<u>Collective Excitations</u> in Exotic Nuclei

David Radford (ORNL)
RIA Summer School, August 2002

I Nuclear Excitations: Single particle motion *vs*. Collective motion

"Do nuclei really rotate?"

Collective Modes: Rotations and Vibrations

- Role of shapes and symmetries
- Particle-rotational couplings
- Shape oscillations; coupling to rotation

II Experimental techniques and examples of results

- Gamma-Ray Spectroscopy
- Giant Resonances (high-frequency vibrations)
- Intermediate-Energy Coulomb Excitation

III Towards RIA: Experiments with n-rich beams at the HRIBF

We will start with *general principles,*
then move to *specific examples.*

Have attempted to avoid jargon and formulas,
and material covered by other lecturers.

Please interrupt at any time!

Superb reference:
Bohr and Mottelson, vol. 2 – “Nuclear Deformations”
Publisher: W.A. Benjamin, Reading, MA 01867, 1975

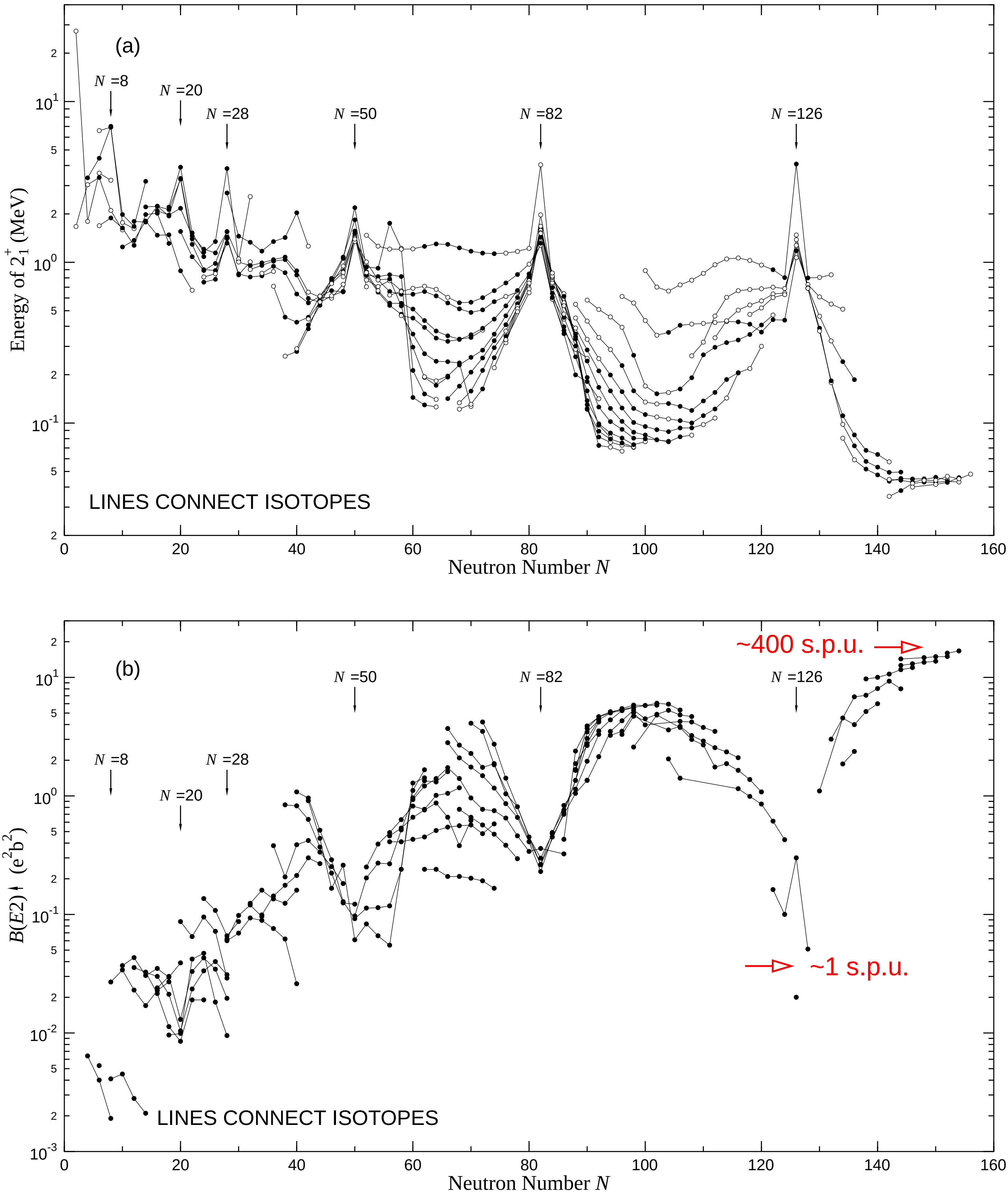
The nucleus is one of nature's most interesting quantal few-body systems. It brings together many types of behavior, almost all of which are found individually in other systems but which, in nuclei, interact with one another.

The major elementary excitations in nuclei can be associated either with **single particle** or **collective** modes.

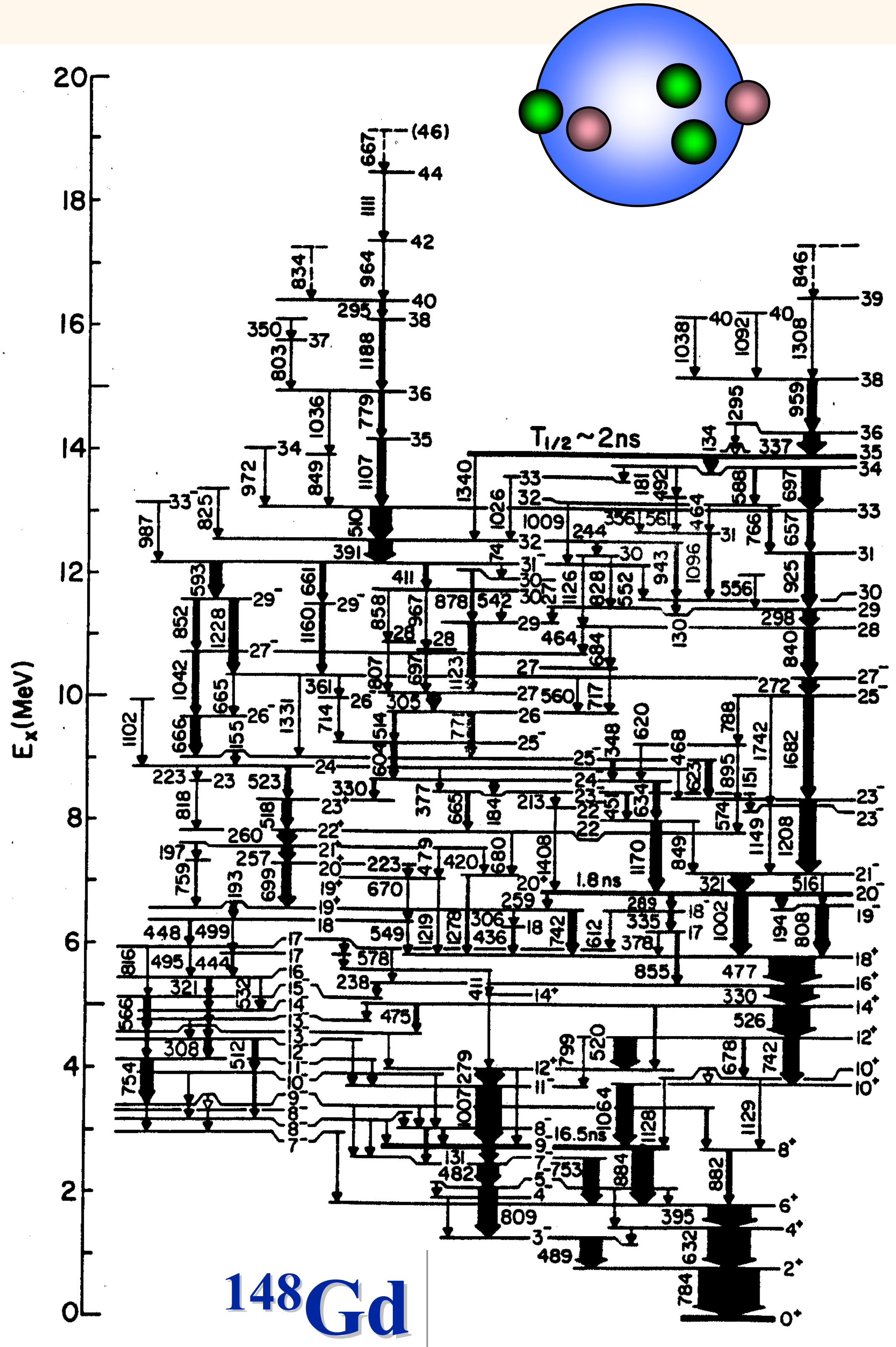
- **Single particle**: nucleons are assumed to move independently in an average potential; behavior is described, for example, within the framework of the nuclear shell model.
- **Collective**: close analogies to molecular and solid-state physics, and to familiar macroscopic systems (e.g. liquid drop.)

While these modes can exist in isolation, it is the *interaction between them* that gives nuclear spectroscopy its rich diversity.

