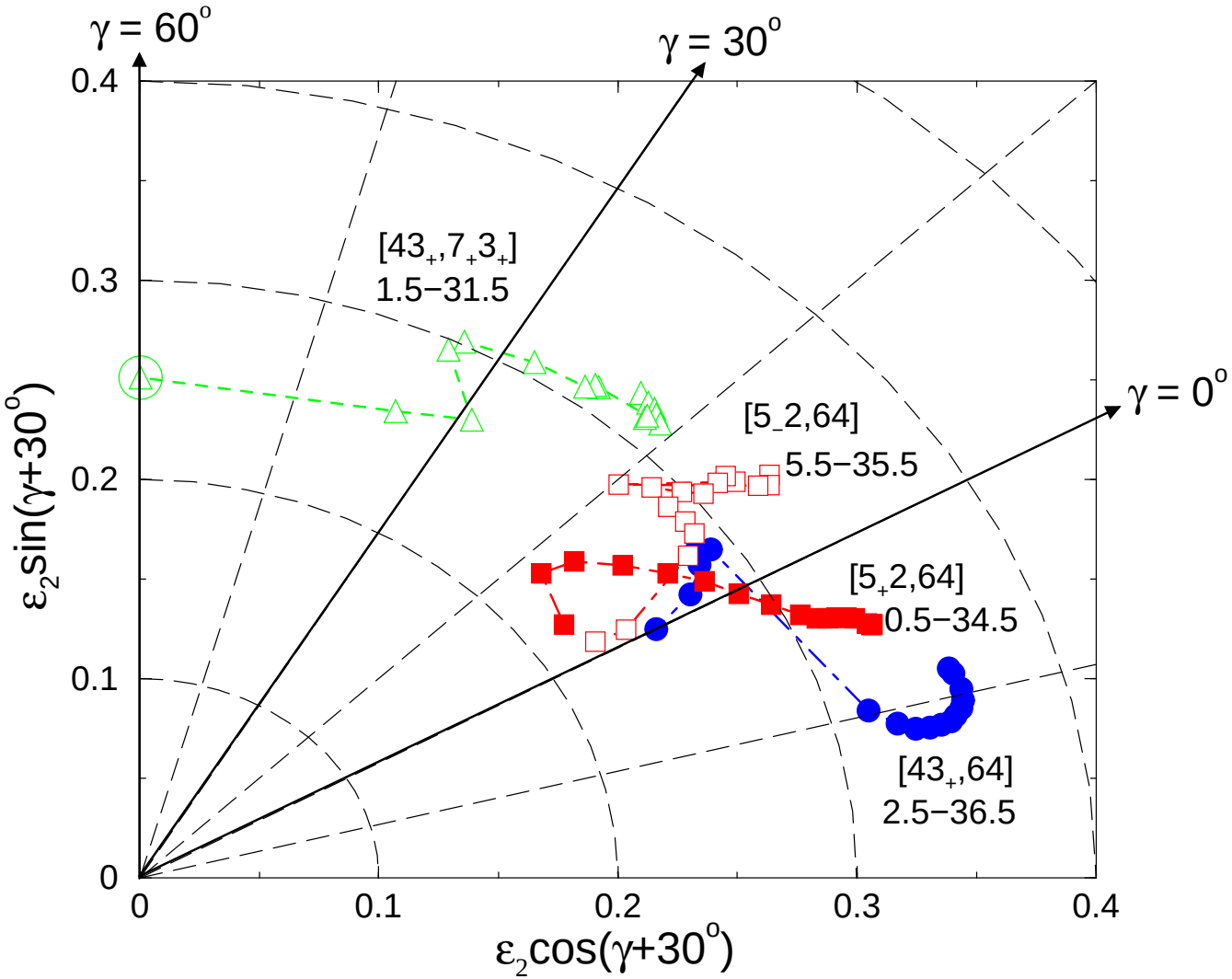
I. Ragnarsson and A.V. Afanasjev, NPA 608 (1996) 176



Cranked Nilsson-Strutinsky calculations for ^{73}Br

I. Ragnarsson and A.V. Afanasjev, NPA 608 (1996) 176

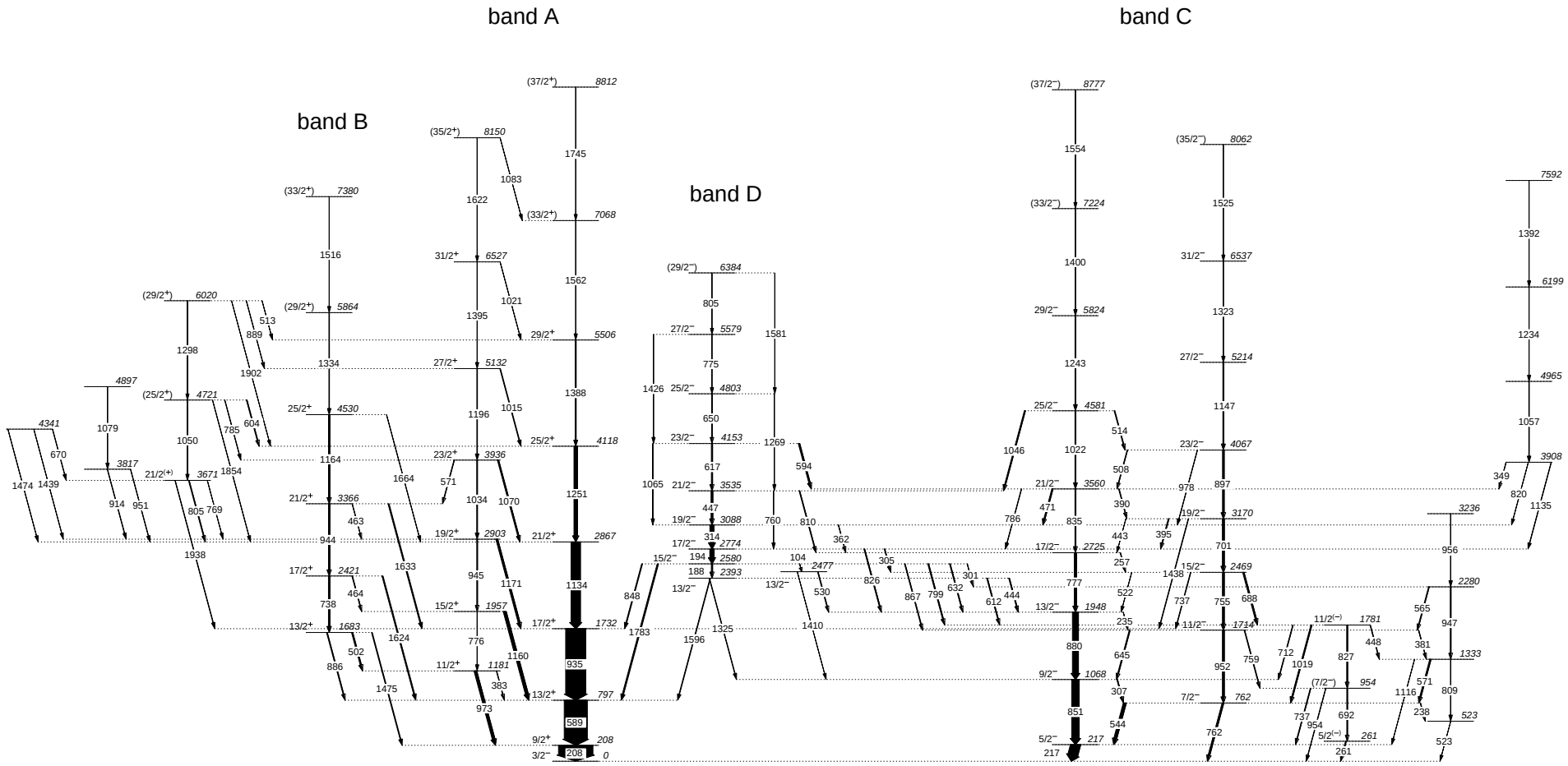
Shape trajectories:



Band termination in ^{73}Br

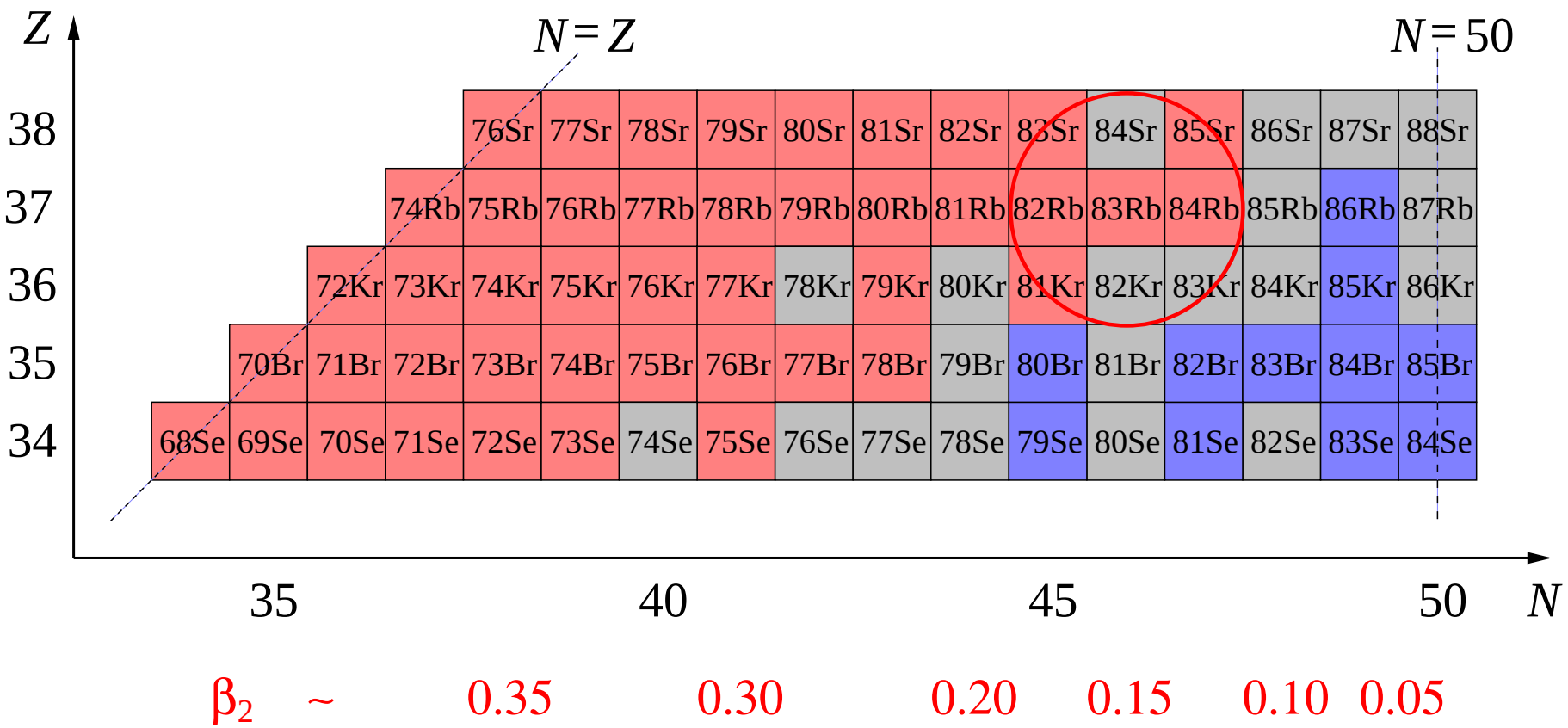
- Rotational bands in ^{73}Br were observed up to spins of 65/2 at excitation energies of 26 MeV.
- The E2 transitions have energies up to 3.7 MeV. This corresponds to rotational frequencies of $\hbar\omega \approx 1.85$ MeV. These are among the highest rotational frequencies ever observed in nuclei with $A > 25$.
- Cranked Nilsson-Strutinsky calculations describe these bands on the basis of multiparticle excitations in the (fp) shell and the $g_{9/2}$ orbital.
- One band is predicted to terminate at the highest observed spin $J^\pi = 63/2^-$ while the others stay collective and continue beyond the maximum spin of the assumed multiparticle excitation.
- This is the first case of band termination in the mass region around $A = 70$.

Level scheme of ^{79}Br



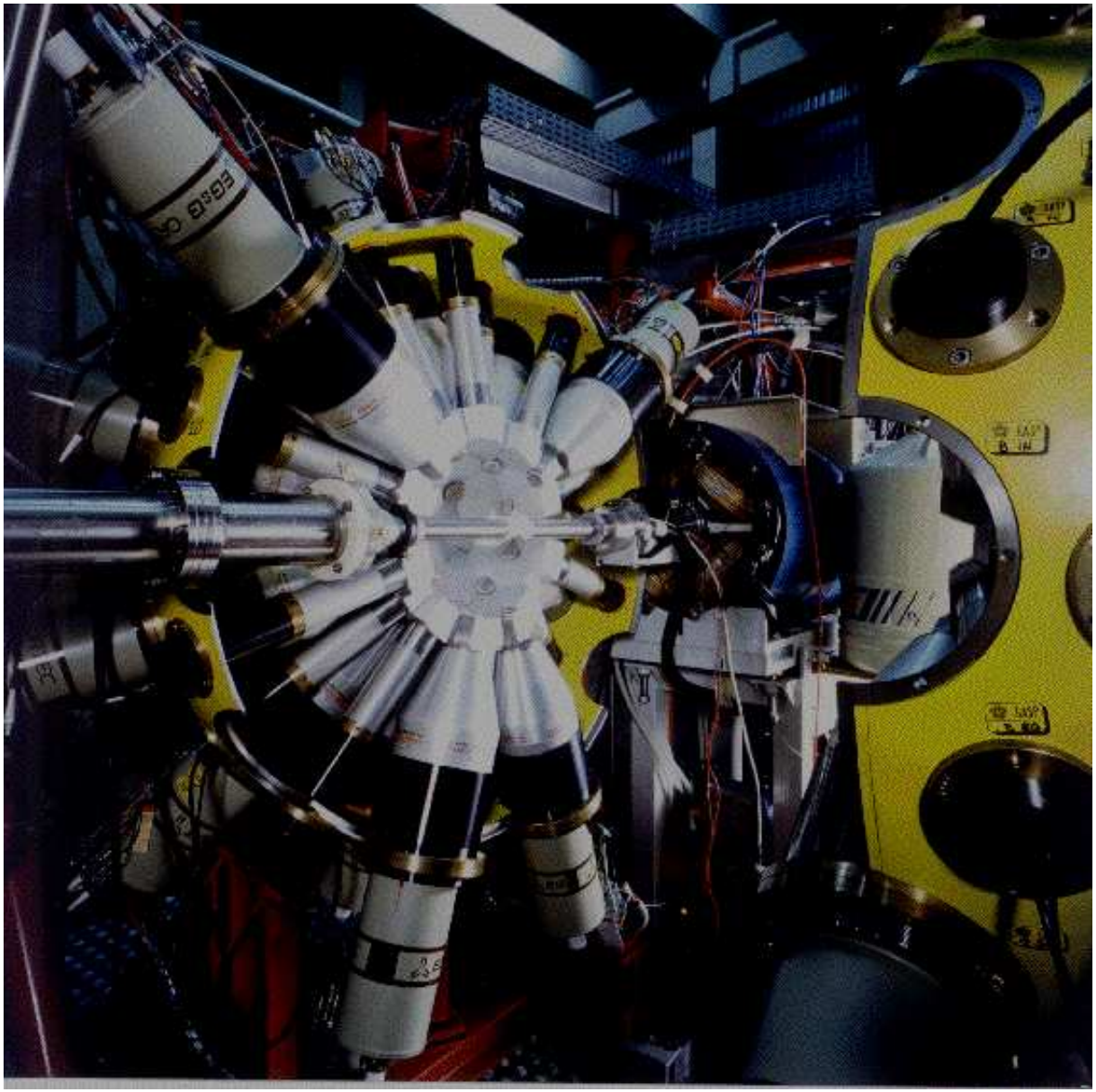
R.S. et al., PRC 65 (2002) 044326

Nuclear chart around A ≈ 70 - 90



β_2 ~ 0.35 0.30 0.20 0.15 0.10 0.05

Multidetector array GASP (INFN - LN Legnaro)



