Peking University 北京大学

Extending nuclear landscape with high-K isomers

Furong Xu

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I. Introduction for isomerism

II. Configuration-constrained PES Model

III. High-K isomerism

1) Along drip lines

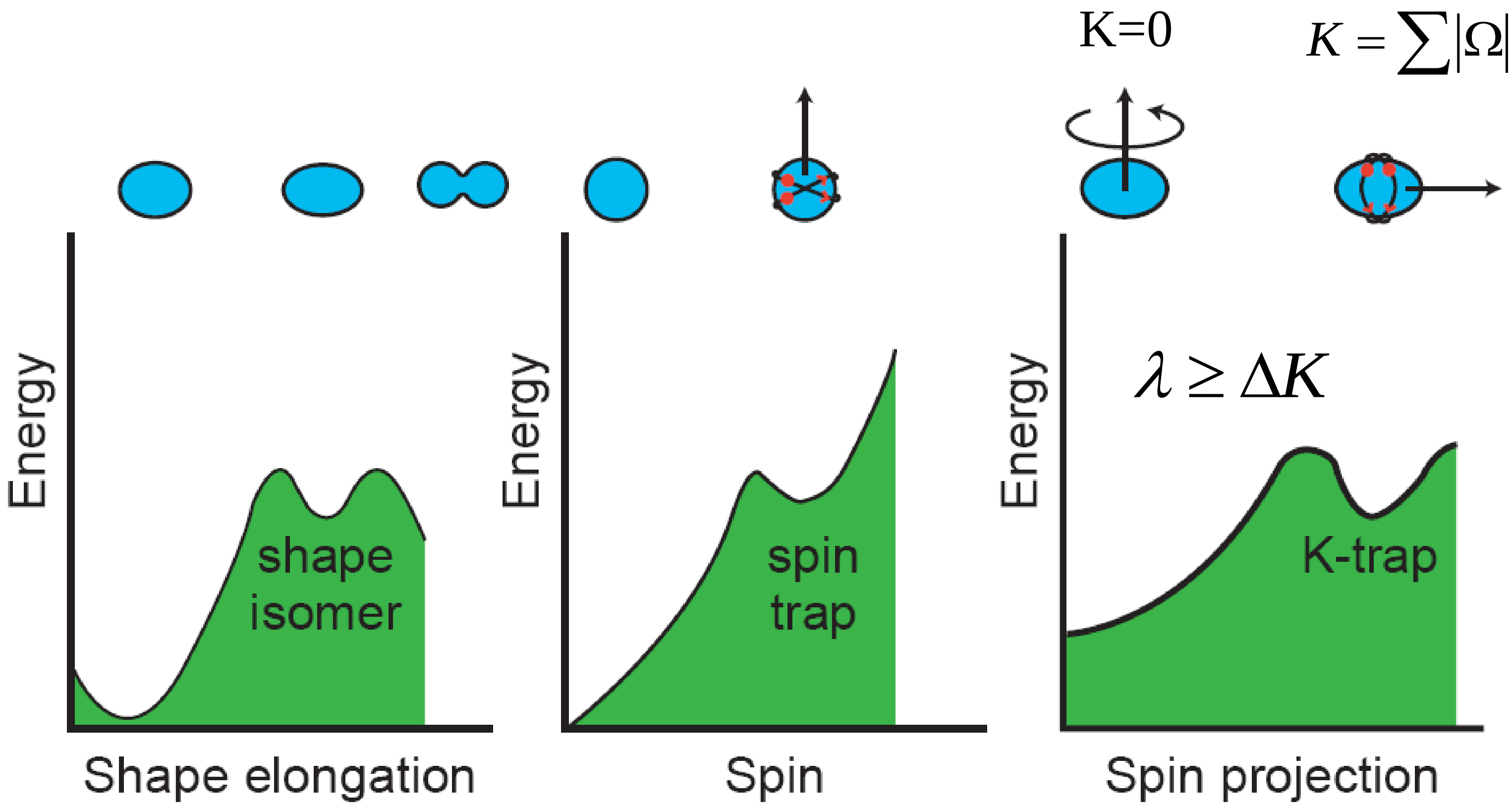
2) In superheavy nuclei

3) High-K fission isomers

4) In superdeformation

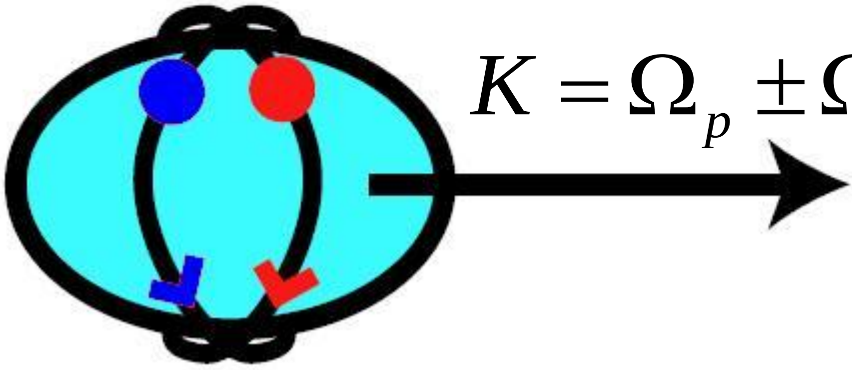
IV. Summary

I. Introduction for isomerism



From: P. Walker, G. Dracoulis, Nature 399 (1999) 35

High-K isomerism

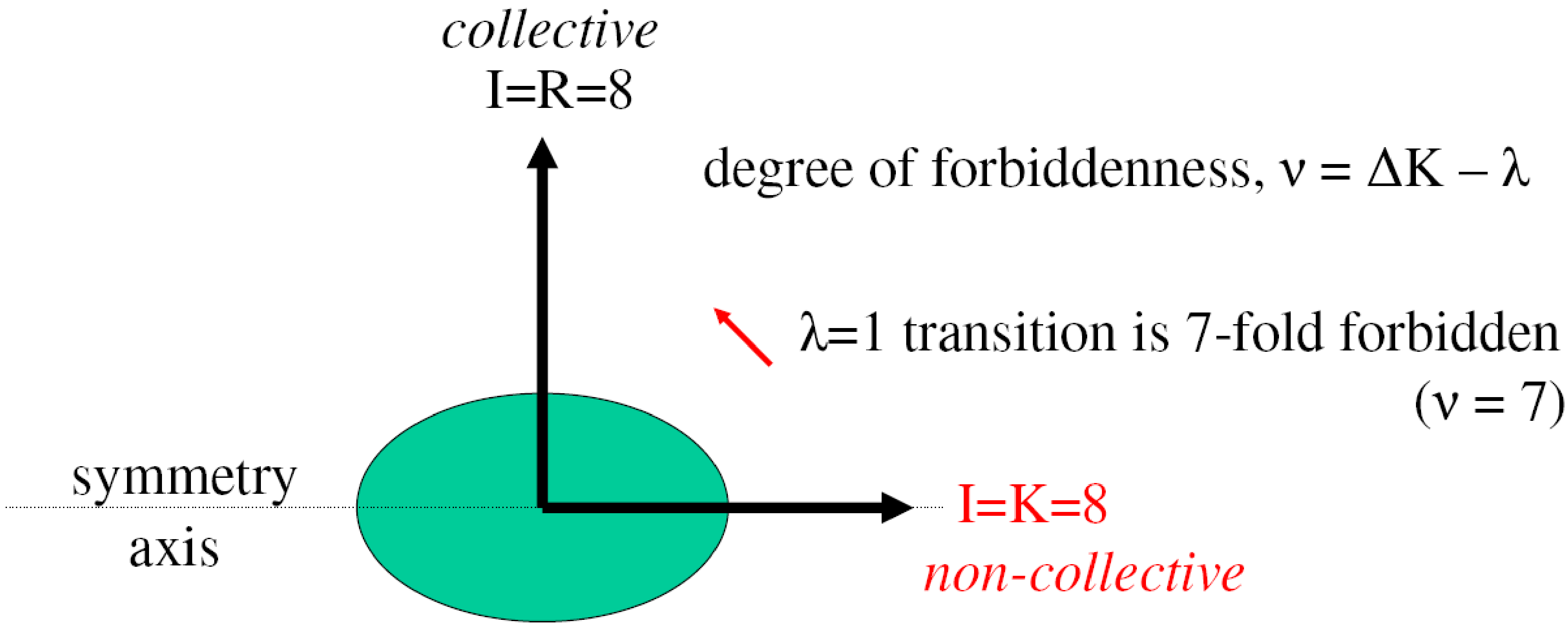


$$K = \Omega_p \pm \Omega_n$$

Non-collective rotation

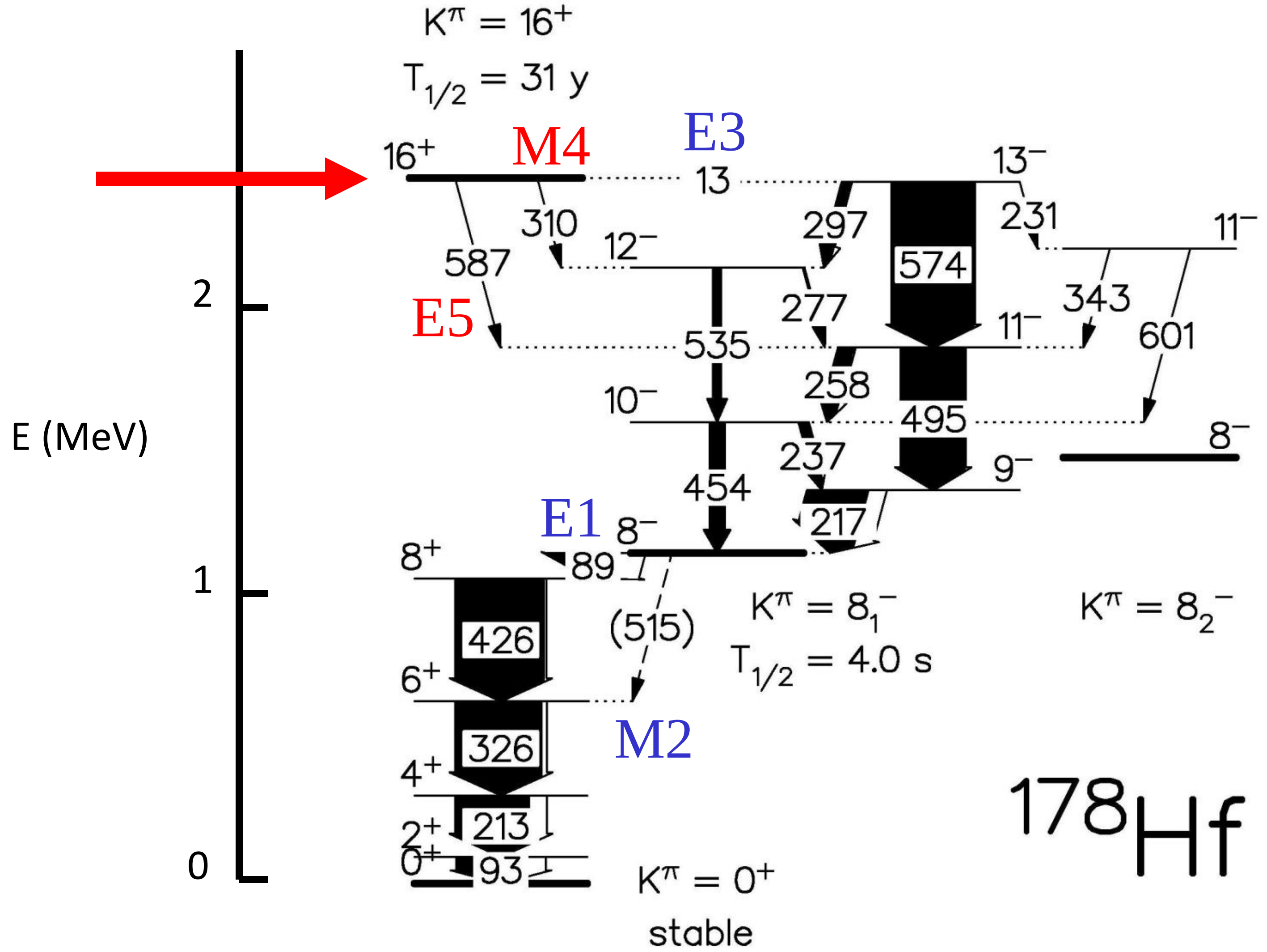
	J^{π}	$T_{1/2}$	E_x (KeV)
^{178}Hf	16^+	31 y	2400
^{180}Ta	1^+	8.15 h	g.s.
	9^-	$>10^{15}$ y	75

K-forbidden γ-ray transitions



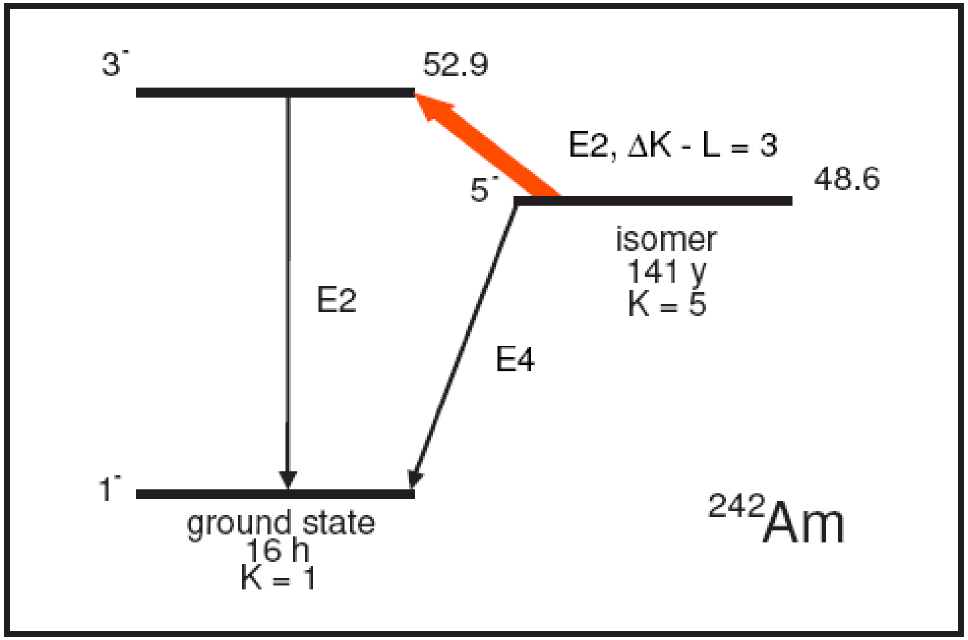
angular momentum has both magnitude and direction!