S. Raman et al., Atomic Data & Nuclear Data Tables 78, 1



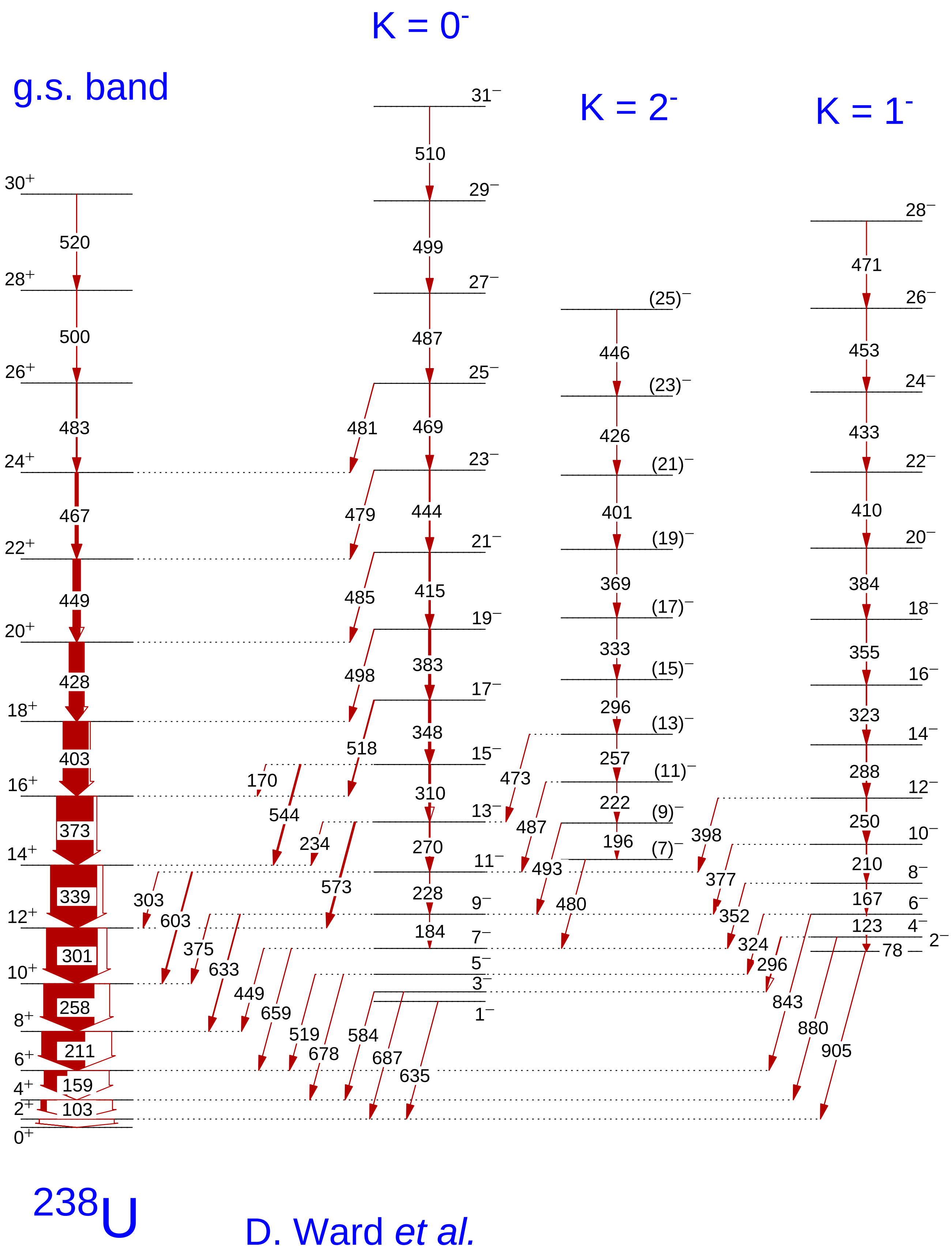
Noncollective excitations



^{148}Gd

M.W. Drigert et al., Nucl. Phys. A515 (1990) 466

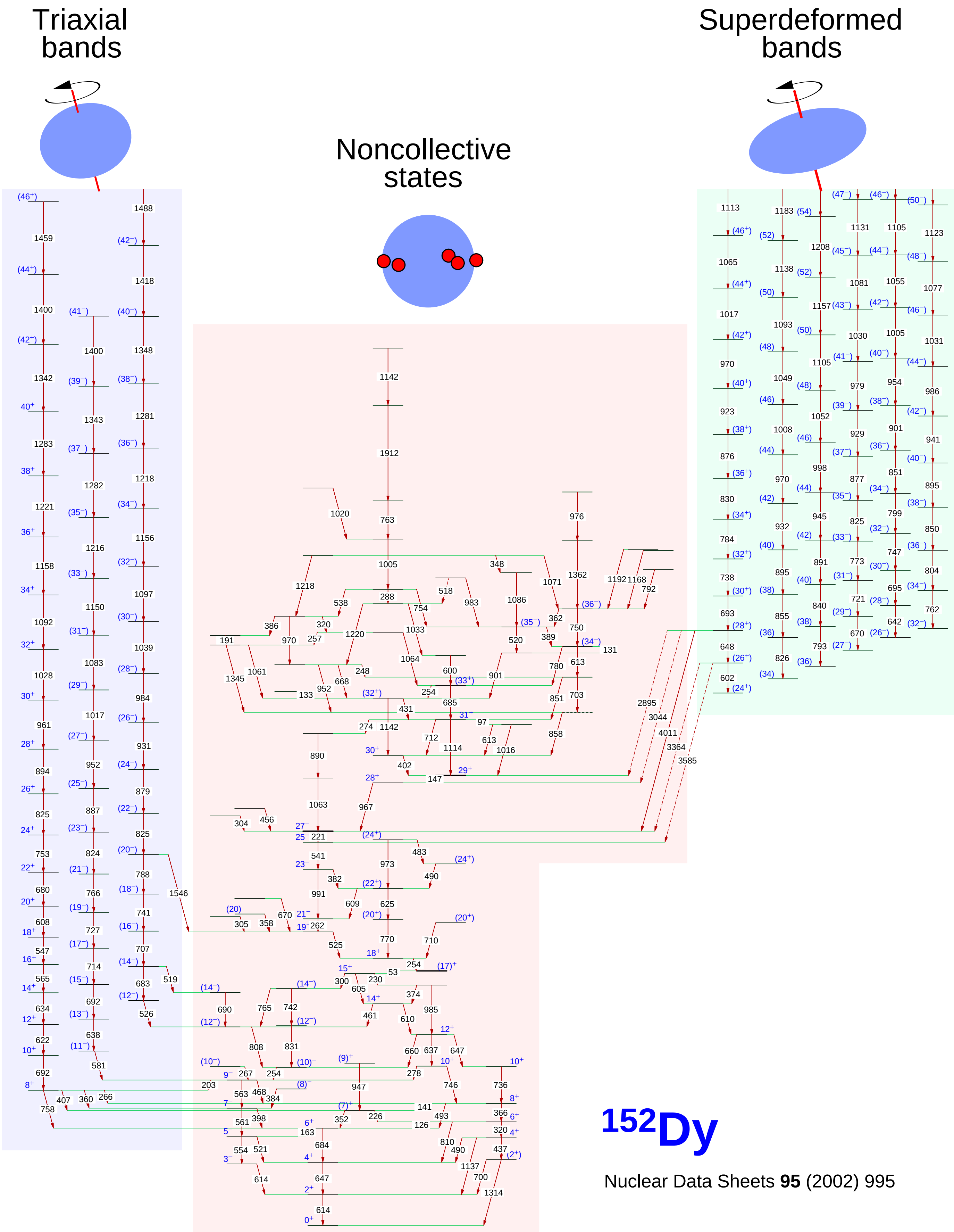
Octupole Vibrations



D. Ward *et al.*

Nucl. Phys. **A600** (1996) 88

Coexistence of collective and noncollective motion



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

Why is it that the Independent Particle picture
of nuclear motion works?

•Pauli Exclusion Principle
-gives nucleons essentially infinite mean free path.

But if the range of the nuclear force was 2 or 3 times larger,
nuclei could have been *crystalline*…

ELSEVIER

Nuclear Physics A649 (1999) 45c

NUCLEAR PHYSICS A

Why are nuclei described by independent particle motion ?

B.R. Mottelson[a*]

[a]The Niels Bohr Institute and NORDITA, Blegdamsvej 17, DK-2100 Copenhagen Ø, Denmark

Constituents	M	V_0 [eV]	a [cm]	Λ	T=0 matter
^3He	3	$9 \cdot 10^{-4}$	$2.9 \cdot 10^{-8}$	0.21	liquid
^4He	4	$9 \cdot 10^{-4}$	$2.9 \cdot 10^{-8}$	0.16	liquid
H_2	2	$3 \cdot 10^{-3}$	$3.3 \cdot 10^{-8}$	0.07	solid
Ne	20	$3 \cdot 10^{-3}$	$3.1 \cdot 10^{-8}$	0.007	solid
nuclei	1	$1 \cdot 10^{8}$	$9 \cdot 10^{-14}$	0.4	liquid

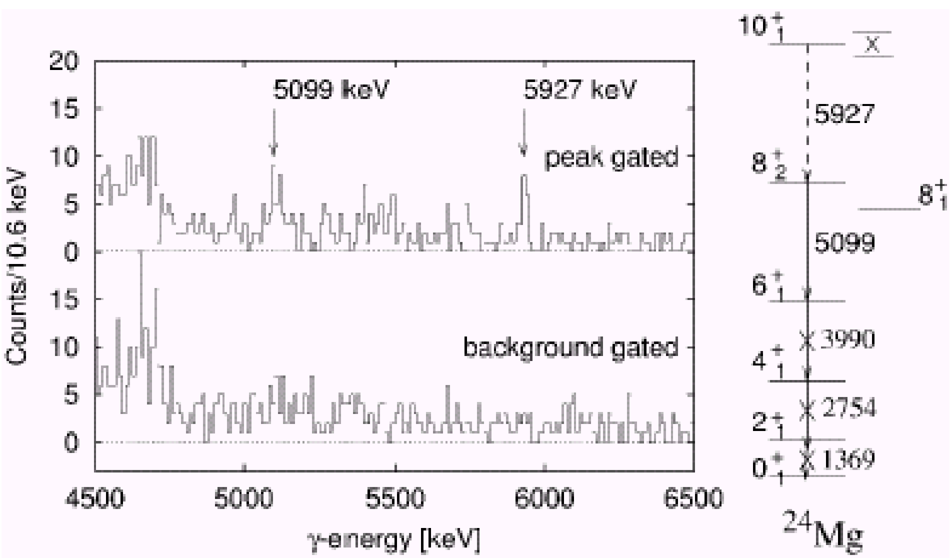
Table 1
The "quantality" parameter $\Lambda = \hbar^2/Ma^2V_0$ measures the strength of the two-body attraction, V_0, expressed in units of the quantal kinetic energy associated with a localization of a constituent particle of mass M within the distance a corresponding to the radius of the force at maximum attraction. For small Λ the quantal effect is small and the ground state of the many body system will be, as in classical mechanics, a configuration in which each particle finds a static optimal position with respect to its nearest neighbors. If Λ is big enough the ground state may be a quantum liquid in which the individual particles are delocalized and the low-energy excitations (quasi-particles) have infinite mean free path. A parameter related to Λ was first used by de Boer in the analysis of quantal constants of the noble gas solids.

