Aspects of nuclear isomerism and shape coexistence

- historical introduction
- energy storage
- enhanced stability
- high-K isomers
- neutron-rich A≈190 isomers

Phil Walker

UNIVERSITY OF SURREY

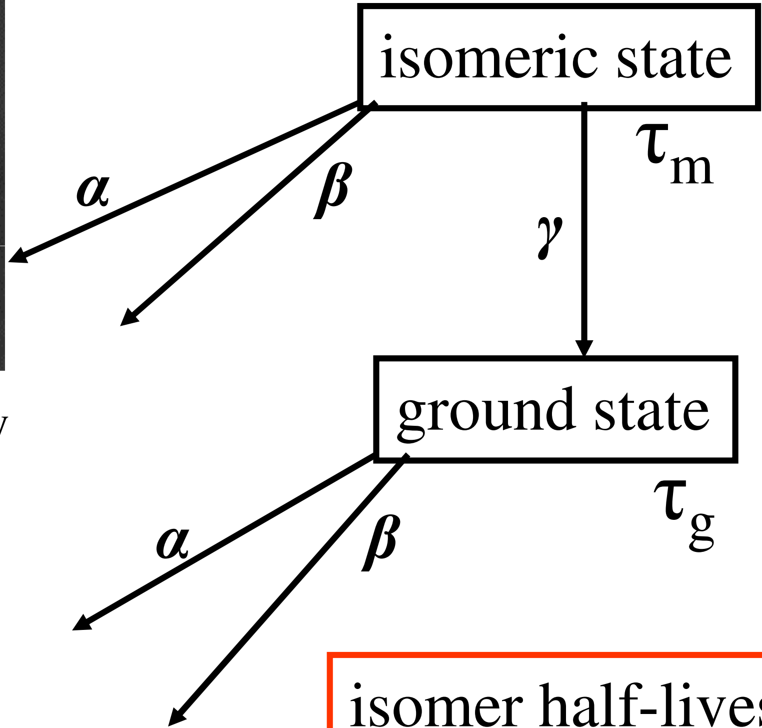
Isomer prediction: *Soddy, Nature 99 (1917) 433*

"We can have isotopes with identity of atomic weight, as well as of chemical character, which are different in their stability and mode of breaking up."

101 years

explanation:
von Weizsäcker, Naturwissenshaften 24 (1936) 813

Frederick Soddy



isomer half-lives range from 10^{-9} seconds to $>10^{16}$ years

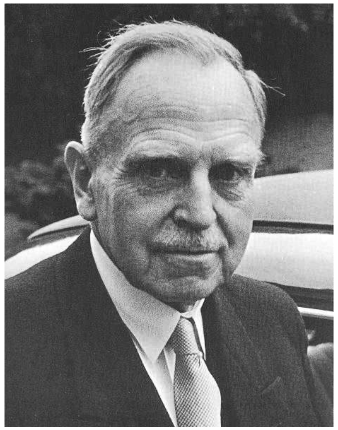
importance of spin

spin doctor at age 24

Carl von Weizsäcker

Historical background: isomers

1917: Soddy predicts existence of isomers
1921: Hahn observations: UZ, UX_2 (^{234}Pa, 7 h; ^{234m}Pa, 1 m)
1935: Kurtchatov observes bromine isomers
1936: von Weizsäcker explains isomers as spin traps
1938: Hahn identifies barium from neutrons on uranium
1939: Meitner and Frisch explain Hahn's discovery: fission
1955: Alaga et al. explain K isomers
1962: Polikanov discovers fission isomers (^{242m}Am, 14 ms)



Otto Hahn
discoverer of isomers and fission

"The whole 'fission' process can thus be described in an essentially classical way ..."
"… it might not be necessary to assume nuclear isomerism".

***Meitner** and Frisch,*
Nature 3615 (Feb 1939) 239

Lise Meitner
"mother of nuclear structure"

1913: Fajans and Göhring observe UX_2 (^{234m}Pa, 1 m activity)

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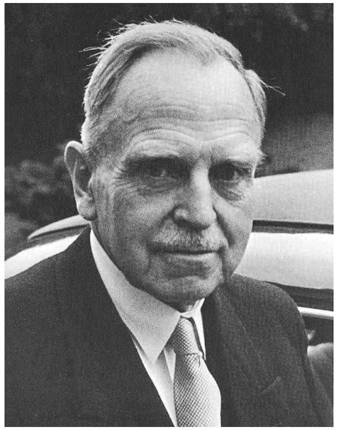

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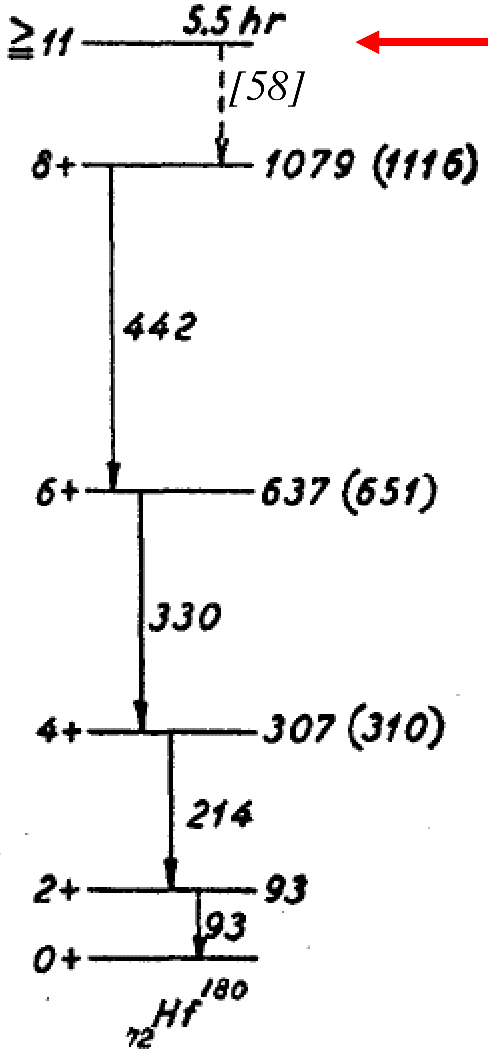
^{180}Hf isomer decay: nuclear collective rotation



$K^{\pi} = I^{\pi} = 8^{-}$: broken-pair excitation
K quantum number not yet recognised

$E(I) = (\hbar^2/2\Im)\ I(I+1)$

$\Im \sim 1/3\ \Im_{rigid}$ => superfluidity

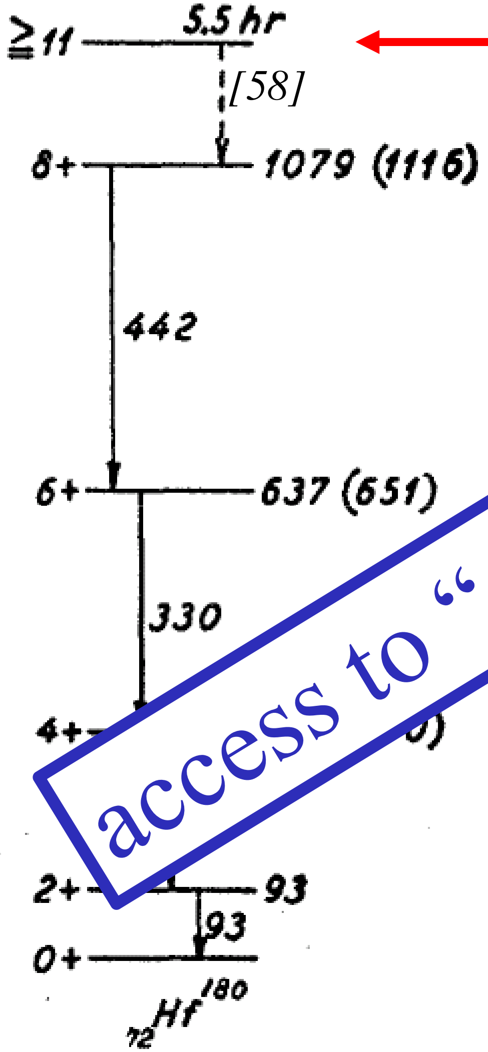
^{180}Hf: $E(4^+)/E(2^+) = 3.30$

perfect rotor: $E(4^+)/E(2^+) = 3.33$

interplay between individual-particle and collective degrees of freedom

Bohr and Mottelson, Phys. Rev. 90 (1953) 717

^{180}Hf isomer decay: nuclear collective rotation



$K^\pi = I^\pi = 8^-$: brok… r excitation

K quantum nu… …et recognised

access to “exotic” nuclear states

…/2ℑ) I(I+1)