From: P.M. Walker

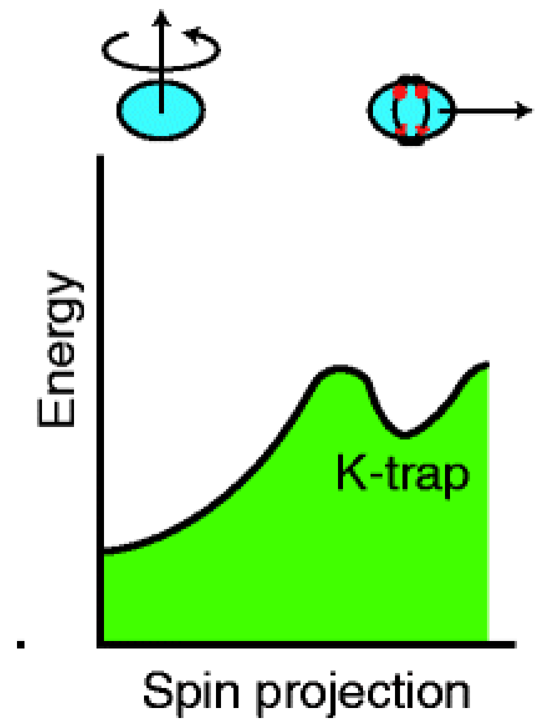


[M.B. Smith et al., Phys. Rev. C68(2003)031302(R)]

TRUIMF 8π data

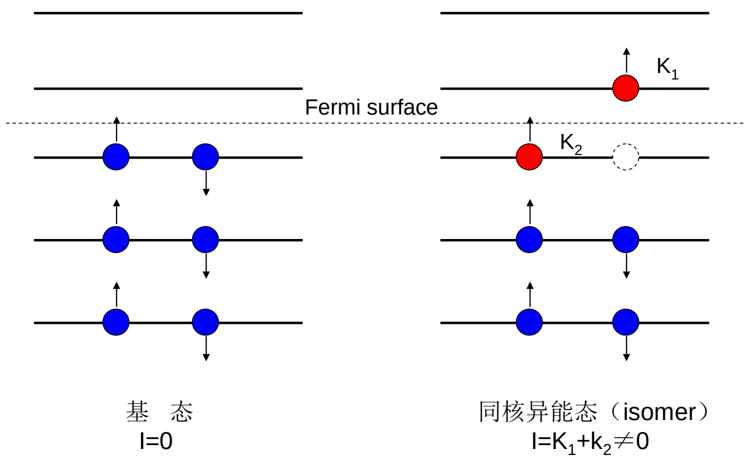


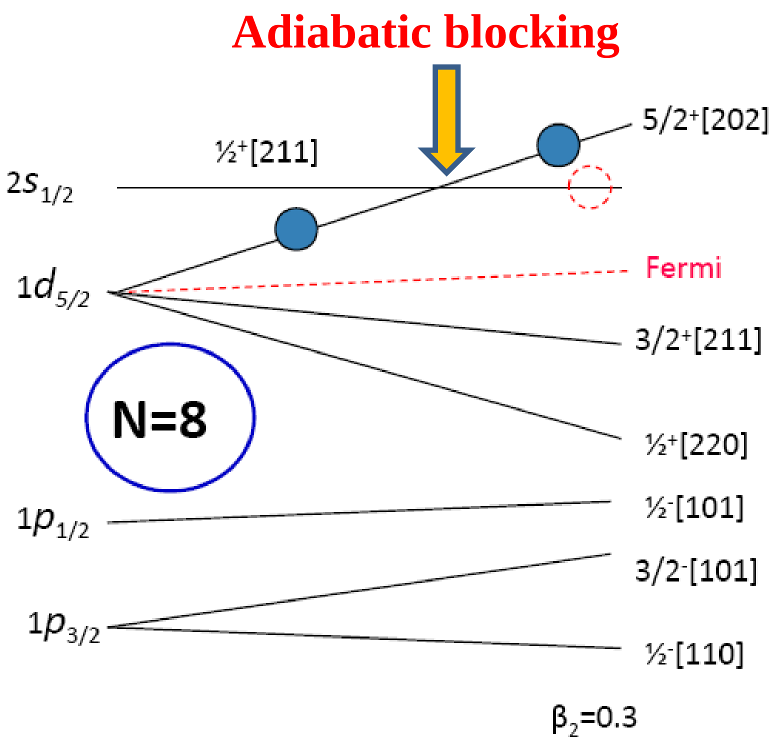
3⁻
52.9
E2, ΔK - L = 3
5⁻
48.6
isomer
141 y
K = 5
E2
E4
1⁻
ground state
16 h
K = 1
242Am



Energy
K-trap
Spin projection

II. The configuration-constrained PES Model

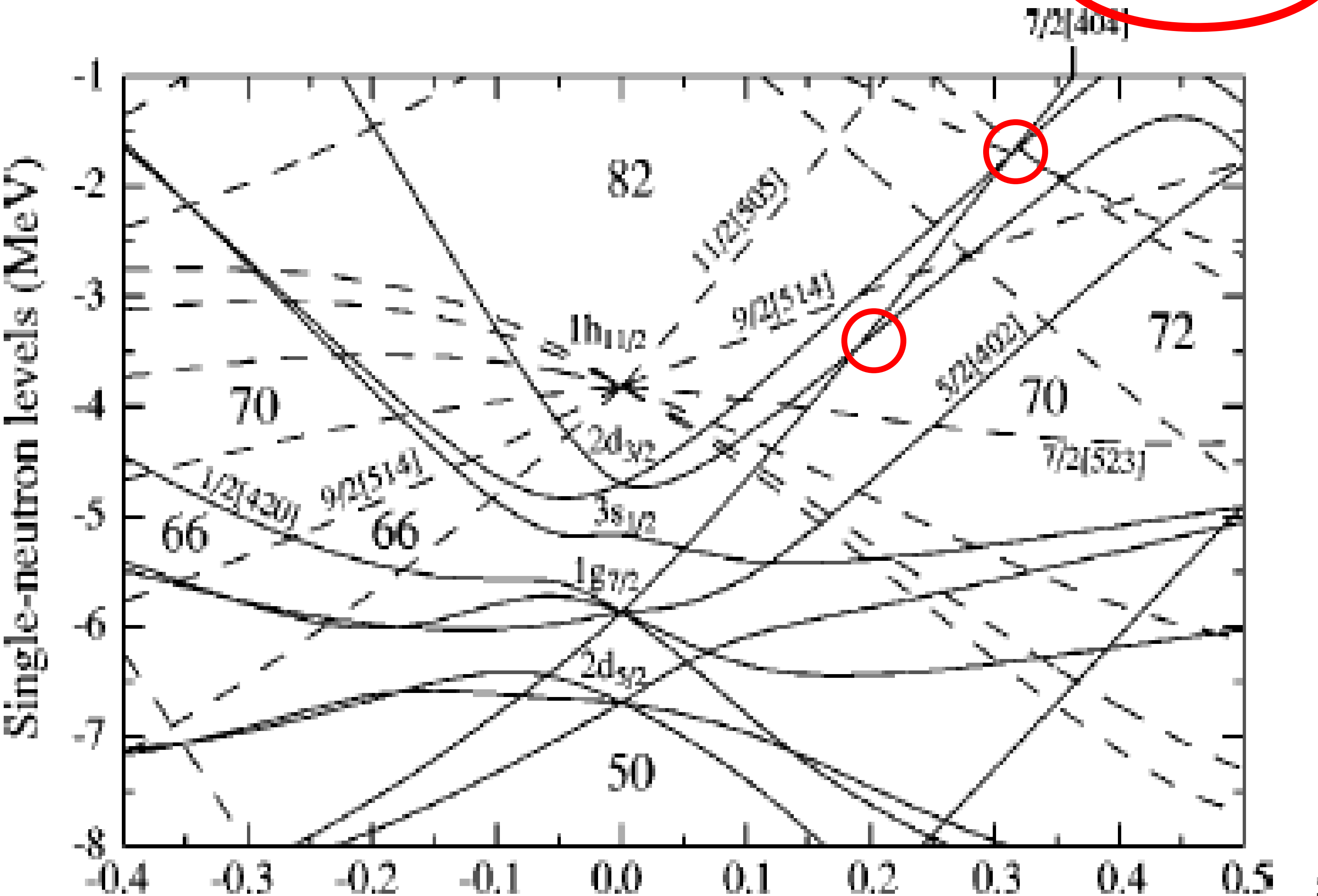




Three important factors which affect the calculations of high-K states:

1. **spacing of single-particle levels;**
2. **effect from shape polarization (adiabatic-blocking is necessary!)**
3. **right pairing strengths**

In adiabatic blocking, identify s.p. orbits using $\Omega[N, n_z, \Lambda]$



Deformed Woods-Saxon Potential

$$E = E_{LD} + \delta E_{shell}$$

E_{LD} is independent on blocking

$$\delta E_{shell} = E_{LN} - \tilde{E}_{Strut}$$

BCS calculation can be collapsed in weak pairing case.

The Lipkin-Nogami pairing can avoid this problem.

$$E_{\mathrm{LN}} = \sum_{j=1}^{S} e_{k_j} + \sum_{k \neq k_j} 2V_k^2 e_k - \frac{\Delta^2}{G} - G \sum_{k \neq k_j} V_k^4 + G\frac{N-S}{2}$$

$$-4\lambda_2 \sum_{k \neq k_j} (U_k V_k)^2, \qquad (1)$$

with

$$N - S = \sum_{k \neq k_j} 2V_k^2, \qquad (2)$$

- ✓ Woods-Saxon potential provides s.p. levels
- ✓Configuration-constrained PES can include the effect from shape polarization of unpaired orbits.
- ✓Right pairing strength is crucial for energy calculations of isomers

Mean-field effect on odd-even mass difference

Satula, Dobaczewski, Nazarewicz, PRL 81, 3599 (1998)

Xu, Wyss, Walker, PRC 60, 051301(R) (1999)

Mean-field effect (due to double degeneracy of s.p. levels):

$$\frac{1}{2}(e_{n+1}-e_n)$$ **using 3 points** $$\Delta(N=2n)=\frac{1}{2}[M(N-1)-2M(N)+M(N+1)]$$

$$\frac{1}{4}(e_{n+1}-e_n)$$ **using 5 points** $$\Delta(N=2n)=\frac{1}{8}[-M(N+2)+4M(N+1)-6M(N)+4E(N-1)-M(N-2)]$$

$$\Delta_{BCS}$$
$$\Delta_{LN}+\lambda_2$$

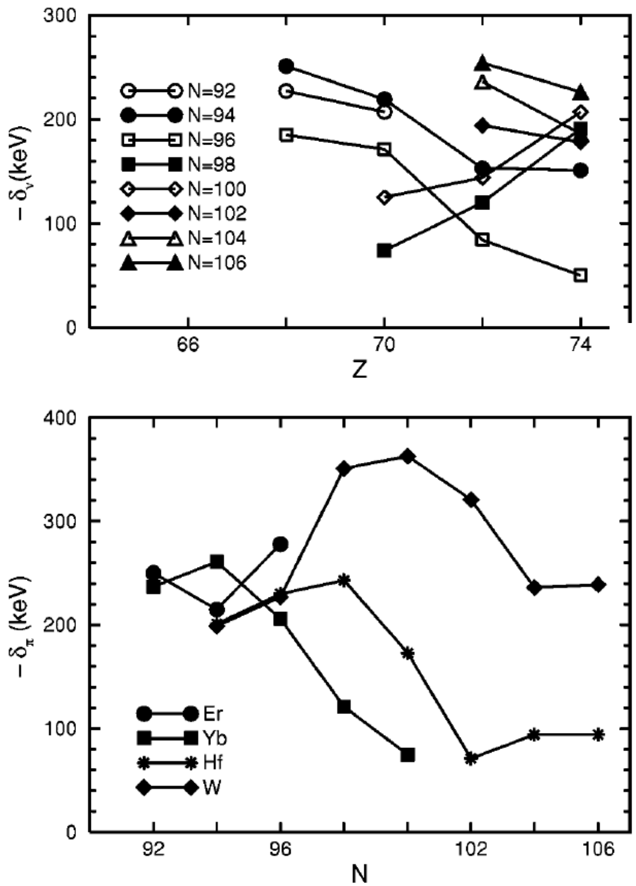
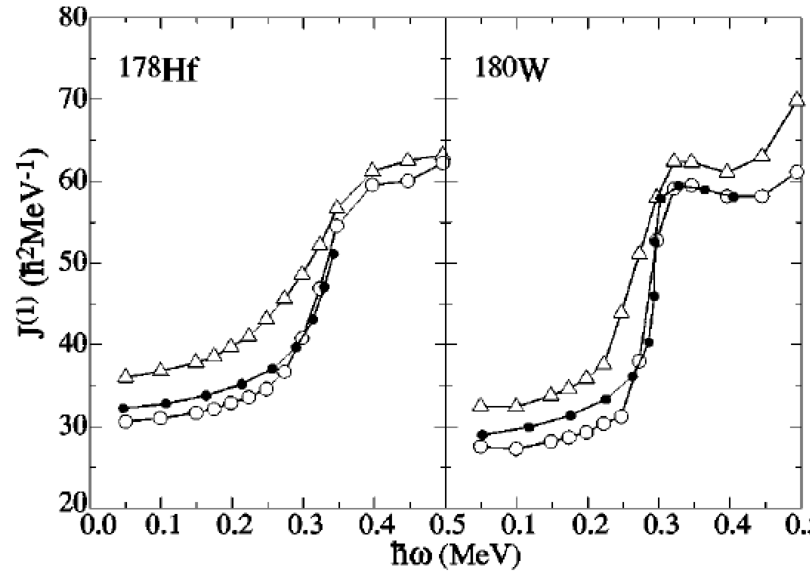


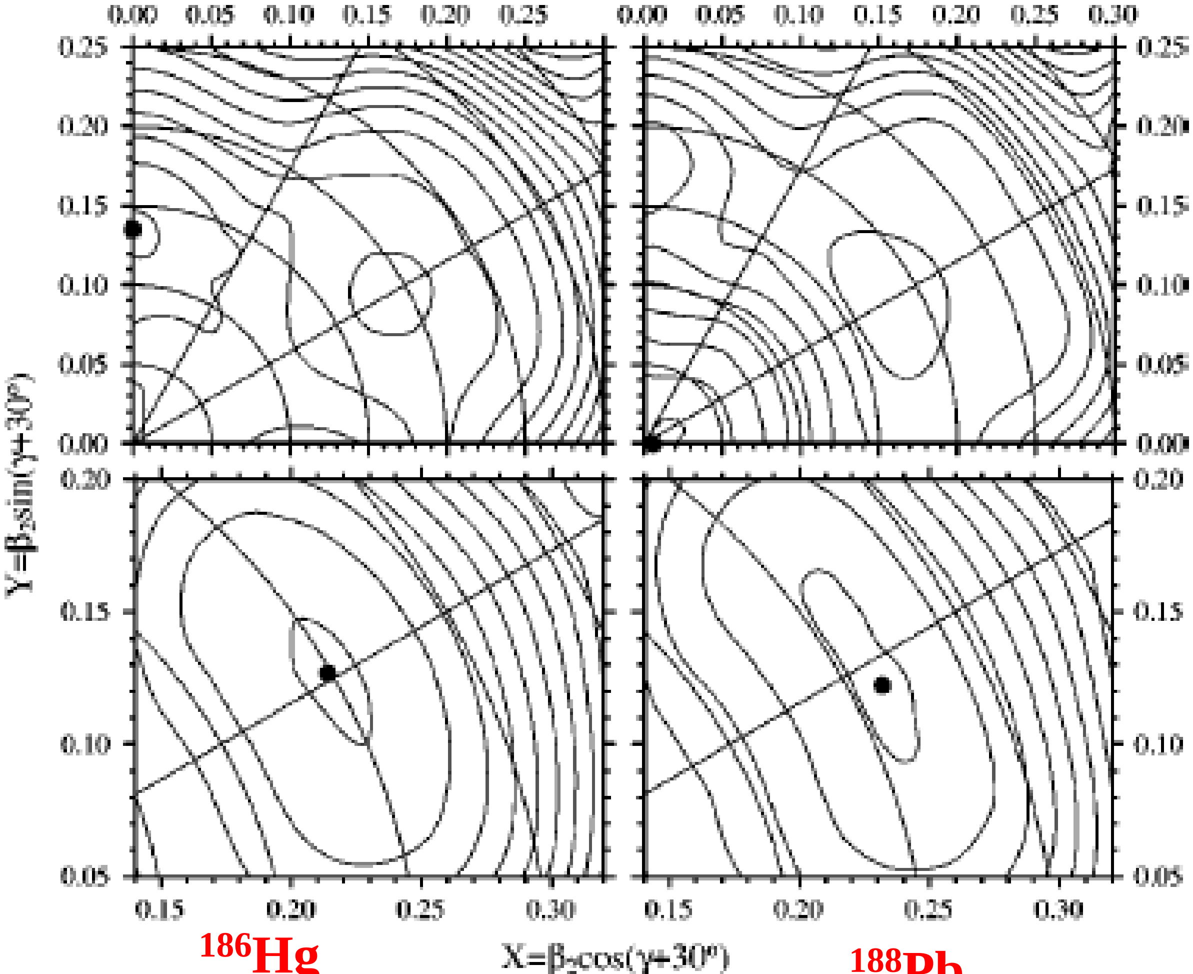
FIG. 1. Obtained mean-field and blocking effects ($\delta=\delta_{MF}+\delta_{block}$) as a function of nucleon number. The upper panel is for neutrons (ν) and the lower panel is for protons (π). Note that the δ values are negative.

$$D_{th}^{oe}=\Delta+\lambda_2+\delta$$



Xu, Wyss, Walker, PRC60, 051301(R) (1999)

Shape polarization Xu, Walker, Wyss, PRC59, 731 (1999)



g.s.

