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Workshop on Nuclear Isomers: Structure and Applications, Isomer WS Guildford, May 2010

High-K Isomers and Gamma Softness

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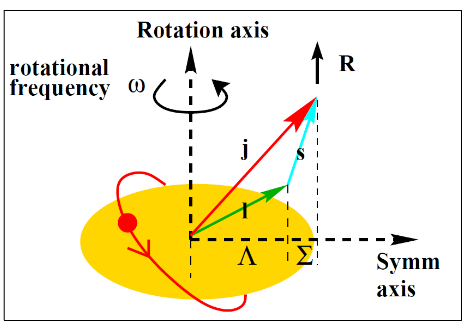
High-K isomers or Isomeric states

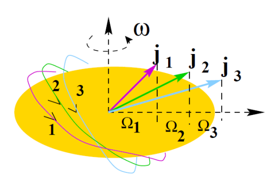
Consider an odd-mass *deformed* nucleus (Nilsson quantum numbers)



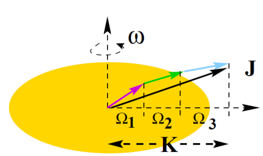
$$\Omega = \Sigma + \Lambda$$

The projection, K is the intrinsic single-particle spin of the band-head state.

Many Unpaired Nucleons



The High-K state



$K = \sum_i \Omega_i$

K = Projection of Total Intrinsic angular momentum onto symmetry axis approx good Q.N. under axial symmetry

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K-hindrance and the K-selection rule

$$f_\nu = \left(\frac{T^{\gamma}_{\frac{1}{2}}}{T^{W}_{\frac{1}{2}}}\right)^{\frac{1}{\nu}}.$$

$T^{\gamma}_{1/2}$= Measured Partial half-life

$T^{W}_{1/2}$= Weisskopf half-life

Reduced Hindrance Factor

$\lambda(E1)$	=	$1.0 \times 10^{14} A^{\frac{2}{3}} E^3$	$\lambda(M1)$	=	$5.6 \times 10^{13} E^3$
$\lambda(E2)$	=	$7.3 \times 10^{7} A^{\frac{4}{3}} E^5$	$\lambda(M2)$	=	$3.5 \times 10^{7} A^{\frac{2}{3}} E^5$
$\lambda(E3)$	=	$34 A^{2} E^7$	$\lambda(M3)$	=	$16 A^{\frac{4}{3}} E^7$
$\lambda(E4)$	=	$1.1 \times 10^{-5} A^{\frac{8}{3}} E^9$	$\lambda(M4)$	=	$4.5 \times 10^{-6} A^{2} E^9$

$\nu = \Delta K - \lambda$ λ = transition multipolarity
ν = degree of K forbiddeness.

The K-Selection Rule:
The change in K should be less than or equal to the multipolarity of the transition making the decay, otherwise the transition should be hindered by 100 per degree of K forbiddeness, ν (Lobner 1965/6)

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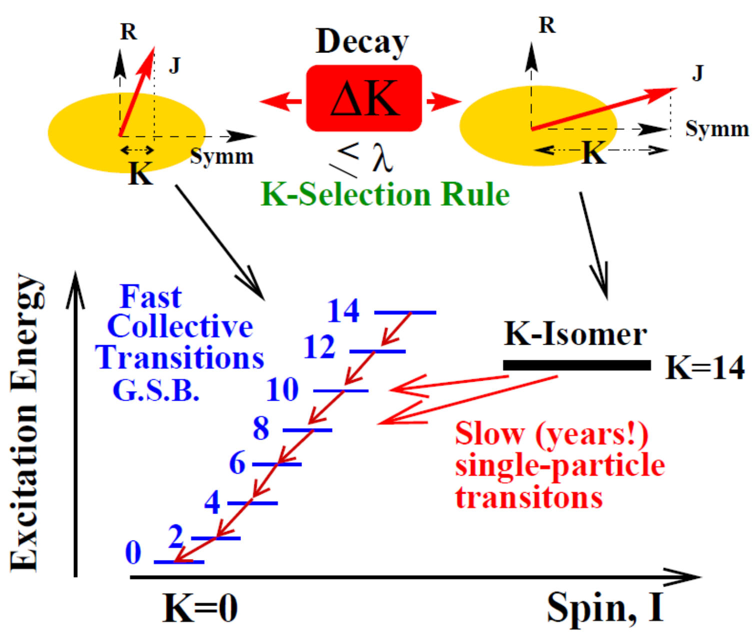
K-hindrance and the K-selection rule

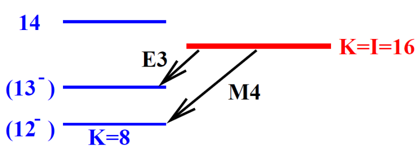


Two examples of Long-Lived Isomers.

Classic "Text-book" example Isomeric Transition

^{178}Hf $K^{\pi} = 16^{+}$ "yrast trap"

(yrast = -defines lowest excitation energy state with a given spin)

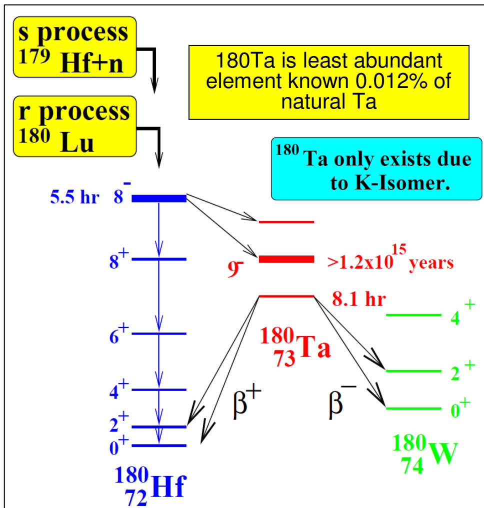


State is "trapped"

(a) by K-selection Rule, ΔK= large

(b) but also since $E_x(16) < E_x(14)$

-> $T_{1/2}$ = 31 years!



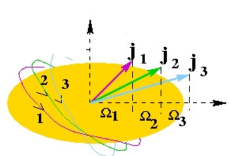
180Ta is least abundant element known 0.012% of natural Ta

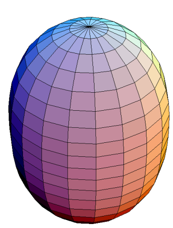
^{180}Ta only exists due to K-Isomer.

- Sits right on Astrophysical s-process

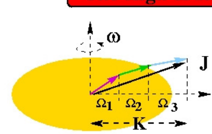
Low-energy excited nuclear states generally produced by

single-particle | collective vibrations | collective rotations





The High-K state



$K = \sum_i \Omega_i$

Yrast states angular momentum generated by collective rotations

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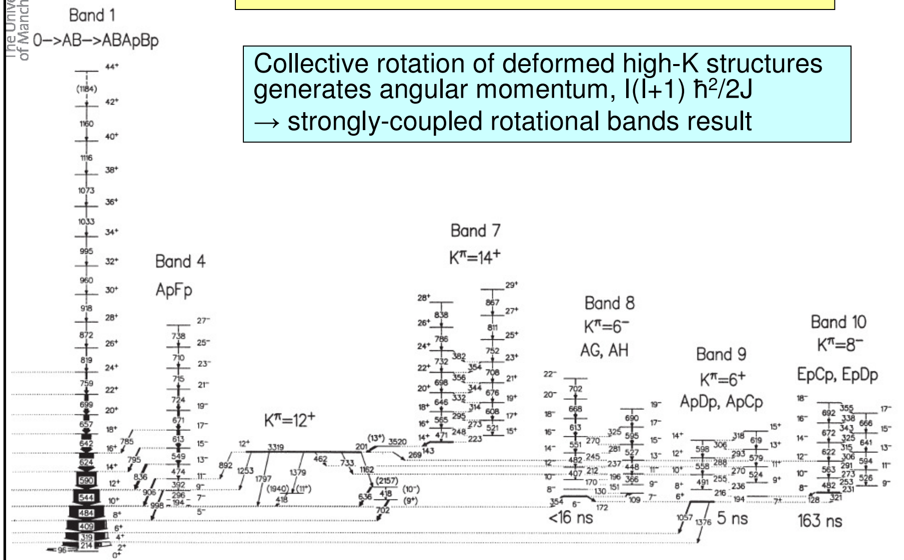
States above the band-head:

Collective rotation of deformed high-K structures generates angular momentum, I(I+1) ħ^2/2J
→ strongly-coupled rotational bands result



D.M. Cullen et al. / Nuclear Physics A 638 (1998) 662–700

Angular momentum of Yrast states usually dominated by Collective Rotation

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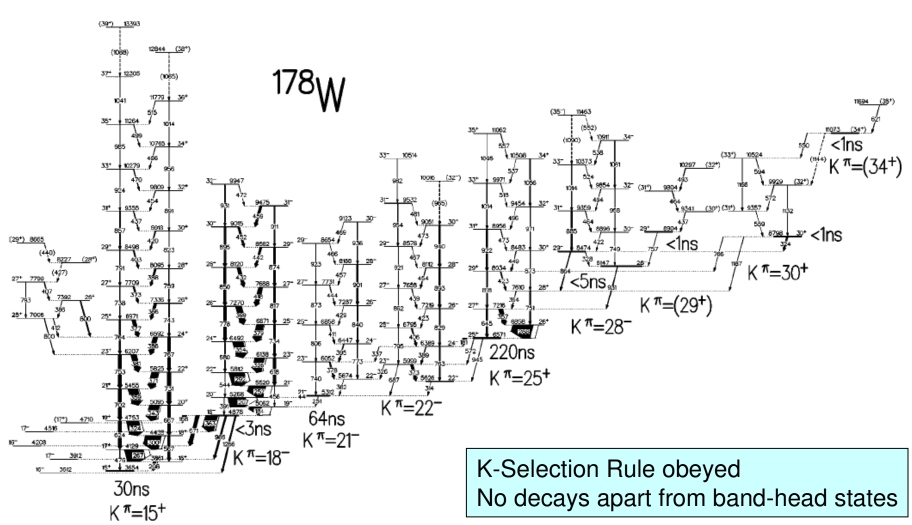
K-Selection Rule implies that Isomer decays follow stepwise path, minimising ΔK – λ at each step

D. M. CULLEN *et al.* PHYSICAL REVIEW C **60** 064301



K-Selection Rule obeyed
No decays apart from band-head states

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Circumvention of K-selection rule in isomer decay

3 main methods where K-Selection Rule is known not to be obeyed:

1. **Coriolis Mixing** (^{172}Hf, T-Bands, Band Crossings…)

2. **Density of States** arguments (K-isomers can be highly non-yrast and decay because of very high-level density.)