But the independent-particle shell model can also describe *rotational* structure:

VOLUME 87, NUMBER 14 PHYSICAL REVIEW LETTERS 1 OCTOBER 2001

Identification of the $I^\pi = 10^+$ Yrast Rotational State in ^{24}Mg

I. Wiedenhöver,[1,*] A. H. Wuosmaa,[1] R. V. F. Janssens,[1] C. J. Lister,[1] M. P. Carpenter,[1] H. Amro,[1,†] P. Bhattacharyya,[2] B. A. Brown,[3] J. Caggiano,[1] M. Devlin,[4,‡] A. Heinz,[1] F. G. Kondev,[1] T. Lauritsen,[1] D. G. Sarantites,[4] S. Siem,[1,§] L. G. Sobotka,[4] and A. Sonzogni[1]



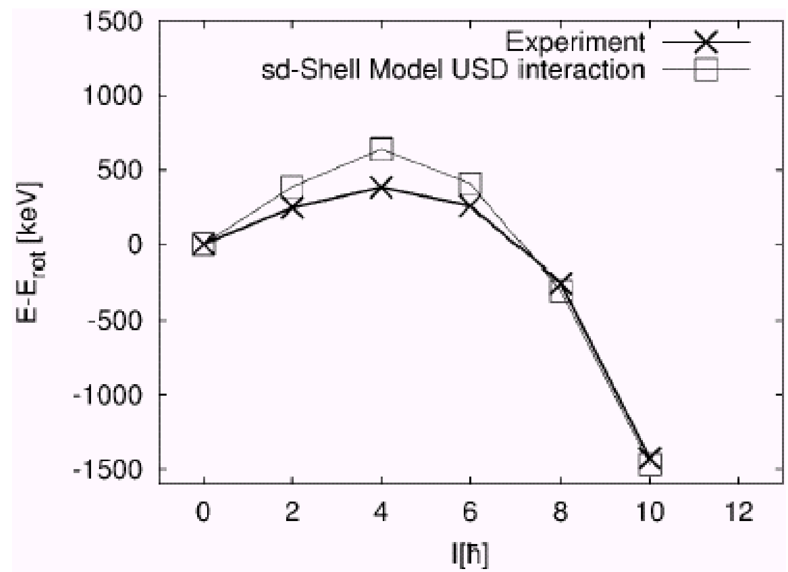


FIG. 5. Excitation energies of the ground state band in ^{24}Mg, with a rotational reference $E_{\rm rot}[\text{keV}] = 187 \times I(I+1)$ subtracted, compared with the results of a *sd*-shell model calculation with the USD Hamiltonian [13].

The shell model does very well at reproducing the energies of the superdeformed band in ^{36}Ar.

C. Svensson et al., Phys. Rev. Lett. 85 (2000) 2693

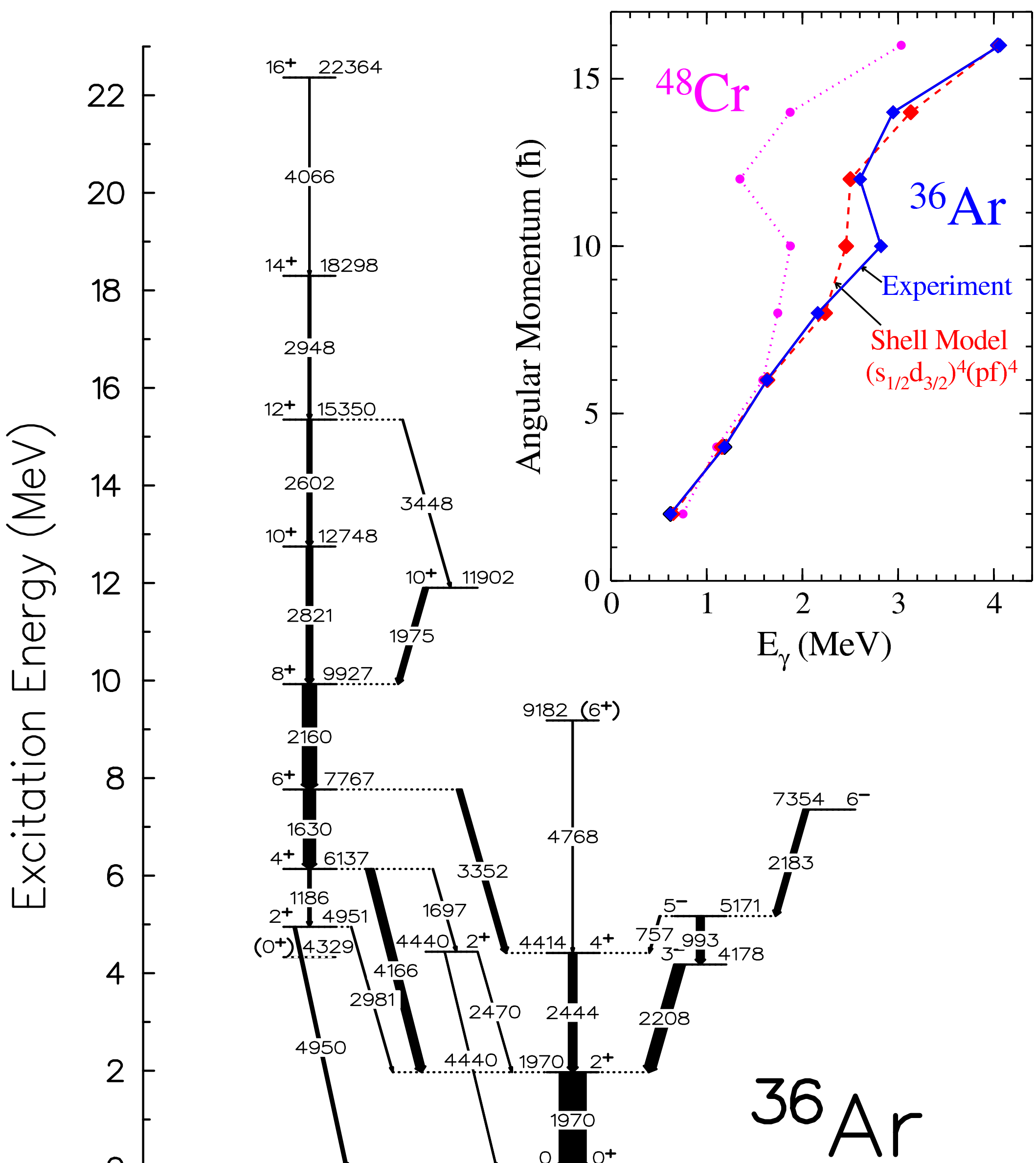


FIG. 2. Partial decay scheme for ^{36}Ar showing the superdeformed band (left). Transition and level energies are given to the nearest keV and arrow widths are proportional to transition intensities. The inset compares the experimental and shell model "backbending" plots for the SD band in ^{36}Ar, as well as experimental values for the ground band of ^{48}Cr [2–4].

The shell model can even reproduce the experimental B(E2) values for the superdeformed band in ^{36}Ar.