$K^\pi = 8^-$

Two-neutron

$9/2^+[624]\otimes 7/2^-[514]$

$K^\pi = 8^-$

E^{cal}=2230 keV; E^{expt} =2217 keV

A.M. Bruce *et al.*, PRC55, 620 (1997)

E^{cal}=2400 keV ; E^{expt}=2576 keV

Dracoulis *et al.*, PRC60, 014303(1999)

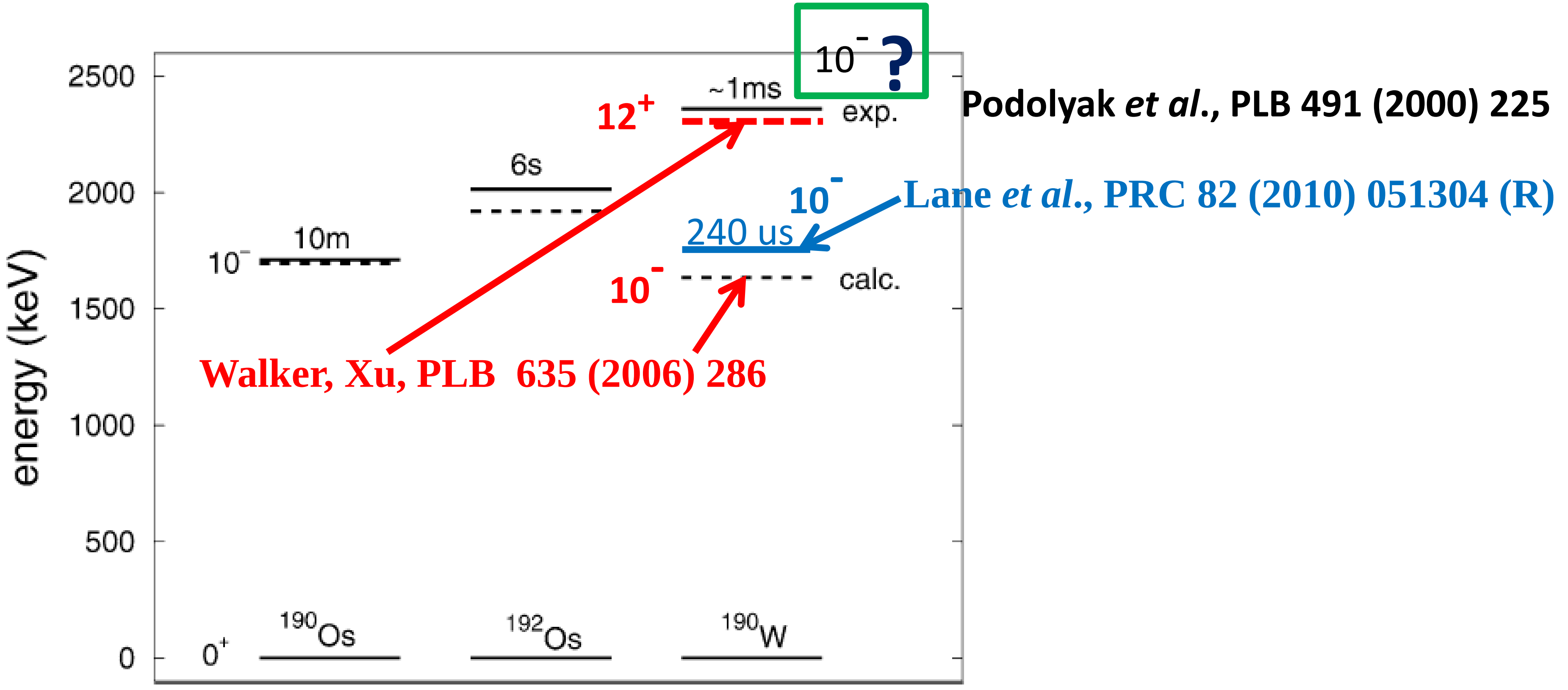


Fig. 2. Comparison of experimental (full line) and calculated (dashed line) isomer energies for ^{190}Os, ^{192}Os and ^{190}W. Experimental half-lives are indicated.

II. Calculations of high-K states

1. Along drip lines

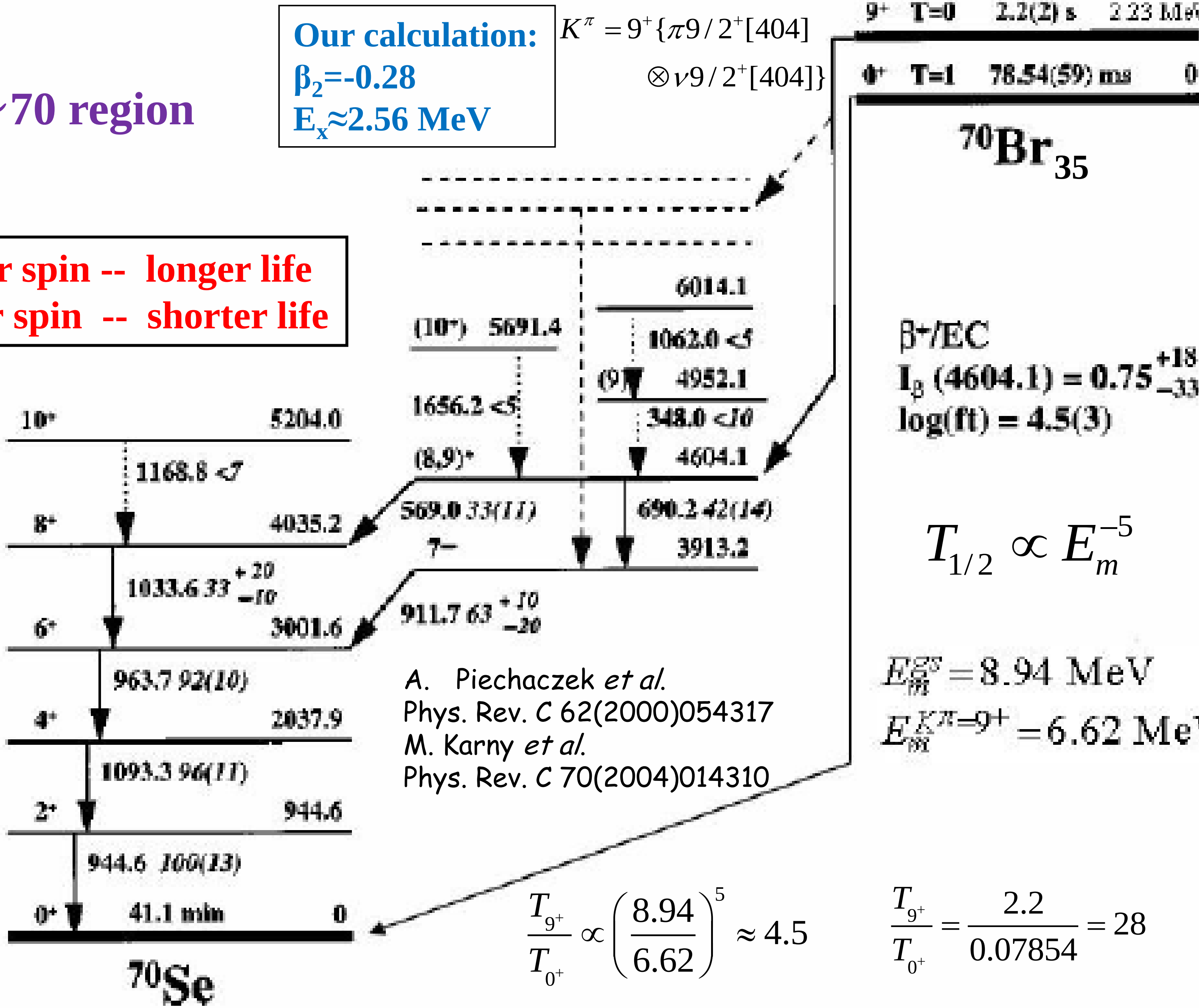
Nuclei near drip lines have extremely short lifetimes!

A～70 region

Our calculation:
β_2=-0.28
E_x≈2.56 MeV

$K^{\pi} = 9^{+}\{\pi 9/2^{+}[404] \otimes \nu 9/2^{+}[404]\}$

Higher spin -- longer life
Lower spin -- shorter life



β^+/EC
I_β (4604.1) = 0.75^{+18}_{-33}
log(ft) = 4.5(3)

$$T_{1/2} \propto E_m^{-5}$$

$$E_m^{gs} = 8.94 \text{ MeV}$$
$$E_m^{K^\pi=9^+} = 6.62 \text{ MeV}$$

A. Piechaczek *et al.*
Phys. Rev. *C* 62(2000)054317
M. Karny *et al.*
Phys. Rev. *C* 70(2004)014310

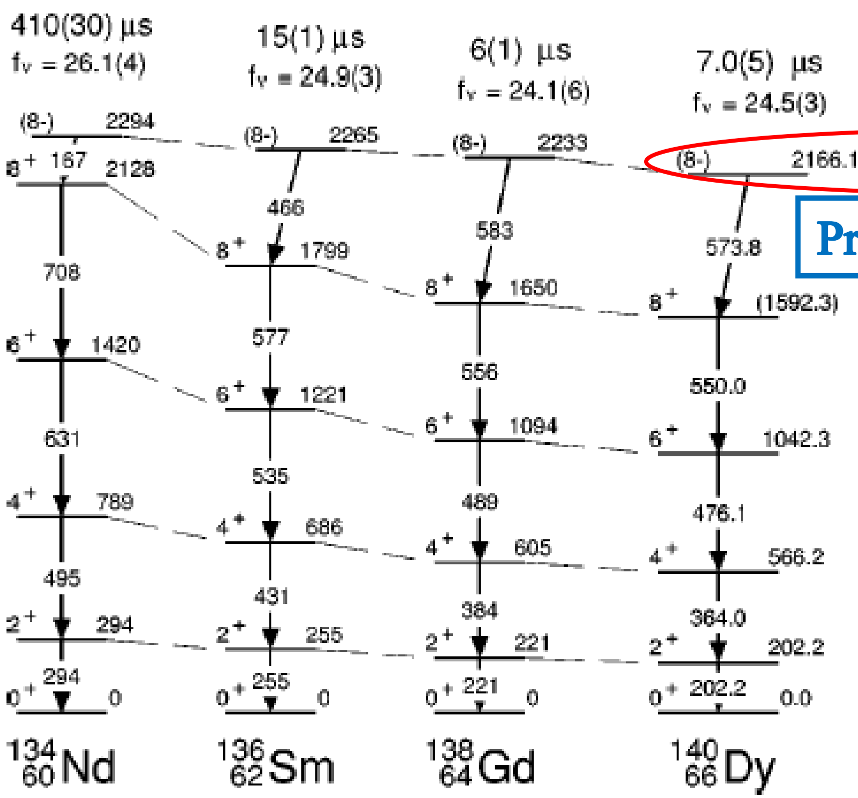
$$\frac{T_{9^+}}{T_{0^+}} \propto \left(\frac{8.94}{6.62}\right)^5 \approx 4.5$$

$$\frac{T_{9^+}}{T_{0^+}} = \frac{2.2}{0.07854} = 28$$

Xu, Walker, Wyss, PRC 59(1999)731

Nuclei	E_{expt}	E_{cal}	β_2	β_4	$\lvert\gamma\rvert$
^{126}Te		2980	0.12	−0.005	0°
^{128}Xe	2787	2490	0.16	−0.008	6°
^{130}Ba	2475	2390	0.18	−0.015	6°
^{132}Ce	2340	2220	0.20	−0.020	5°
^{134}Nd	2294	2140	0.22	−0.023	10°
^{136}Sm	2264	2120	0.24	−0.024	12°
^{138}Gd	2233	2130	0.25	−0.028	13°
^{140}Dy		2150	0.26	−0.039	9°