3. **Gamma-Softness** (^{182}Os), loss of axial symmetry and gamma tunnelling.

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1. Coriolis mixing (^{172}Hf, ^{138}Gd,… T-Bands, Band Crossings…)

Coriolis interaction **mixes** states differing in K by $\Delta K=\pm1$

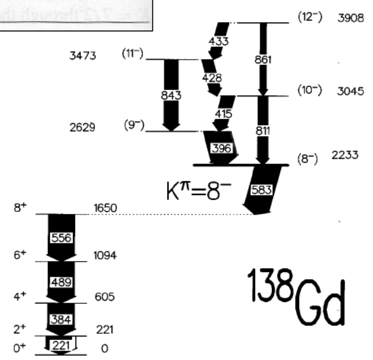
Table 9.3 *Theoretical values* $\langle K|j_-|K+1\rangle$*

	9/2⁻[505]	7/2⁻[503]	3/2⁻[512]	1/2⁻[510]	5/2⁻[512]	1/2⁻[521]	7/2⁻[514]
9/2⁻[505]		−0.973					2.847
7/2⁻[503]	−0.973				2.858		
3/2⁻[512]				0.951	0.045	2.546	
1/2⁻[510]			0.951			−2.541	
5/2⁻[512]		2.858	0.045				−1.151
1/2⁻[521]			2.546	−2.541			
7/2⁻[514]	2.847				−1.151		

High-K isomeric state with e.g. K=8 can **mix** with ground-state rotational band (expected K≈0)

Happens especially in the band-crossing region where nucleons are aligning with the rotation axis.

This reduces the effective ΔK for the isomer decay



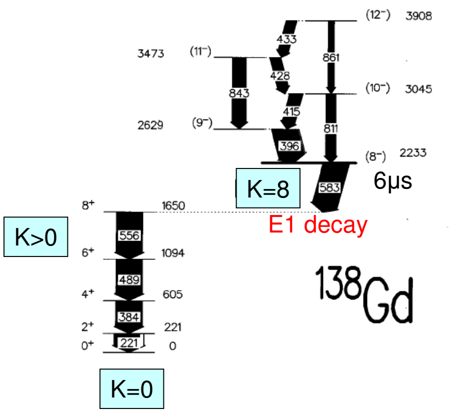
1. Coriolis mixing (^{172}Hf, T-Bands, Band Crossings…)

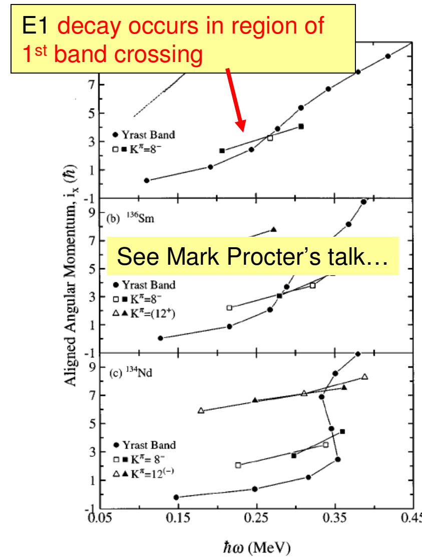
Coriolis force **mixes** states differing in K by ΔK=±1

Identification of the $K^{\pi}=8^{-}$ rotational band in ^{138}Gd

D. M. Cullen, N. Amzal, A. J. Boston, P. A. Butler, A. Keenan, E. S. Paul, and H. C. Scraggs
Oliver Lodge Laboratory, Department of Physics, University of Liverpool, Liverpool L69 7ZE, United Kingdom

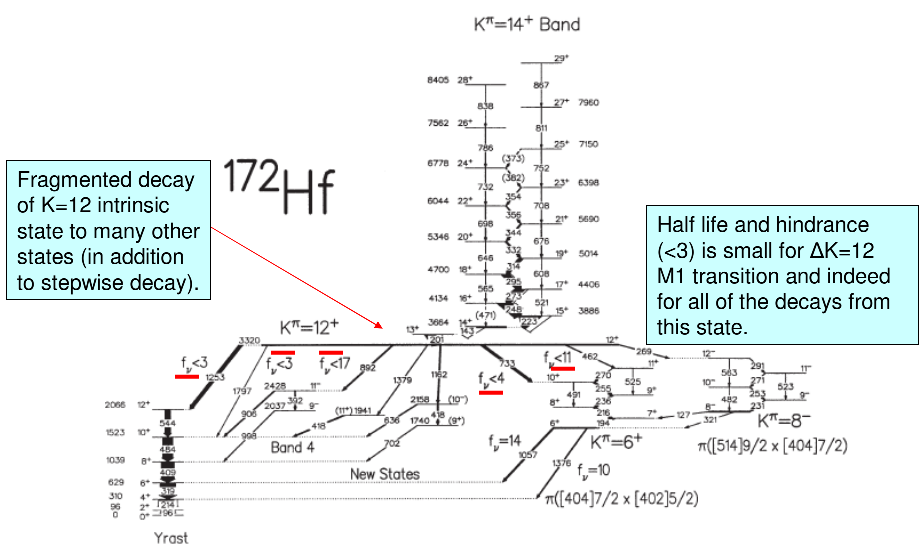
Phys Rev C58 (98) 846





2. Density of states arguments (K-isomers can be highly non-yrast and decay because of very high-level density.)

D.M. Cullen et al. / Nuclear Physics A 638 (1998) 662–700 677



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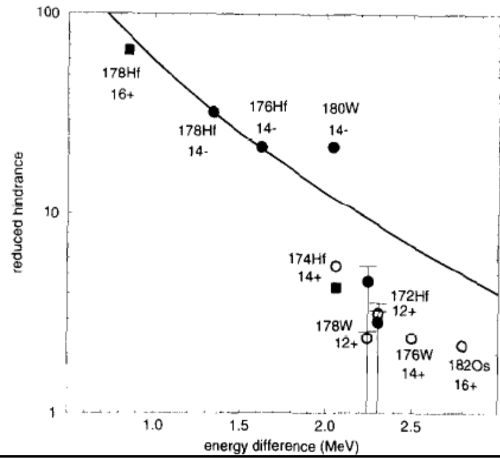
2. Density of states arguments (K-isomers can be highly non-yrast and decay because of very high-level density.)

K-forbidden transitions from multi-quasiparticle states

P.M. Walker[a,1], D.M. Cullen[b], C.S. Purry[a], D.E. Appelbe[b], A.P. Byrne[c], G.D. Dracoulis[c], T. Kibédi[c], F.G. Kondev[c,2], I.Y. Lee[d], A.O. Macchiavelli[d], A.T. Reed[b], P.H. Regan[a], F. Xu[a]

Physics Letters B 408 (1997) 42–46



$$f_\nu = F_\nu \exp\left[-\frac{3}{\nu}\sqrt{\frac{\pi^2}{6} g_0 \Delta E}\right],$$

Fig. 1. Reduced hindrance, f_ν, as a function of energy relative to a rigid rotor, $E_K - E_R$, for $\Delta K \geq 6$, E2 and E3 decays from 4-quasiparticle states. Open circles correspond to E2 decays to $K^\pi = 0^+$ bands, and filled circles correspond to E2, $\Delta K = 6$ decays. The filled squares are for $\Delta K = 8$ decays in ^{178}Hf (E3) and ^{174}Hf (E2). The data points for ^{172}Hf and ^{178}W correspond to half their upper-limit half-lives. The values for the other nuclei have statistical uncertainties that are smaller than the data points. Note that there are two data points for each of ^{172}Hf (12^+), ^{174}Hf (14^+) and ^{178}W (12^+). The line through the data represents a statistical-mixing estimate for $\Delta K = 6$ transitions, normalised at ^{178}Hf (14^-).