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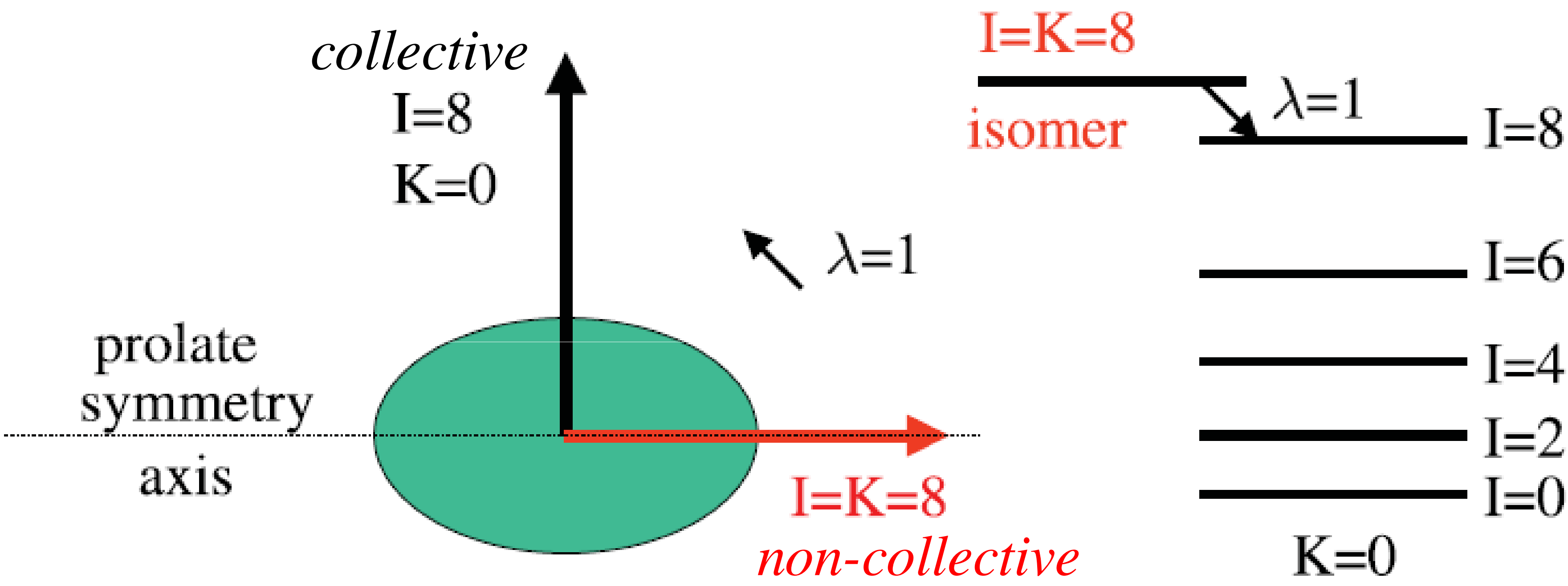
K-forbidden γ-ray transitions



degree of forbiddenness, $\nu = \Delta K - \lambda$

=> λ=1 transition is 7-fold K-forbidden ($\nu = 7$)

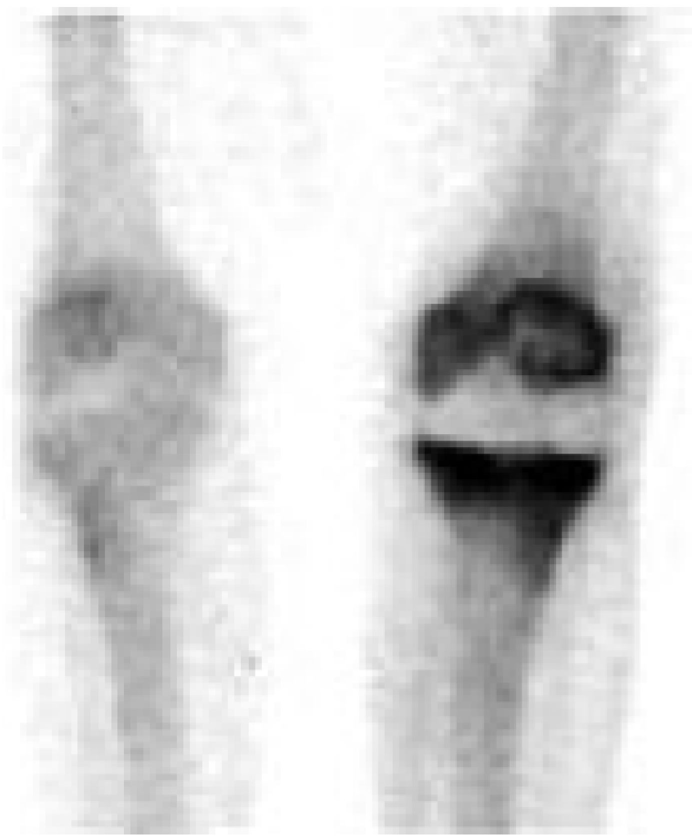
Extreme isomers

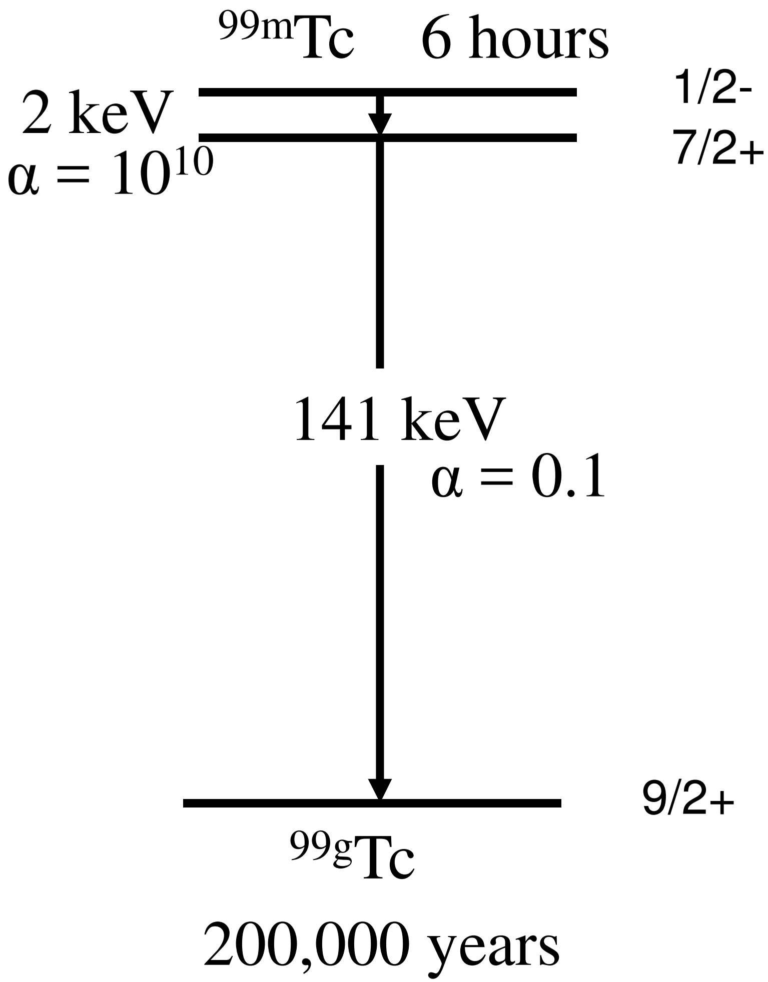
long half-life:	^{180}Ta, 9^-,	75 keV,	>4.5x10^{16} y	PRC 2017
high spin:	^{212}Rn, 38^+,	12.5 MeV*,	8 ns	PLB 2008
high energy:	^{152}Er,	13.4 MeV*,	11 ns	PRC 1992
low energy:	^{229}Th, $3/2^+$,	8 eV,	7 μs	PRL 2017
low mass:	^{12}Be, 0^+,	2.2 MeV,	230 ns	PLB 2010
high mass:	^{270}Ds, 10^-,	1 MeV,	6 ms	EPJA 2001

decay rates vary over at least 32 orders of magnitude

* *unbound to both* p *and* n *emission*

^{99m}Tc: an isomer in the clinic

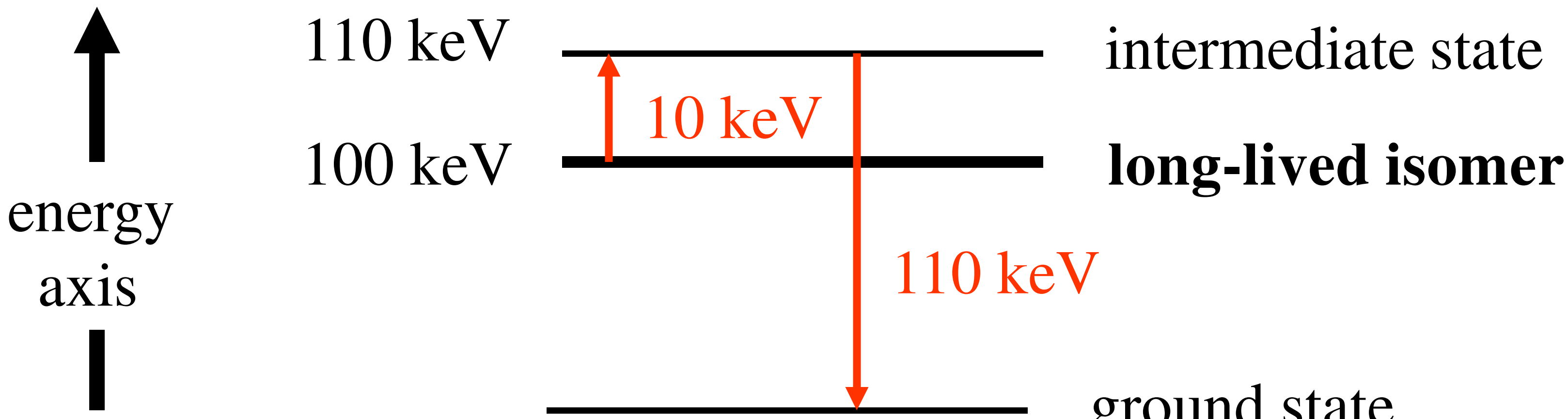




isomers as nuclear “batteries”?