C. Svensson et al., Phys. Rev. C63 (2001) 061301

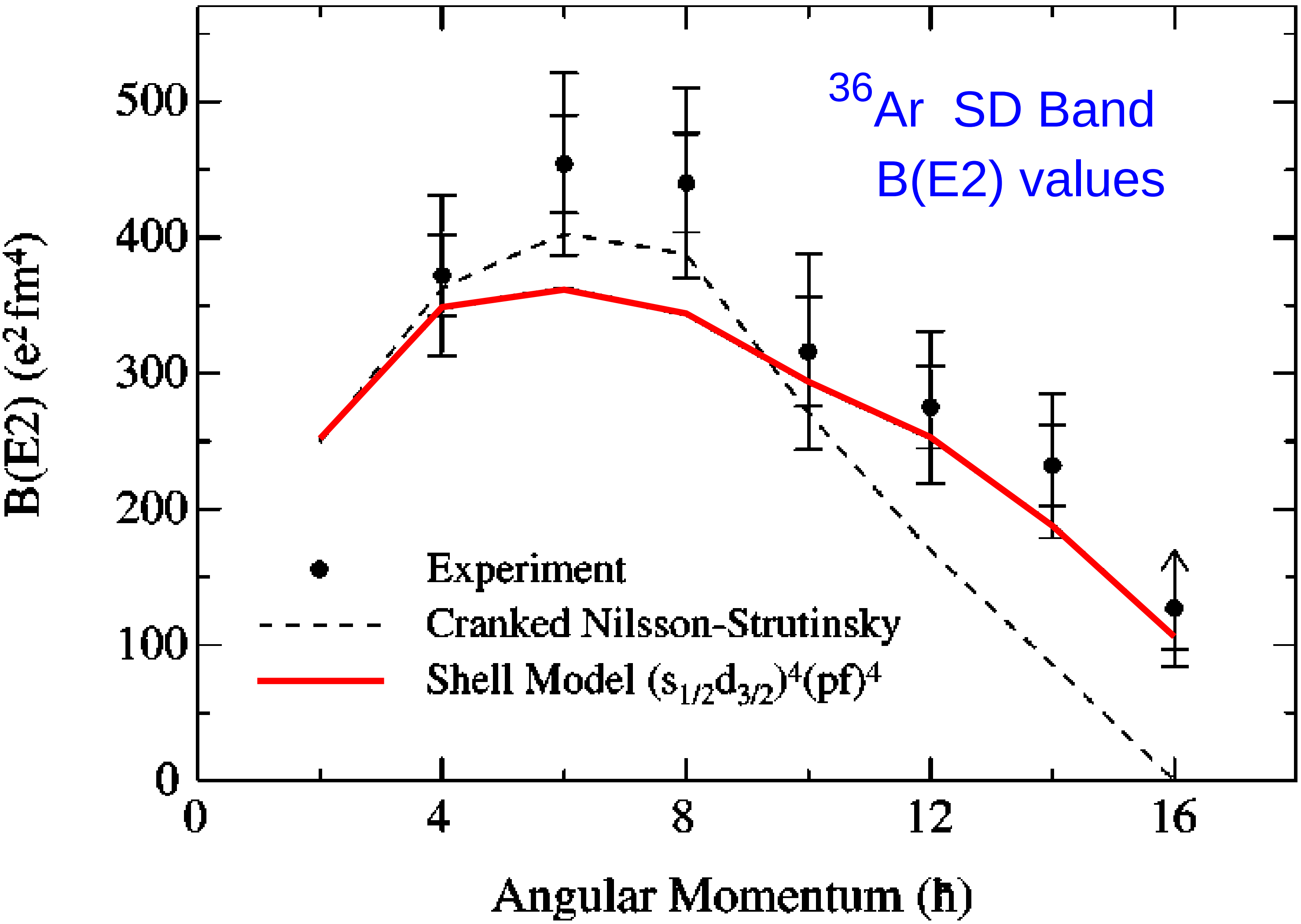


FIG. 5. $B(E2;I\rightarrow I-2)$ values for the SD band in ^{36}Ar compared with the results of cranked Nilsson-Strutinsky (dashed line) and $(s_{1/2}d_{3/2})^4(pf)^4$ shell model (solid line) calculations. The inner

Should we really talk about Collective Motion in nuclei?

- "Do nuclei rotate?"

Use concepts introduced by Jeff Tostevin yesterday:

Adiabatic approximation:

- identify the fast and slow degrees of freedom.

Example: excited states of molecules.

electronic motion - fastest

vibrations - $\sim 10^2$ times slower

rotations - $\sim 10^6$ times slower

The different motions have very different time scales, so the wavefunction (approximately) separates into products of terms.

Nuclei: Examine time scales for single-particle and collective motion.

1. Fermi Energy ~ 10 MeV $\frac{V_F}{c} = \sqrt{\frac{2E_F}{mc^2}} = 0.14$

$\Rightarrow$ $V_F \sim 4\times10^{22}$ fm/s

Nuclear radius $R = 1.2\ A^{1/3}$

$T_F = 4R / V_F$

R = 3.3 fm	A = 20
R = 5.6 fm	A = 100
$T_F \sim 3\times10^{-22}$ s	A = 20
$T_F \sim 6\times10^{-22}$ s	A = 100

2. Rotation $\hbar\omega = \frac{1}{2}E\gamma\ (I \rightarrow I\text{-}2)$

~ 1.5 MeV	A = 20
~ 500 keV	A = 100

$\hbar = 6.6\times10^{-16}$ eV s

$T_R = 2\pi / \omega$ $\Rightarrow$

$T_R \sim 4\times10^{-21}$ s	A = 20
$T_R \sim 1\times10^{-20}$ s	A = 100

$T_R / T_F \sim 11$	A = 20
$T_R / T_F \sim 16$	A = 100

$T_R \propto \mathscr{I} \sim R^2$ $T_F \propto R$ Ratio $\sim R \sim A^{1/3}$

Finite size effects are also stronger in light nuclei.

$\Rightarrow$ Heavy nuclei provide many of the best examples of regular collective motion; e.g. SDBs to > 60 $\hbar$.

But $\hbar\omega$ is larger for light nuclei.

What can we conclude from this?

- Collective and single-particle modes can perhaps be separated, but they will interact strongly!

e.g:

- Core polarization
- Coriolis forces → backbending, modification of shell structure, quenching of pairing.
- Finite size effects → band termination, blocking of collective excitations

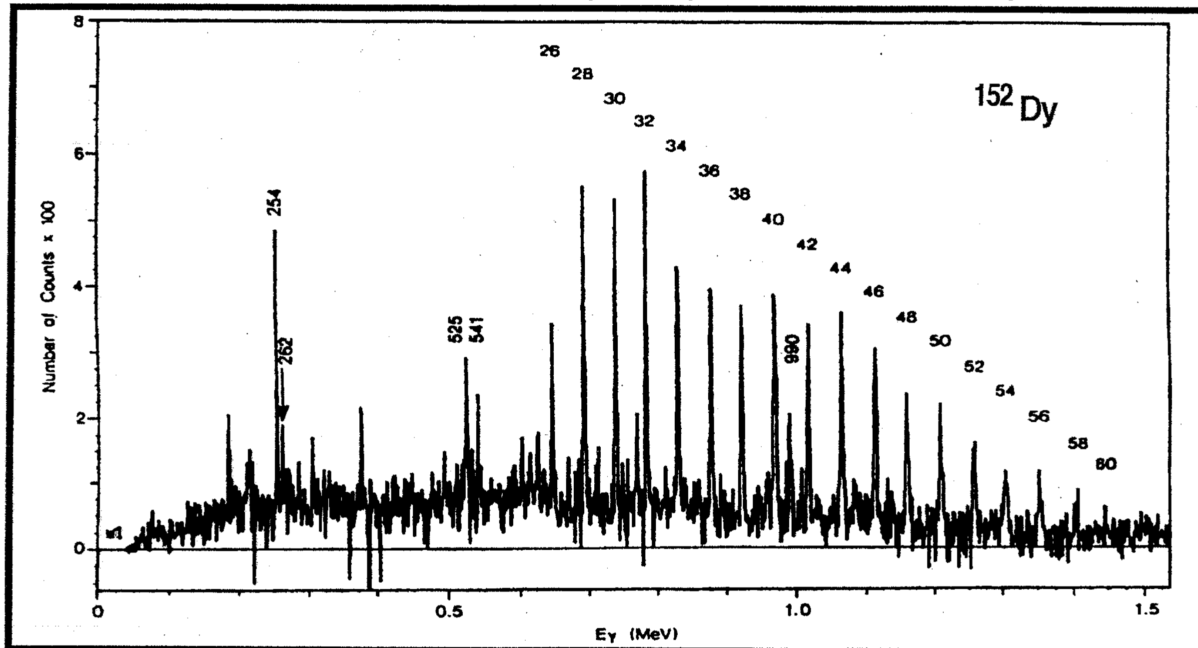
Nevertheless, the collective/unified model has proven to be a very powerful and useful tool.

Next: **Rotations**

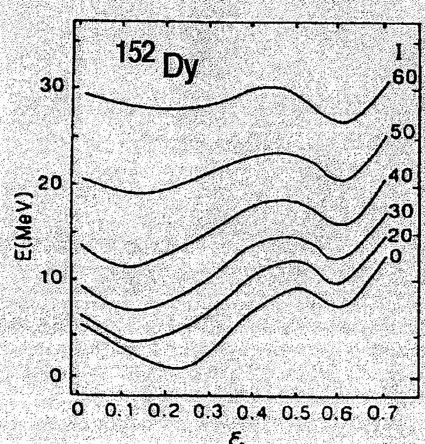
VOLUME 57, NUMBER 7 PHYSICAL REVIEW LETTERS 18 AUGUST 1986

Observation of a Discrete-Line Superdeformed Band up to $60\hbar$ in ^{152}Dy

P. J. Twin, B. M. Nyakó,[a] A. H. Nelson, and J. Simpson
Science and Engineering Research Council, Daresbury Laboratory, Warrington WA4 4AD, United Kingdom



Nilsson Strutinsky Calculations



Ragnarson *et al.* Nucl. Phys. **A347** (1980) 387

- 12 Compton Suppressed Ge Detectors (TESSA3)
- $\Delta E_\gamma \sim 47$ keV
- $Q_t = 19 \pm 3$ eb $\rightarrow \beta_2 = 0.6$ (2:1 axis ratio)

B(E2) ~ 2000 s.p.u.!

Detour - Superdeformed Rotation

e.g. ^{152}Dy

Superdeformed band: ~ 20 gammas in ~ 10^{-13} s

$\sum E\gamma \sim 20$ MeV   1 eV = 1.6×10^{-19} J

$\Rightarrow$ Power = (3.2×10^{-12} J) / (10^{-13} s) = 32 W (!)

Rotational frequency $\hbar\omega \cong 500$ keV

$\omega \cong 8\times10^{20}$ radians/s $\rightarrow$ ~ 10^{20} Hz

or 10^{7} rotations in 10^{-13} s

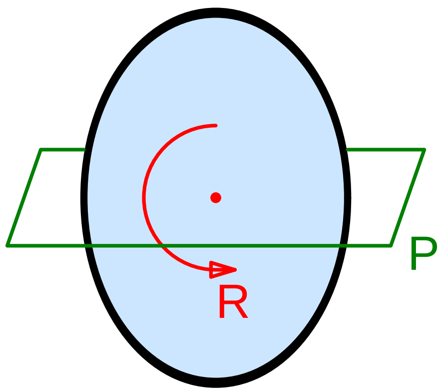
- same as number of days in 30,000 years!