GASP experiment

- Detectors:

  40 detectors with escape-suppression shield

- Reaction:

  $^{11}B + {}^{76}Ge$; $E = 45$ MeV; $\sigma_T \approx 1000$ mb

- Reaction channels:

  $^{76}Ge(^{11}B,5n)^{82}Rb$ ($\approx$ 20 % $\cdot\ \sigma_T$)

  $^{76}Ge(^{11}B,4n)^{83}Rb$ ($\approx$ 50 % $\cdot\ \sigma_T$)

  $^{76}Ge(^{11}B,3n)^{84}Rb$ ($\approx$ 10 % $\cdot\ \sigma_T$)

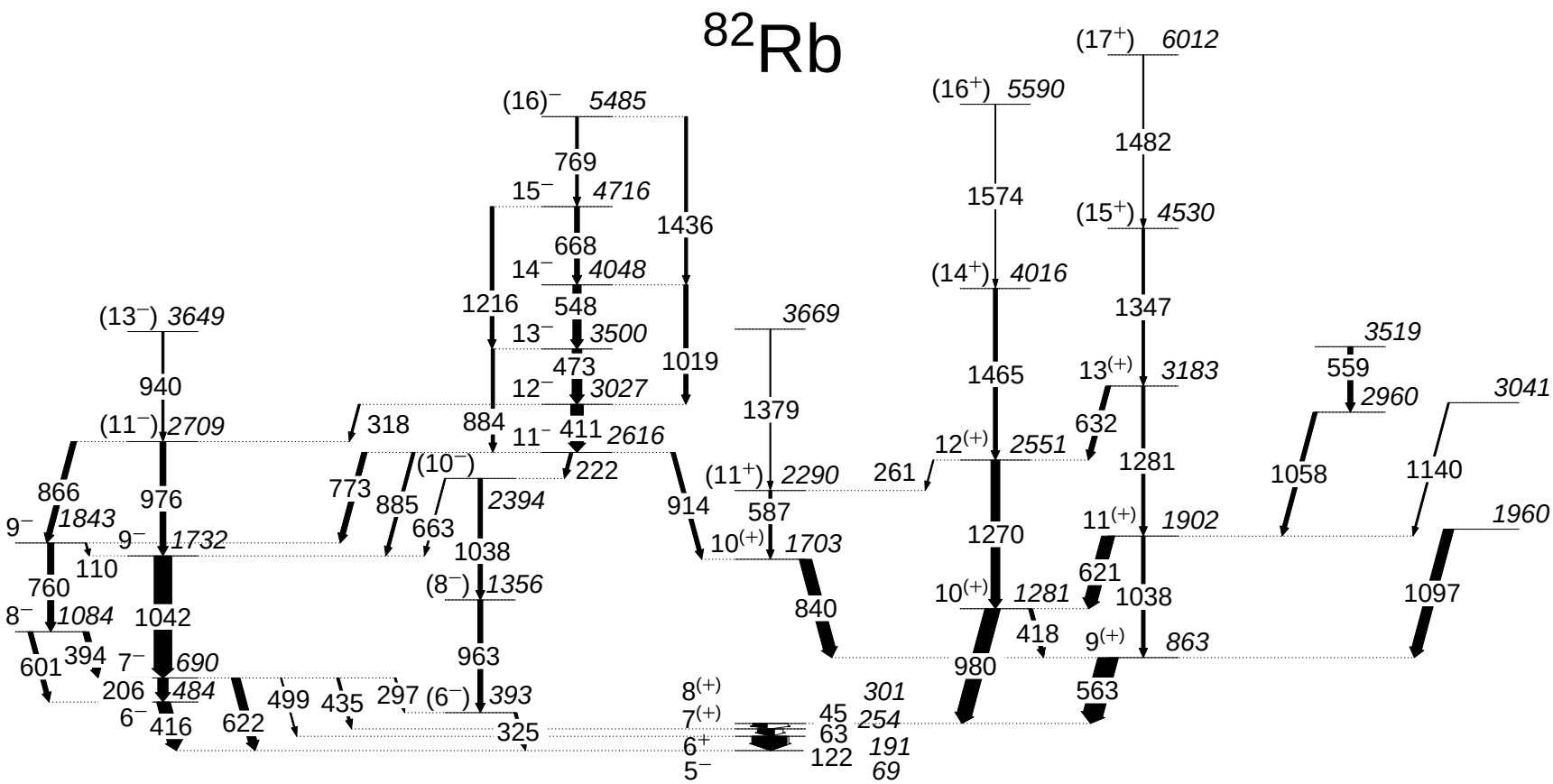
- Target:

  1.2 mg/cm^2 ^{76}Ge (enrichment 99.96 %) on a 3 mg/cm^2 tantalum backing

- Total number of recorded events:

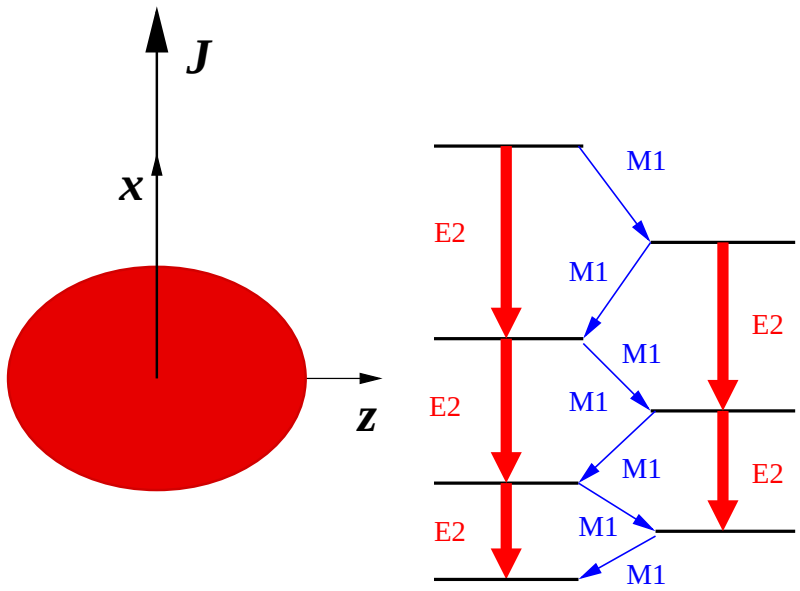
  $\approx 10^9$ of fold two or higher

Level scheme of ^{82}Rb



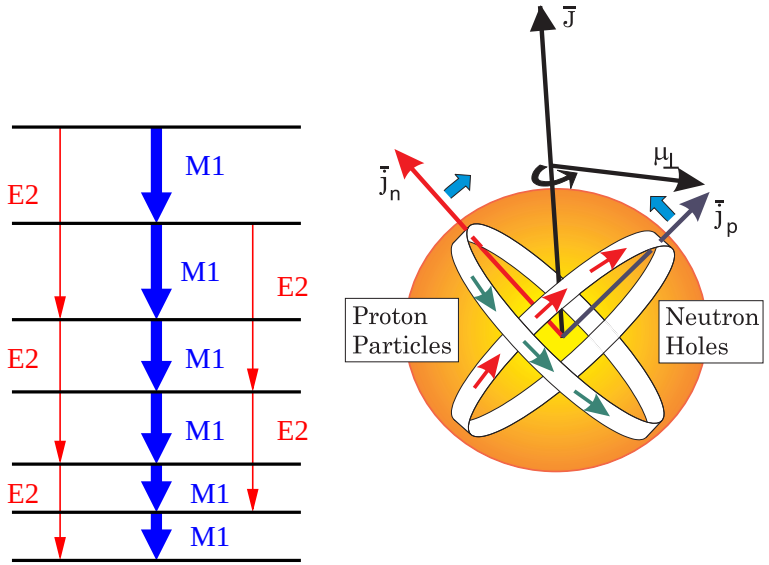
Nuclear rotation

electric rotation



$B(\mathrm{E2}) \propto Q_0^2$

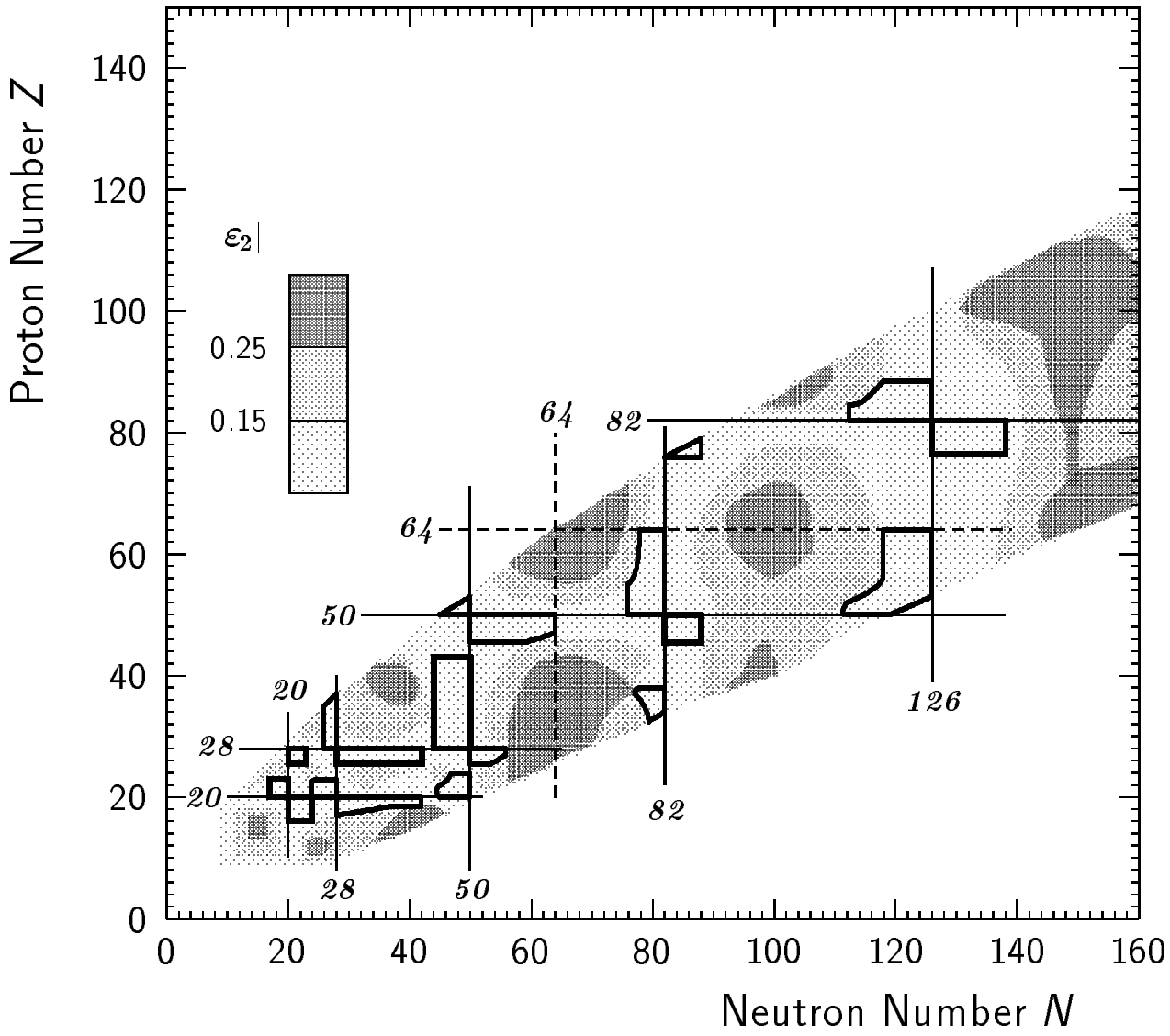
magnetic rotation



$B(\mathrm{M1}) \propto \mu_\perp^2$

$$E = \frac{\hbar^2}{2\Theta} J(J+1); \quad E_\gamma \propto J$$

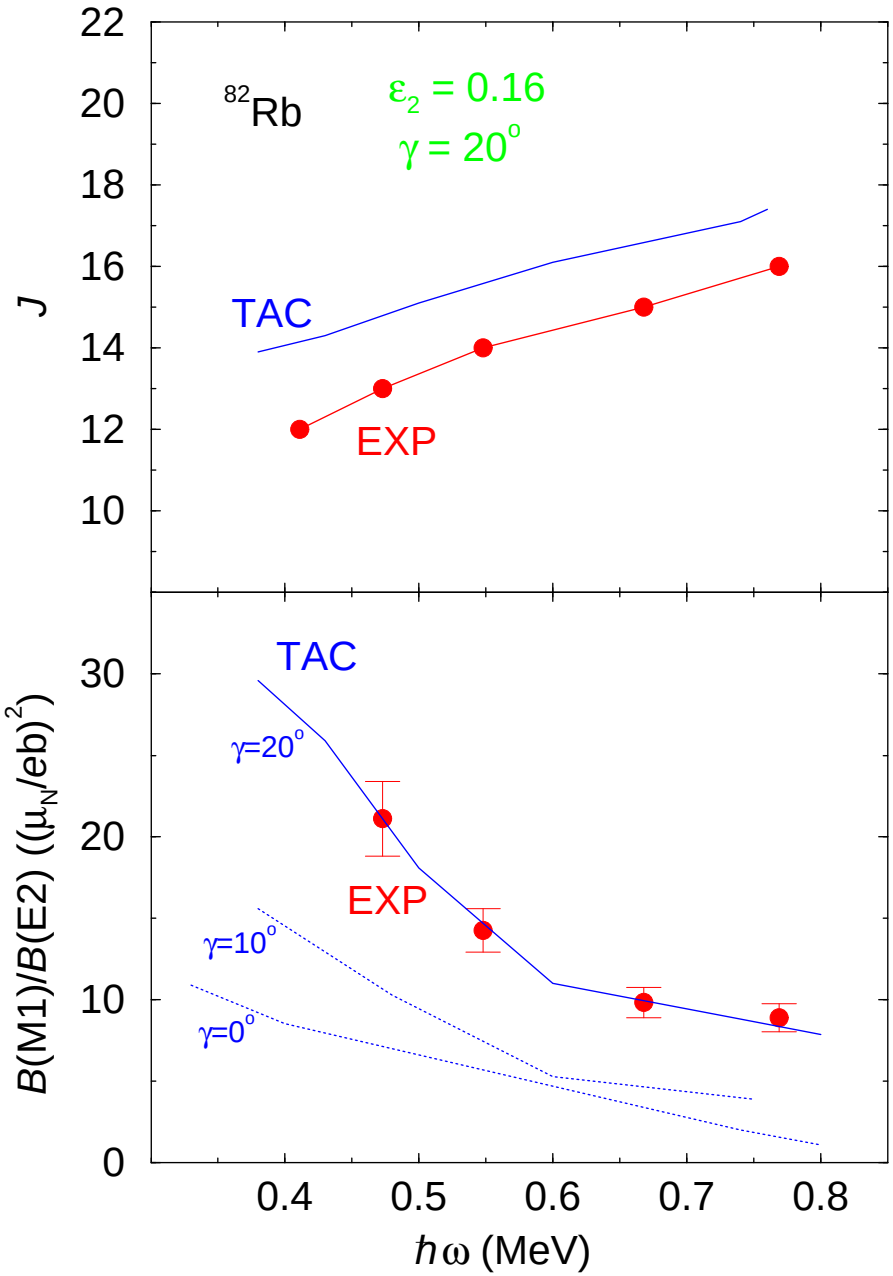
Appearance of magnetic rotation