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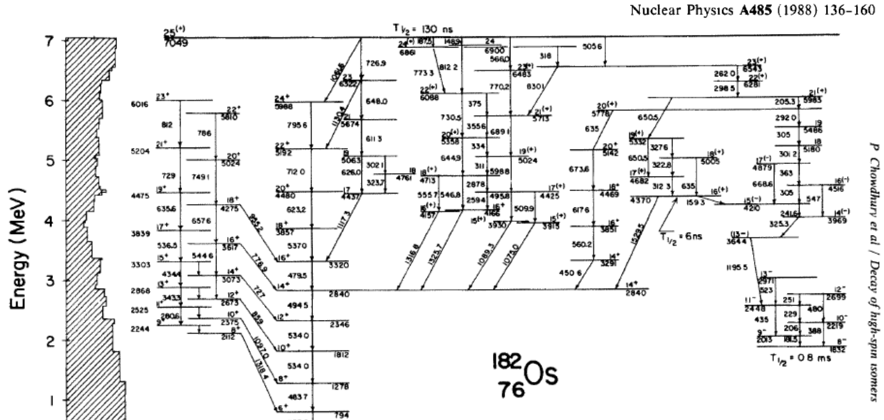
3. **Gamma-softness** (^{182}Os), loss of axial symmetry and gamma tunnelling.

Nuclear Physics A485 (1988) 136–160



DECAY OF HIGH-SPIN ISOMERS IN Os NUCLEI BY BARRIER PENETRATION

P. CHOWDHURY[1], B. FABRICIUS[2], C. CHRISTENSEN, F. AZGUI[3],

Long-Standing Issue:

The K=25 isomer in ^{182}Os, decays to the ground-state band (K≈0) with a 1061-keV ΔK=25 M1 transition.

According to the K-Selection Rule, this should have a very long half-life not 130 ns!

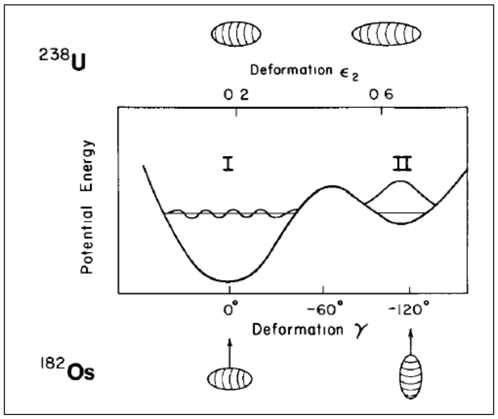
3. **Gamma-softness** (^{182}Os), loss of axial symmetry and gamma tunnelling

DECAY OF HIGH-SPIN ISOMERS IN Os NUCLEI BY BARRIER PENETRATION

P CHOWDHURY[1], B FABRICIUS[2], C CHRISTENSEN, F AZGUI[3], S BJØRNHOLM, J BORGGREEN, A HOLM, J PEDERSEN and G SLETTEN

Niels Bohr Institute, DK-4000 Roskilde, Denmark

Nuclear Physics **A485** (1988) 136–160



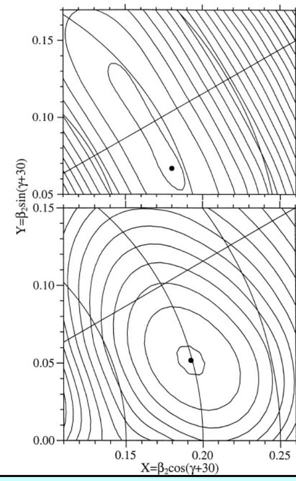
Physics Letters B 435 (1998) 257–263

Multi-quasiparticle potential-energy surfaces

F.R. Xu [a,1], P.M. Walker [a], J.A. Sheikh [a,2], R. Wyss [b]

[a] *Department of Physics, University of Surrey, Guildford, Surrey GU2 5XH, UK*

[b] *Royal Institute of Technology, Physics Department, Frescativägen 24, S-104 05 Stockholm, Sweden*



K=25
|γ|=10°

K=0, I=24
|γ|=-15°

The loss of axial symmetry implies K is no longer a good quantum number…

Mentioned Gamma softness in ^{182}Os

→ possibility of nuclear vibrations (gamma vibration)

Nuclear Vibrations

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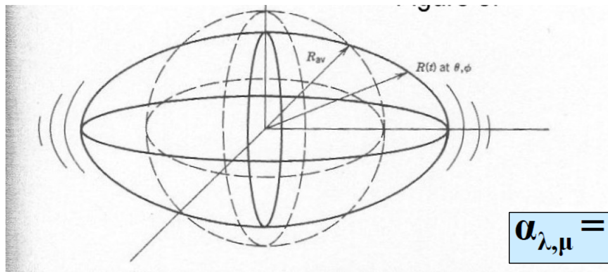
Nuclear Vibrations

Nuclear vibrations are considered as a liquid vibrating at <u>high</u> frequency.

Although the *average* nuclear shape is spherical, at any given instant it may <u>not</u> be spherical.



$\alpha_{\lambda,\mu} = \alpha_{\lambda,-\mu}$

$$R(t) = R_{av} \left\{ 1 + \sum_{\lambda=0}^{\text{infinity}} \sum_{\mu=-\lambda}^{\mu=+\lambda} \alpha_{\lambda,\mu} Y_{\lambda\mu}(\theta,\Phi) \right\}$$

$Y_{\lambda\mu}(\theta,\Phi)$ are the spherical harmonics with amplitude $\alpha_{\lambda,\mu}$

Consider λ=2 **Quadrupole** Phonons in Mass 180 Region (quadrupole deformed shape)

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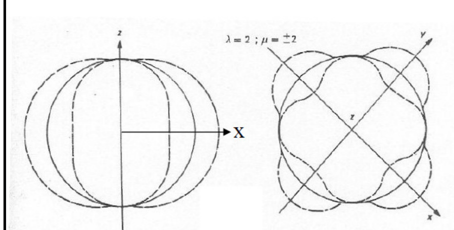
$$R(t) = R_{av} \left\{ 1 + \sum_{\lambda=0}^{\text{infinity}} \sum_{\mu=-\lambda}^{\mu=+\lambda} \alpha_{\lambda,\mu} Y_{\lambda\mu}(\theta,\Phi) \right\}$$

Gamma Vibrations

For λ=2, μ=±2,
$Y_{2\pm2}(\theta,\Phi)=3 \sin^2\theta \cos 2\Phi$



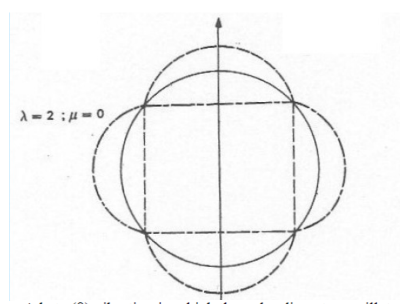
A gamma (γ) vibration in which a wave runs equatorially with no variation of polar diameter

The transportation of mass involves increasing the angular momentum about the z-axis, for this second-order harmonic, by 2 ħ units.

"Pushing" & "pulling" on sides of rugby ball

Beta Vibrations

For λ=2, μ=0,
$Y_{2\pm0}(\theta,\Phi) = ½ (3 \cos^2\theta – 1)$



A beta (β) vibration in which the polar diameter oscillates with no variation in shape of section at different values of Φ

This mode transports mass away from the nuclear poles, i.e. in a plane of constant Φ.

This does <u>not</u> involve any angular momentum generation about the z-axis.

"Pushing" & "pulling" on ends of rugby ball

Consider adding one $\lambda=2$ phonon vibration to the 0^+ ground state of an even-even nucleus.

This phonon adds $2\hbar$ of angular momentum & has even parity due to the $(-1)^\lambda$ dependence of the $Y_{\lambda\mu}(\theta,\Phi)$

Adding 2^+ units of angular momentum to a 0^+ ground state gives a 2^+ state, in exact agreement with the observed spin and parity of the 1st excited states of spherical even-Z even-N nuclei, see Fig. 1.

Figure 1.

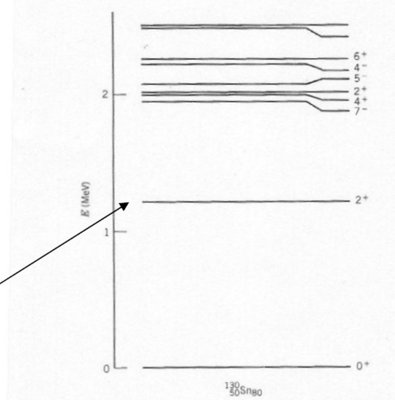


Figure 5.14 The low-lying energy levels of ^{130}Sn.

Possibility to generate angular momentum by ***vibrations*** in competition with collective ***rotation***

$E_\lambda = n_\lambda \cdot \hbar \cdot \omega_\lambda$ Vibration

This 0^+, 2^+, 4^+ triplet is a common feature of vibrational nuclei & gives strong support to the model.

A similar calculation for 3-phonon states gives 0^+, 2^+, 4^+, 6^+

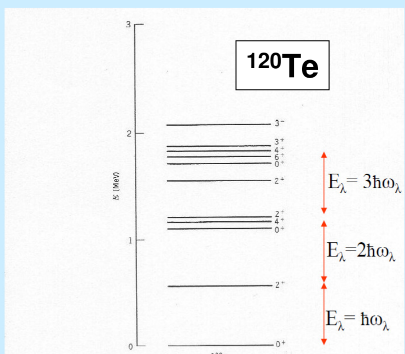
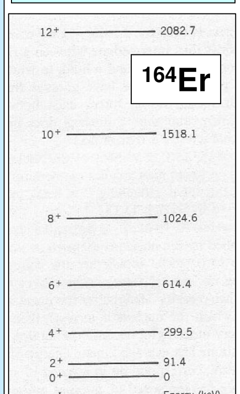


Figure 5.19 The low-lying levels of ^{120}Te. The single quadrupole phonon state (first 2^+), the two-phonon triplet, and the three-phonon quintuplet are obviously seen. The 3^- state presumably is due to the octupole vibration. Above 2 MeV the structure becomes quite complicated, and no vibrational patterns can be seen.