Decay of ^{152}Dy SDB to ground state passes through a long-lived (86 ns) level

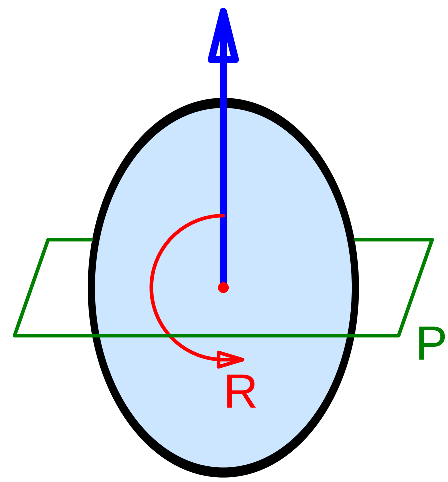
$\Rightarrow$ ~ 5×10^{12} rotations $\cong$ days since the big bang.

Symmetries of the Intrinsic Hamiltonian:
Axial Symmetry, Reflection-symmetric

K = angular momentum projection
on symmetry axis



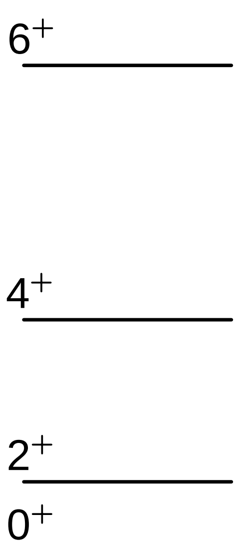
K = 0



K > 0

P: parity (reflection)
R: rotation by 180°
T: time reversal

P: parity (reflection)
RT: rotation by 180°
AND time reversal
(which reverses K)



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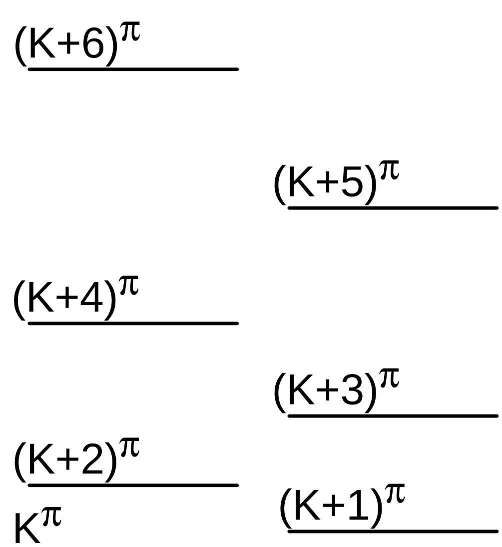
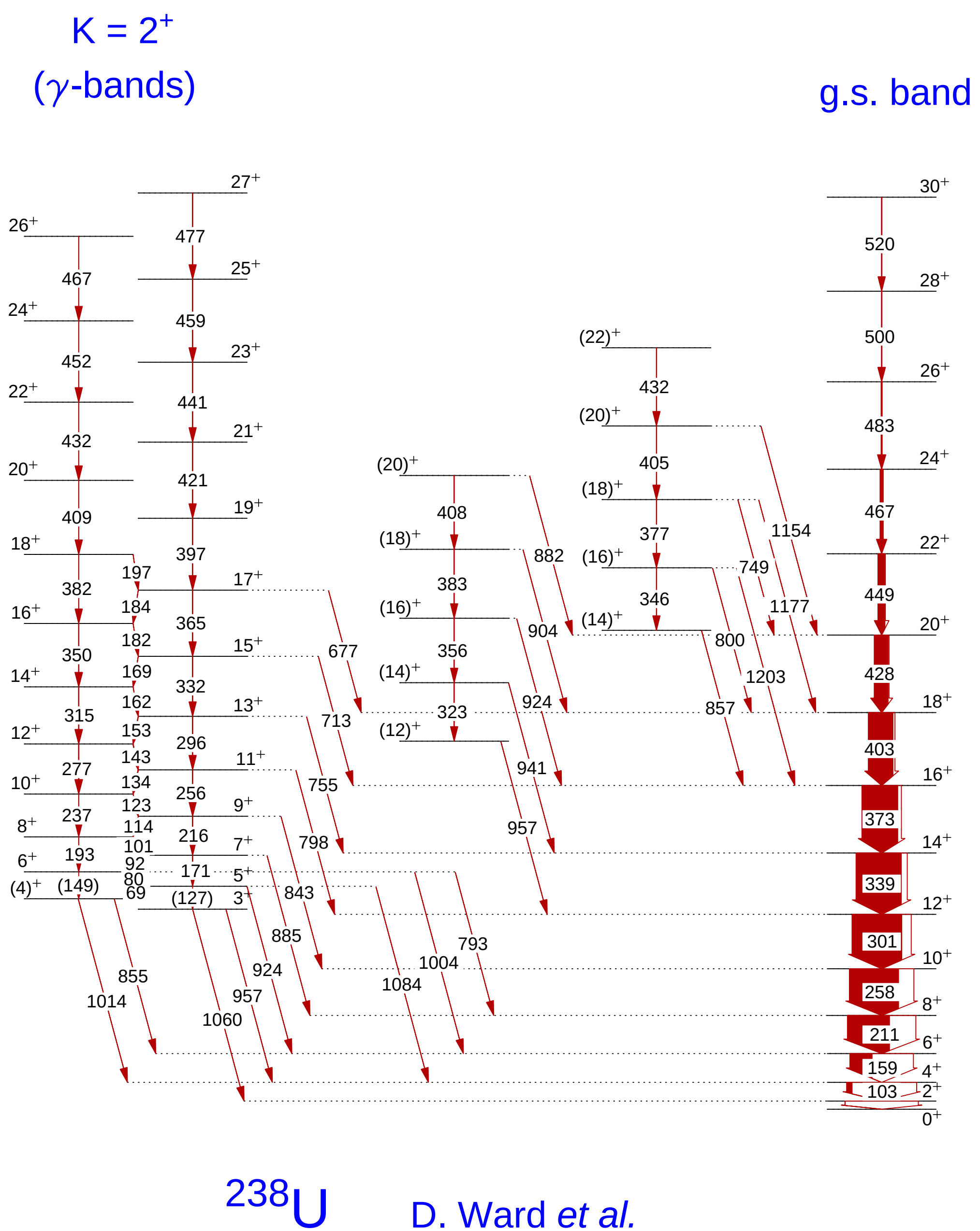