can isomer energy be released in a controlled manner?

conceptual picture:

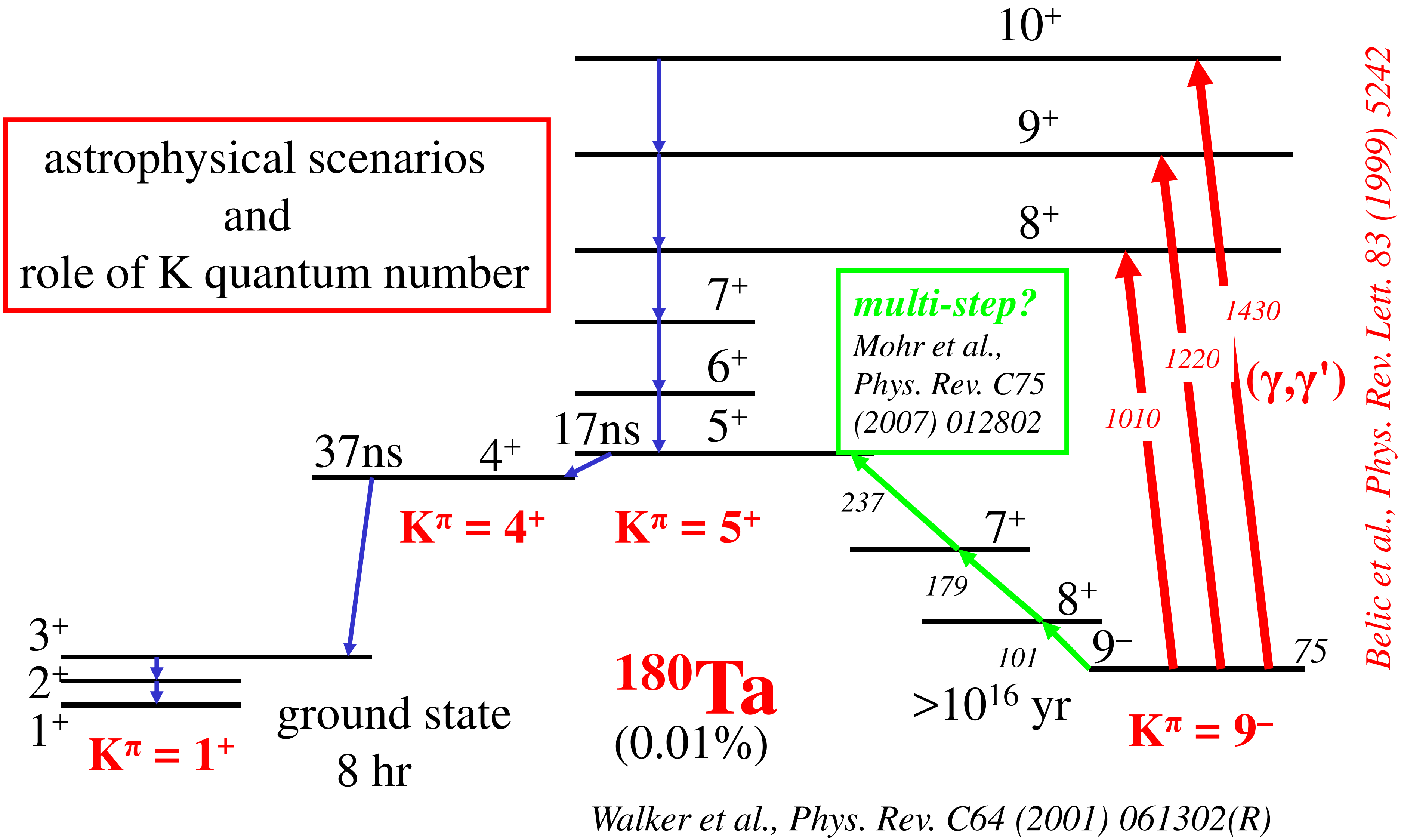


energy release ~100 keV per atom

cf. chemical energy ~ 1 eV per atom

^{180}Ta photoexcitation and decay

nature's only "stable" isomer

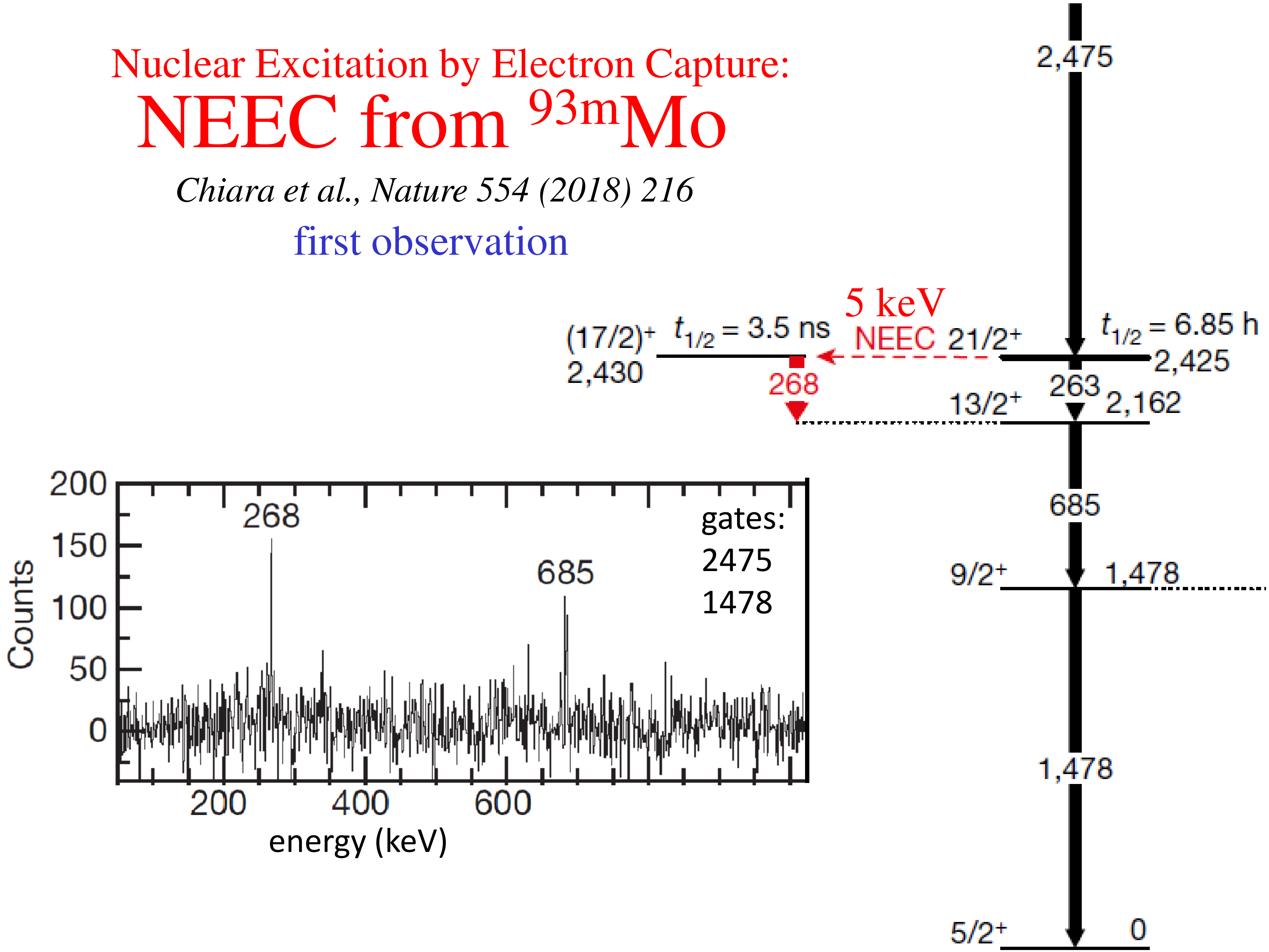


Nuclear Excitation by Electron Capture:

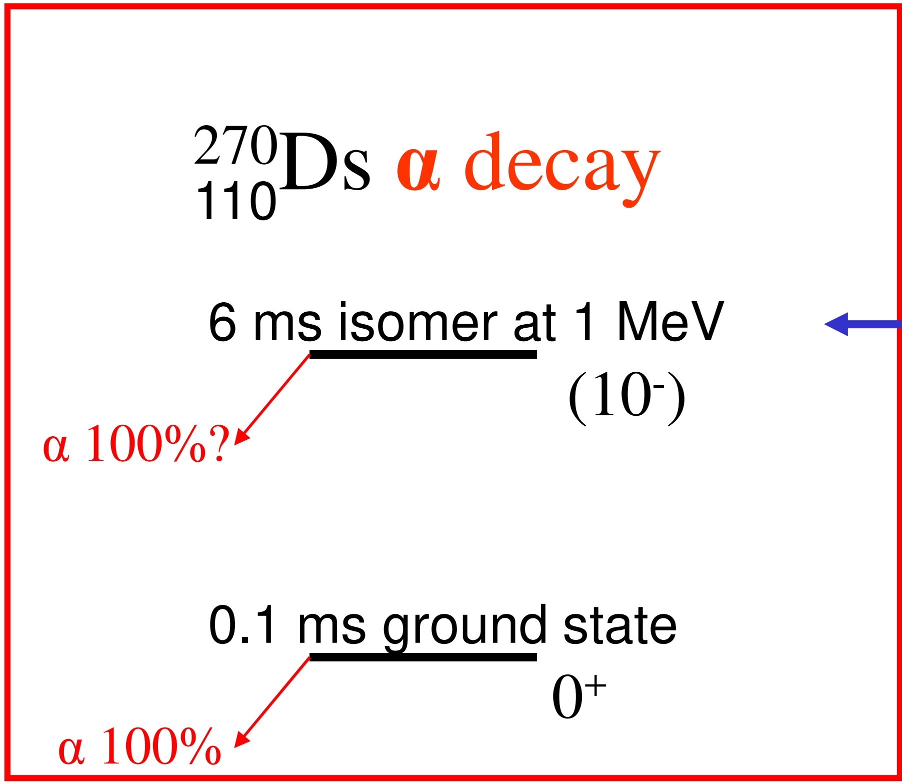
NEEC from ^{93m}Mo

Chiara et al., Nature 554 (2018) 216

first observation



isomers in superheavy nuclei: **α decay**

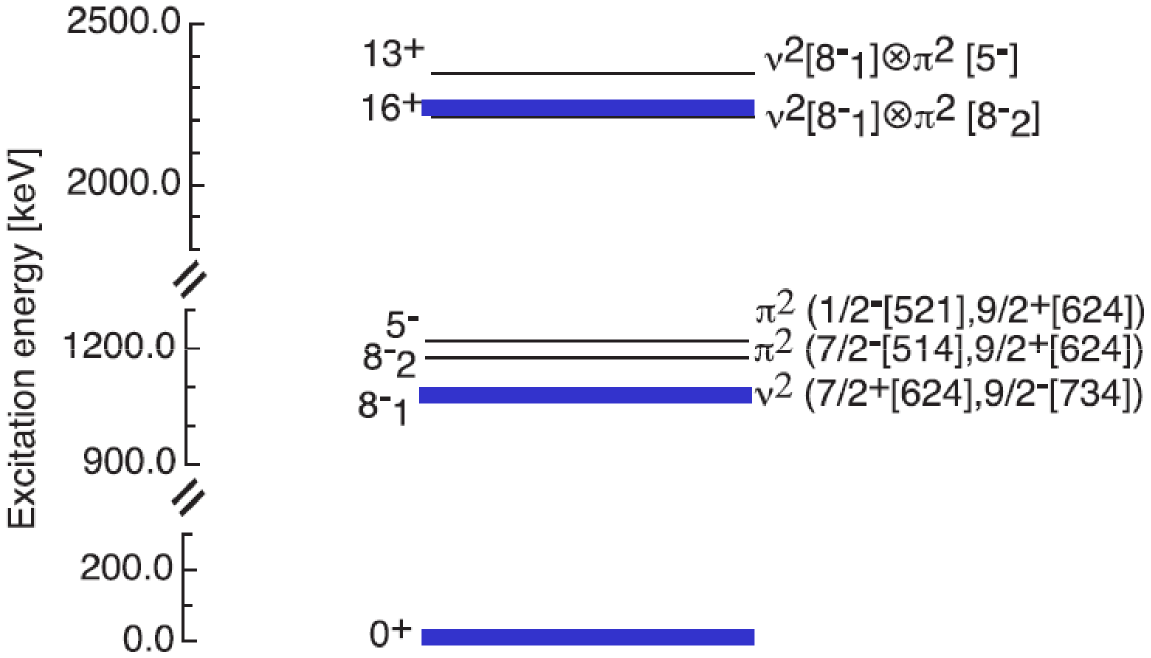


isomers can provide extra stability for superheavy nuclei

Hofmann et al., Eur. Phys. J. 10 (2001) 5
Xu et al., Phys. Rev. Lett. 92 (2004) 252501

isomers in superheavy nuclei: **fission**

$^{254}_{104}$Rf



250 μs (<40% SF)

5 μs (<10% SF)

23 μs (100% SF)

calculation experiment

David et al., Phys. Rev. Lett.115 (2015) 132502

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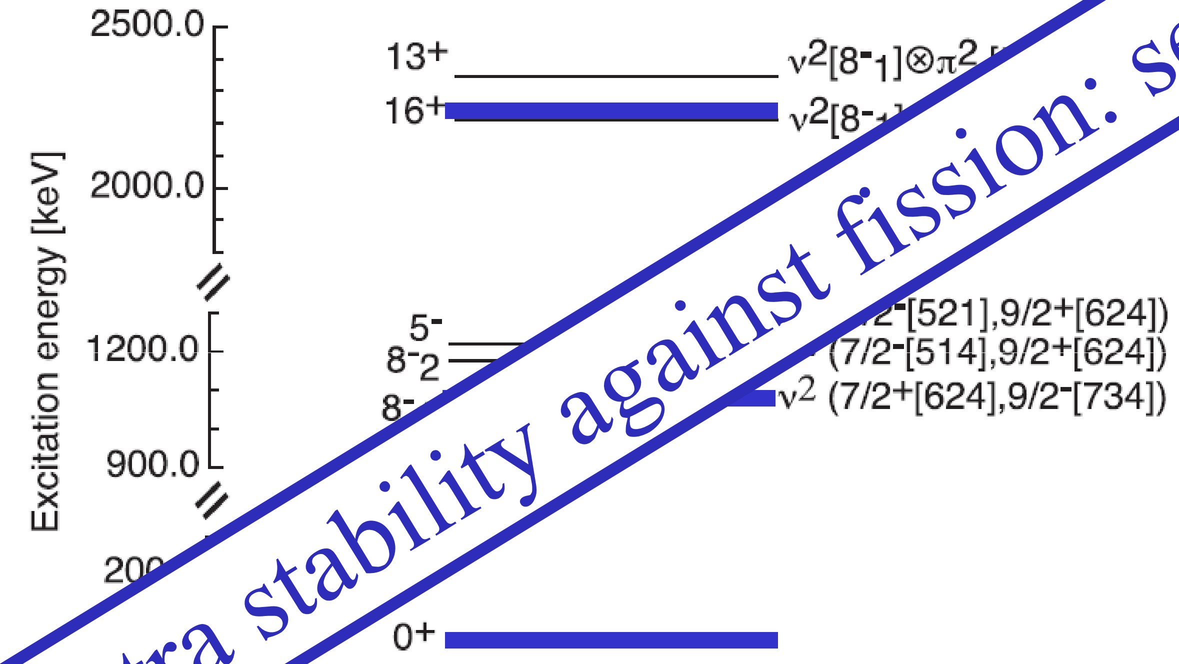


250 μs (<40% SF)

5 μs (<10% SF)

23 μs (100% SF)

