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 $A \approx 70 - 90$

$\beta_2 \sim 0.35, 0.30, 0.20, 0.15, 0.10, 0.05$
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 ∆ E - E telescopes)
  Neutron wall (50 liquid scintillation detectors)

- **Reaction:**
  \[ {^{40}\text{Ca}} + {^{40}\text{Ca}}; \ E = 185 \text{ MeV}; \ \sigma_T \approx 1060 \text{ mb} \]

- **Reaction channels:**
  \[ {^{40}\text{Ca}}(^{40}\text{Ca},1\alpha3p1n)^{72}\text{Br} \ (\approx 4 \% \cdot \sigma_T) \]
  \[ {^{40}\text{Ca}}(^{40}\text{Ca},1\alpha3p)^{73}\text{Br} \ (\approx 4 \% \cdot \sigma_T) \]

- **Target:**
  0.9 mg/cm² self-supporting (enrichment 99.96 %)

- **Total number of recorded events:**
  \(2 \cdot 10^9\) of fold three or higher
Channel selection:

Energy (keV) vs. Counts*

- $^{70}$Se $2\alpha 2p$
- $^{72}$Se $1\alpha 4p$
- $^{73}$Br $1\alpha 3p$
- $^{75}$Kr $4p1n$
- $^{76}$Kr $4p$
- $^{75}$Kr $4p1n$
- $^{72}$Br $1\alpha 3p1n$

Counts*10^3 vs. Energy (keV):

- $^{70}$Se $2\alpha 2p$
- $^{72}$Se $1\alpha 4p$
- $^{73}$Br $1\alpha 3p$
- $^{75}$Kr $4p1n$
- $^{76}$Kr $4p$
- $^{75}$Kr $4p1n$
- $^{72}$Br $1\alpha 3p1n$
Level scheme of $^{72}\text{Br}$
The signature quantum number defines the admissible spins via the relation:

\[ J = \alpha + 2n \]  
\[ (n = 0, 1, 2, \ldots) \]

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

\[ \frac{(E_I - E_{I-1})}{2I} \] vs. $I$ (keV)

- Experiment
- CNS calc.

C. Plettner et al., PRL 85 (2000) 2454
Cranked Nilsson-Strutinsky calculations for $^{72}\text{Br}$

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

Assumed configurations of the bands:

\[ \pi(f_{5/2} p_{3/2})^6 \pi(g_{9/2}) \nu(f_{5/2} p_{3/2})^6 \nu(g_{9/2})^3 \equiv \langle 1,3 \rangle \]

\[ \pi(f_{5/2} p_{3/2})^5 \pi(g_{9/2})^2 \nu(f_{5/2} p_{3/2})^6 \nu(g_{9/2})^3 \equiv \langle 2,3 \rangle \]

\[ \pi = + \]

\[ \pi = - \]
Cranked Nilsson-Strutinsky calculations for $^{72}$Br

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

Shape trajectories for the negative-parity configurations:

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

\[ \epsilon_2 \sin(\gamma + 30^\circ) \]

\[ \epsilon_2 \cos(\gamma + 30^\circ) \]
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 $^{73}_{\text{Br}}$

$h\omega = 1.85$ MeV

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**
  
  $-(f_{5/2}p_{3/2})^4 (g_{9/2})^3 \Rightarrow J_{\text{max}} = 33/2, \pi = +$
  
  $-(f_{5/2}p_{3/2})^5 (g_{9/2})^2 \Rightarrow J_{\text{max}} = 27/2, 29/2, \pi = −$

- **Neutrons**
  
  $-(f_{5/2}p_{3/2})^6 (g_{9/2})^4 \Rightarrow J_{\text{max}} = 18, \pi = +$
  
  $-(f_{5/2}p_{3/2})^7 (g_{9/2})^3 \Rightarrow J_{\text{max}} = 15, 16, \pi = −$

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:** $[43,64] \Rightarrow J_{\text{max}}^{\pi} = 69/2^+$

- **Band B:** $[43,73] \Rightarrow J_{\text{max}}^{\pi} = 63/2^−$

- **Band C:** $[52,64] \Rightarrow J_{\text{max}}^{\pi} = 63/2^−$
Cranked Nilsson-Strutinsky calculations for $^{73}$Br

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

![Graph showing energy levels for different bands and calculated versus experimental values.](image-url)
Cranked Nilsson-Strutinsky calculations for $^{73}\text{Br}$

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

*Shape trajectories:*

![Graph showing shape trajectories for $^{73}\text{Br}$]
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 $^{79}\text{Br}$

$^{79}\text{Br}$

band A

band B

band C

band D

R.S. et al., PRC 65 (2002) 044326
Nuclear chart around $A \approx 70 - 90$

$N = Z$

$\beta_2 \sim 0.35, 0.30, 0.20, 0.15, 0.10, 0.05$
Multidetector array GASP (INFN - LN Legnaro)
GASP experiment

- **Detectors:**
  40 detectors with escape-suppression shield

- **Reaction:**
  $^{11}\text{B} + ^{76}\text{Ge}; \ E = 45 \text{ MeV}; \ \sigma_T \approx 1000 \text{ mb}$

- **Reaction channels:**
  - $^{76}\text{Ge}({}^{11}\text{B},5n)^{82}\text{Rb} \ (\approx 20\% \cdot \sigma_T)$
  - $^{76}\text{Ge}({}^{11}\text{B},4n)^{83}\text{Rb} \ (\approx 50\% \cdot \sigma_T)$
  - $^{76}\text{Ge}({}^{11}\text{B},3n)^{84}\text{Rb} \ (\approx 10\% \cdot \sigma_T)$