Proton-drop line

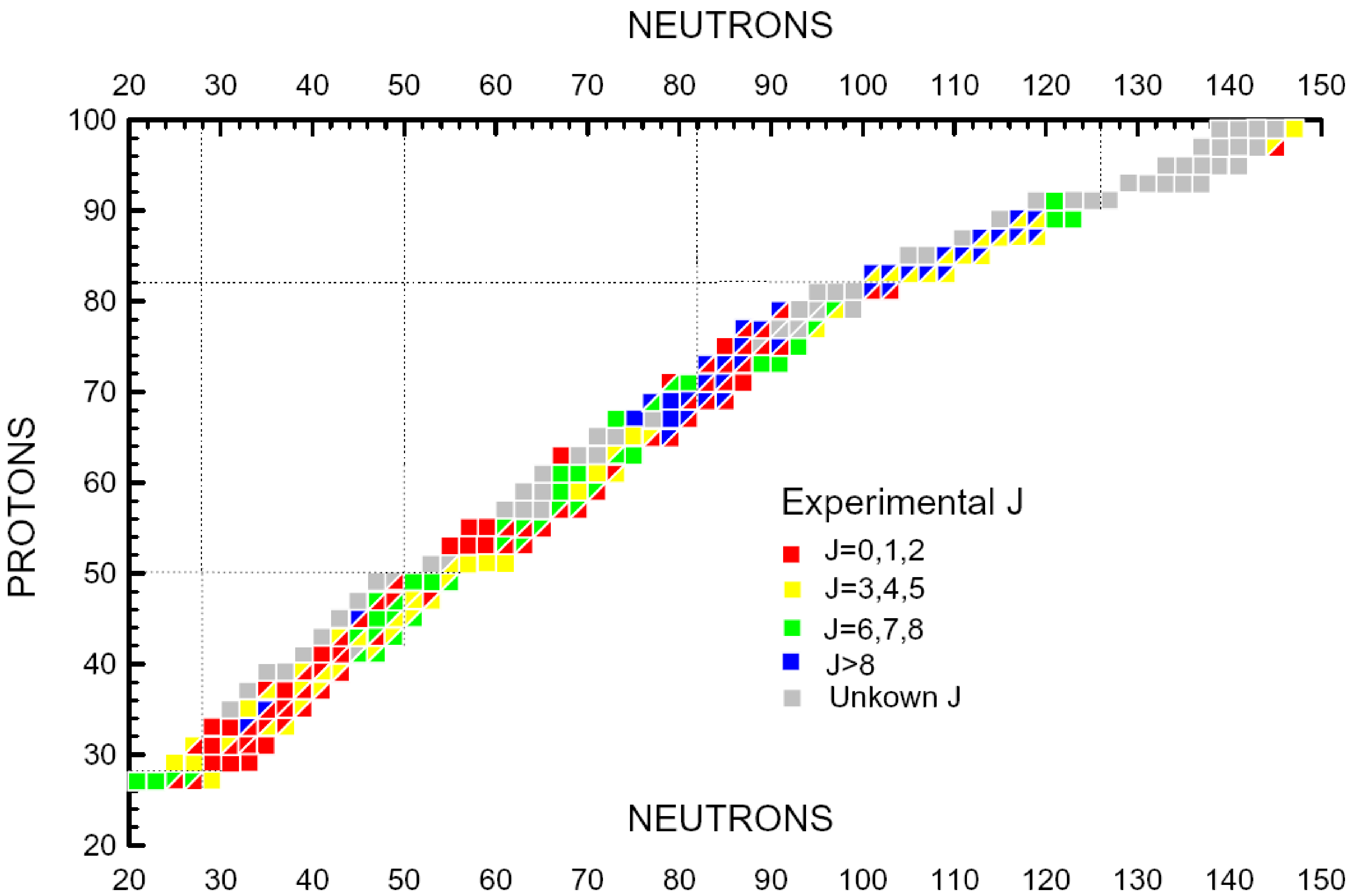


Cullen *et al.*, PLB 29 (2002) 42

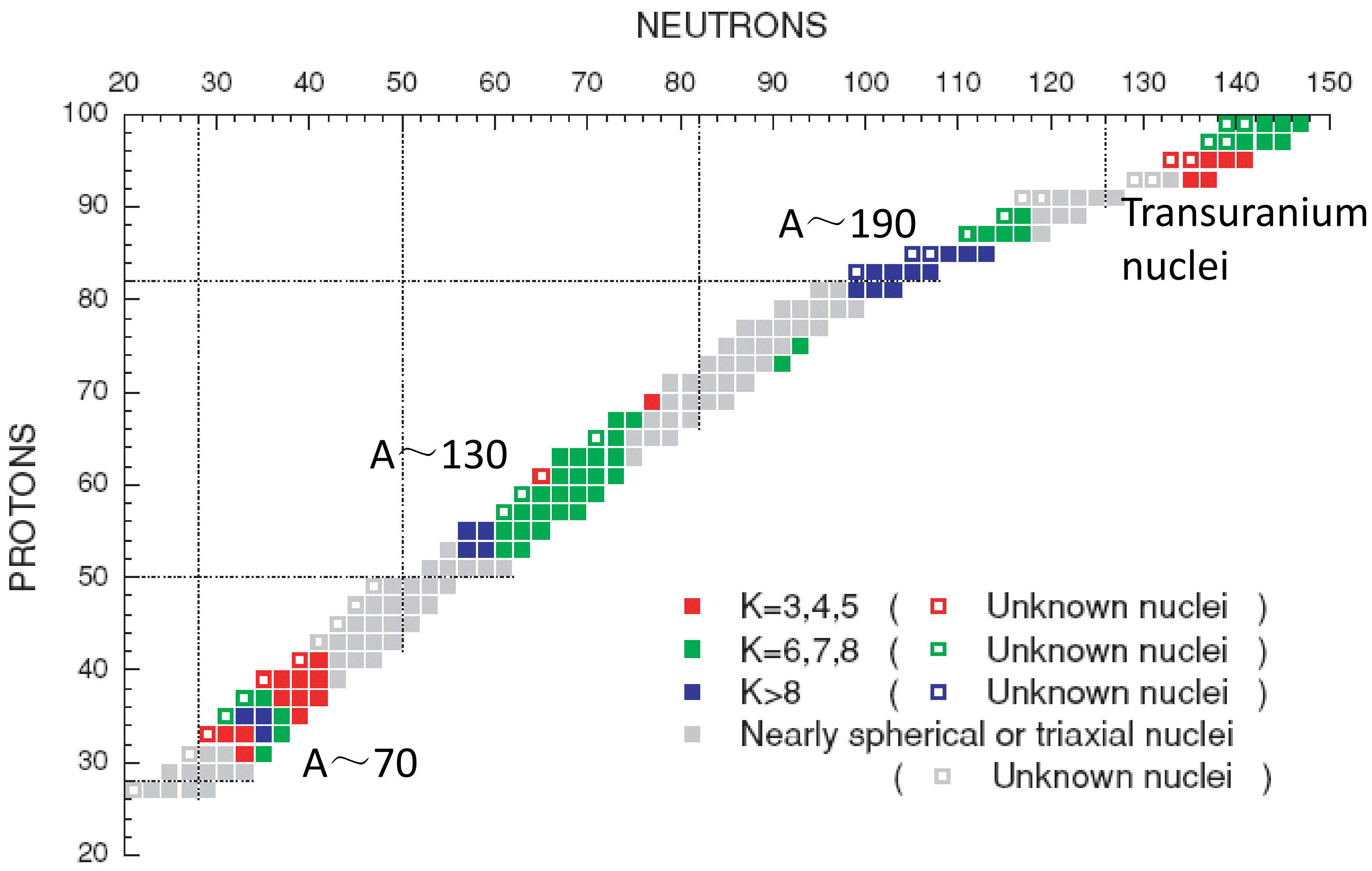
β_2=0.24 (3)

Krolas *et al.*, PRC 65 (2002) 031303

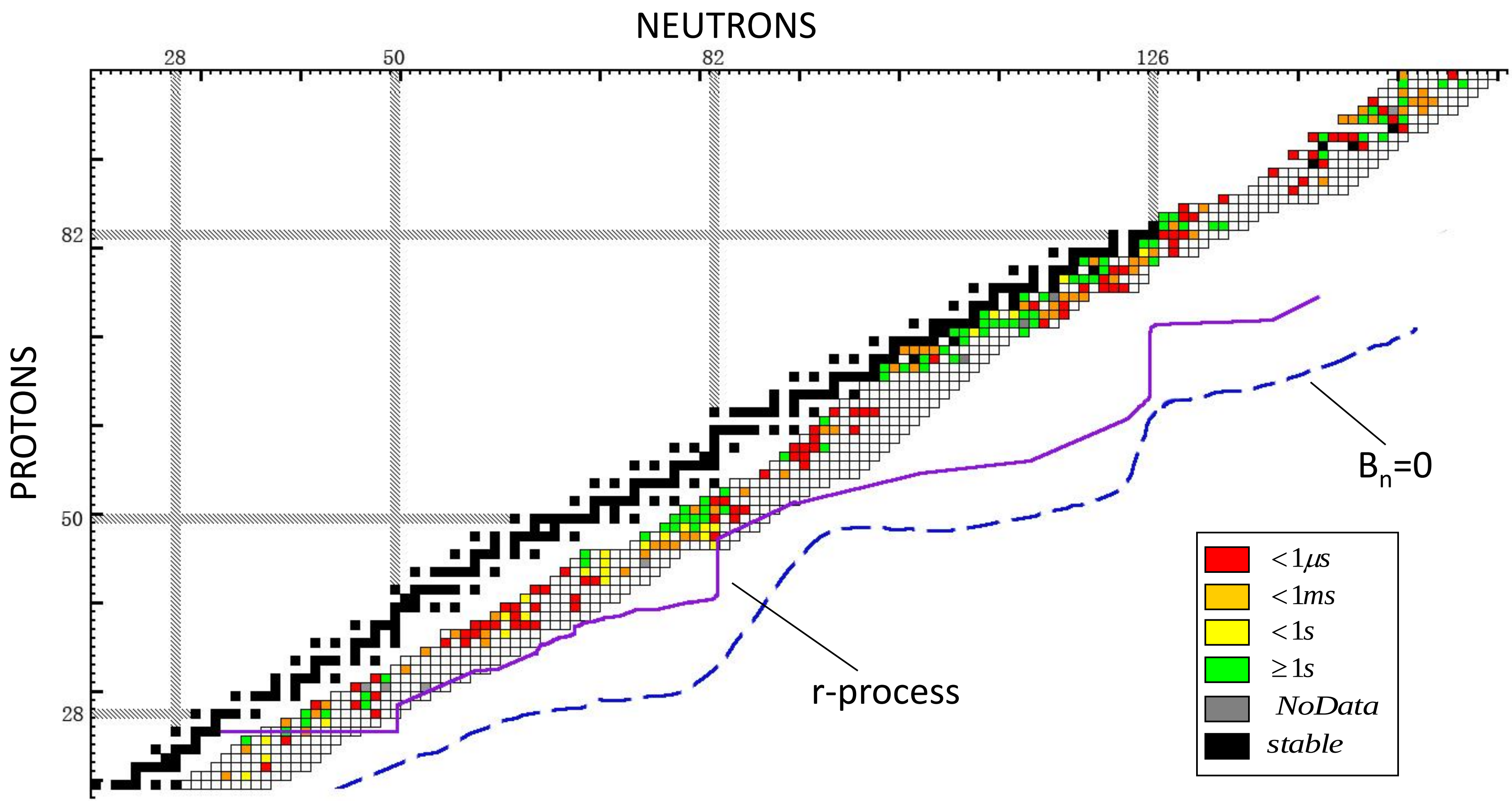
Observed isomers in odd-odd nuclei along proton-rich border



Prediction of deformed high-K states:
Exploration of the proton drip line and beyond



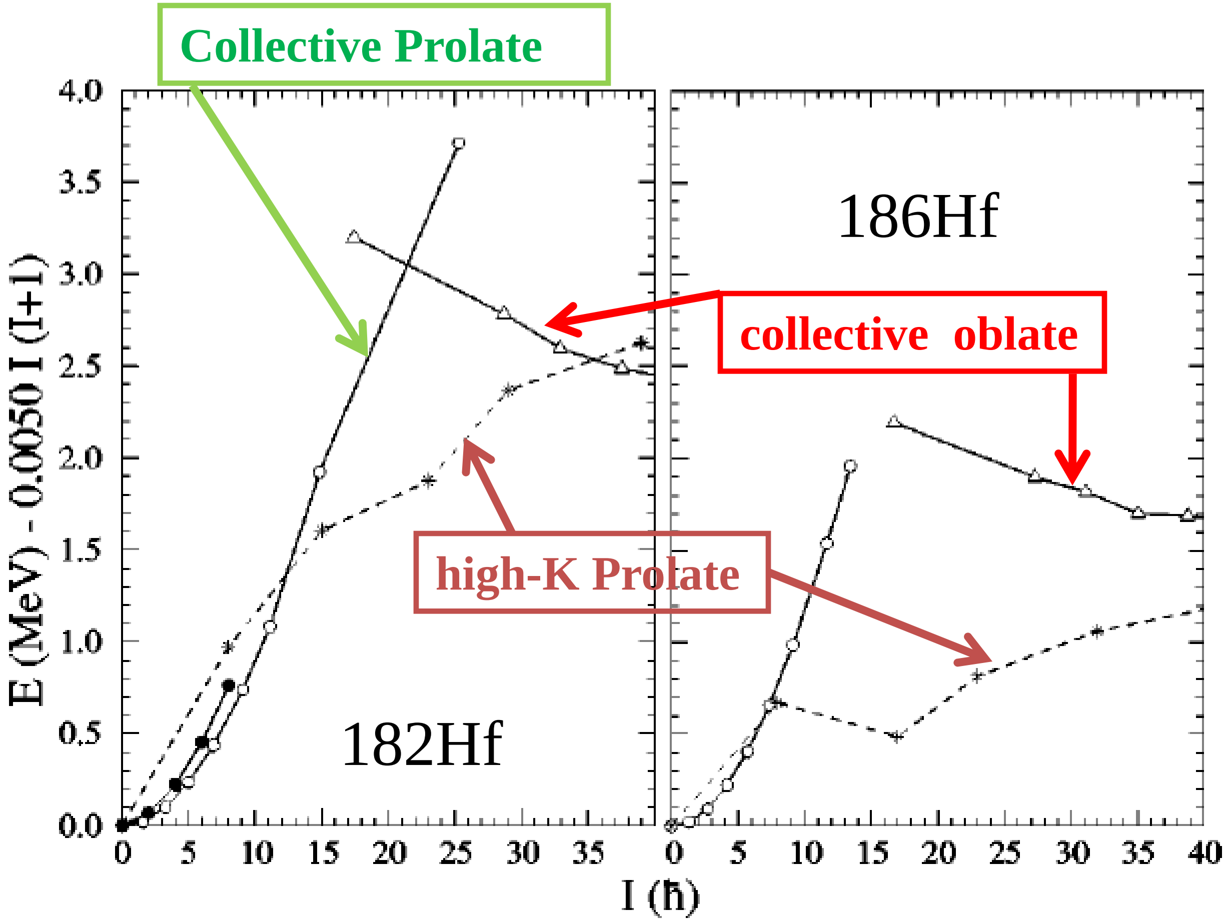
Liu, Xu, Wyss, Walker, PRC 76, 034313 (2007)



Isomers in neutron-rich nuclei, experimentally observed yet

High-spin limit in neutron-rich nuclei

Long lived isomers predicted



Xu, Walker, Wyss, PRC 62 (2000) 014301

2. High-k isomerism in SHE

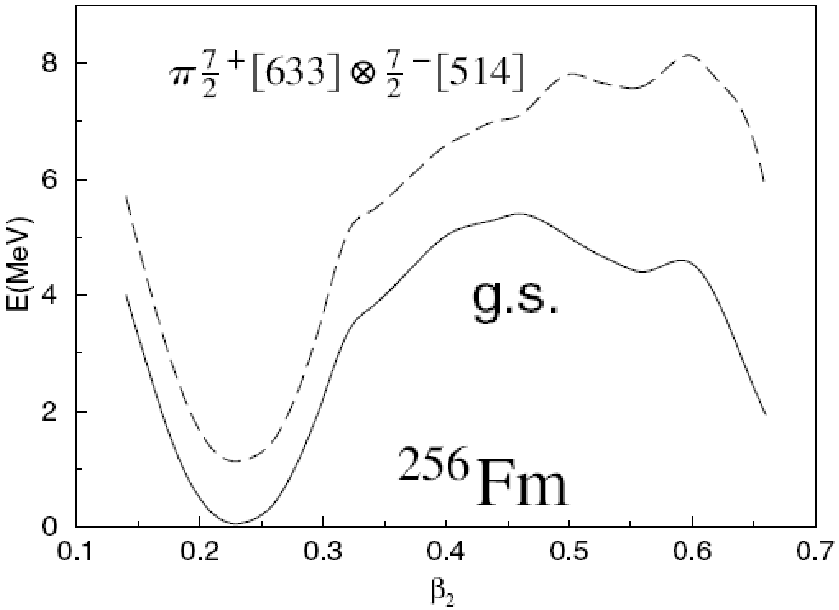
- **Superheavy decays by α emissions or/and spontaneous fissions.**
- **Multi-qp excitations decrease α-particle preformation and increase the height and width of fission barrier, and hence increase the stability of SHE.**