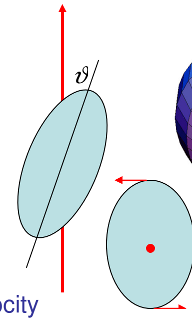
Contrast with rotor
$E_I = I(I+1)\hbar^2/2J$

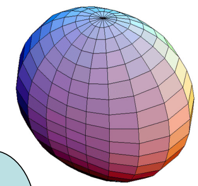


"Nuclear Tidal waves"

- Stefan Frauendorf

Combination of
- Angular momentum reorientation
- Triaxial deformation





→ Shape change at nearly constant angular velocity

Rotating mean field gives a reliable microscopic description
No new parameters

$$R(\vartheta,\varphi,t) = R_0[1 + 2a_2\cos(2\varphi - \Omega t)Y_{22}(\vartheta,\varphi = 0)]$$

$$\omega = \frac{\Omega}{2} \qquad E = \omega L_z$$

Spin ($\hbar$)	$\gamma°$	$\theta°$
26.0	−7.4	19.0
27.0	−9.7	23.7
28.0	−12.2	26.8
29.0	−15.0	28.5
30.0	−17.6	29.2
31.0	−20.4	30.7
32.0	−22.9	31.9
33.0	−25.1	33.3
34.0	−27.2	34.8
35.0	−29.0	36.3
36.0	−31.1	37.3
37.0	−33.4	37.4
38.0	−35.0	36.0

Experimental rotational frequency well defined & constant in SC-TAC calculations.

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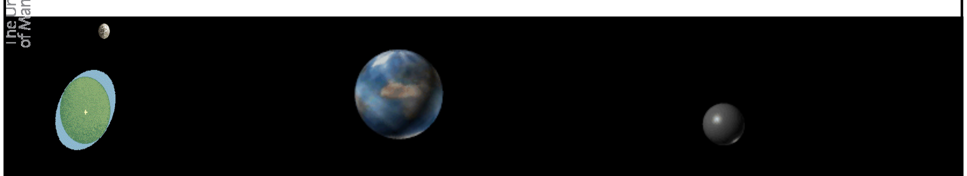
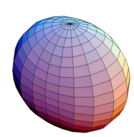
Multi-phonon Quadrupole Vibrations.



Nuclear Tidal Wave :

Angular momentum generated by:
- phonon vibration in intrinsic frame
- coupled with collective rotation
- Shape change at nearly constant angular velocity



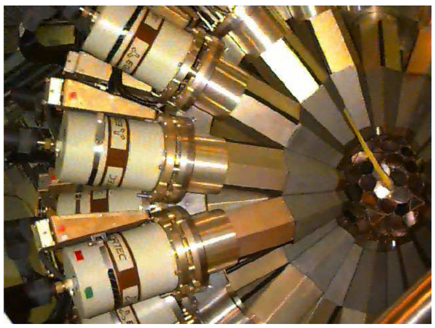
Can become Favoured high-spin mode in soft osmium nuclei where the energy of rotation is > energy of vibration

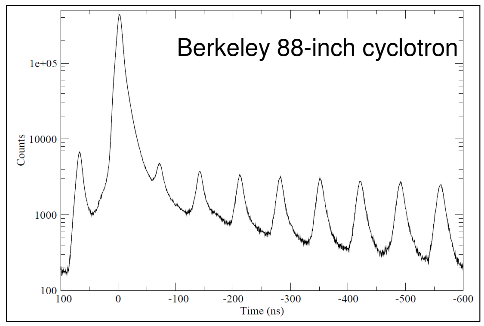
(PRL 91(03)182501)

Results of Gammasphere Experiments

^{181}Os, ^{182}Os, ^{183}Os (Berkeley)

^{36}S + ^{150}Nd $\rightarrow$ ^{183}Os (3n),
$\rightarrow$ ^{182}Os (4n),
$\rightarrow$ ^{181}Os (5n).
Thick target 1.0mg/cm^2





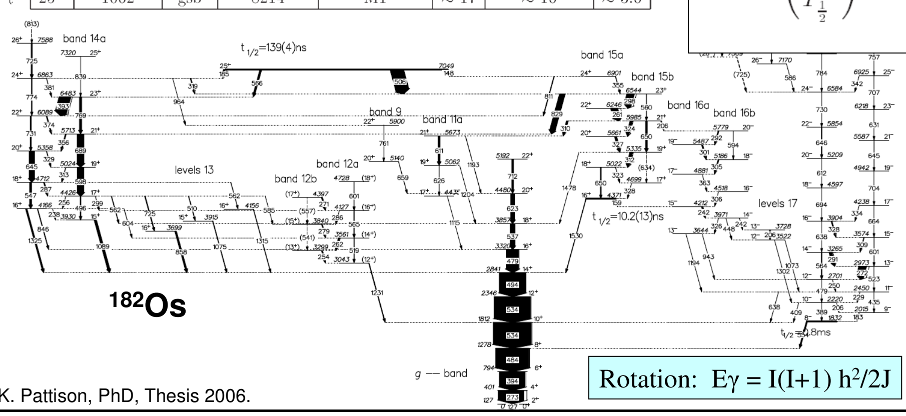
K^π =25$^+$ Six Quasi-particle Isomer Decay in ^{182}Os.

Table 6.2: Reduced hindrance factor calculations for the decay paths of the $K^\pi = 25^+$, 139±4ns isomer.

K^π	E_γ (KeV)	Band	$T_{\frac{1}{2}}^{partial}$ (ns)	Multipolarity	ΔK	$\nu = \Delta K - \lambda$	f_ν
25$^+$	186	14	1534	M1	10	9	4.5
25$^+$	566	14	1970	E2	10	8	3.3
25$^+$	506	15	297	E2	9	7	2.7
25$^+$	148	15	16655	M1	9	8	6.8
25$^+$	386	8	6819	(M1)	(5)	(4)	75
25$^+$	727	11	435	E2	8	6	4.6
25$^+$	679	7	20771	(M1)	(7)	(6)	28
25$^+$	1062	gsb	8214	M1	≈ 17	≈ 16	≈ 3.6

Small hindrance factors for new decays

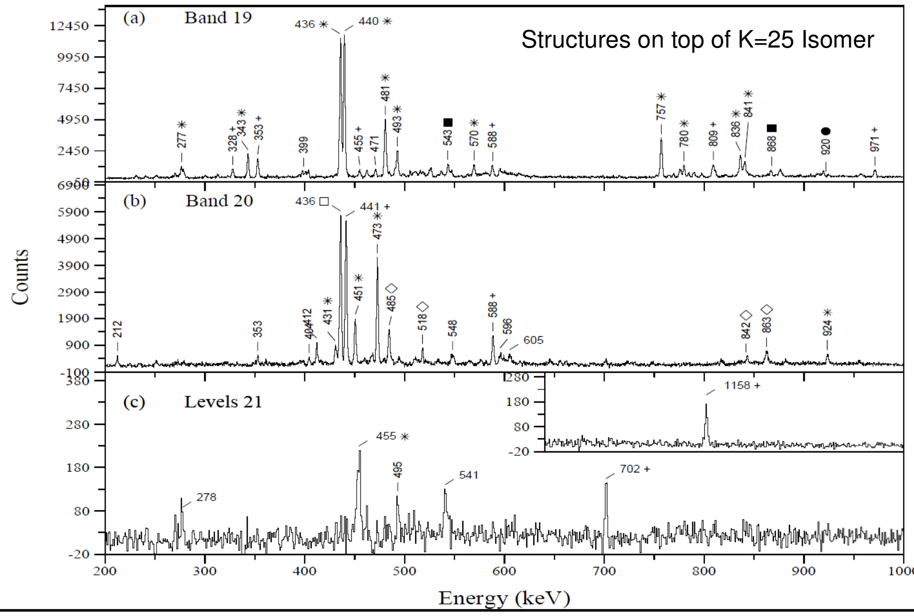
$$f_\nu = \left(\frac{T^\gamma_{\frac{1}{2}}}{T^W_{\frac{1}{2}}}\right)^{\frac{1}{\nu}}.$$



Rotation: Eγ = I(I+1) h^2/2J

L.K. Pattison, PhD, Thesis 2006.

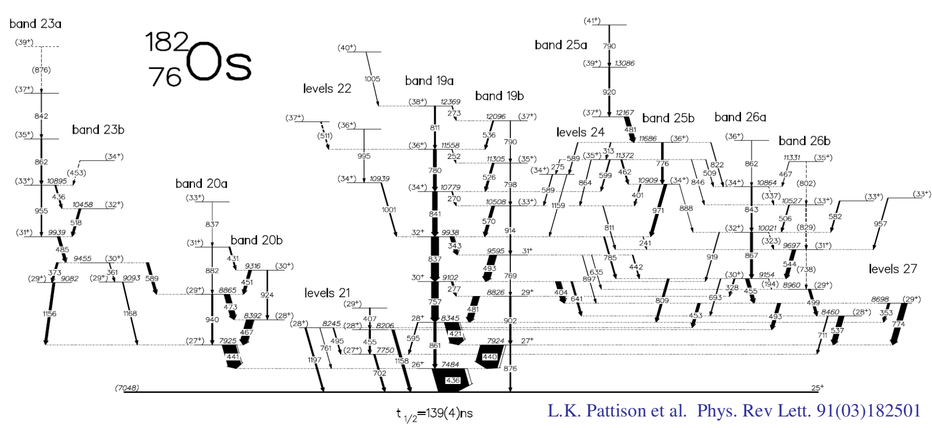
^{182}Os Very clean Prompt spectra produced from careful time gating on delayed transitions from Isomer decay.