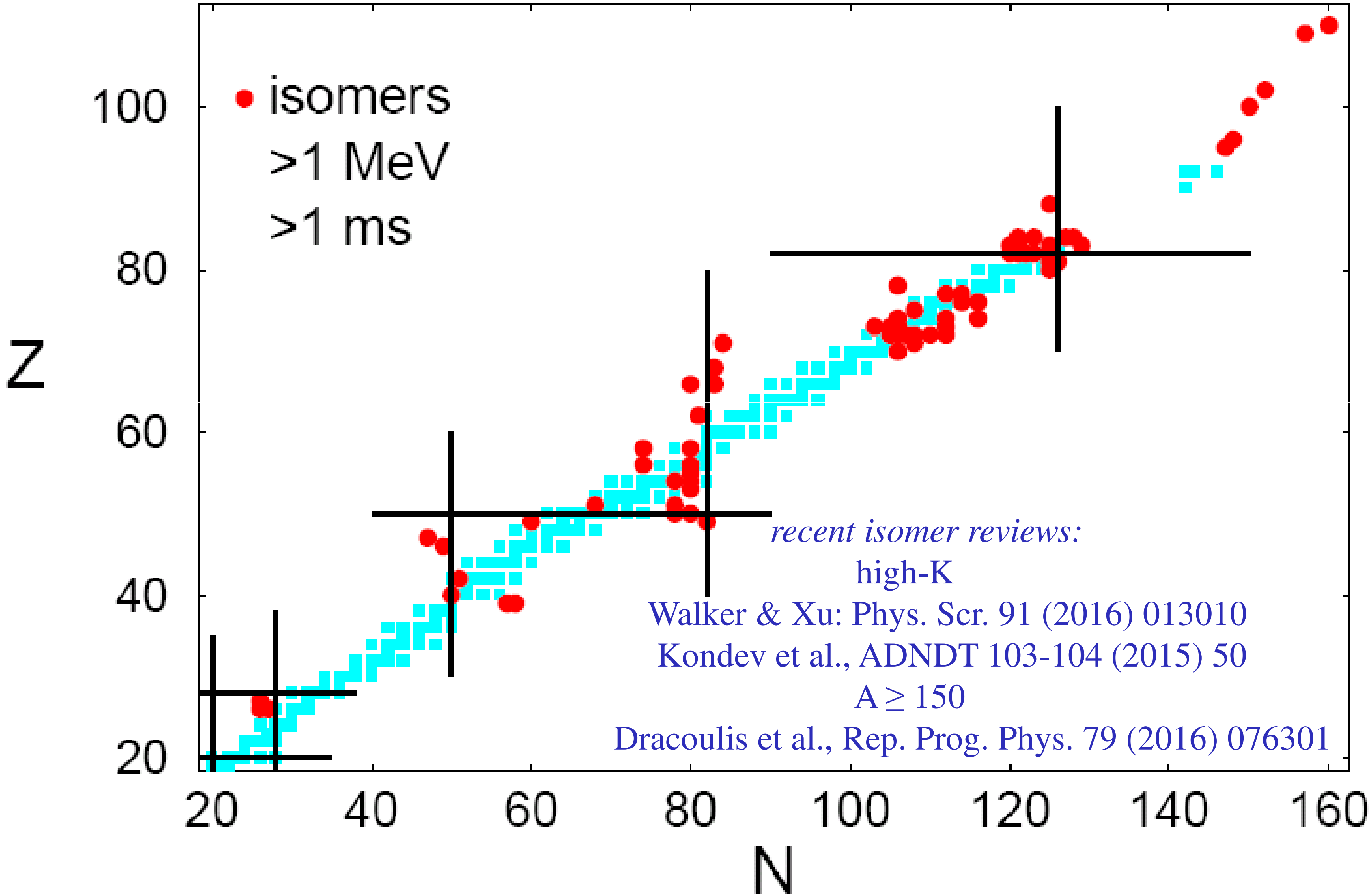
calculation

experiment

extra stability against fission: see also ^{250}No

David et al., Phys. Rev. Lett.115 (2015) 132502

nuclear chart with >1 MeV isomers



recent isomer reviews:

high-K

Walker & Xu: Phys. Scr. 91 (2016) 013010

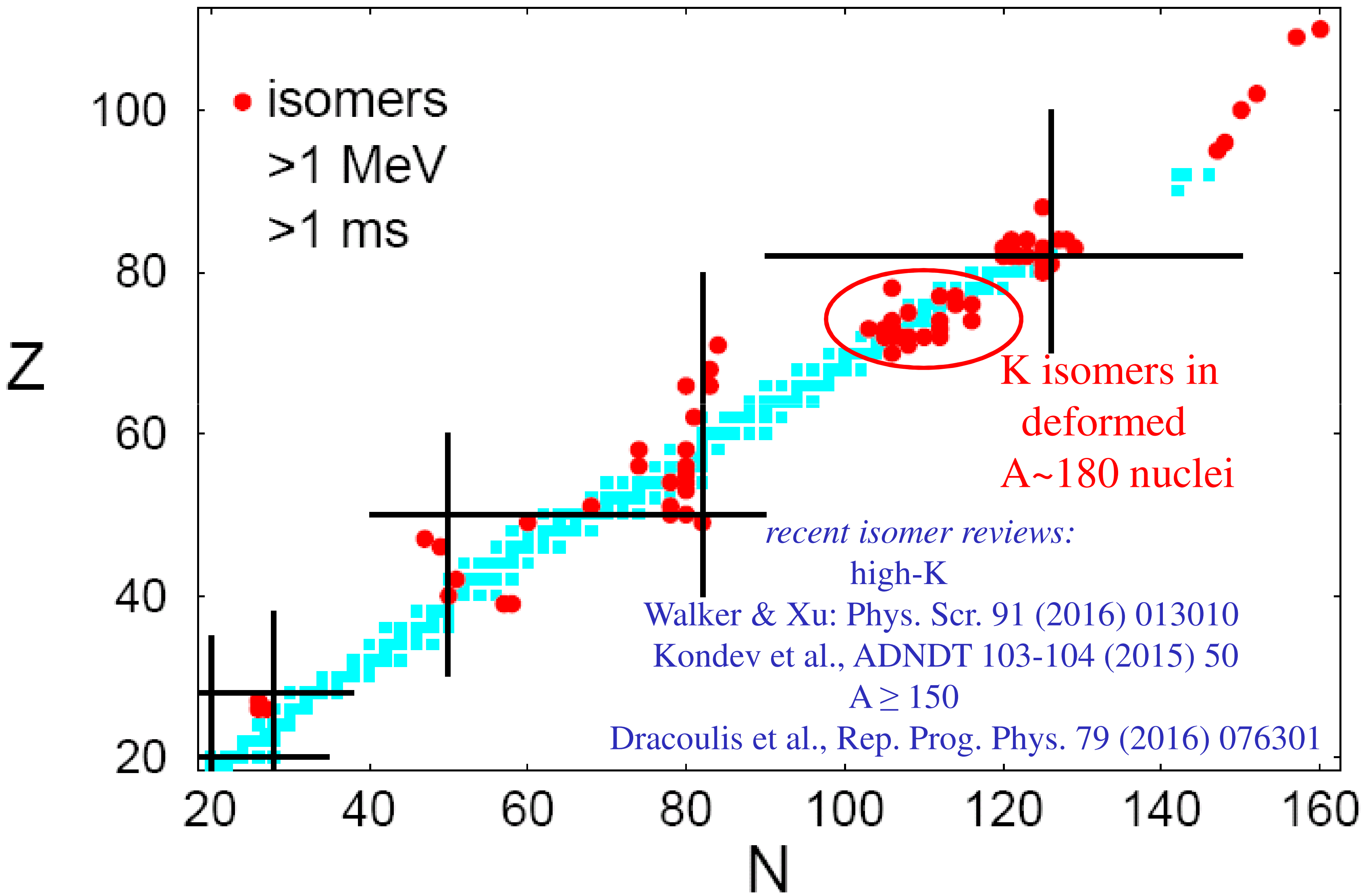
Kondev et al., ADNDT 103-104 (2015) 50

A ≥ 150

Dracoulis et al., Rep. Prog. Phys. 79 (2016) 076301

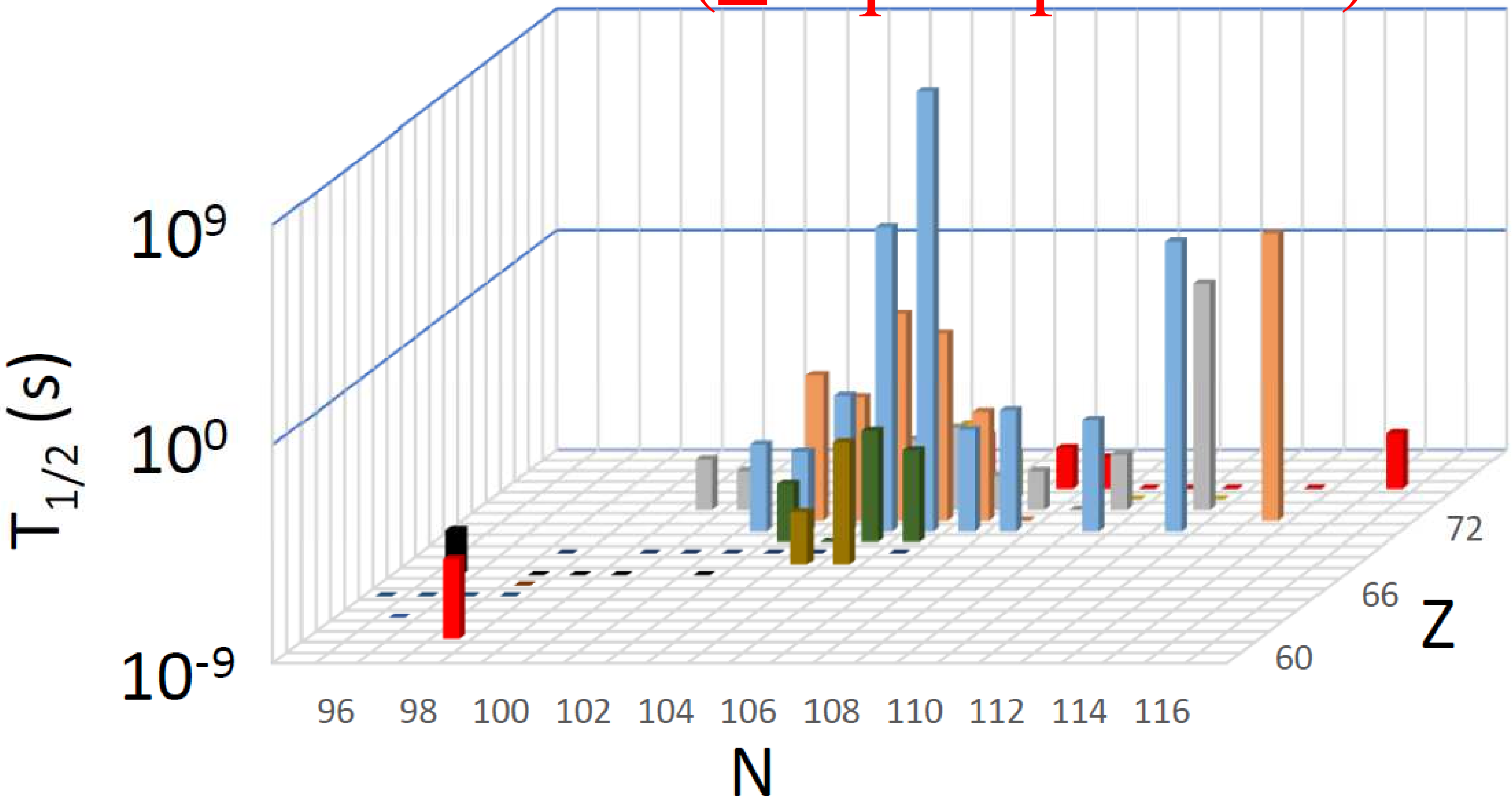
adapted from Walker and Dracoulis, Nature 399 (1999) 35

nuclear chart with >1 MeV isomers



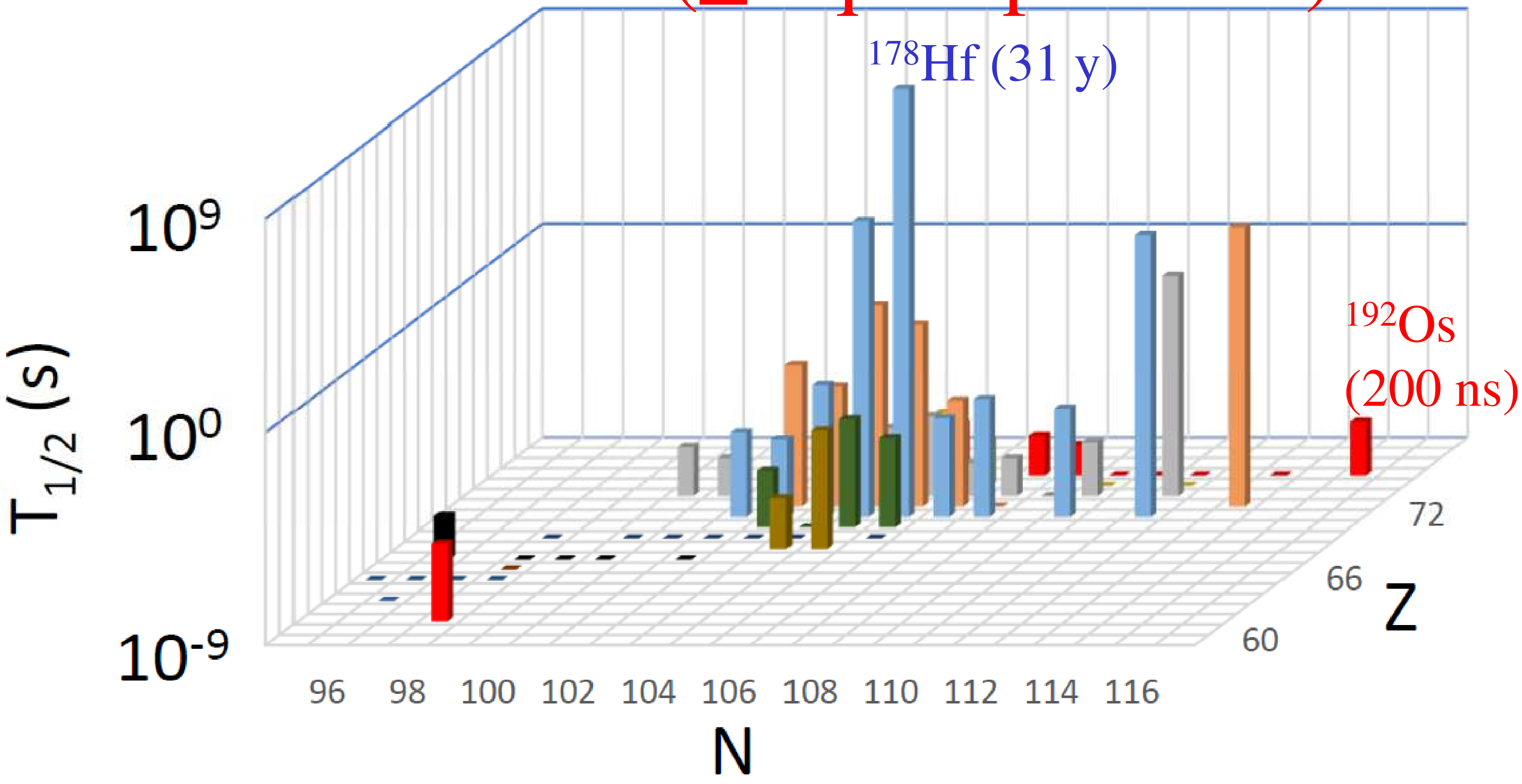
adapted from Walker and Dracoulis, Nature 399 (1999) 35

A~180 isomers with at least 2 broken pairs (≥4 quasiparticles)



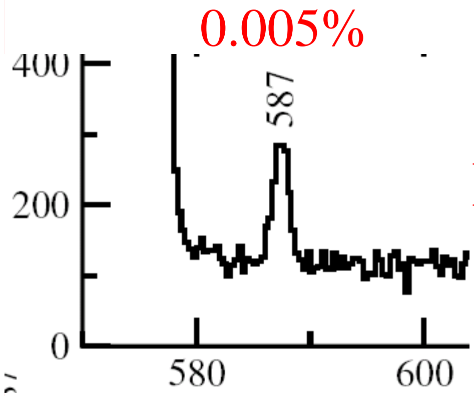
Walker, Prog. Part. Nucl. Phys. to be published

A~180 isomers with at least 2 broken pairs ($\geq$4 quasiparticles)