K > 0

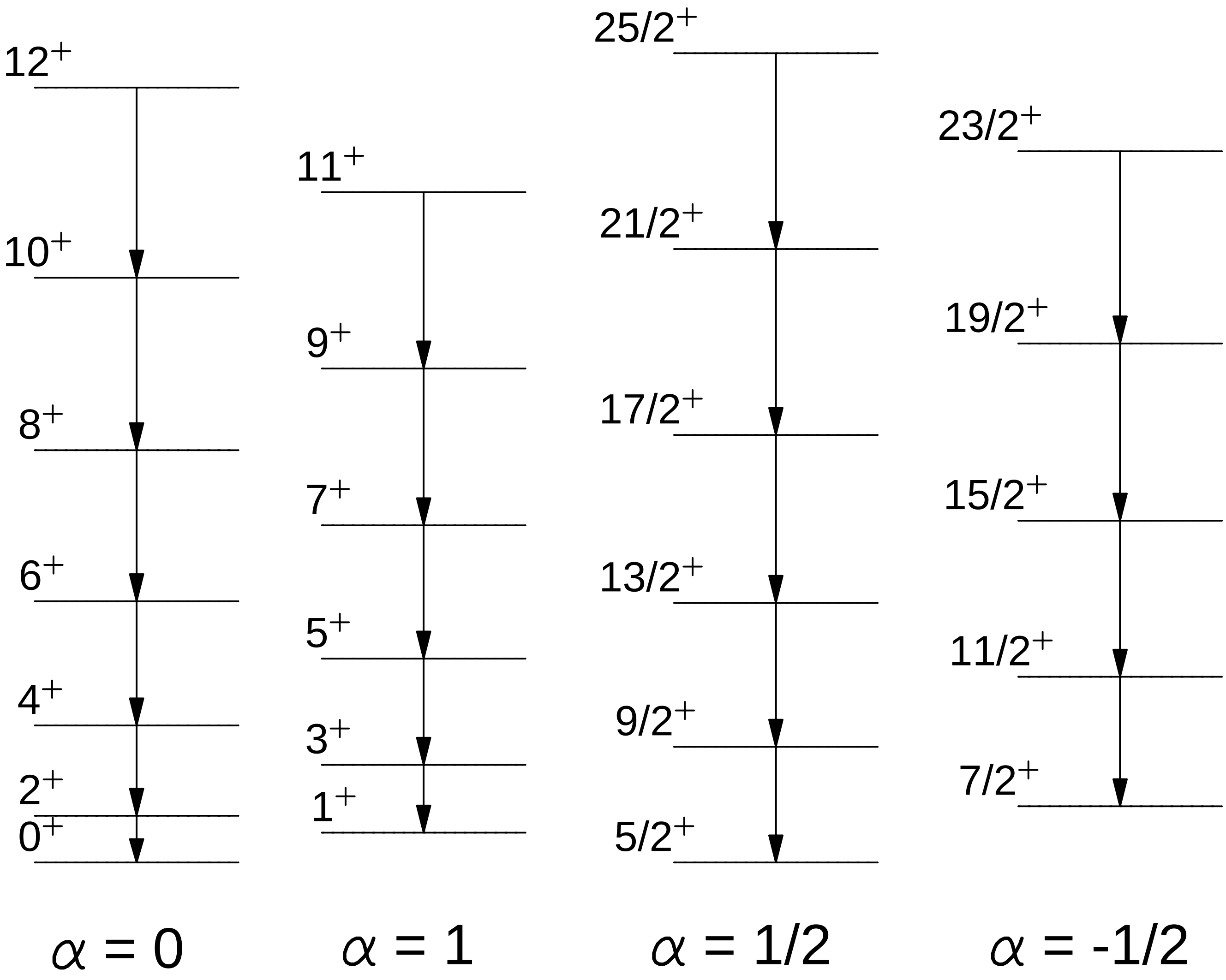


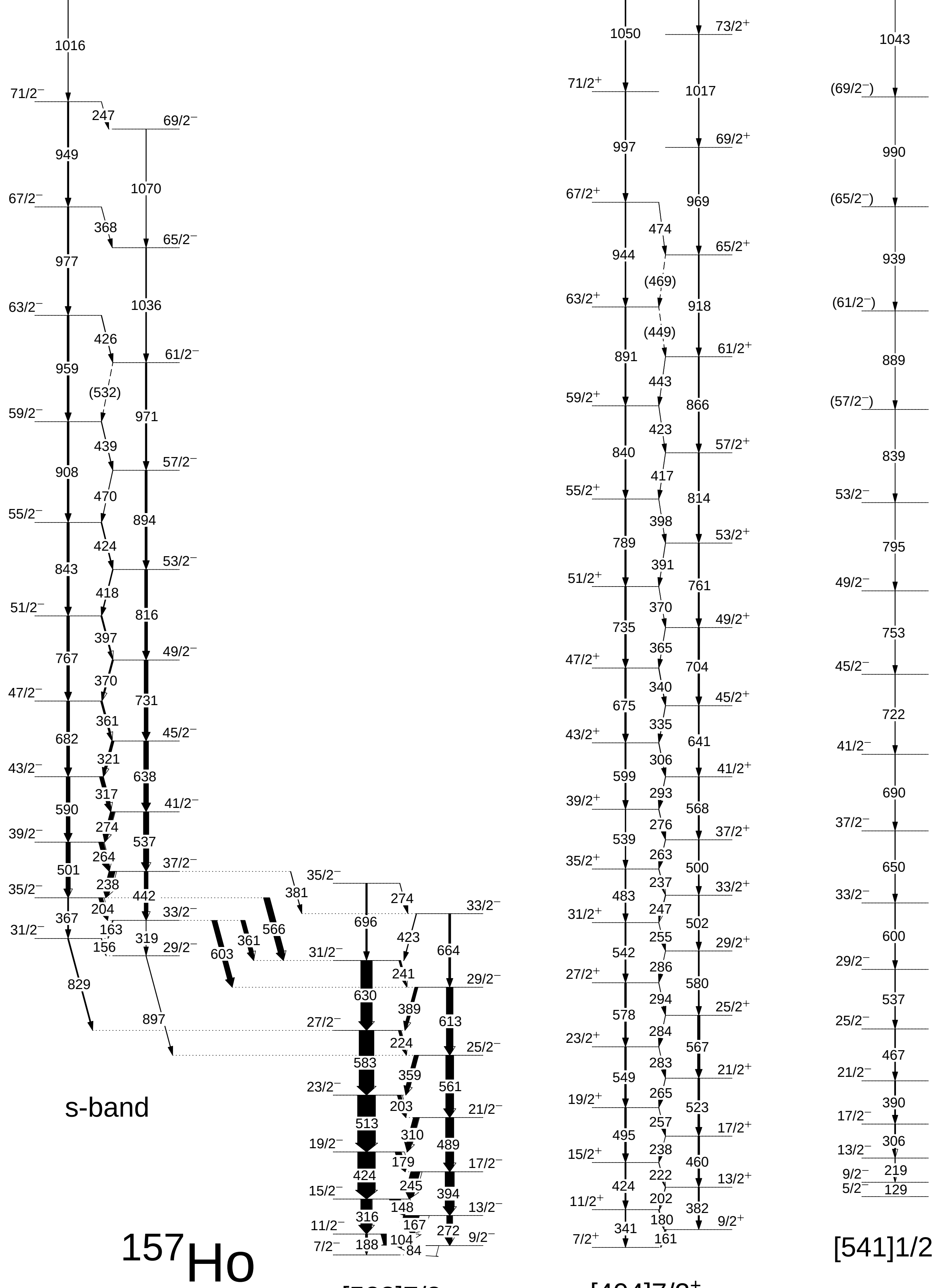
D. Ward *et al.*

Nucl. Phys. **A600** (1996) 88

Signature quantum number α

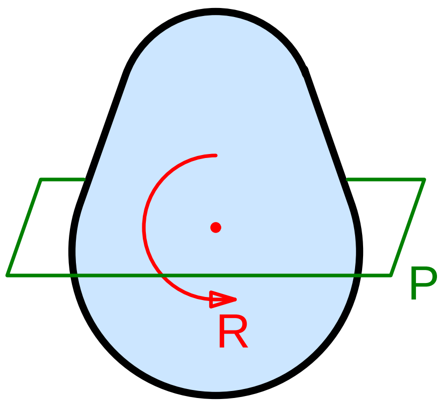
$$J = 2n + \alpha$$




s-band
71/2− 67/2− 63/2− 59/2− 55/2− 51/2− 47/2− 43/2− 39/2− 35/2− 31/2−
1016 949 977 959 908 843 767 682 590 501 367 829
69/2− 65/2− 61/2− 57/2− 53/2− 49/2− 45/2− 41/2− 37/2− 33/2− 29/2−
1070 1036 971 894 816 731 638 537 442 319 897
247 368 426 (532) 439 470 424 418 397 370 361 321 317 274 264 238 204 163 156
381 603 361 566
^{157}Ho
[523]7/2-
35/2− 31/2− 27/2− 23/2− 19/2− 15/2− 11/2− 7/2−
696 630 583 513 424 316 188
33/2− 29/2− 25/2− 21/2− 17/2− 13/2− 9/2−
664 613 561 489 394 272
274 423 241 389 224 359 203 310 179 245 148 167 104 84
[404]7/2+
71/2+ 67/2+ 63/2+ 59/2+ 55/2+ 51/2+ 47/2+ 43/2+ 39/2+ 35/2+ 31/2+ 27/2+ 23/2+ 19/2+ 15/2+ 11/2+ 7/2+
1050 997 944 891 840 789 735 675 599 539 483 542 578 549 495 424 341
73/2+ 69/2+ 65/2+ 61/2+ 57/2+ 53/2+ 49/2+ 45/2+ 41/2+ 37/2+ 33/2+ 29/2+ 25/2+ 21/2+ 17/2+ 13/2+ 9/2+
1017 969 918 866 814 761 704 641 568 500 502 580 567 523 460 382
474 (469) (449) 443 423 417 398 391 370 365 340 335 306 293 276 263 237 247 255 286 294 284 283 265 257 238 222 202 180 161
[541]1/2-
(69/2−) (65/2−) (61/2−) (57/2−) 53/2− 49/2− 45/2− 41/2− 37/2− 33/2− 29/2− 25/2− 21/2− 17/2− 13/2− 9/2− 5/2−
1043 990 939 889 839 795 753 722 690 650 600 537 467 390 306 219 129

Symmetries of the Intrinsic Hamiltonian:
Axial Symmetry, Reflection-asymmetric

K = angular momentum projection
on symmetry axis



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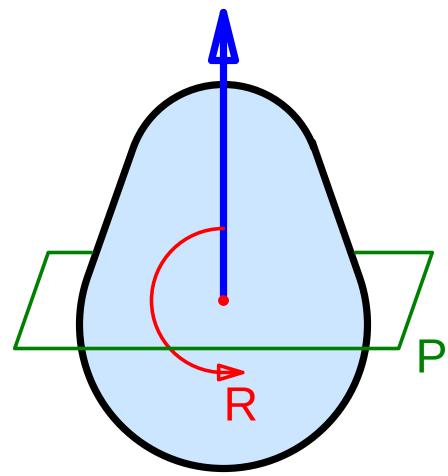
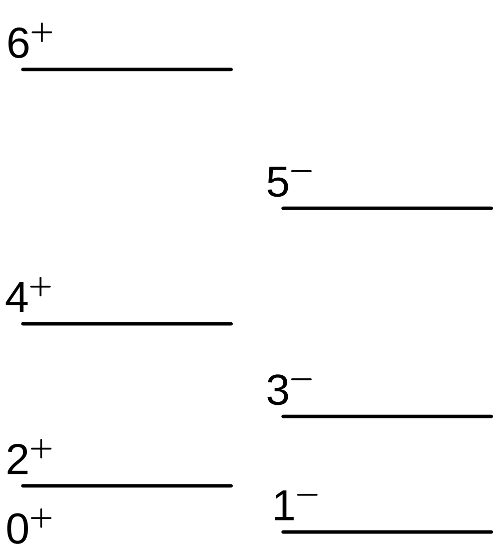