Several New Structures discovered above K=25 isomer in ^{182}Os

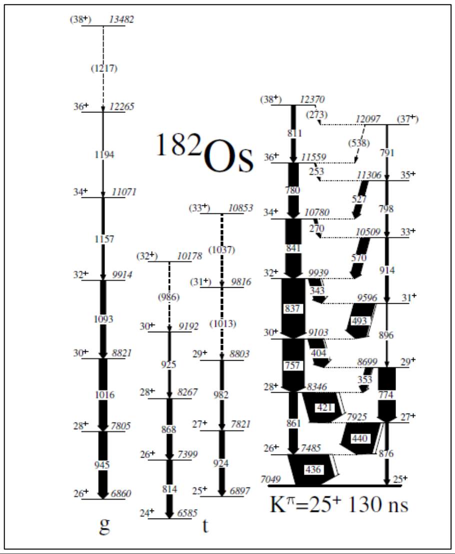
Anomalous features of high-K Structure:

Decays to other structures above bandhead



L.K. Pattison et al. Phys. Rev Lett. 91(03)182501

Focus on main structure above K=25 isomer in ^{182}Os

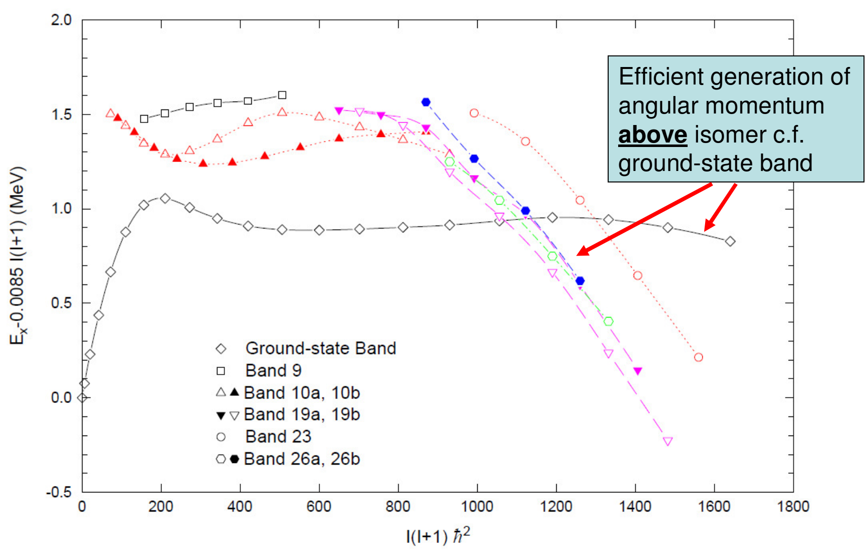


Anomalous features of high-K Band:

1. Strong E2s
2. Intensity Staggering of Signatures
3. $\Delta E\gamma \approx$ Constant (c.f. rotational g and t bands)

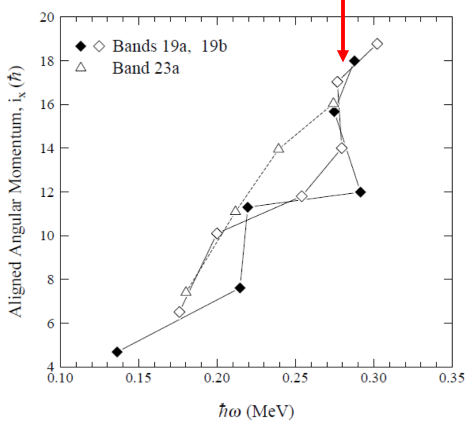
L.K. Pattison et al. Phys. Rev Lett. 91(03)182501

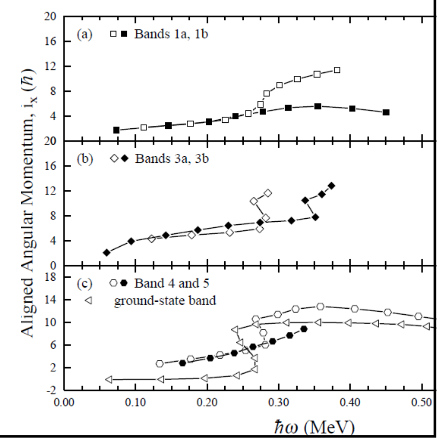
^{182}Os Excitation energy minus rigid-rotor reference.



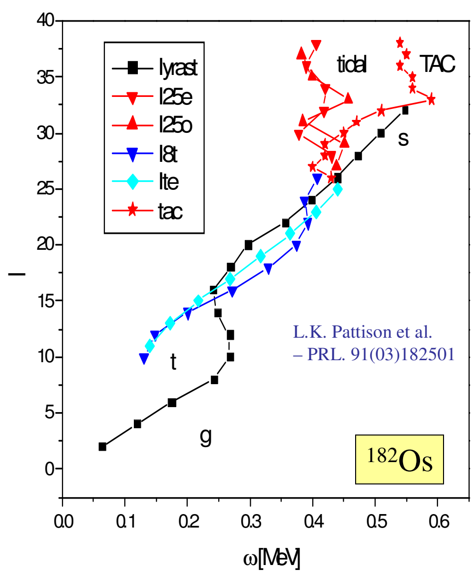
^{182}Os Aligned-Angular Momentum.