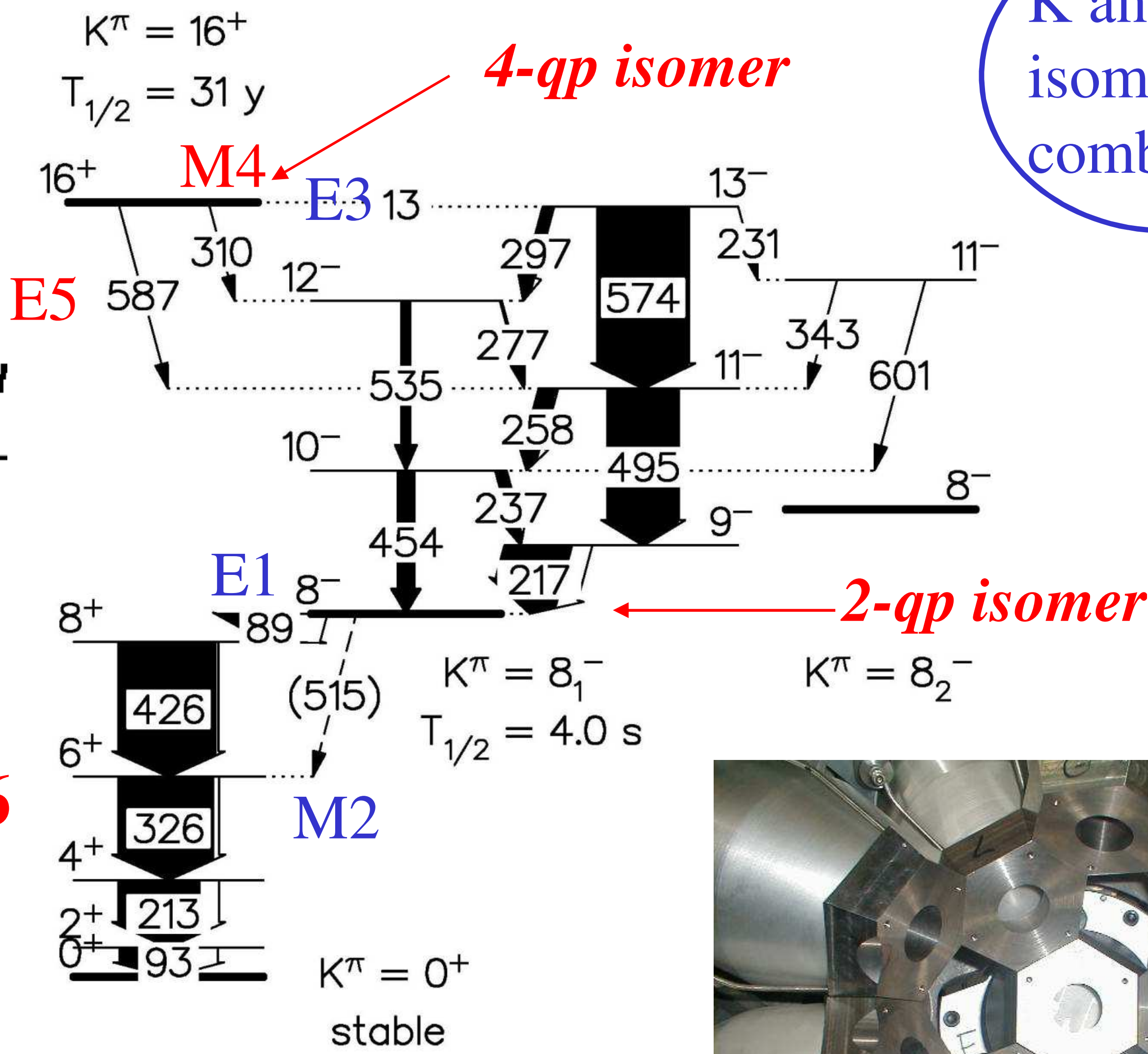


Walker, Prog. Part. Nucl. Phys. to be published

K and spin isomerism combined



495-keV gate

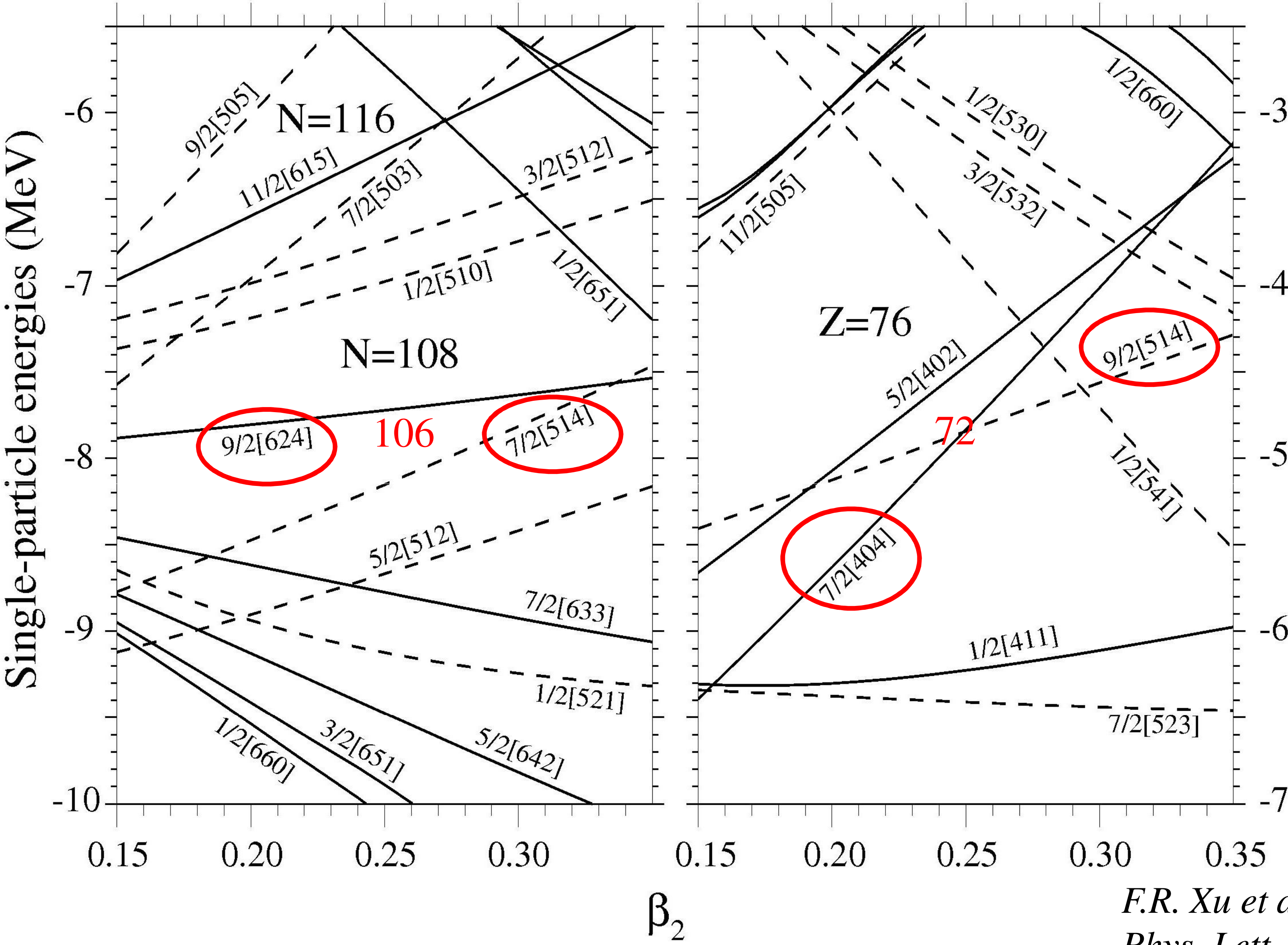


$^{178}_{72}Hf_{106}$

data from the 8π spectrometer at TRIUMF

Smith et al., Phys. Rev. C68 (2003) 031302(R)

^{178}Hf has N=106, Z=72, β_2~0.25



Woods-Saxon potential

F.R. Xu et al., Phys. Lett. B435 (1998) 257

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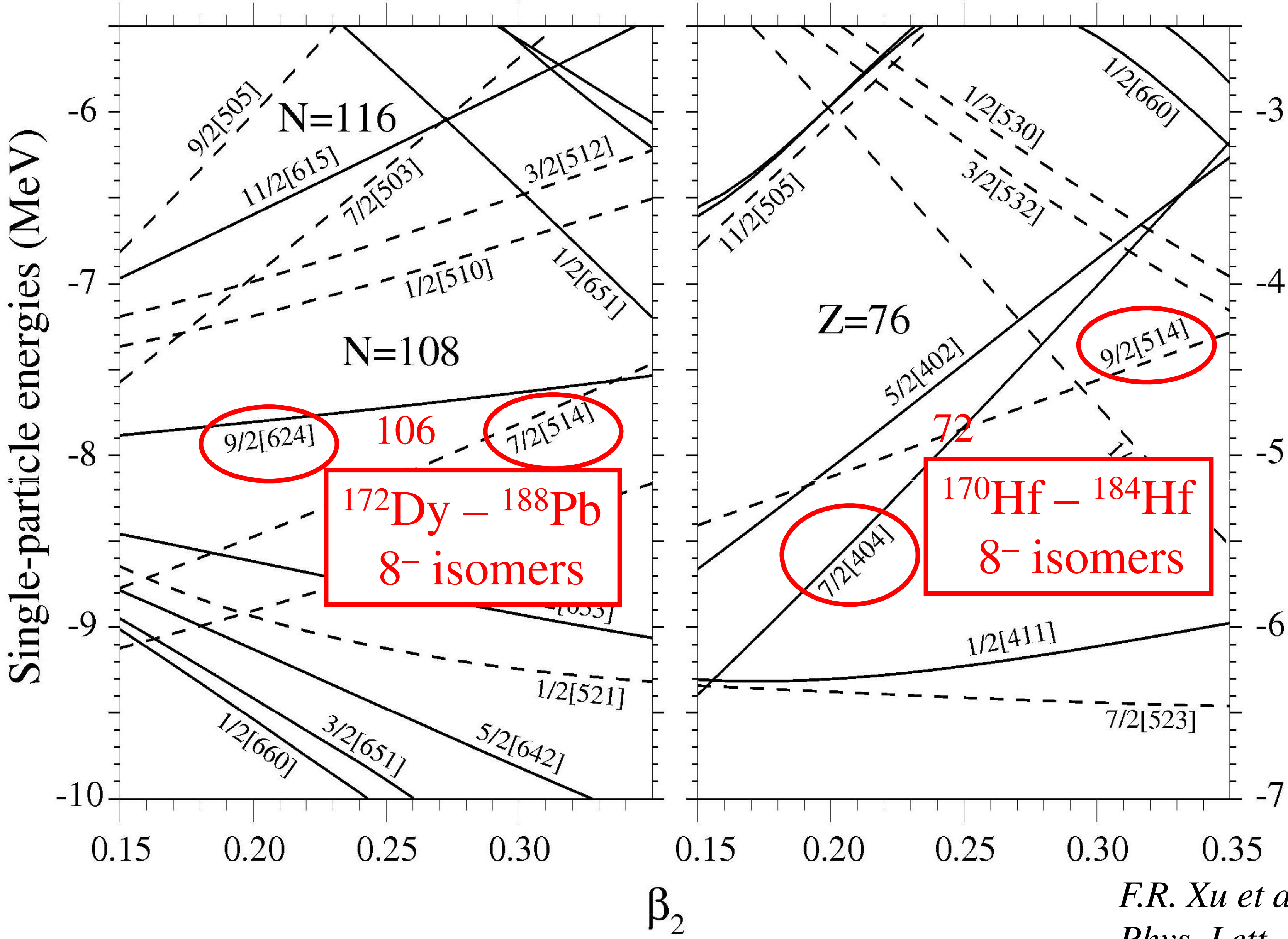