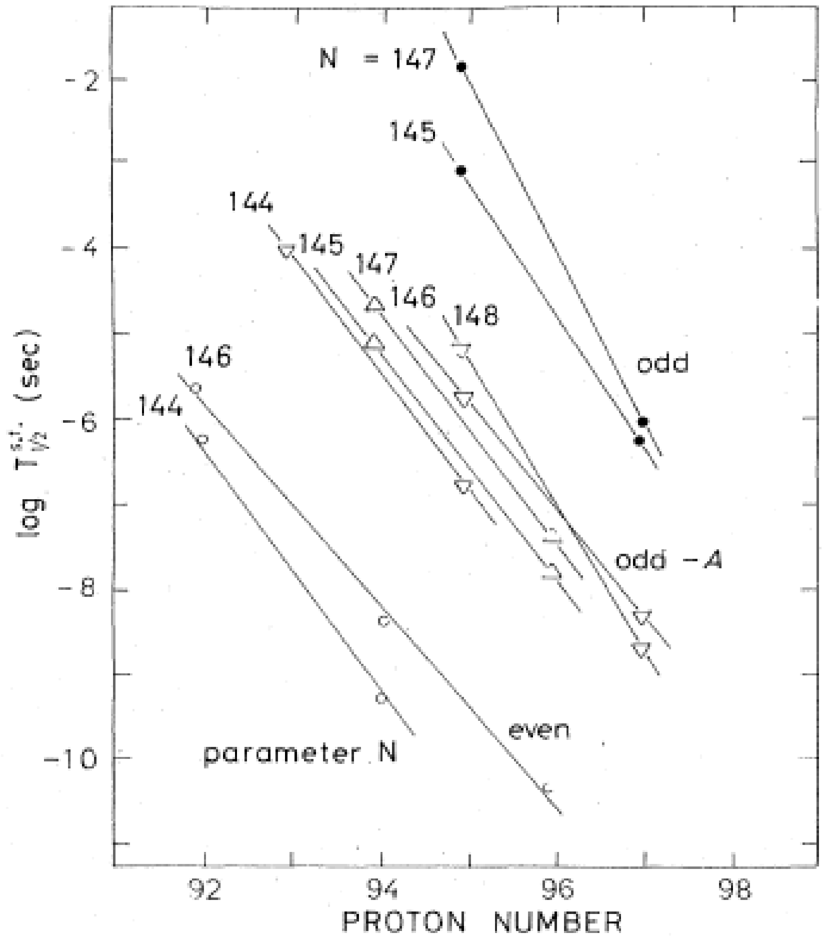
✓ **α-particle preformation reduced in odd and odd-odd nuclei,**
J.K. Poggenburk *et al.*, Phys. Rev. 181, 1697 (1969).

✓ **Fission probability in odd-odd and odd nuclei is reduced,**
S. Bjornholm & J.E. Lynn, Rev. Mod. Phys. 52(1980)725.

Unpaired nucleons increase the height and width of the fission barrier

Xu, Zhao, Wyss, Walker, PRL92 (2004) 252501

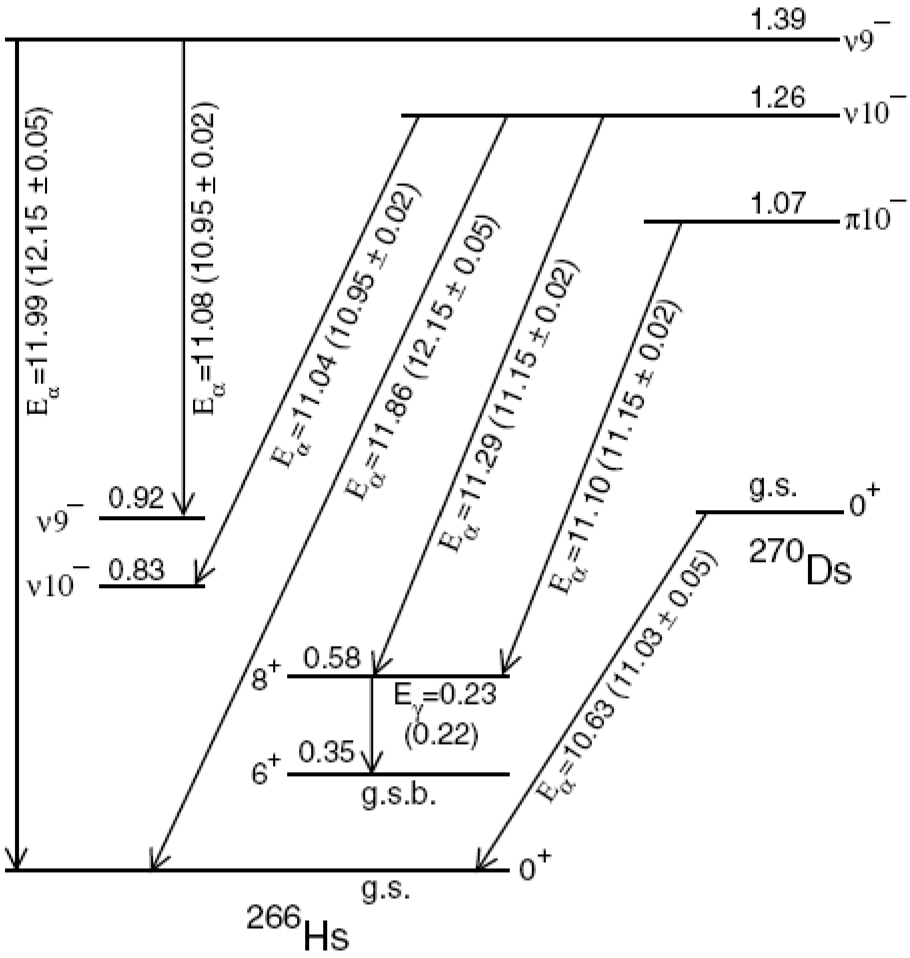




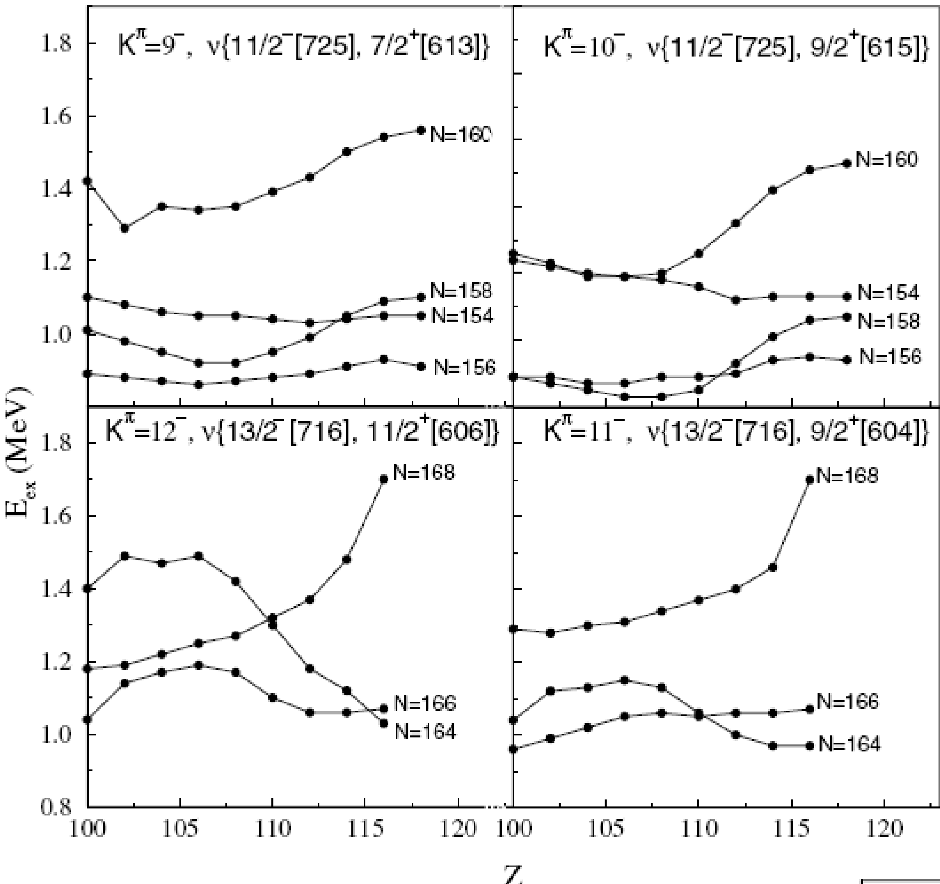
Even-odd difference in half-lives for fissions from the second well in actinides

Bjornholm & Lynn Rev. Mod. Phys. 52(1980)725

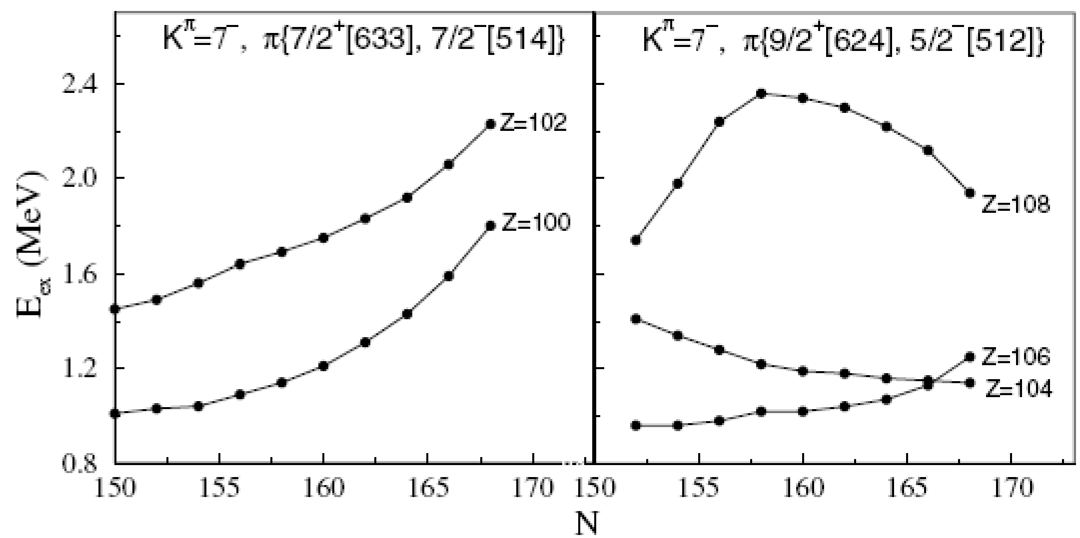
α decays observed from high-K isomers , Hofmann *et al*., EPJA 10, 5 (2001)



Xu, Zhao, Wyss, Walker, PRL 92, 252501 (2004)



Xu, Zhao, Wyss, Walker, PRL 92, 252501 (2004)



R.-D. Herzberg *et al.*, Nature 442 (2006) 24

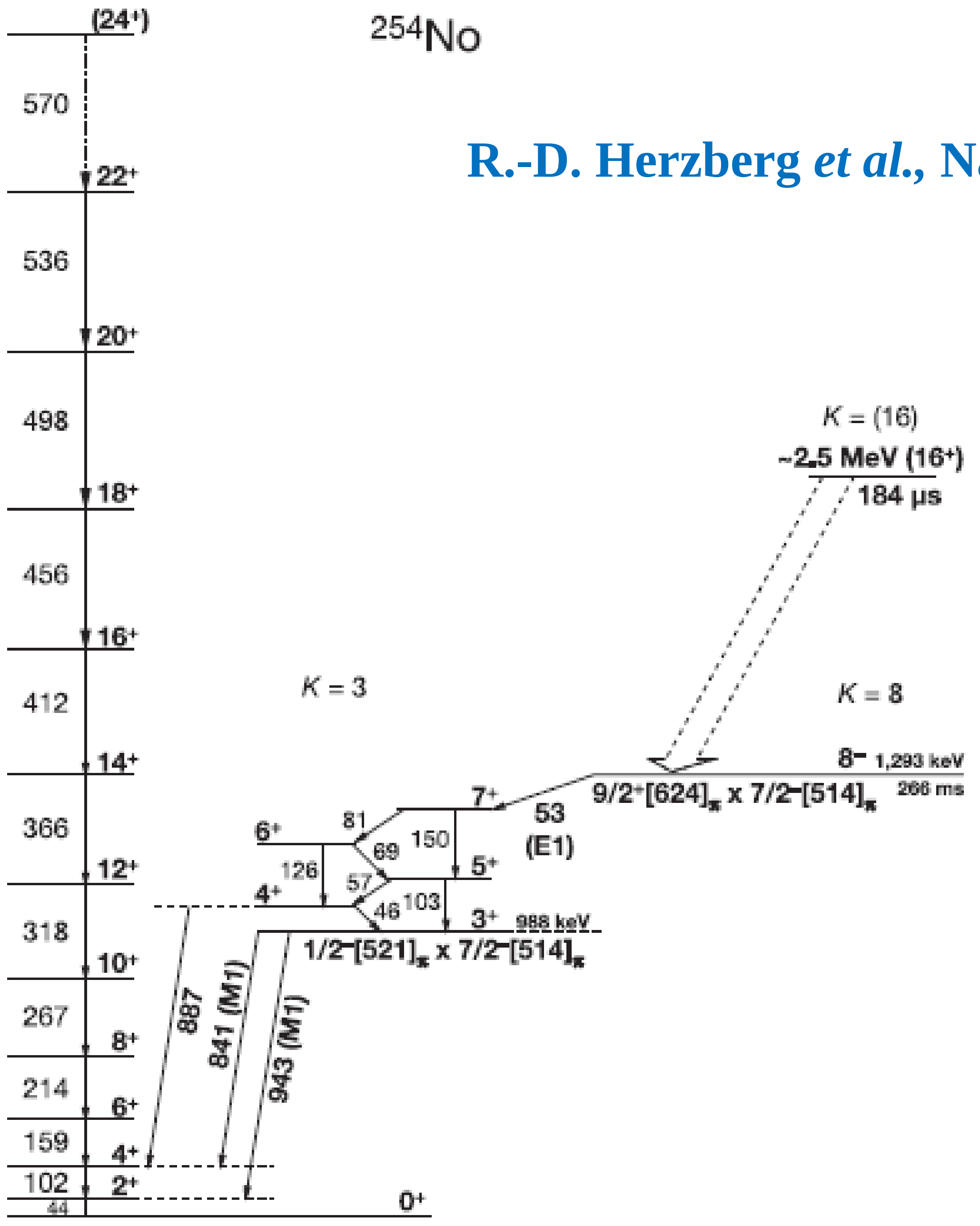
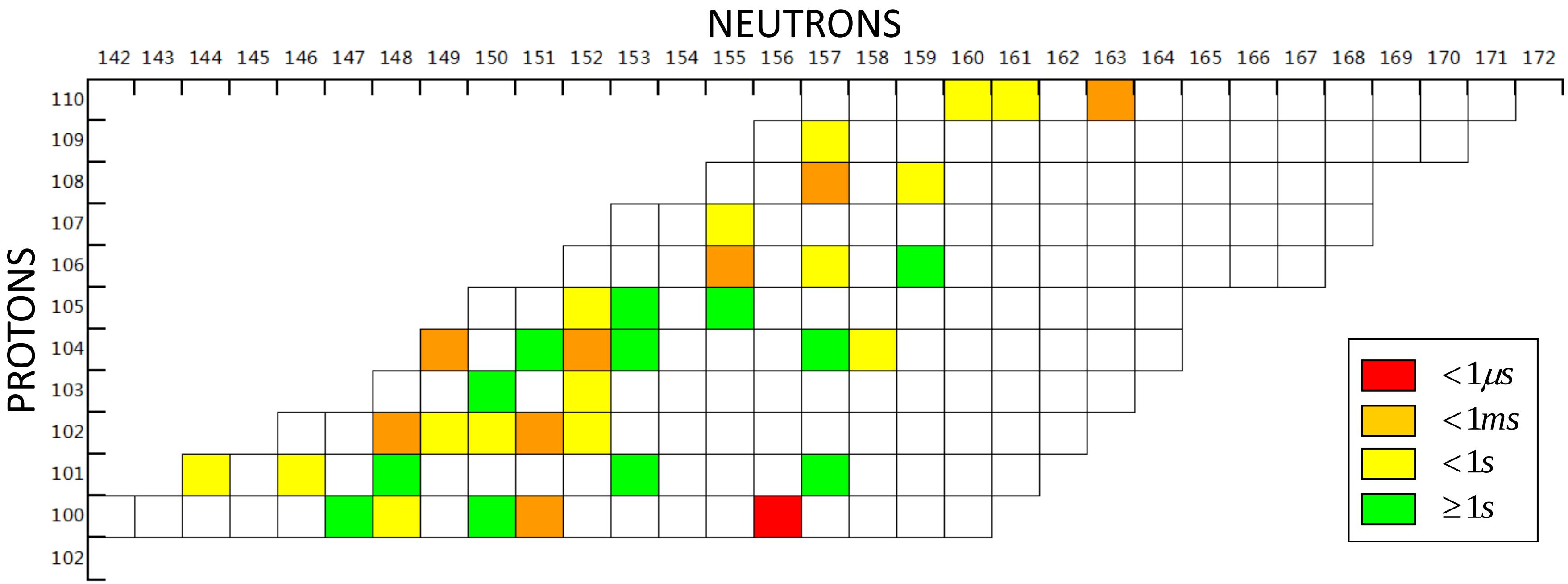