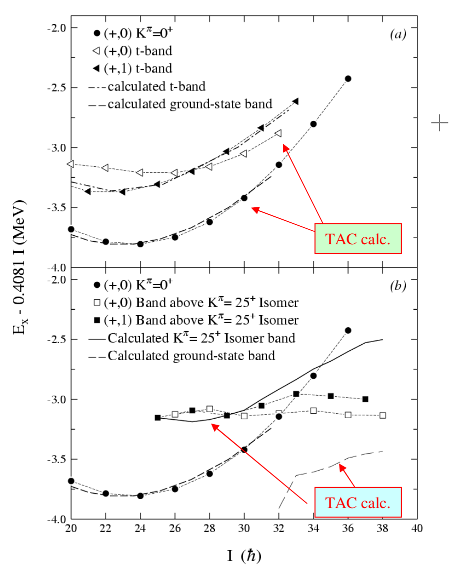
Spin generated at constant frequency



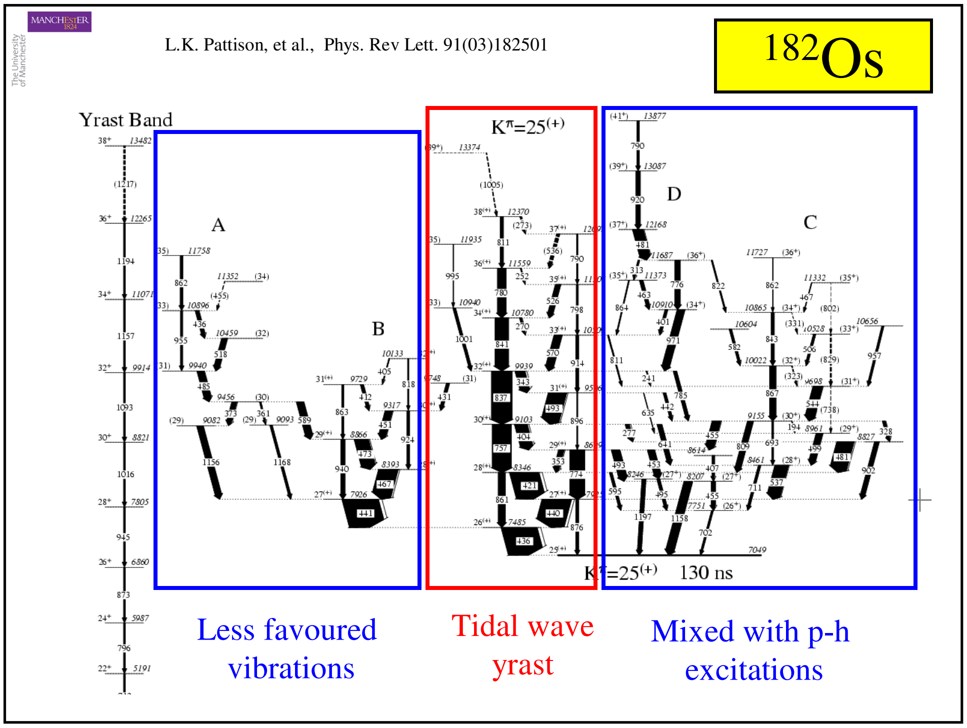


SC-TAC Calculations, S. Frauendorf





Conclude gamma vibrations in ^{182}Os contribute but also rotational contribution.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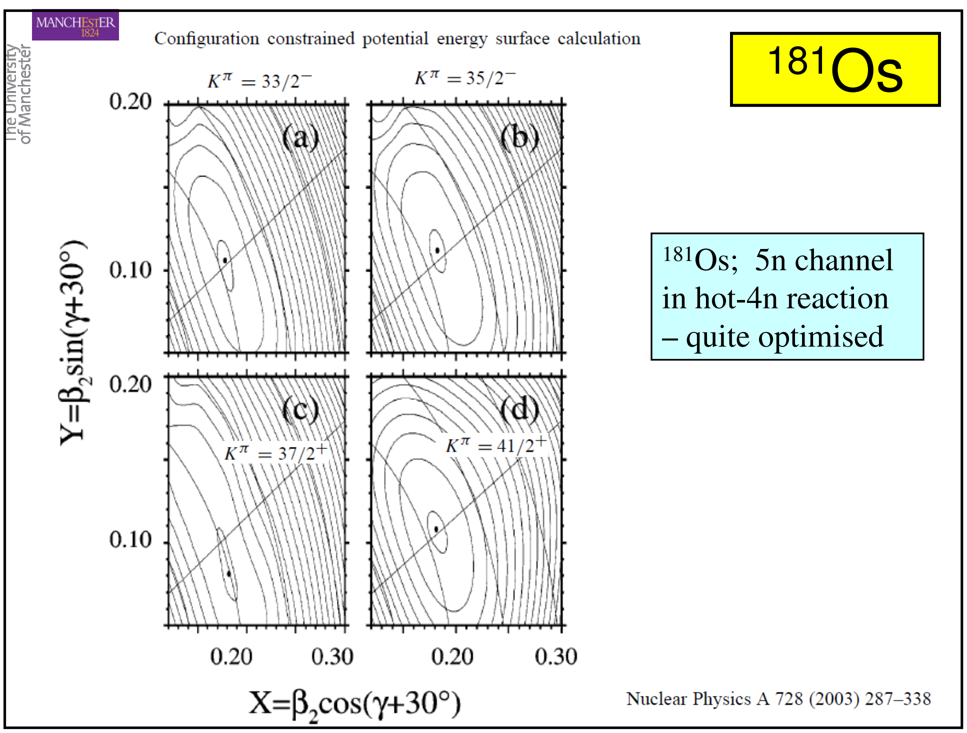
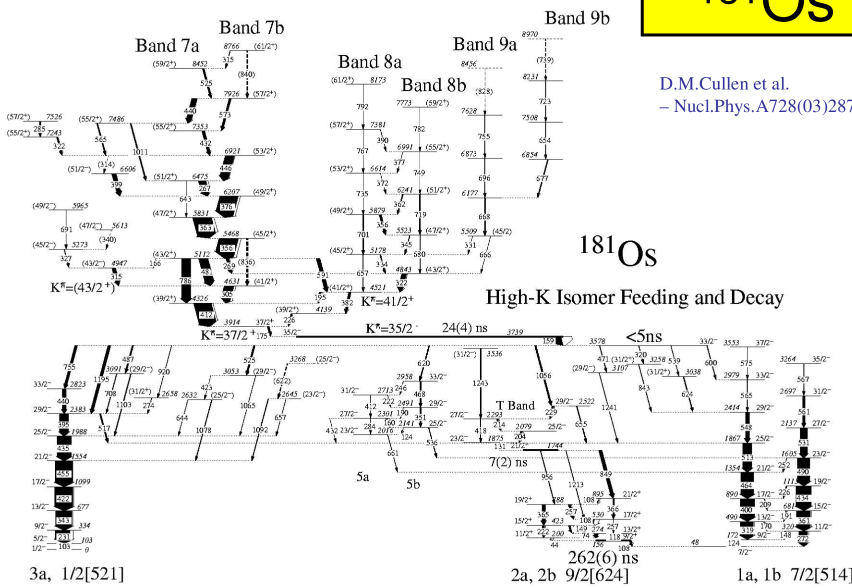
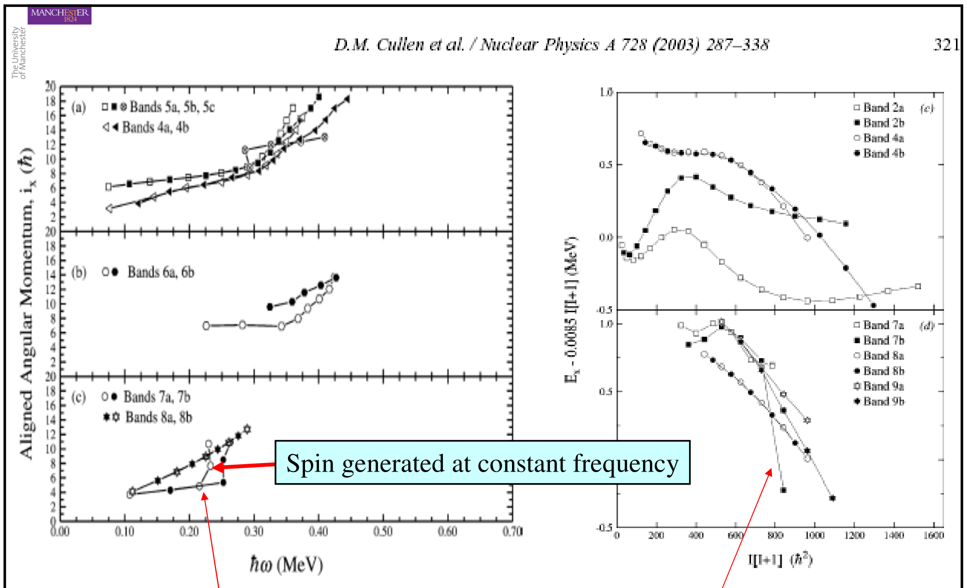
L.K. Pattison, et al., Phys. Rev Lett. 91(03)182501
^{182}Os
Yrast Band
A
B
C
D
$K^{\pi}=25^{(+)}$
$K^{\pi}=25^{(+)}$ 130 ns
Less favoured vibrations
Tidal wave yrast
Mixed with p-h excitations


The University of Manchester
Configuration constrained potential energy surface calculation
^{181}Os
$K^{\pi} = 33/2^{-}$
$K^{\pi} = 35/2^{-}$
(a)
(b)
(c)
(d)
$K^{\pi} = 37/2^{+}$
$K^{\pi} = 41/2^{+}$
0.20
0.10
0.20
0.10
0.20 0.30 0.20 0.30
$Y=\beta_2\sin(\gamma+30°)$
$X=\beta_2\cos(\gamma+30°)$
^{181}Os; 5n channel in hot-4n reaction – quite optimised
Nuclear Physics A 728 (2003) 287–338

^{181}Os



D.M.Cullen et al.
– Nucl.Phys.A728(03)287

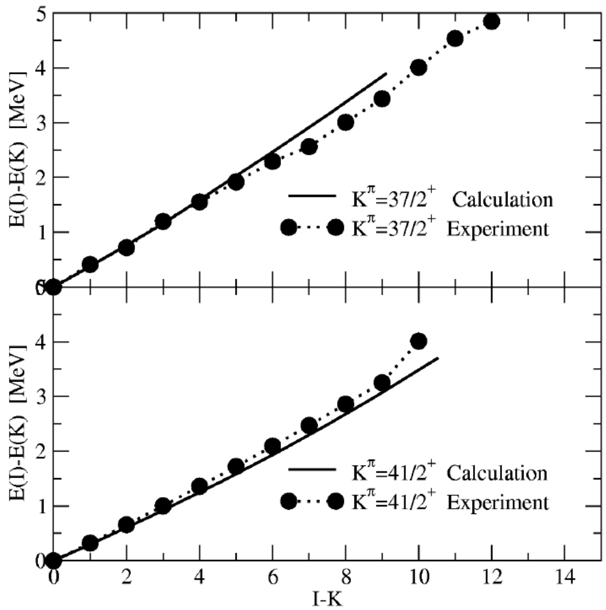


Spin generated at constant frequency

Multi-phonon angular momentum generation **competes** with collective rotation.

Shell-Corrected TAC calculations

^{181}Os

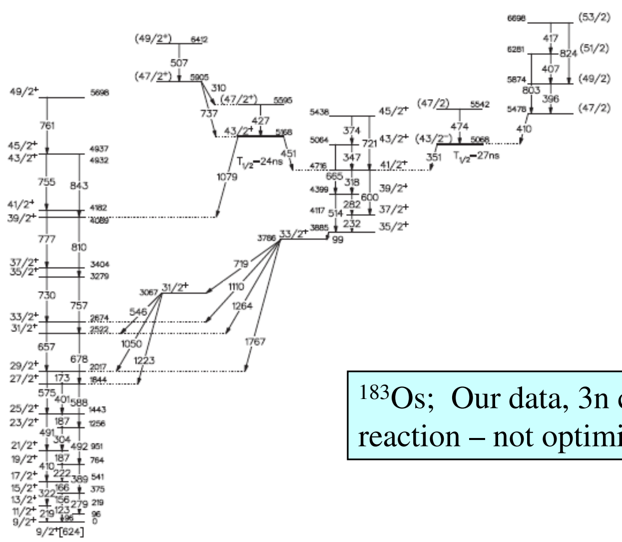


Nuclear Tidal Wave / multi-phonon vibration interpretation *partially* fits ^{181}Os data…

High-spin isomers in ^{183}Os

Eur. Phys. J. A **1**, 245–246 (1998)

T. Shizuma[1], K. Furuno[1], K. Hata[1], H. Ishiyama[1], T. Jumatsu[1], M. Kato[1], T. Komatsubara[1], K. Matsuura[1], Y. Sasaki[1], K. Uchiyama[1], T. Hayakawa[2]