S. Frauendorf, ZPA 358 (1997) 163

Tilted-axis-cranking-model calculations

$\pi = -$ $M1$ band in ^{82}Rb
configuration $\pi\ (fp)\ \pi\ g^2_{9/2}\ \nu g_{9/2}$

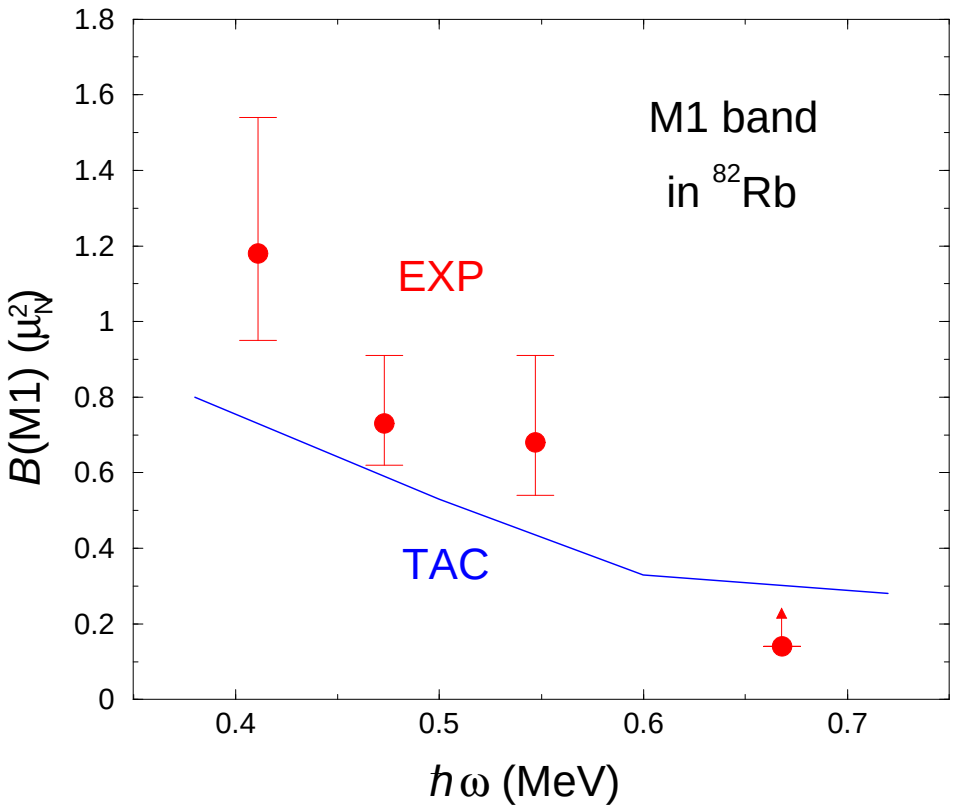


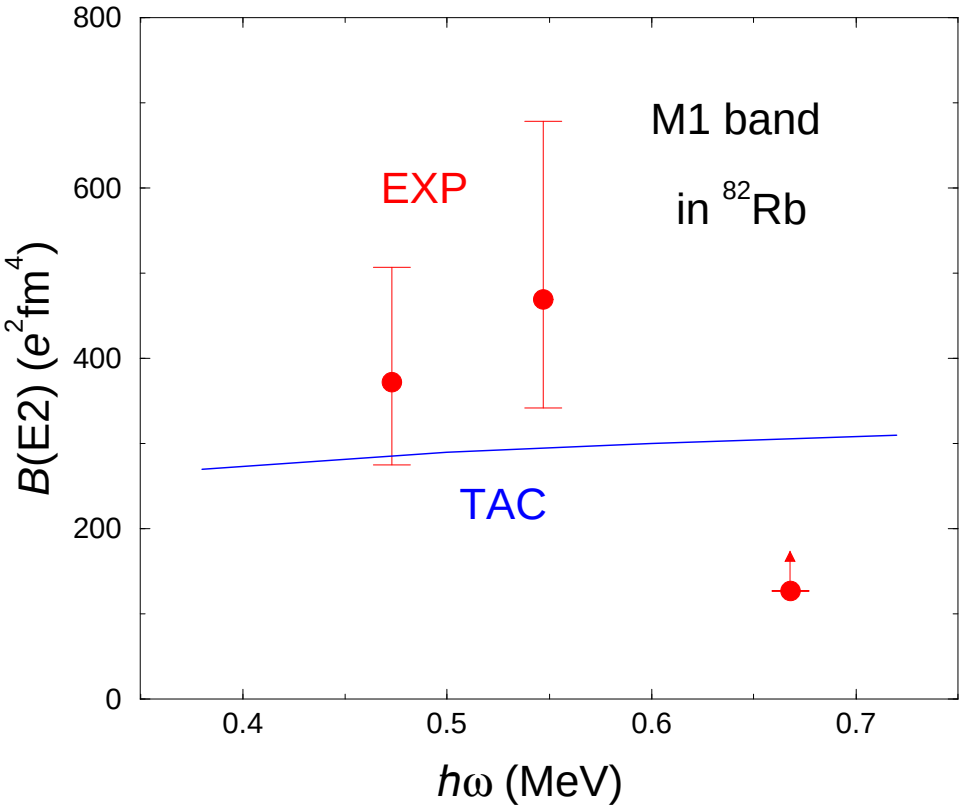
H. Schnare et al., PRL 82 (1999) 4408

Transition strengths in the M1 band of ^{82}Rb

$\pi = -$ $M1$ band in ^{82}Rb

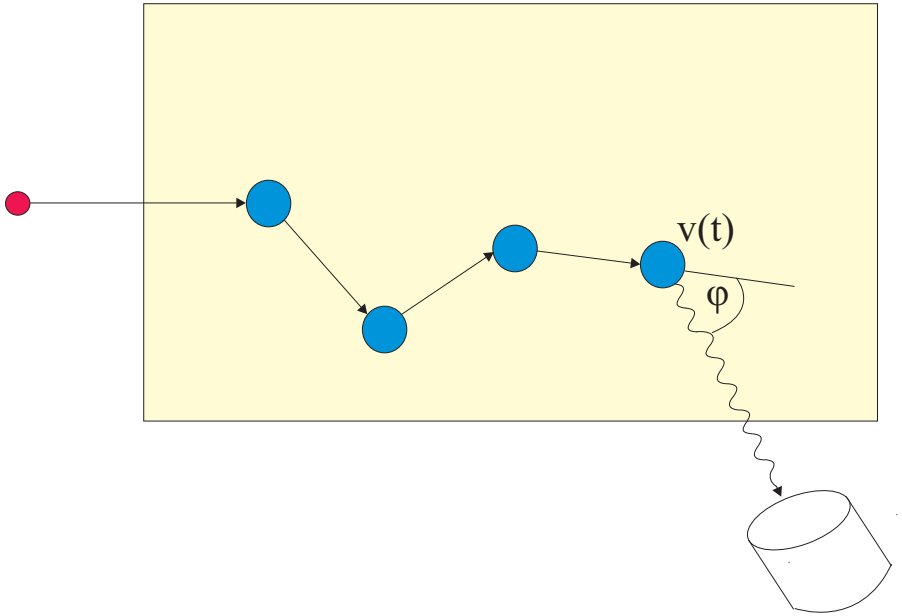
configuration $\pi\ (fp)\ \pi\ g_{9/2}^2\ \nu g_{9/2}$