Figure 3 | Proposed level scheme of ^{254}No. The 266 ms 8^- isomer is



Z=100~110

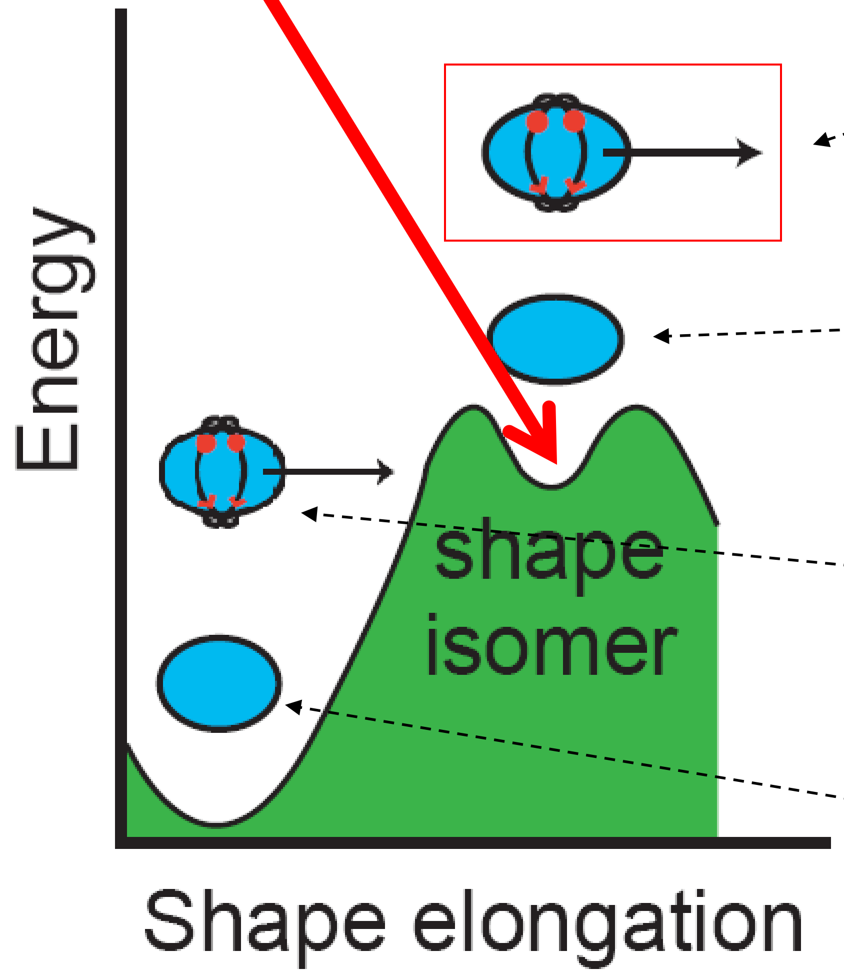
Collection of experimentally observed yet isomers in SHE