K > 0

RP: rotation & reflection
T: time reversal

RPT: need all three operations



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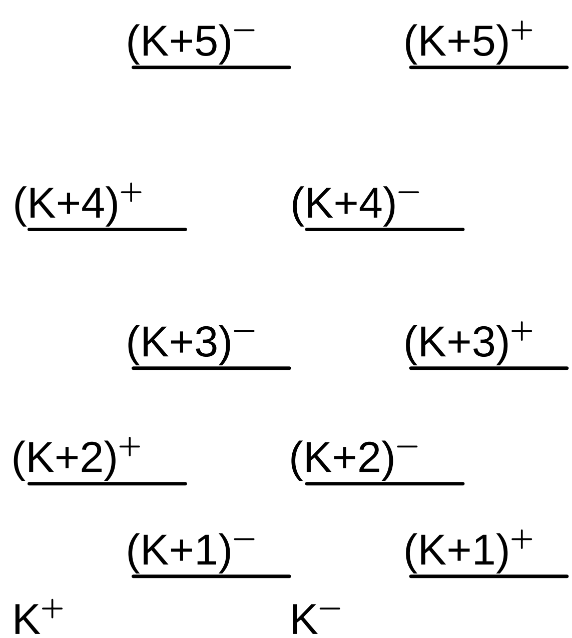
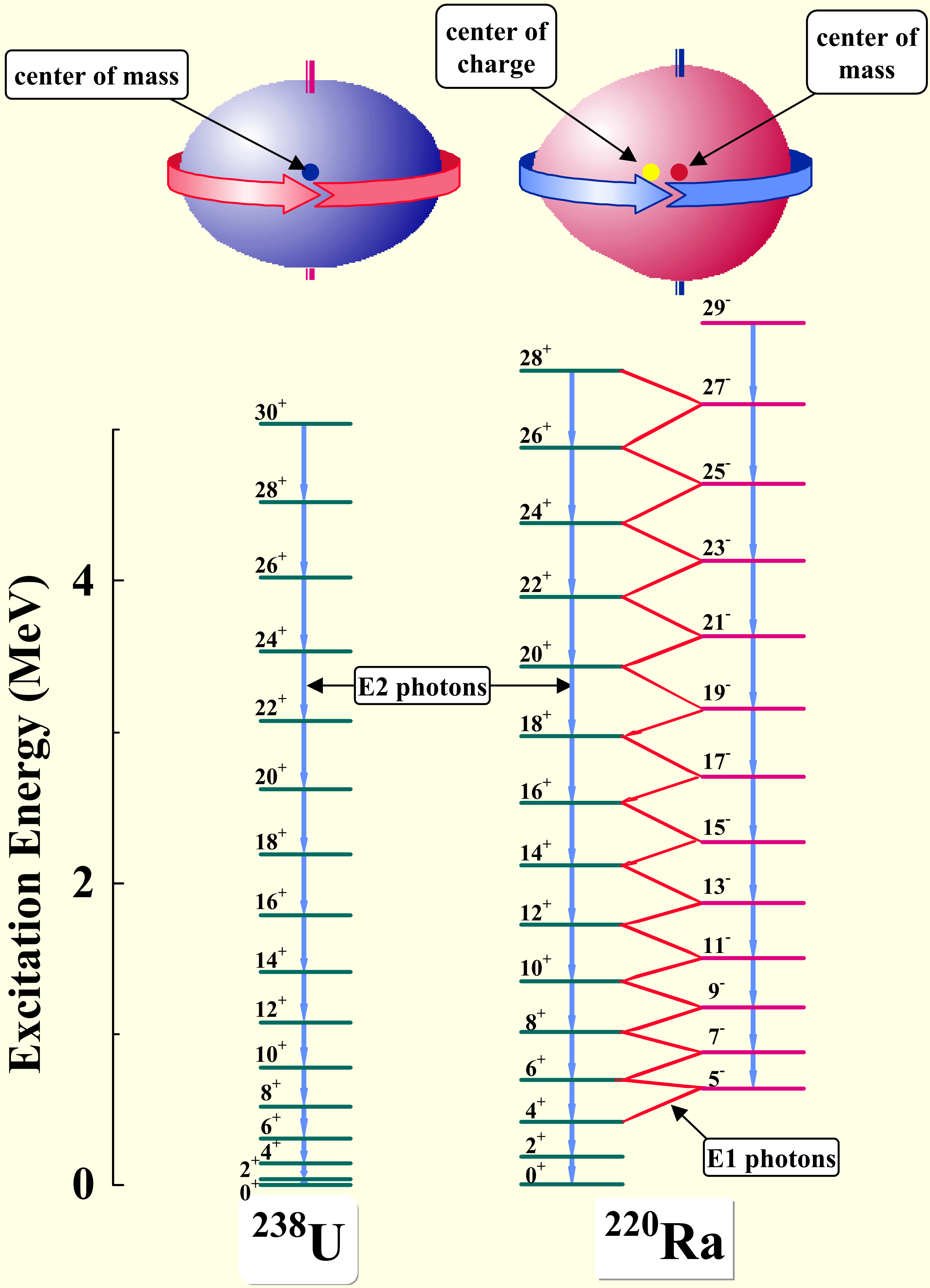
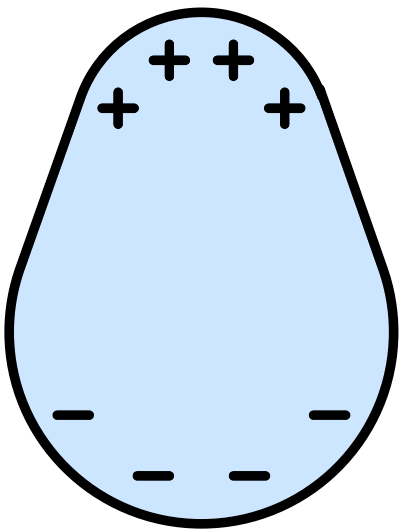


K > 0



NRC Report on Nuclear Physics, 1999, "The Core of the Matter…", p. 70

In a nucleus with octupole deformation, the center of mass and center of charge tend to separate, creating a non-zero electric dipole moment.



Bohr and Mottelson
vol. 2 p.74

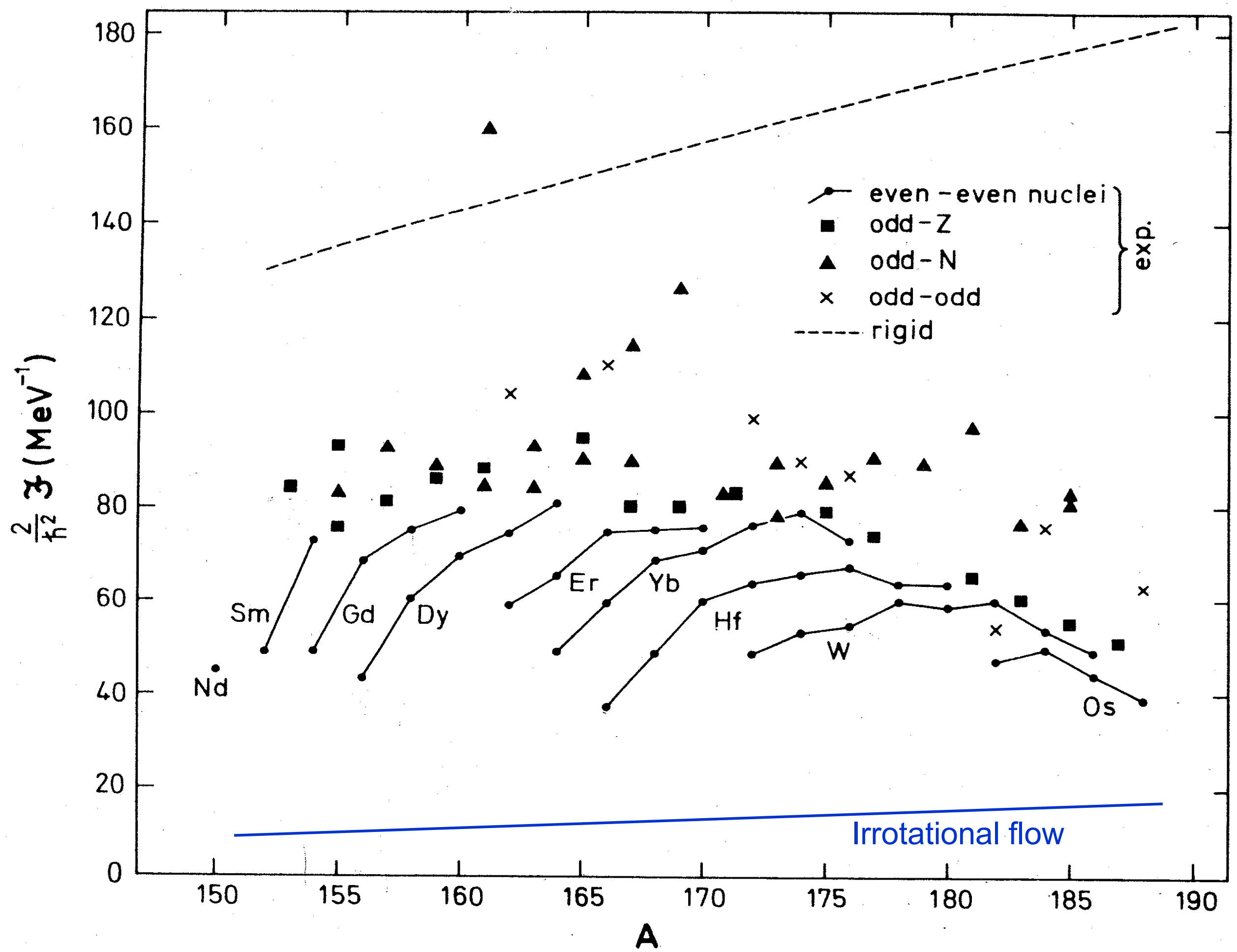
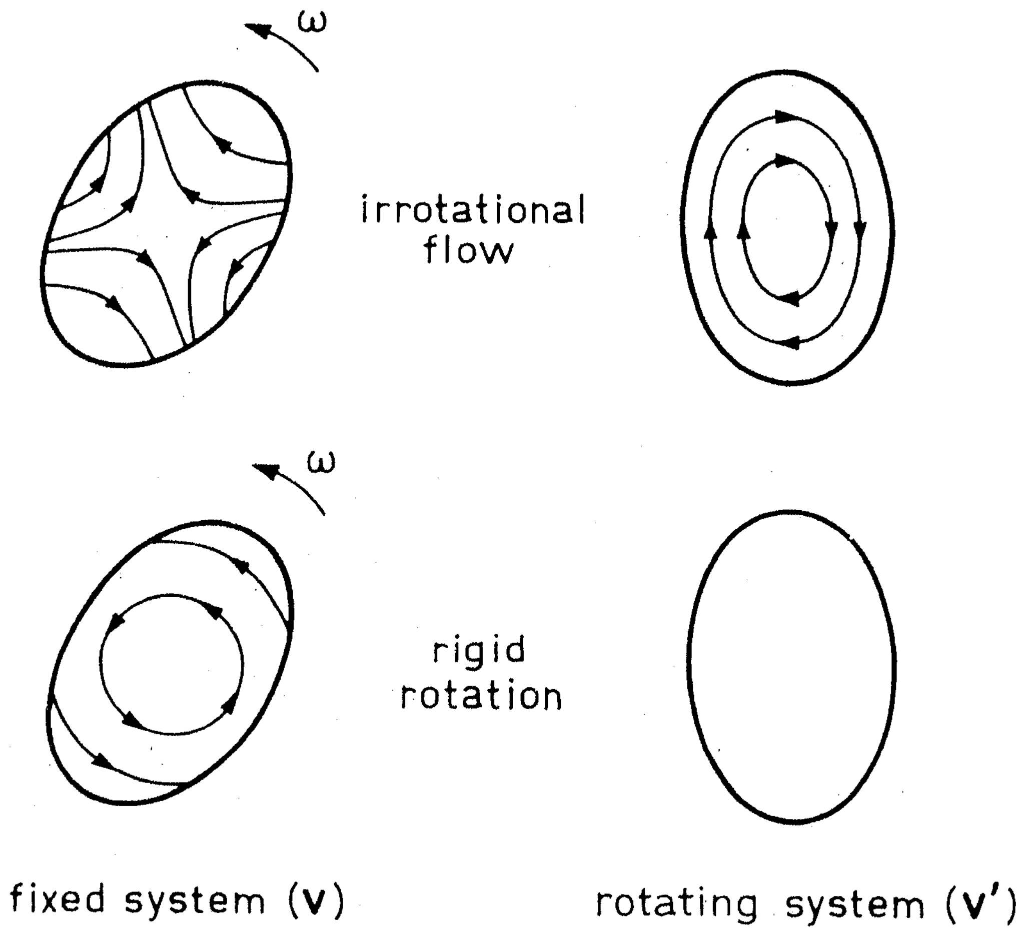