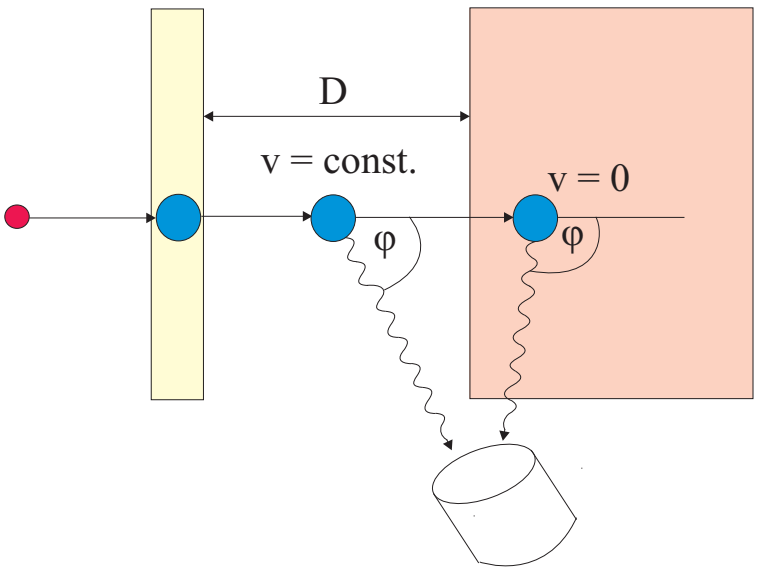
R.S. et al., PRC 66 (2002) 024310

Doppler-shift methods



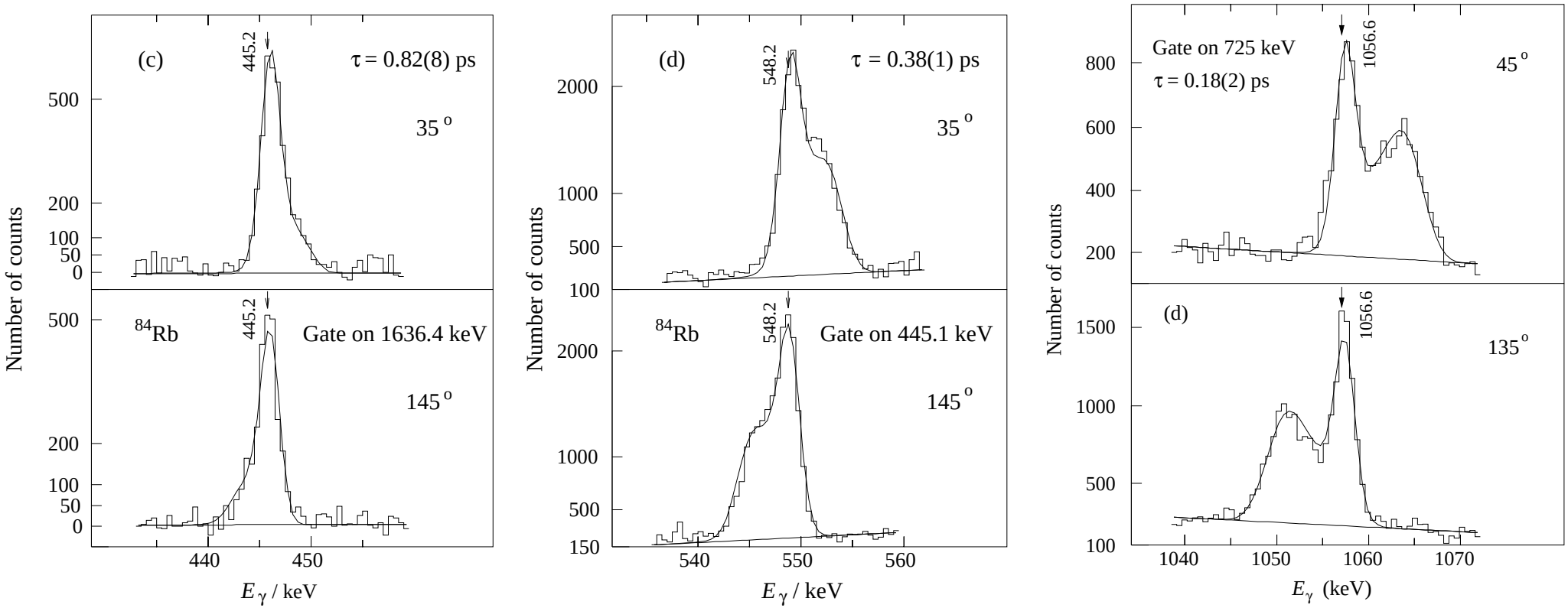
Doppler-shift attenuation (DSA): recoiling nuclei are stopped in a thick target and decay during the slowing-down process.

$$E_\gamma = E_\gamma^0 \left[1 + v(t)/c \cdot \cos\varphi(t)\right]$$



Recoil-distance Doppler shift (RDDS): recoiling nuclei leave the thin target and decay either in flight or in the stopper at rest.