^{183}Os

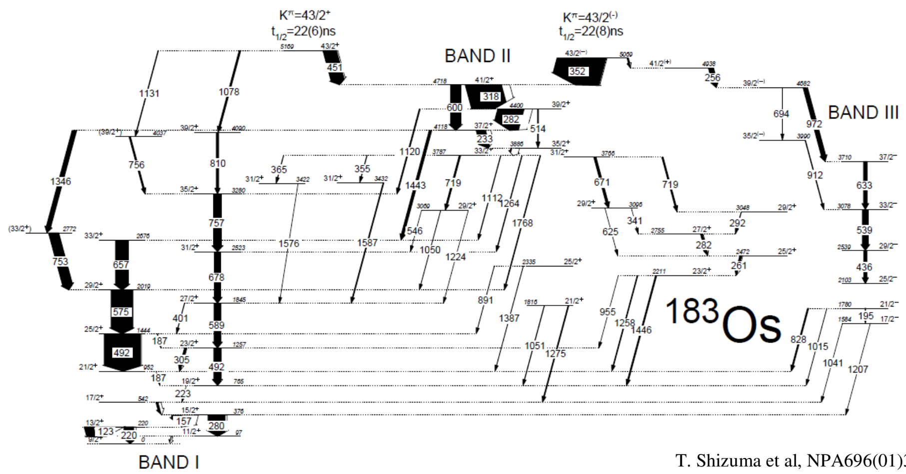
^{183}Os; Our data, 3n channel in hot-4n reaction – not optimised but…

E_γ	$K_i^\pi \to K_f^\pi$	ΔK	$L\lambda$	ν	$t_{1/2}^{\gamma}$	F	f_ν
451	$43/2^+ \to 41/2^+$	5	M1	4	25	$1.1\text{x}10^5$	18
1078	$43/2^+ \to 39/2^+$	17	E2	15	206	$3.3\text{x}10^4$	2.0
1131	$43/2^+ \to (39/2^+)$	-	-	-	619	-	-
133	$43/2^{(-)} \to 41/2^{(+)}$	-	E1	-	846	$3.0\text{x}10^8$	-
352	$43/2^{(-)} \to 41/2^+$	5	E1	4	23	$1.5\text{x}10^8$	111

Table 6.3: New hindrance factors calculated for transitions feeding directly from the K^π=43/2$^+$ and 43/2$^{(-)}$ isomers.

Small hindrance factors for new decays

$$f_\nu = \left(\frac{T^\gamma_{\frac{1}{2}}}{T^W_{\frac{1}{2}}}\right)^{\frac{1}{\nu}}.$$



T. Shizuma et al, NPA696(01)337

^{183}Os; 3n channel in hot-4n reaction!

INSTITUTE OF PHYSICS PUBLISHING — JOURNAL OF PHYSICS G: NUCLEAR AND PARTICLE PHYSICS
J. Phys. G: Nucl. Part. Phys. 31 (2005) 1–5 — doi:10.1088/0954-3899/31/0/000

Nuclear-tidal waves in the osmium nuclei

D M Cullen[1], R Glover[1,2], L K Pattison[1], P M Walker[3], S Frauendorf[4] and D Almehed[3]

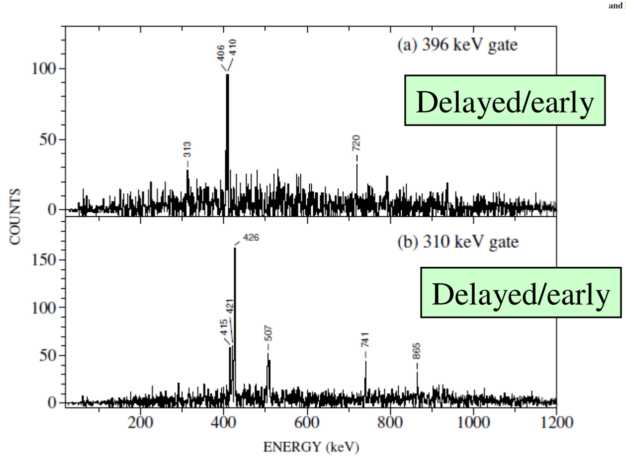


Figure 1. Early (above-isomer) γ-ray spectra from a matrix gated on the known delayed (below isomer) transitions in ^{183}Os; (a) an early 396 keV gate in the $K^\pi = 43/2^{(-)}$ band; (b) an early 310 keV gate in the $K^\pi = 43/2^+$ band.

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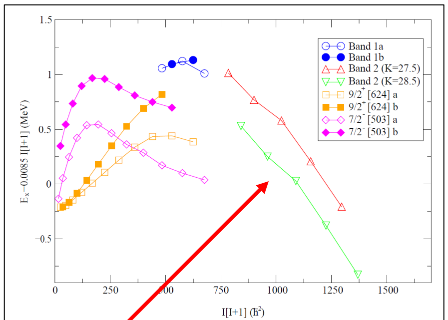

Efficient generation of angular momentum **above** isomer c.f. ground-state band

Institute of Physics Publishing Journal of Physics G: Nuclear and Particle Physics
J. Phys. G: Nucl. Part. Phys. 31 (2005) 1–5 doi:10.1088/0954-3899/31/0/000

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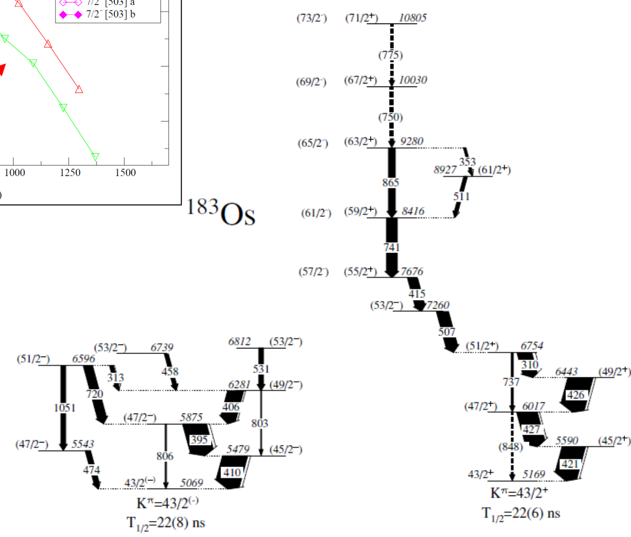

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^{183}Os

Spin generated at constant frequency

Institute of Physics Publishing Journal of Physics G: Nuclear and Particle Physics
J. Phys. G: Nucl. Part. Phys. 31 (2005) 1–5 doi:10.1088/0954-3899/31/0/000

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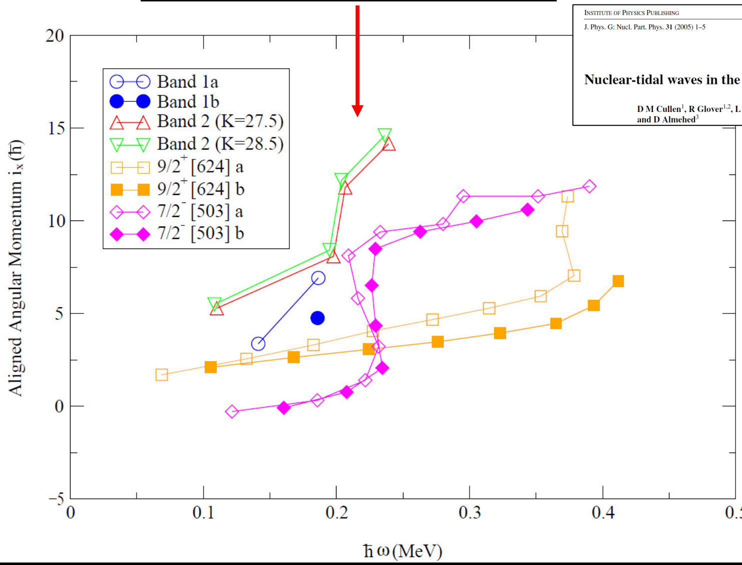

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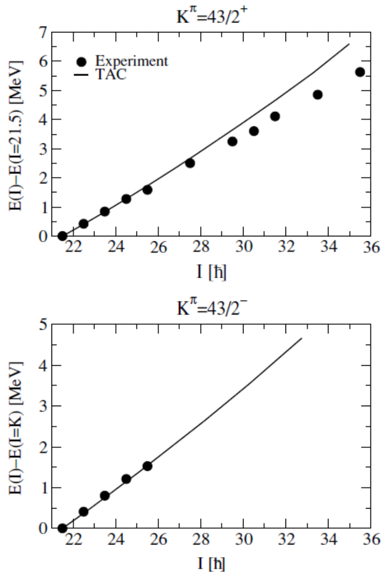
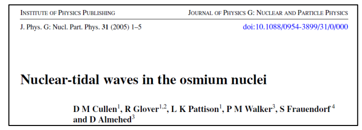
Shell-Corrected TAC calculations

^{183}Os





INSTITUTE OF PHYSICS PUBLISHING — JOURNAL OF PHYSICS G: NUCLEAR AND PARTICLE PHYSICS

J. Phys. G: Nucl. Part. Phys. 31 (2005) 1–5 — doi:10.1088/0954-3899/31/0/000

Nuclear-tidal waves in the osmium nuclei

D M Cullen[1], R Glover[1,2], L K Pattison[1], P M Walker[3], S Frauendorf[4] and D Almehed[5]

Nuclear Tidal Wave / Multi-phonon vibration interpretation fits ^{183}Os data reasonably well (but some evidence for other interactions)

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^{180}Os

^{36}S + ^{150}Nd → ^{180}Os (6n) Gammasphere experiment - Argonne National Lab.