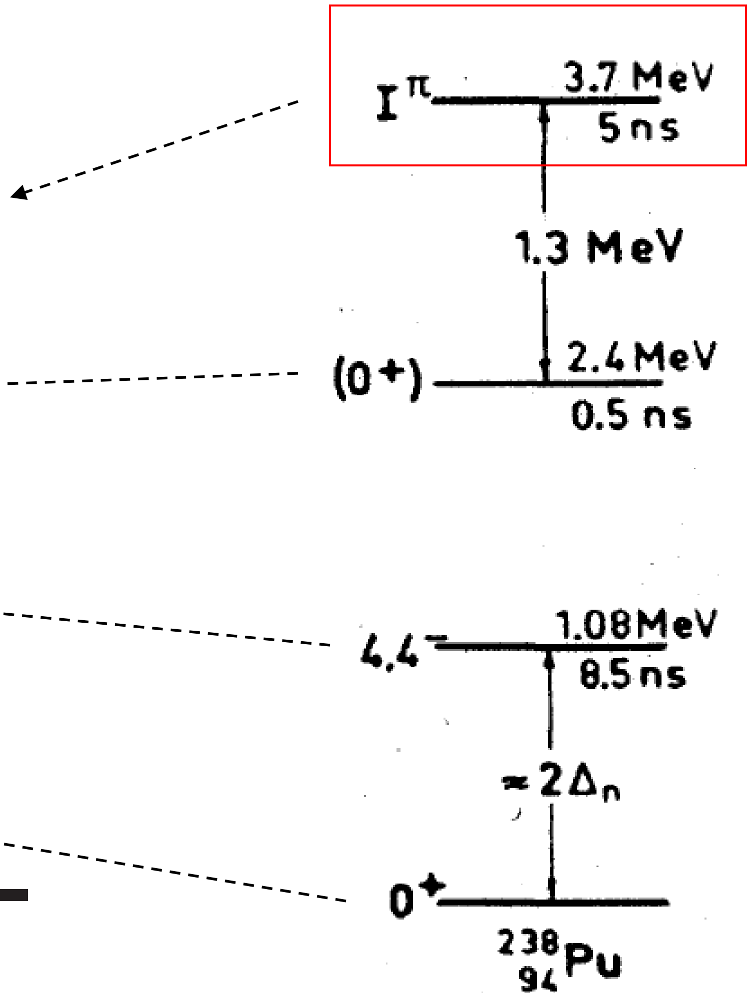
3. High-K fission isomers in actinides

Deformation space in calculations: β_2, β_3, β_4, β_5

Shape isomerism + K isomerism

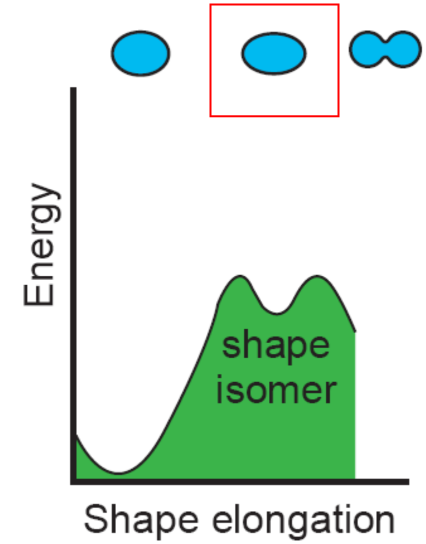
High-K in the 2nd well

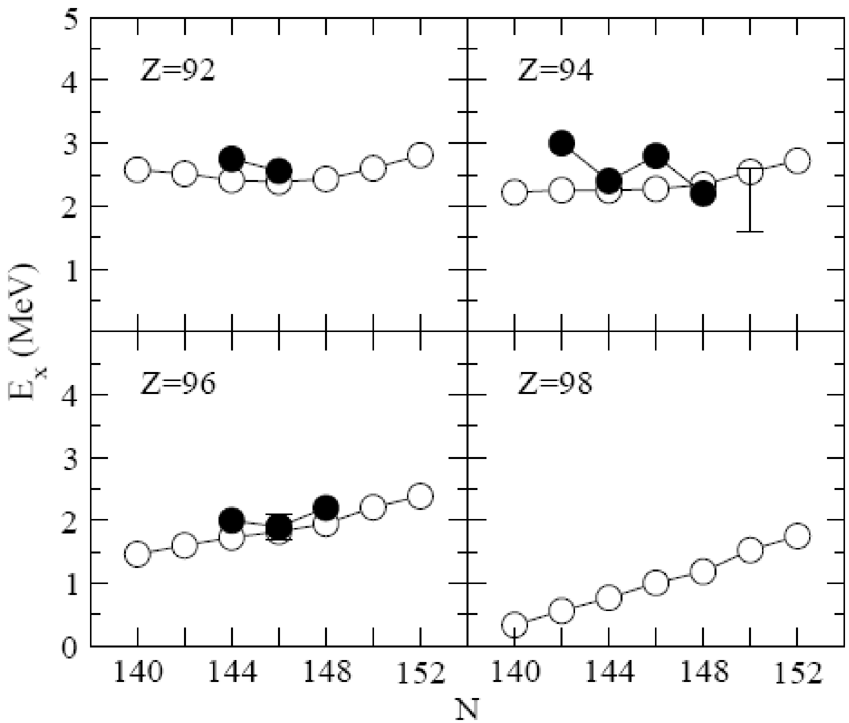


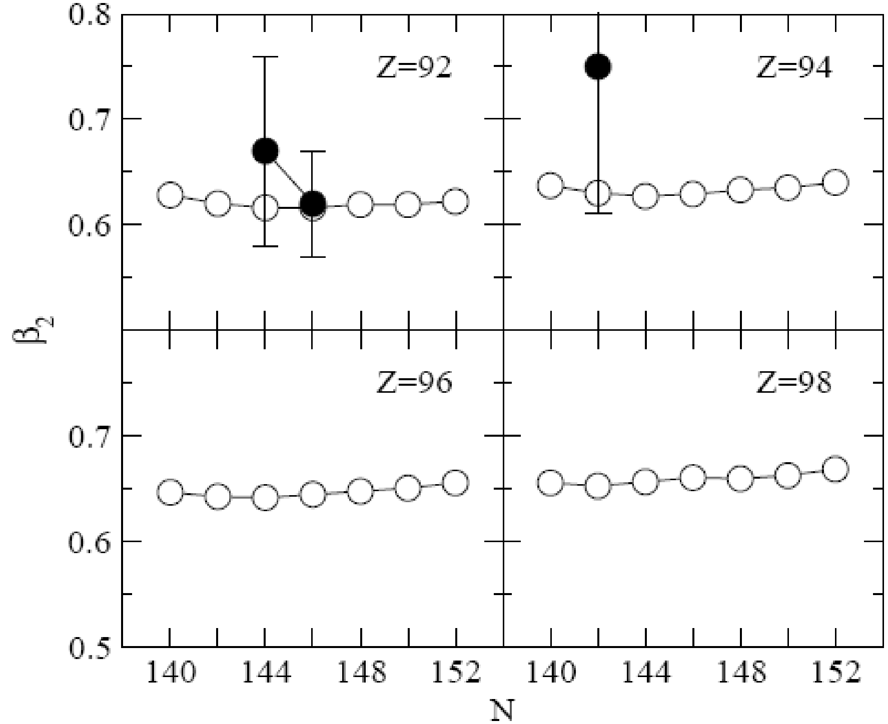


P. Limkilde & G. Sletten
Nucl. Phys. A 199(1973)504

Shape isomers in the 2nd well

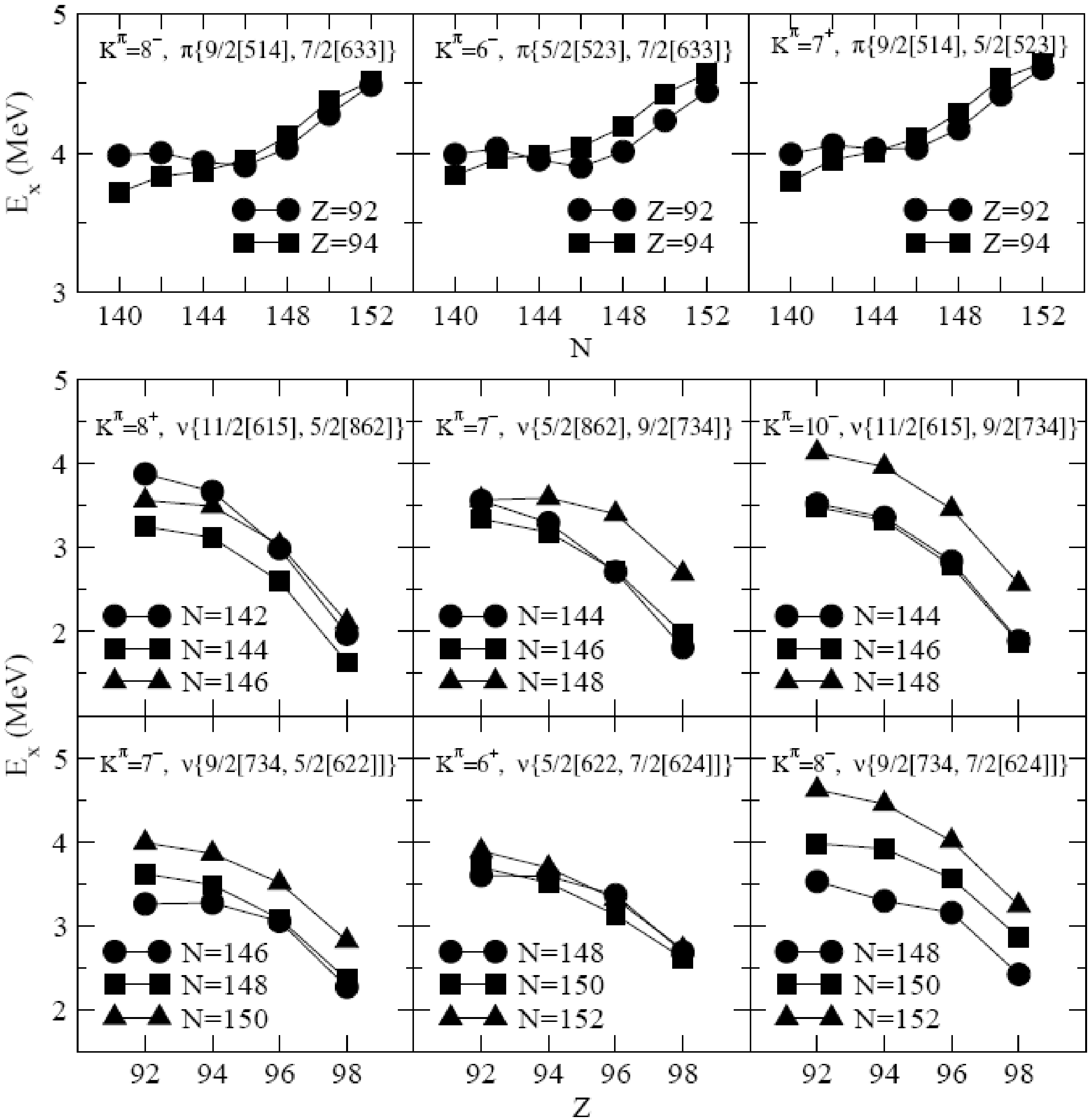


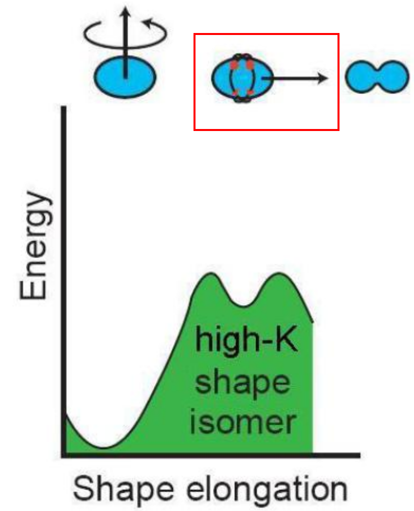




Data from: Singh *et al.*
Nucl. Data Sheets 97 (2002) 241

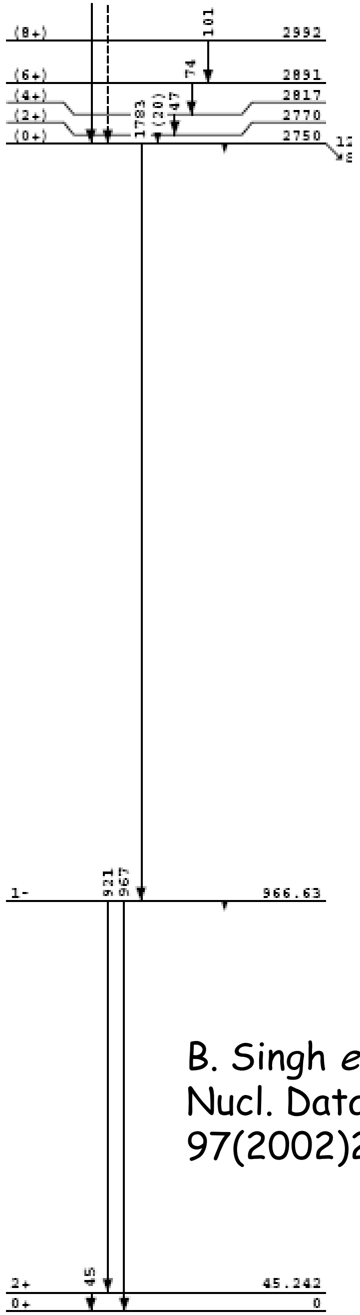
Two-qp high-K shape isomers in the 2nd well





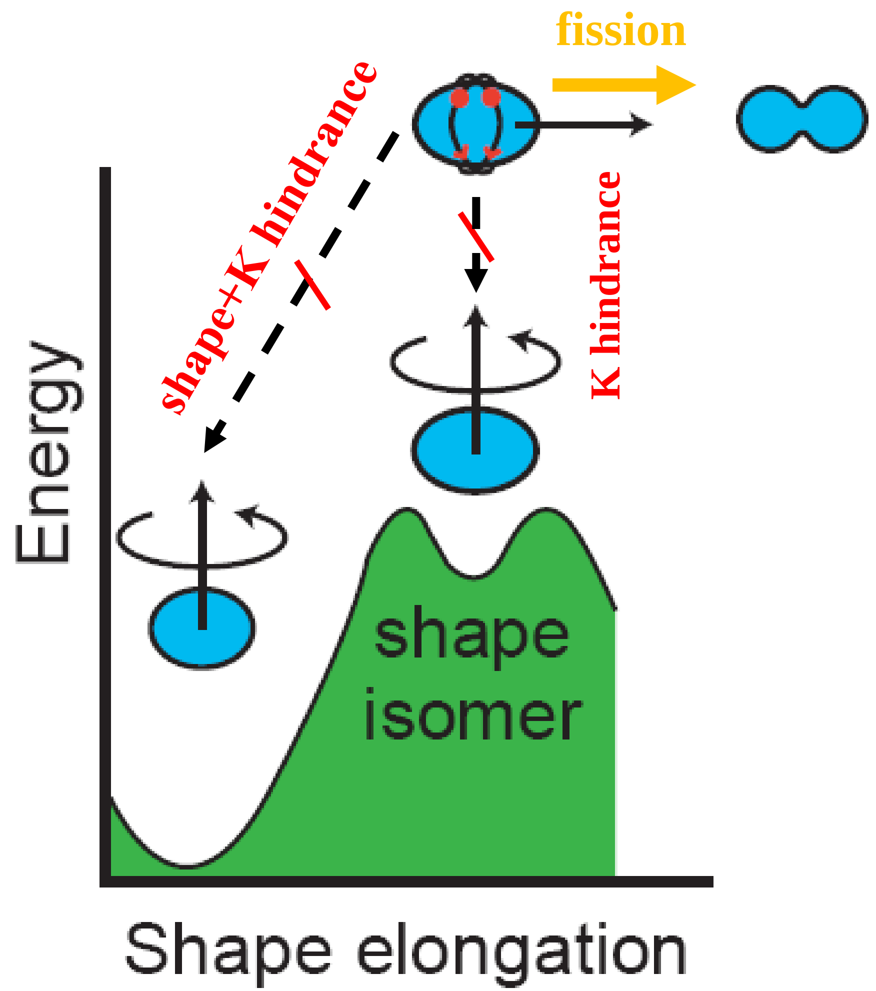
~ 1 MeV higher than the shape isomer

Experimentally, only fission observed, no γ transition observed



$^{236}_{92}U_{144}$

B. Singh *et al.*
Nucl. Data Sheets
97(2002)241



Transuranium region

Odd-odd nuclei

	Longer lived/high spin			Shorter lived/low spin		
	$T_{1/2}$	I^{π}	E_x	$T_{1/2}$	I^{π}	E_x
^{236}Np	115×10^3 y	(6^-)	?	22.5 h	$1^{(-)}$	?
^{244}Am	10.1 h	(6^-)	g.s.	~26 m	1^-	69 KeV
^{248}Bk	>9 y	$(6^+, 8^-)$	?	23.7 h	$1^{(-)}$	?
^{254}Es	275.5 d	(7^+)	g.s.	39.3 h	2^+	78 KeV
^{248}Md	55 d	(8^-)	?	43 m	(1^-)	?

Higher spin -- longer life
Lower spin -- shorter life

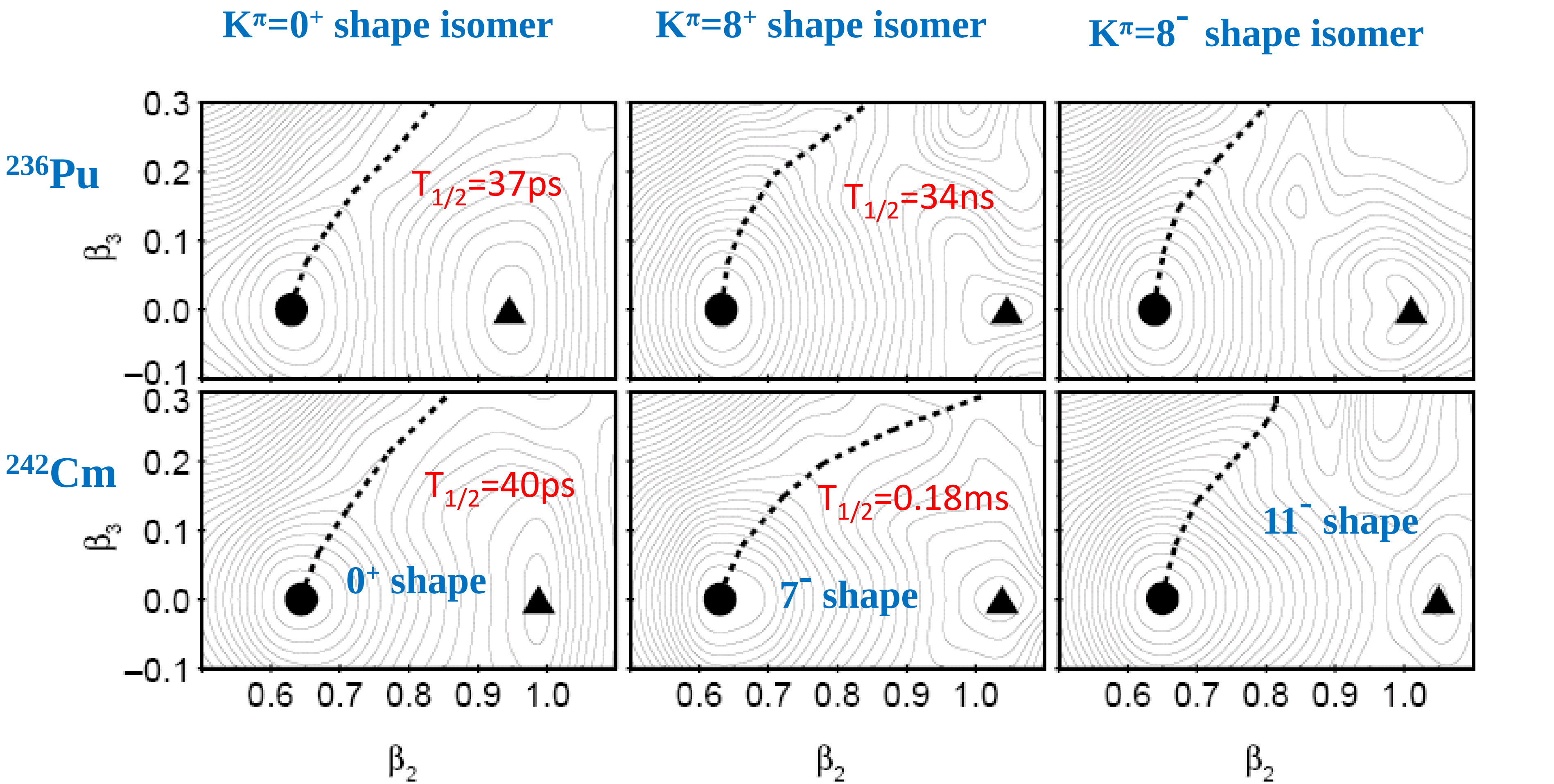


FIG. 4: Representative PESs for the shape isomeric (top left), $K^{\pi} = 8^{+}\{\nu 11/2[615] \otimes 5/2[862]\}$ (top middle) and $K^{\pi} = 8^{-}\{\pi\ 9/2[514] \otimes 7/2[633]\}$ (top right) states of ^{236}Pu as well as shape isomeric (bottom left), $K^{\pi} = 7^{-}\{\nu\ 5/2[862] \otimes 9/2[734]\}$ (bottom middle) and $K^{\pi} = 10^{-}\{\nu 11/2[615] \otimes 9/2[734]\}$ (bottom right) states of ^{242}Cm.

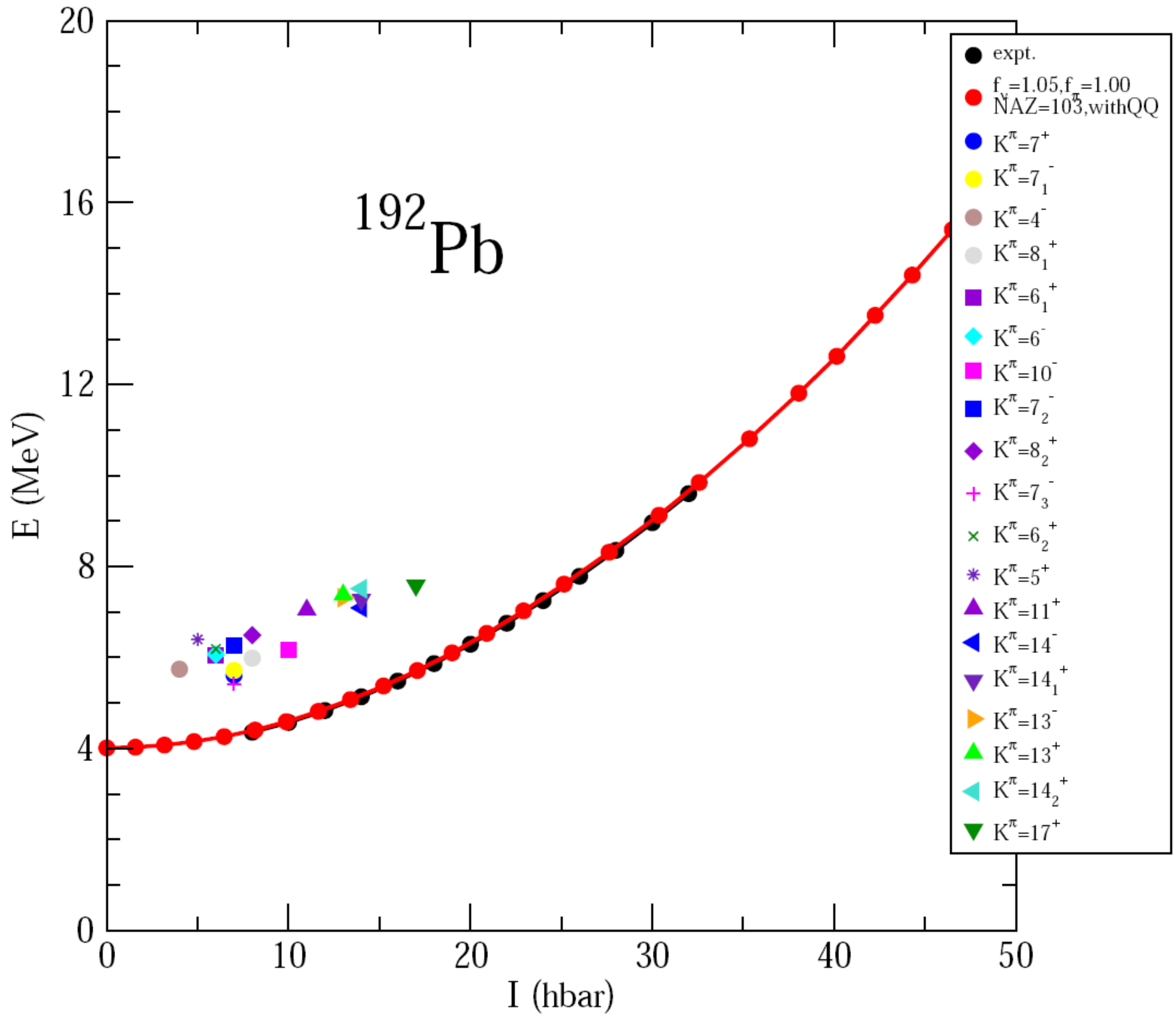
Experimental spins and parities have not been known