Lineshape analysis using the Doppler-shift attenuation method

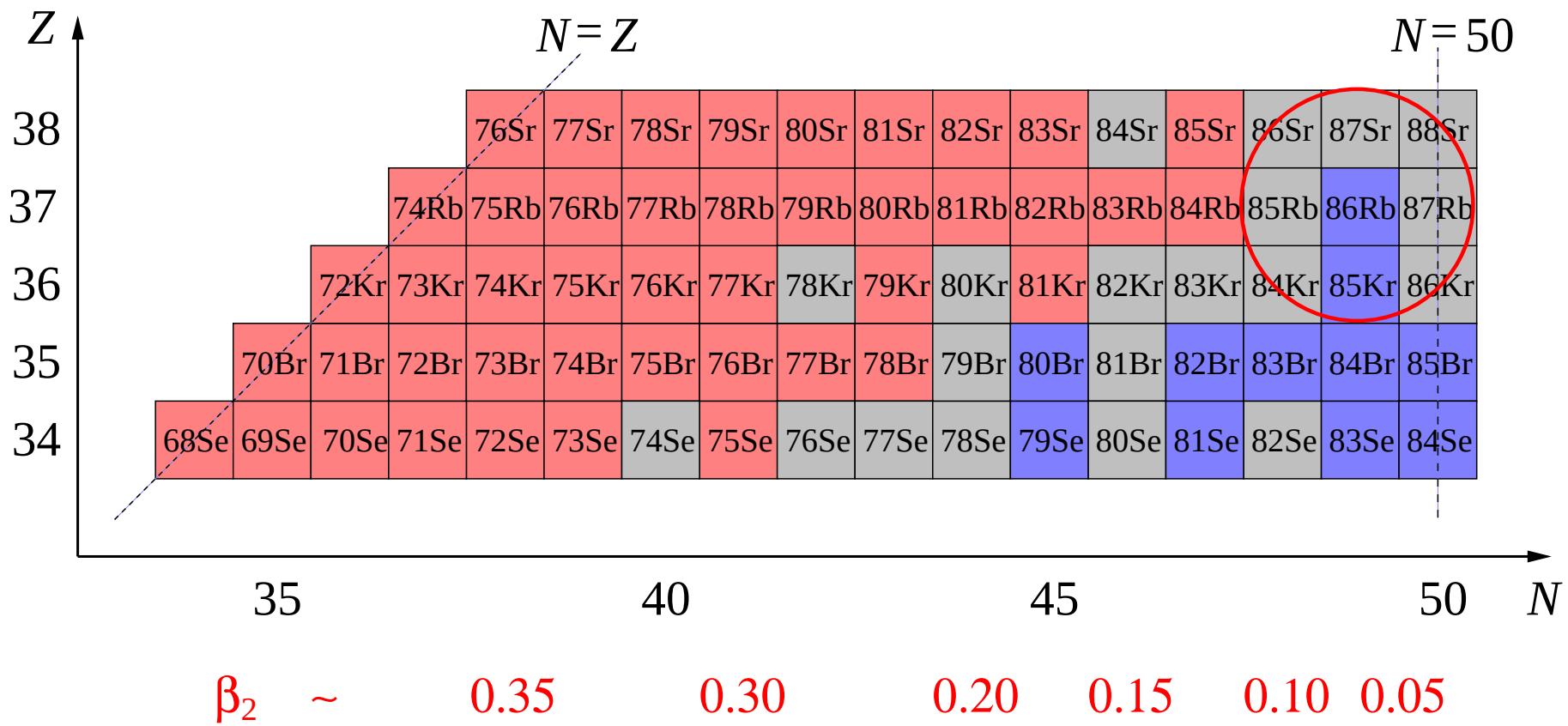


R.S. et al., PRC 66 (2002) 024310

Summary

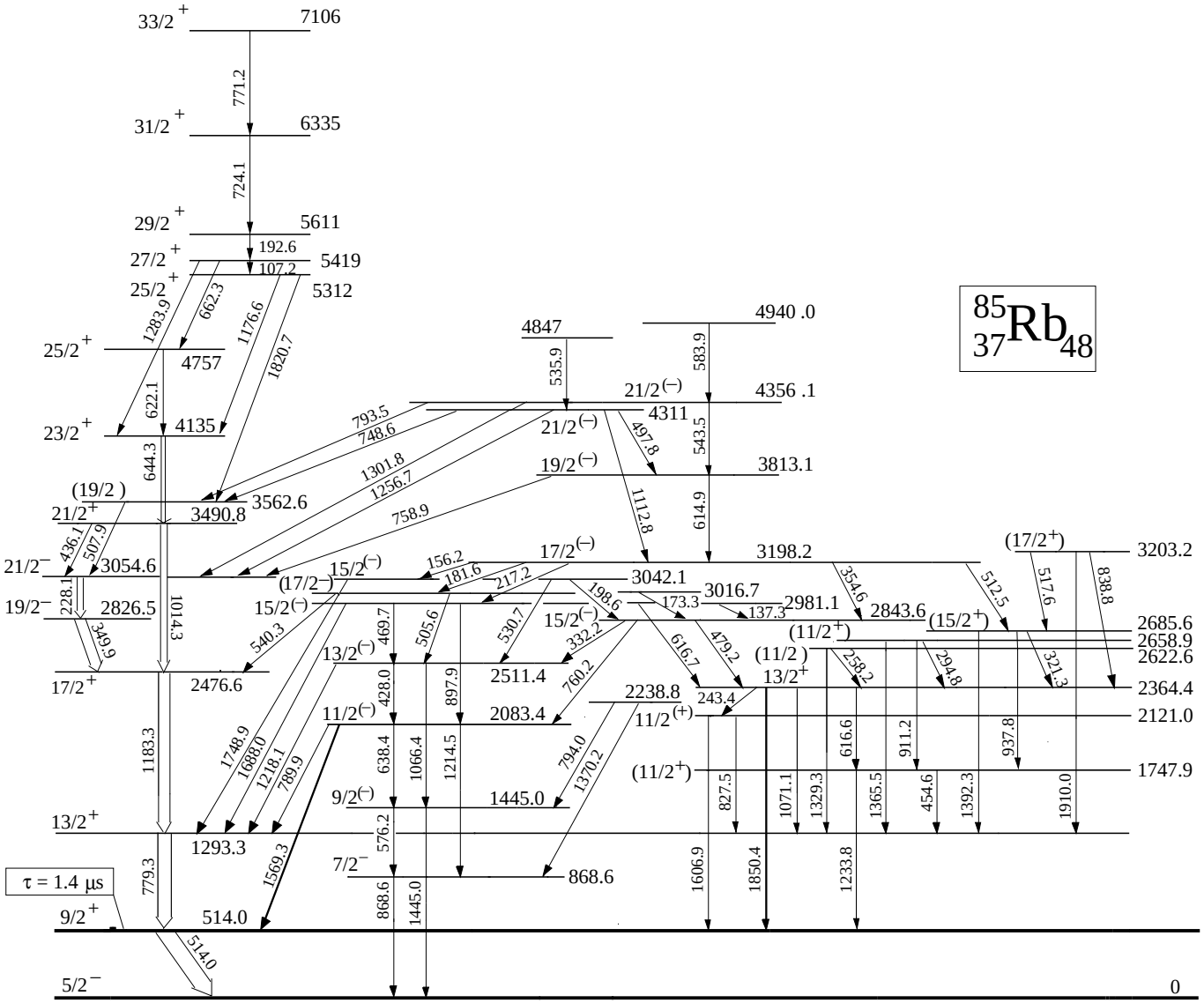
- The regular magnetic dipole bands in ^{82}Rb and ^{84}Rb can be described in the tilted-axis cranking model on the basis of the 4-qp configuration $\pi\ (fp)\ \pi\ g^2_{9/2}\ \nu g_{9/2}$.
- The absolute $M1$ transition strengths within decrease smoothly with increasing rotational frequency up to $\hbar\omega \approx 0.6$ MeV, which reflects the shears mechanism.
- This is the first evidence of magnetic rotation in the mass region with $A \approx 80$.