- **Target:**
  1.2 mg/cm$^2$ $^{76}\text{Ge}$ (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**

\[ B(\text{E}2) \propto Q_0^2 \]

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

**magnetic rotation**

\[ B(\text{M}1) \propto \mu_\perp^2 \]
Appearance of magnetic rotation

S. Frauendorf, ZPA 358 (1997) 163
\[ \pi = - M1 \text{ band in } ^{82}\text{Rb} \]
configuration \( \pi (fp) \pi g_{9/2}^2 \nu g_{9/2} \)

\[ B(M1)/B(E2) \left( \mu_N/e_b^2 \right) \]

\[ J \]

\[ h_\omega \text{ (MeV)} \]

\[ \varepsilon_2 = 0.16 \]
\[ \gamma = 20^\circ \]

\[ \varepsilon_2 = 0.16 \]
\[ \gamma = 20^\circ \]

\[ H. \text{ Schnare et al., PRL 82 (1999) 4408} \]
Transition strengths in the M1 band of $^{82}$Rb

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

$B(M1)$ (\(\mu N^{2}\))
$B(E2)$ (\(e^{2}fm^{4}\))

$R.S. \ et \ al., \ PRC \ 66 \ (2002) \ 024310$
Doppler-shift methods

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

\[ E_\gamma = E_\gamma^0 \left[ 1 + \frac{v(t)}{c} \cos \varphi(t) \right] \]

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

(c) $^{84}\text{Rb}$ Gate on 1636.4 keV
$\tau = 0.82(8)\text{ ps}$

(d) $^{84}\text{Rb}$ Gate on 445.1 keV
$\tau = 0.38(1)\text{ ps}$

Gate on 725 keV
$\tau = 0.18(2)\text{ ps}$

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 $\pi (fp) \pi g_{9/2}^2 \nu g_{9/2}$.
- 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 $A \approx 70 - 90$

$\beta_2 \sim 0.35$ 0.30 0.20 0.15 0.10 0.05
Level scheme of $^{85}\text{Rb}$

R.S. et al., NPA 584 (1995) 159
Shell-model calculations

Configuration space:

\begin{align*}
\pi & \quad \nu \\
0g_{9/2} & \quad 0g_{9/2} \\
1p_{1/2} & \quad 1p_{1/2} \\
1p_{3/2} & \quad 1d_{5/2} \\
0f_{5/2} & \quad 2s_{1/2} \\
\text{Core} & \quad ^{66}_{28}\text{Ni}^{38}\end{align*}

Two-body matrix elements:

\begin{itemize}
  \item \(\pi\pi\): empirical from fit to \(N=50\) nuclei, \(^{78}\text{Ni}\) core; X. Ji, B.H. Wildenthal, PRC 37 (1988) 1256
  \item \(\pi\nu, \nu\nu\ (0g_{9/2}, 1p_{1/2})\): emp. from fit to \(N=48, 49, 50\) nuclei, \(^{88}\text{Sr}\) core; R. Gross, A. Frenkel, NPA 267 (1976) 85
  \item \(\pi\nu\ (\pi 0f_{5/2}, \nu 0g_{9/2})\): experimental from transfer reactions; P.C. Li et al., NPA 469 (1987) 393
  \item \(\nu\nu\ (0g_{9/2}, 1d_{5/2})\): exp. from energies of the multiplet in \(^{88}\text{Sr}\); P.C. Li, W.W. Daehnick, NPA 462 (1987) 26
\end{itemize}

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

Code: RITSSCHIL
Shell-model calculations for $^{85}$Rb

\[ B(M1) \] (W.u.)

$^{85}$Rb

\( \pi \left( f_{5/2}^{-1} p_{3/2}^{-1} \right)_4 \) \( \pi \left( g_{9/2}^1 \right)_8 \)

\( \nu \left( g_{9/2}^{-2} \right)_8 \)

\( \left( g_{9/2}^{9/2} \right)_1 \nu \left( g_{9/2}^{9/2} \right)_4 \)

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\( 21/2^+ \)
\( 23/2^+ \)
\( 25/2^+ \)
\( 27/2^+ \)
\( 29/2^+ \)
\( 31/2^+ \)
\( 33/2^+ \)

\( B(M1) \) values:

- \( 9/2^+ \) level:
  - \( J_\pi = 4 \)
  - \( J_\nu = 8 \)

- \( 21/2^+ \) level:
  - \( J_\pi = 8 \)
  - \( J_\nu = 8 \)

- \( 23/2^+ \) level:
  - \( J_\pi = 8 \)
  - \( J_\nu = 8 \)

- \( 25/2^+ \) level:
  - \( J_\pi = 8 \)
  - \( J_\nu = 8 \)

- \( 27/2^+ \) level:
  - \( J_\pi = 8 \)
  - \( J_\nu = 8 \)

- \( 29/2^+ \) level:
  - \( J_\pi = 8 \)
  - \( J_\nu = 8 \)

- \( 31/2^+ \) level:
  - \( J_\pi = 8 \)
  - \( J_\nu = 8 \)

- \( 33/2^+ \) level:
  - \( J_\pi = 8 \)
  - \( J_\nu = 8 \)
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.