Figure 4-12 Systematics of moments of inertia for nuclei with $150 \leqslant A \leqslant 188$. The moments of inertia are obtained from the empirical energy levels in *Table of Isotopes* by Lederer *et al.*, 1967.

Note how the moments of inertia (MOI) are only about ½ of the rigid body values. This is related to pairing; the odd and odd-odd nuclei have weaker pairing and larger MOI. On the other hand, the motion is not purely irrotational; the irrotational MOI are about $^1/_{10}$ the rigid value.



Flow patterns for rotation of ellipsoidal body.

Bohr and Mottelson vol. 2 p.675

Vibrations

(Shape oscillations)

Bohr and Mottelson vol. 2 p.363

For animated pictures of shape vibrations, go to

http://radware.phy.ornl.gov/movies.html

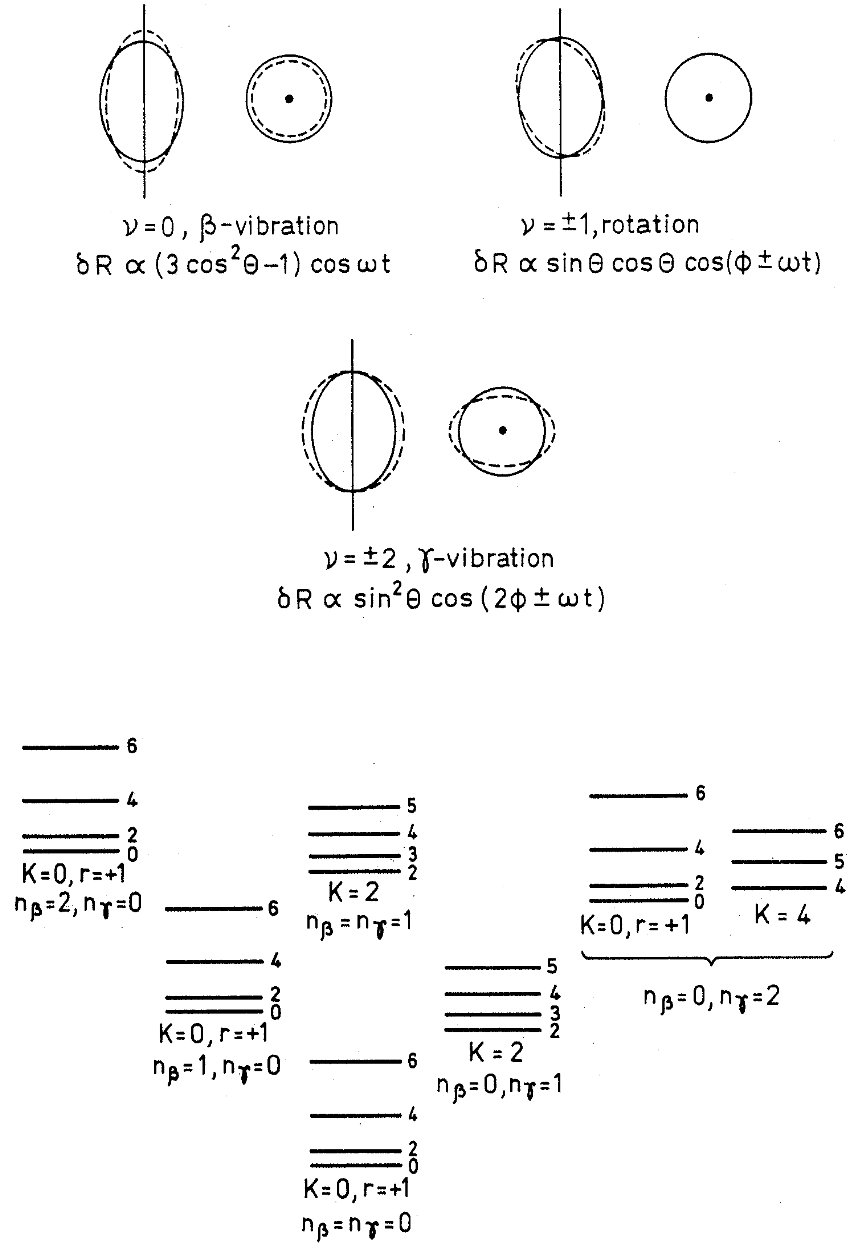


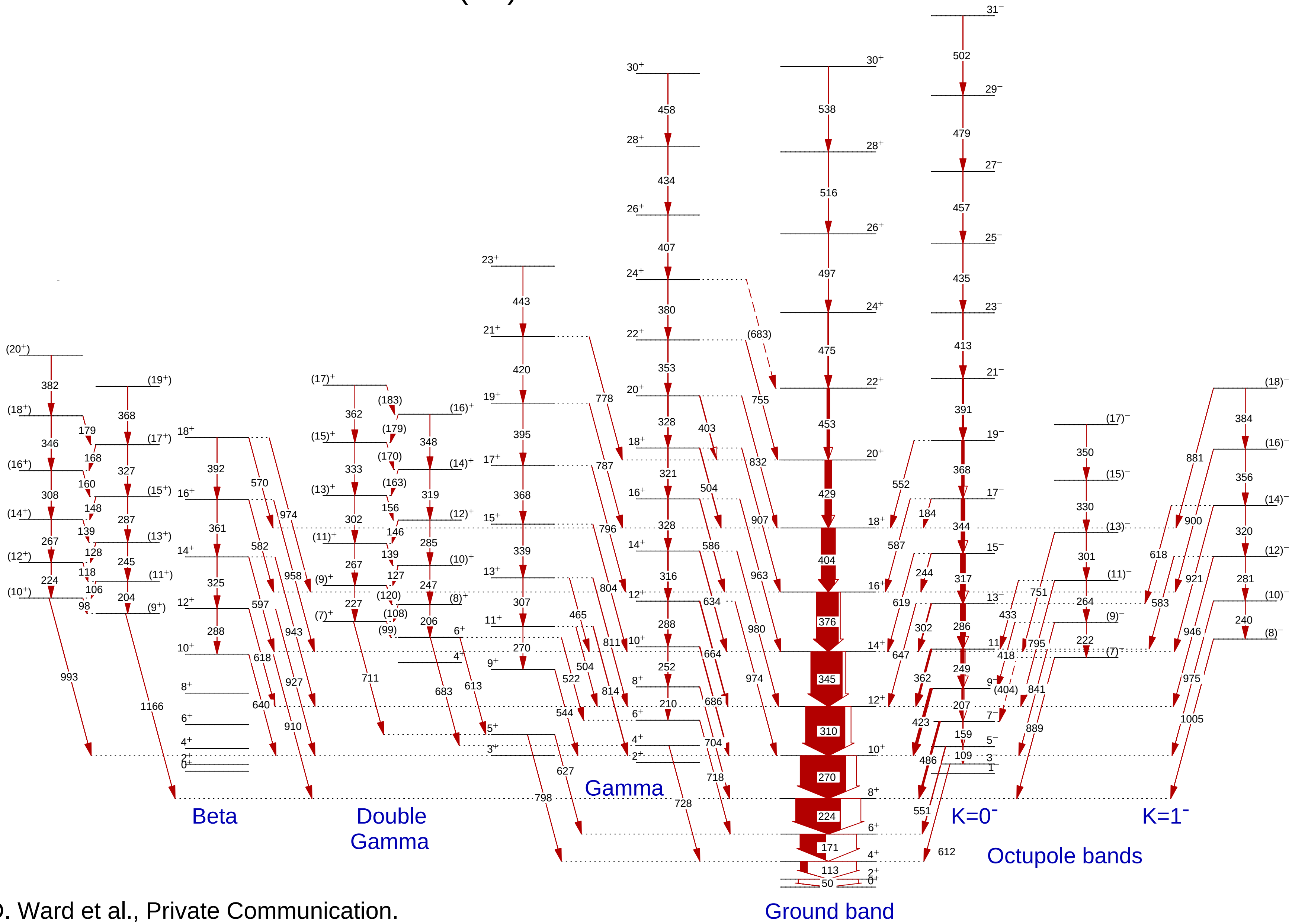
Figure 6-3 Quadrupole shape oscillations in a spheroidal nucleus. The upper part of the figure shows projections of the nuclear shape in directions perpendicular and parallel to the symmetry axis. The lower part of the figure shows the spectrum associated with excitations of one or two quanta.

^{232}Th

Coulomb Excited by ^{209}Bi at E = 6 MeV/u

"Unsafe Coulex" - some contribution from nuclear interactions

No absolute B(E2)'s extracted



D. Ward et al., Private Communication.

Spectroscopy in the Superdeformed Minimum of ^{240}Pu

Pansegrau et al., Phys. Lett. **484B** (2000) 1