Nuclear chart around A ≈ 70 - 90



β_2 ~ 0.35 0.30 0.20 0.15 0.10 0.05

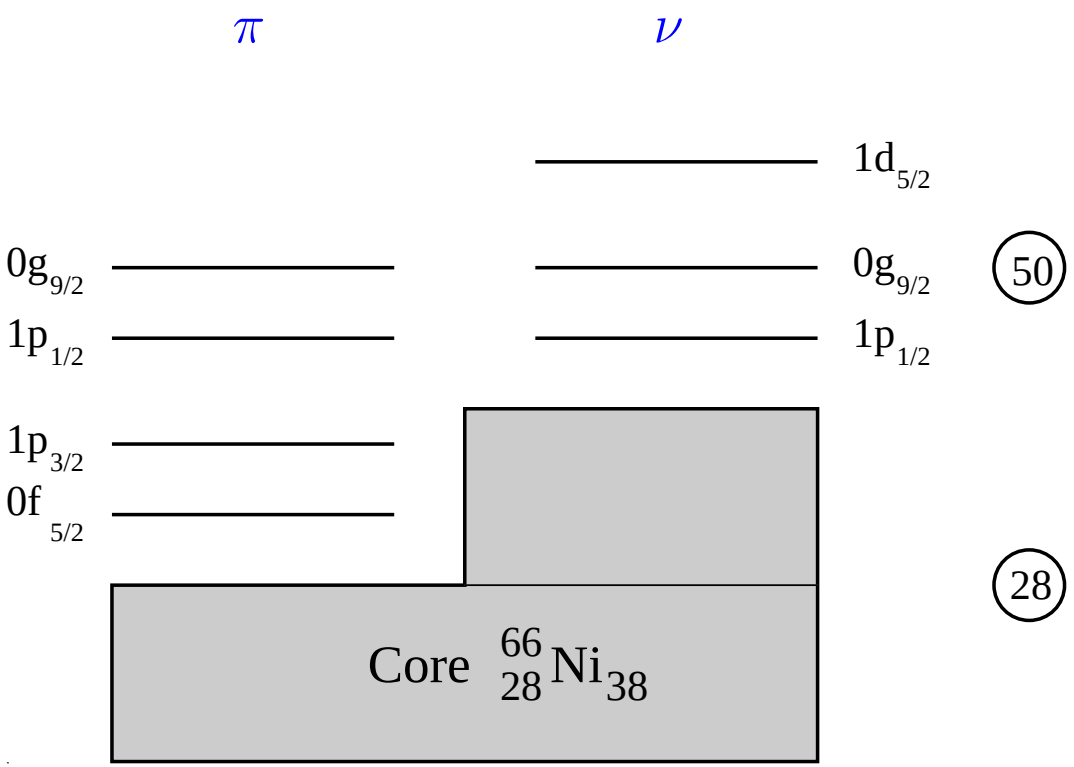
Level scheme of ^{85}Rb



R.S. et al., NPA 584 (1995) 159

Shell-model calculations

Configuration space:



Code: RITSSCHIL

Two-body matrix elements:

$\pi\pi$:
empirical from fit to N=50 nuclei, ^{78}Ni core;
X. Ji, B.H. Wildenthal, PRC 37 (1988) 1256

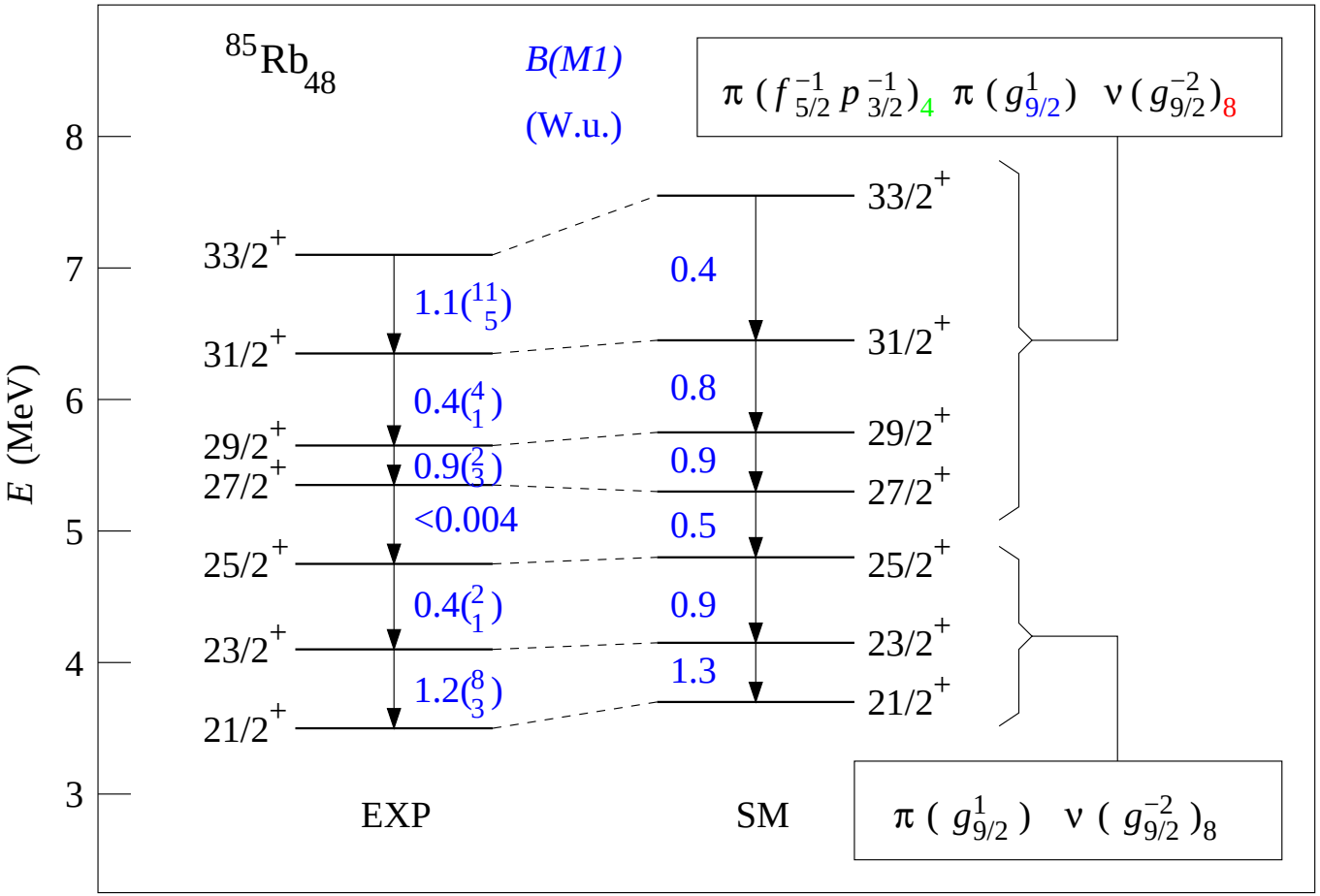
$\pi\nu, \nu\nu$ ($0g_{9/2}$,$1p_{1/2}$):
emp. from fit to N=48,49,50 nuclei, ^{88}Sr core;
R. Gross, A. Frenkel, NPA 267 (1976) 85

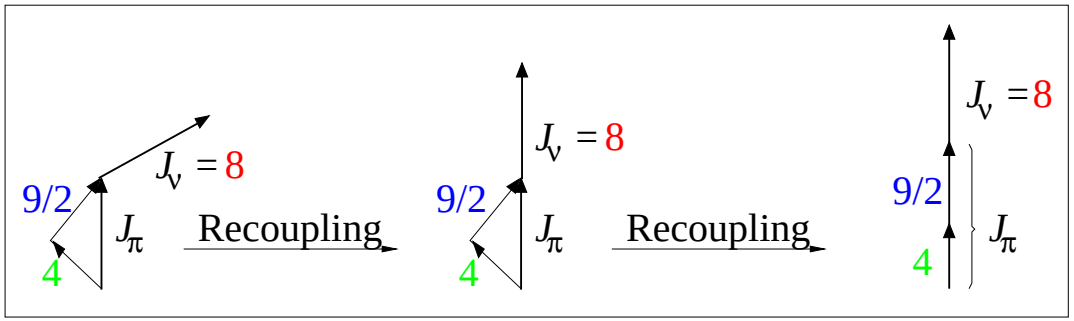
$\pi\nu$ ($\pi 0f_{5/2}$,$\nu 0g_{9/2}$):
experimental from transfer reactions;
P.C. Li et al., NPA 469 (1987) 393

$\nu\nu$ ($0g_{9/2}$,$1d_{5/2}$):
exp. from energies of the multiplet in ^{88}Sr;
P.C. Li, W.W. Daehnick, NPA 462 (1987) 26

remaining:
MSDI;
K. Muto et al., PLB 135 (1984) 349

Shell-model calculations for $^{85}Rb_{48}$





Summary

- The structure of nuclei close to the neutron-shell closure at $N = 50$ can be well described by the shell model.
- Level sequences with strong $M1$ transitions arise from the recoupling of the spins of unpaired particles.
  This is an analogue to the shears mechanism in magnetic rotation.