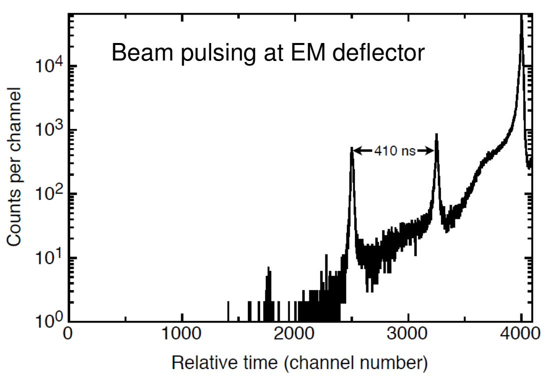
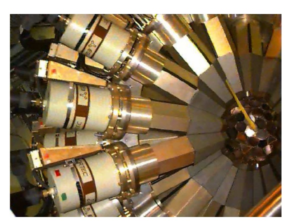
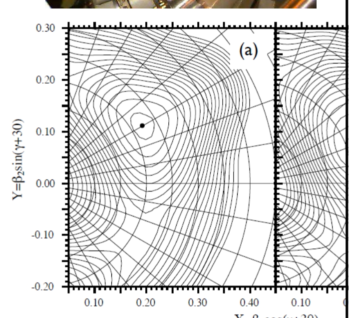


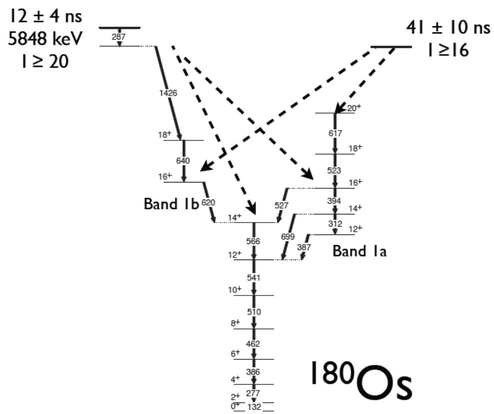
Figure 3.13: A reverse-time spectrum for a single detector produced in this experiment. The γ ray is timed with respect to the RF signal.





^{180}Os Gammasphere experiment

(N. Lumley PhD thesis 2010)



No structures on top of isomers

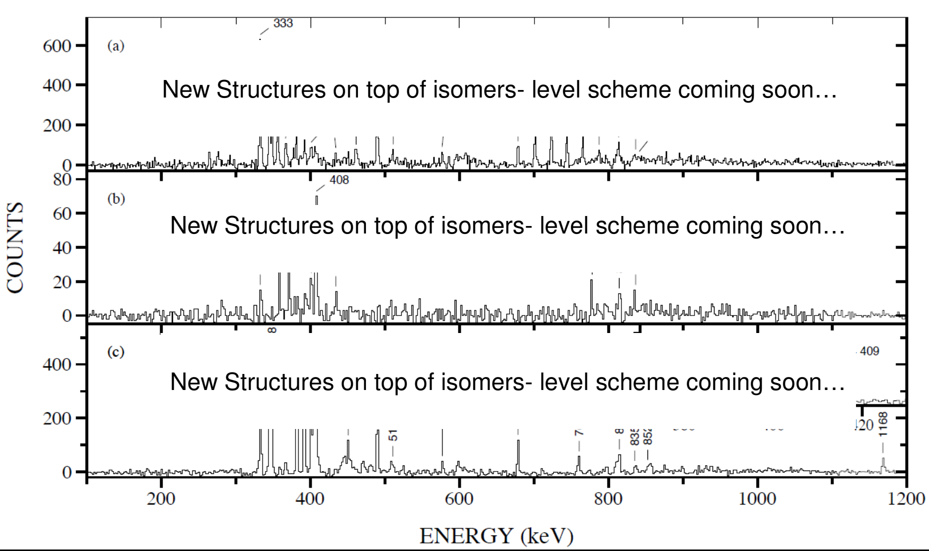
Isomers not well linked into yrast

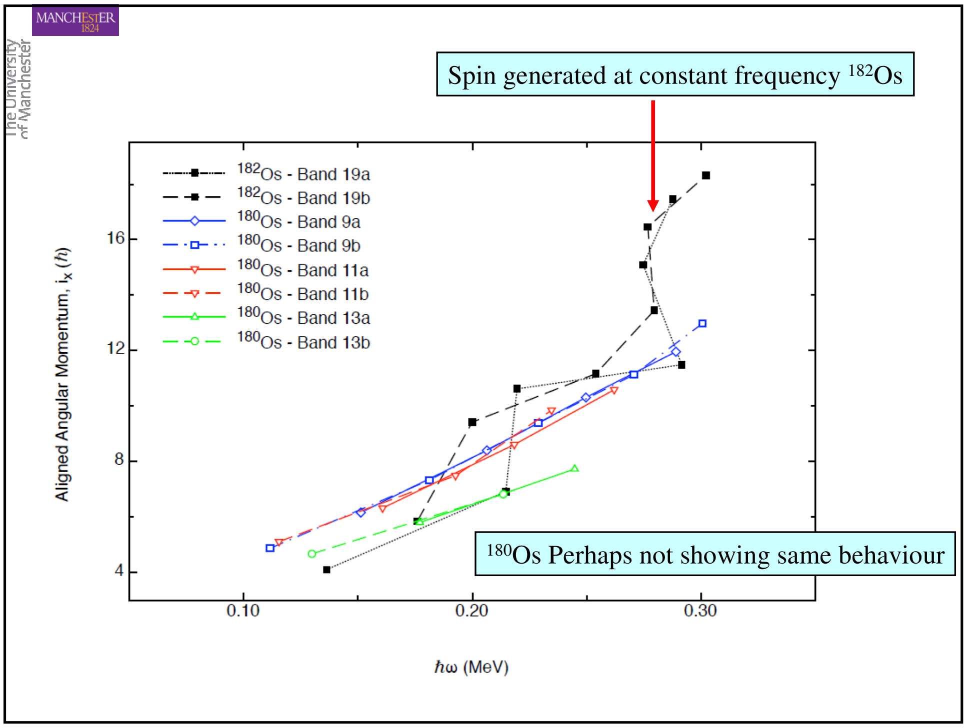
Problems with half-life.

T. Venkova *et al.*, Zeitschrift fur Physik A (1993).

^{180}Os Gammasphere experiment

(N. Lumley PhD thesis 2010)





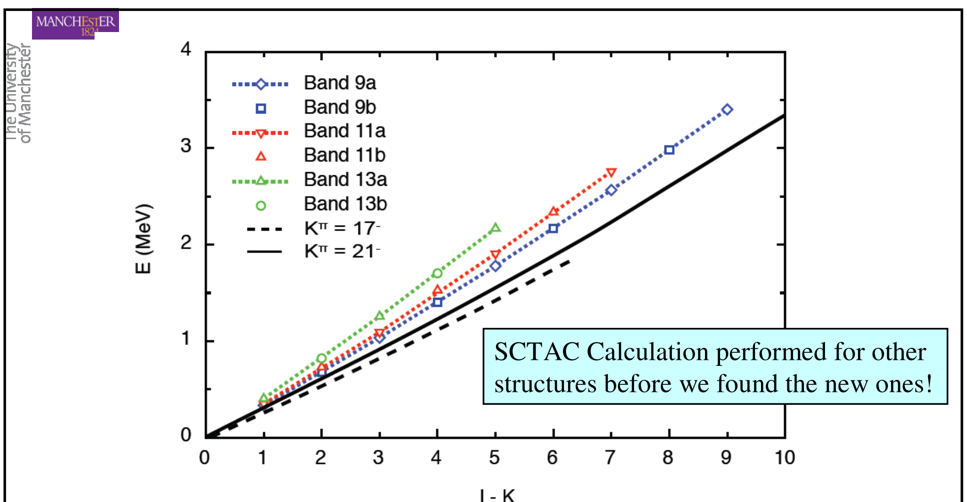


Figure 6.12: [Colour] SCTAC calculations for $K^{\pi} = 17^-$ and 21^- bands in ^{180}Os. The experimental excitation energy minus the band-head energy is given against the spin of the state, I, for bands 9, 11 and 13.

PES Calculations for the new isomers would also be of use to see how gamma soft the new isomeric states are…

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Conclusions

Nuclear Tidal Wave / Multi-phonon Interpretation:

- Gives good explanation for anomalous high-K behaviour in **soft** osmium nuclei ^{181}Os ^{182}Os, ^{183}Os [and perhaps ^{180}Os?]
- Angular momentum generated by shape change at nearly constant angular velocity
- **Competes** with collective rotation
- Look for future examples…
  2006 - Octupole (λ=3) tidal waves in discovered in ^{220}Th
  W. Reviol, Phys Rev. C 74 (06) 044305

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Thanks to the collaborators…

VOLUME 91, NUMBER 18 PHYSICAL REVIEW LETTERS week ending 31 OCTOBER 2003

Multiphonon Vibrations at High Angular Momentum in ^{182}Os

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