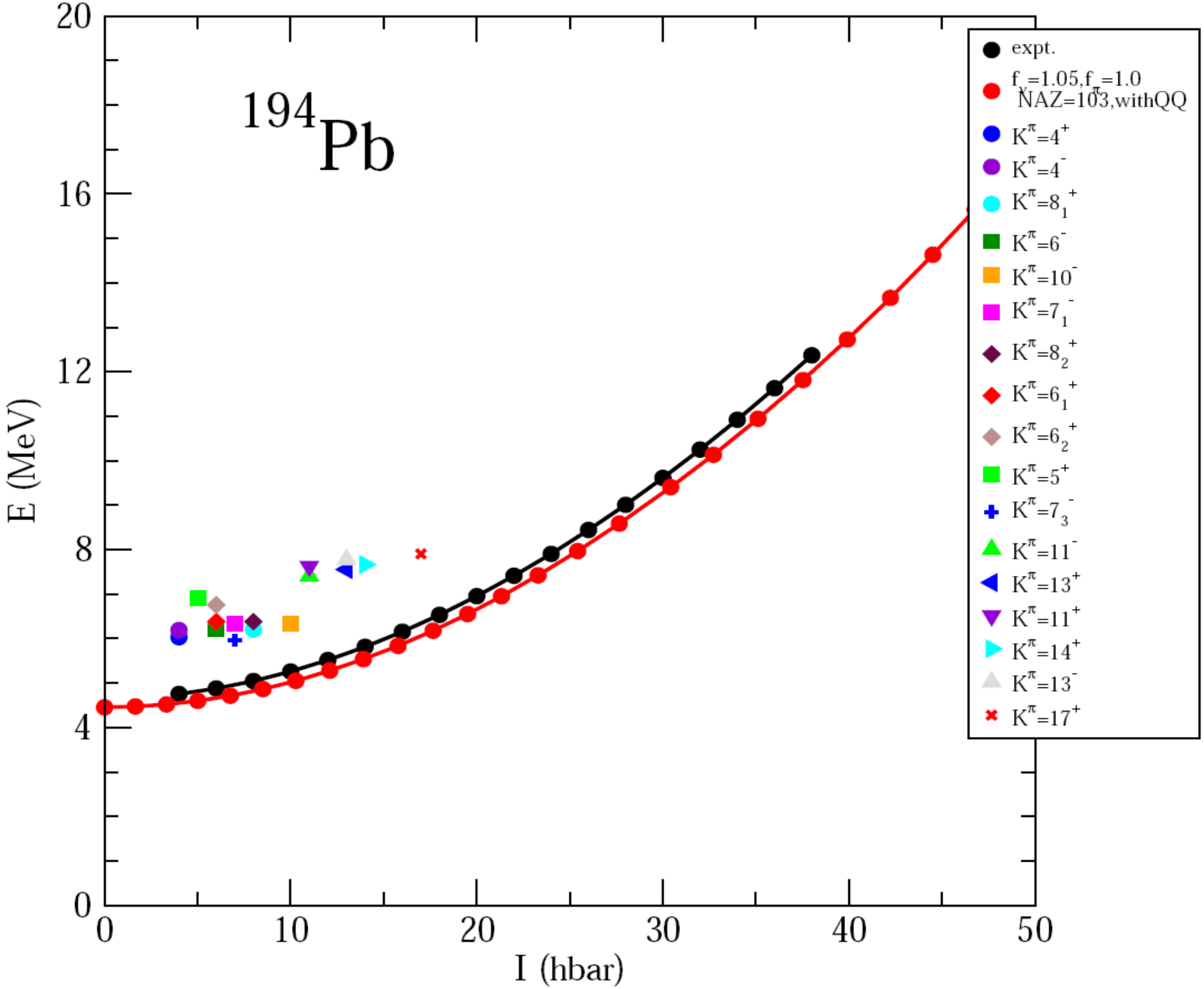
Calculations can predict configurations (spins and parities) and energies.

Longer lifetimes with “shape+K” double isomerism

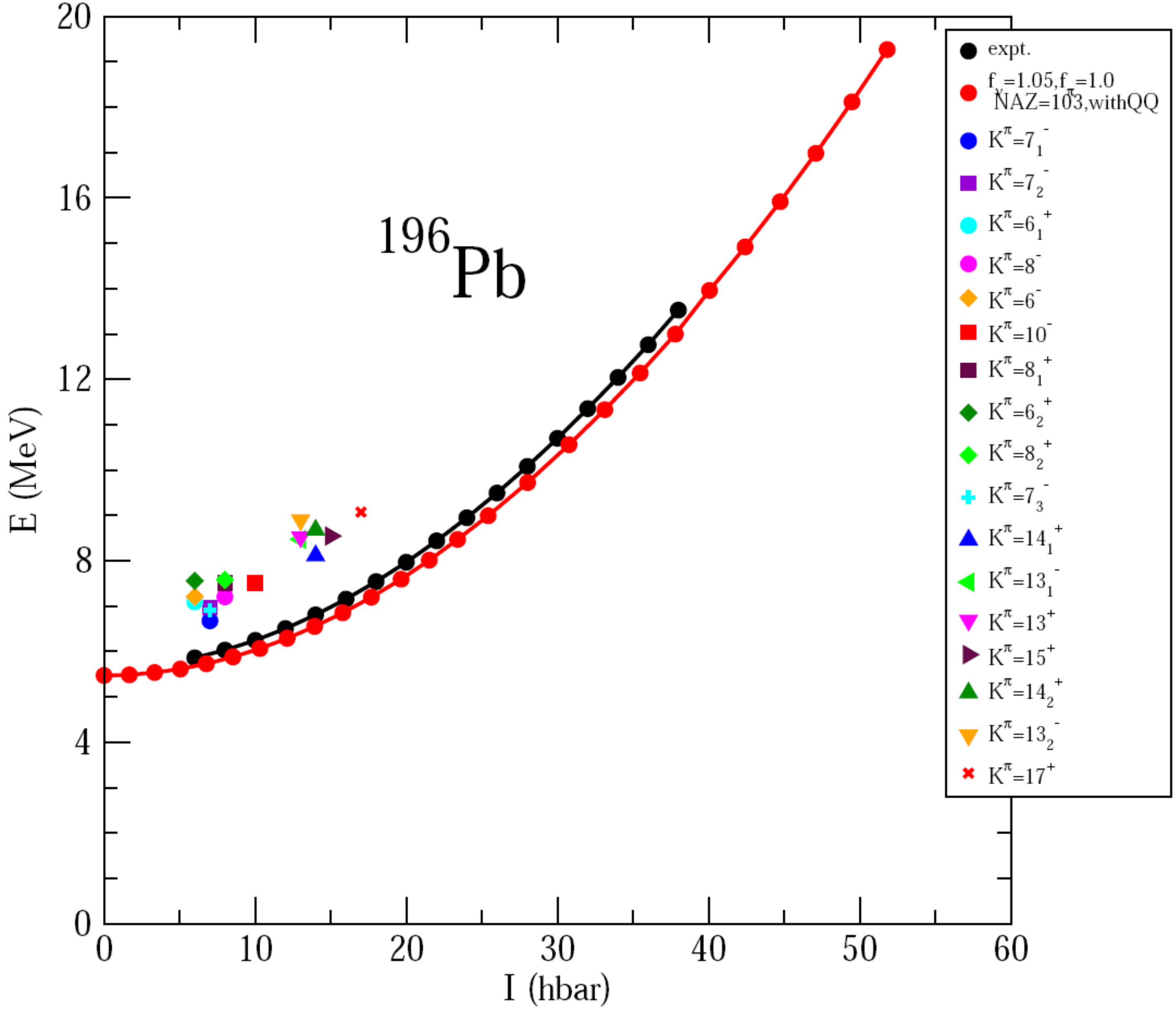
Nuclei	K^π	Configurations	β_2	β_4	Δ_n(keV)	Δ_p(keV)	$E_x^{cal.}$(keV)	$E_x^{expt.}$(keV)	$T_{1/2}$
^{238}U	0^+	Shape Isomer	0.62	0.029	610	840	2383	2557.9	298 ns
	7^-	$\nu\{9/2[734],5/2[622]\}$	0.61	0.022	428	840	3258	< 3558	> 1 ns
	7^-	$\nu\{5/2[862],9/2[734]\}$	0.63	0.037	417	853	3344		
	10^-	$\nu\{11/2[615],9/2[734]\}$	0.62	0.036	423	851	3486		
	8^+	$\nu\{11/2[615],5/2[862]\}$	0.62	0.043	430	852	3563		
	6^-	$\pi\{5/2[523],7/2[633]\}$	0.62	0.033	574	630	3899		
	8^-	$\pi\{9/2[514],7/2[633]\}$	0.62	0.037	573	630	3907		
	7^+	$\pi\{9/2[514],5/2[523]\}$	0.63	0.042	574	638	4032		
^{236}Pu	0^+	Shape Isomer	0.63	0.045	600	830	2252	≈ 3000	37 ps
	8^+	$\nu\{11/2[615],5/2[862]\}$	0.63	0.053	459	841	3671	4000	34 ns
	8^-	$\pi\{9/2[514],7/2[633]\}$	0.64	0.056	596	621	3833		
	7^+	$\pi\{9/2[514],5/2[523]\}$	0.64	0.060	596	627	3951		
	6^-	$\pi\{5/2[523],7/2[633]\}$	0.64	0.055	597	628	3958		
^{238}Pu	0^+	Shape Isomer	0.63	0.038	610	830	2249	≈ 2400	0.6 ns
	8^+	$\nu\{11/2[615],5/2[862]\}$	0.62	0.048	425	839	3120	≈ 3500	6.0 ns
	7^-	$\nu\{5/2[862],9/2[734]\}$	0.64	0.042	528	833	3299		
	10^-	$\nu\{11/2[615],9/2[734]\}$	0.62	0.034	448	831	3363		
	8^-	$\pi\{9/2[514],7/2[633]\}$	0.64	0.048	584	620	3868		
	6^-	$\pi\{5/2[523],7/2[633]\}$	0.64	0.045	582	626	3982		
	7^+	$\pi\{9/2[514],5/2[523]\}$	0.64	0.051	586	627	4010		
^{242}Pu	0^+	Shape Isomer	0.63	0.016	570	820	2341	≈ 2200	3.5 ns
	8^-	$\nu\{9/2[734],7/2[624]\}$	0.62	0.013	420	813	3473	< 3200	28 ns
	7^-	$\nu\{9/2[734],5/2[622]\}$	0.63	0.026	417	826	3484		
	6^+	$\nu\{5/2[622],7/2[624]\}$	0.62	0.013	427	812	3587		
	7^-	$\nu\{5/2[862],9/2[734]\}$	0.61	0.025	427	823	3595		
	10^-	$\nu\{11/2[615],9/2[734]\}$	0.65	0.037	453	831	3966		
	8^-	$\pi\{9/2[514],7/2[633]\}$	0.64	0.033	579	618	4120		
	6^-	$\pi\{5/2[523],7/2[633]\}$	0.64	0.027	576	621	4188		
	7^+	$\pi\{9/2[514],5/2[523]\}$	0.65	0.036	583	626	4288		
^{240}Cm	0^+	Shape Isomer	0.64	0.036	630	790	1729	≈ 2000	10 ps
	8^+	$\nu\{11/2[615],5/2[862]\}$	0.64	0.046	423	801	2602	≈ 3000	55 ns
	7^-	$\nu\{5/2[862],9/2[734]\}$	0.64	0.042	524	797	2714		
	10^-	$\nu\{11/2[615],9/2[734]\}$	0.64	0.032	445	791	2841		
^{242}Cm	0^+	Shape Isomer	0.64	0.025	630	780	1822	1900	40 ps
	7^-	$\nu\{5/2[862],9/2[734]\}$	0.64	0.035	418	794	2728	≈ 2800	0.18 ms
	10^-	$\nu\{11/2[615],9/2[734]\}$	0.65	0.030	421	787	2786		
	8^+	$\nu\{11/2[615],5/2[862]\}$	0.64	0.038	431	794	3034		
	7^-	$\nu\{9/2[734],5/2[622]\}$	0.61	0.024	426	797	3049		
^{244}Cm	0^+	Shape Isomer	0.65	0.016	570	770	1947	≈ 2200	< 5 ps
	7^-	$\nu\{9/2[734],5/2[622]\}$	0.64	0.025	419	786	3082	≈ 3500	> 100 ns
	8^-	$\nu\{9/2[734],7/2[624]\}$	0.64	0.013	419	778	3153		
	6^+	$\nu\{5/2[622],7/2[624]\}$	0.62	0.015	426	784	3364		
	7^-	$\nu\{5/2[862],9/2[734]\}$	0.62	0.026	430	797	3404		
	10^-	$\nu\{11/2[615],9/2[734]\}$	0.66	0.034	453	789	3462		

4. Prediction of high-K states in superdeformation





^{194}Pb
E (MeV)
I (hbar)
expt.
f_ν=1.05,f_π=1.0
NAZ=103,withQQ
$K^\pi=4^+$
$K^\pi=4^-$
$K^\pi=8_1^+$
$K^\pi=6^-$
$K^\pi=10^-$
$K^\pi=7_1^-$
$K^\pi=8_2^+$
$K^\pi=6_1^+$
$K^\pi=6_2^+$
$K^\pi=5^+$
$K^\pi=7_3^-$
$K^\pi=11^-$
$K^\pi=13^+$
$K^\pi=11^+$
$K^\pi=14^+$
$K^\pi=13^-$
$K^\pi=17^+$



^{196}Pb
E (MeV)
I (hbar)
expt.
f_ν=1.05,f_π=1.0
NAZ=103,withQQ
$K^\pi=7_1^-$
$K^\pi=7_2^-$
$K^\pi=6_1^+$
$K^\pi=8^-$
$K^\pi=6^-$
$K^\pi=10^-$
$K^\pi=8_1^+$
$K^\pi=6_2^+$
$K^\pi=8_2^+$
$K^\pi=7_3^-$
$K^\pi=14_1^+$
$K^\pi=13_1^-$
$K^\pi=13^+$
$K^\pi=15^+$
$K^\pi=14_2^+$
$K^\pi=13_2^-$
$K^\pi=17^+$

Summary

High-K isomers increase the stability of unstable nuclei,

and hence extend the landscape of nuclei.

1. **Along drip lines;**
2. **In superheavy;**
3. **Fission from the second well in actinides**
4. **In superdeformation in A~190.**

Collaborators:

R. Wyss (KTH, Sweden)

P. Walker (Univ. Surrey, UK)

H.L. Liu (Texas A&M-Commerce)

Y. Shi, Y. Gao… (Peking Univ.)

Thank you

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