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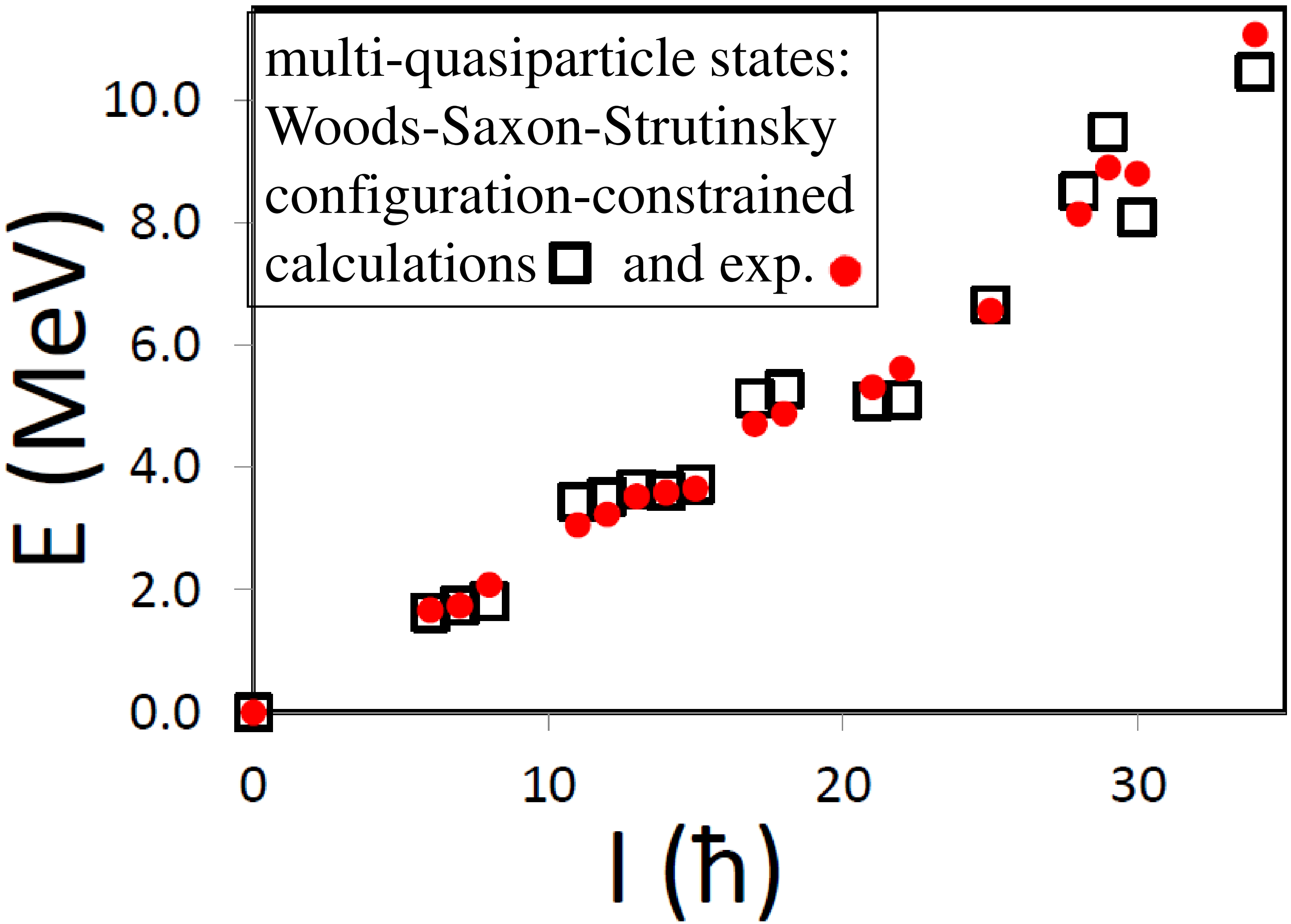
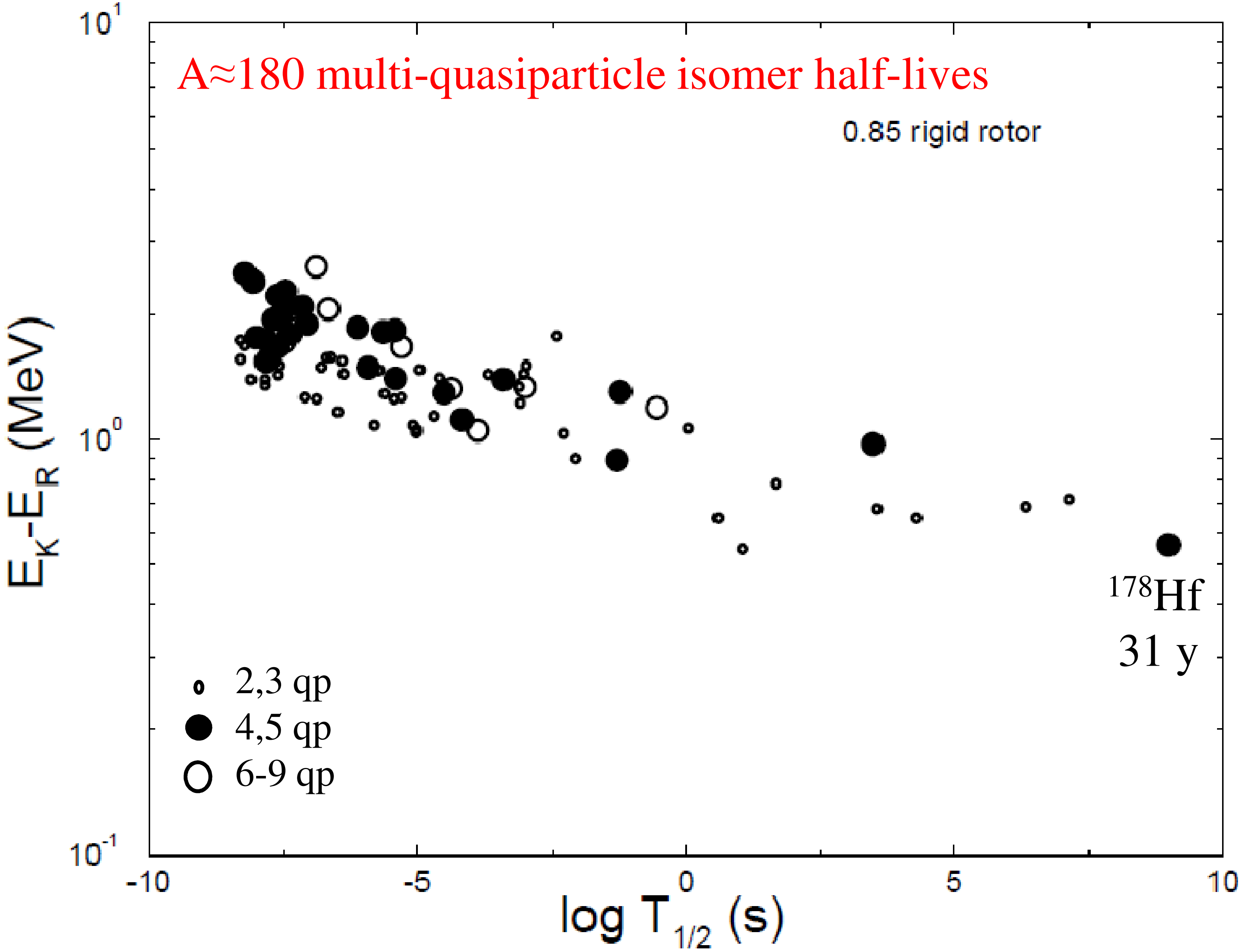
F.R. Xu et al.,
Phys. Lett. B435
(1998) 257

^{178}W energy vs. spin



rms deviation ≈1.7%

Xu et al., Phys. Lett. B435 (1998) 257
Walker, Prog. Part. Nucl. Phys. to be published

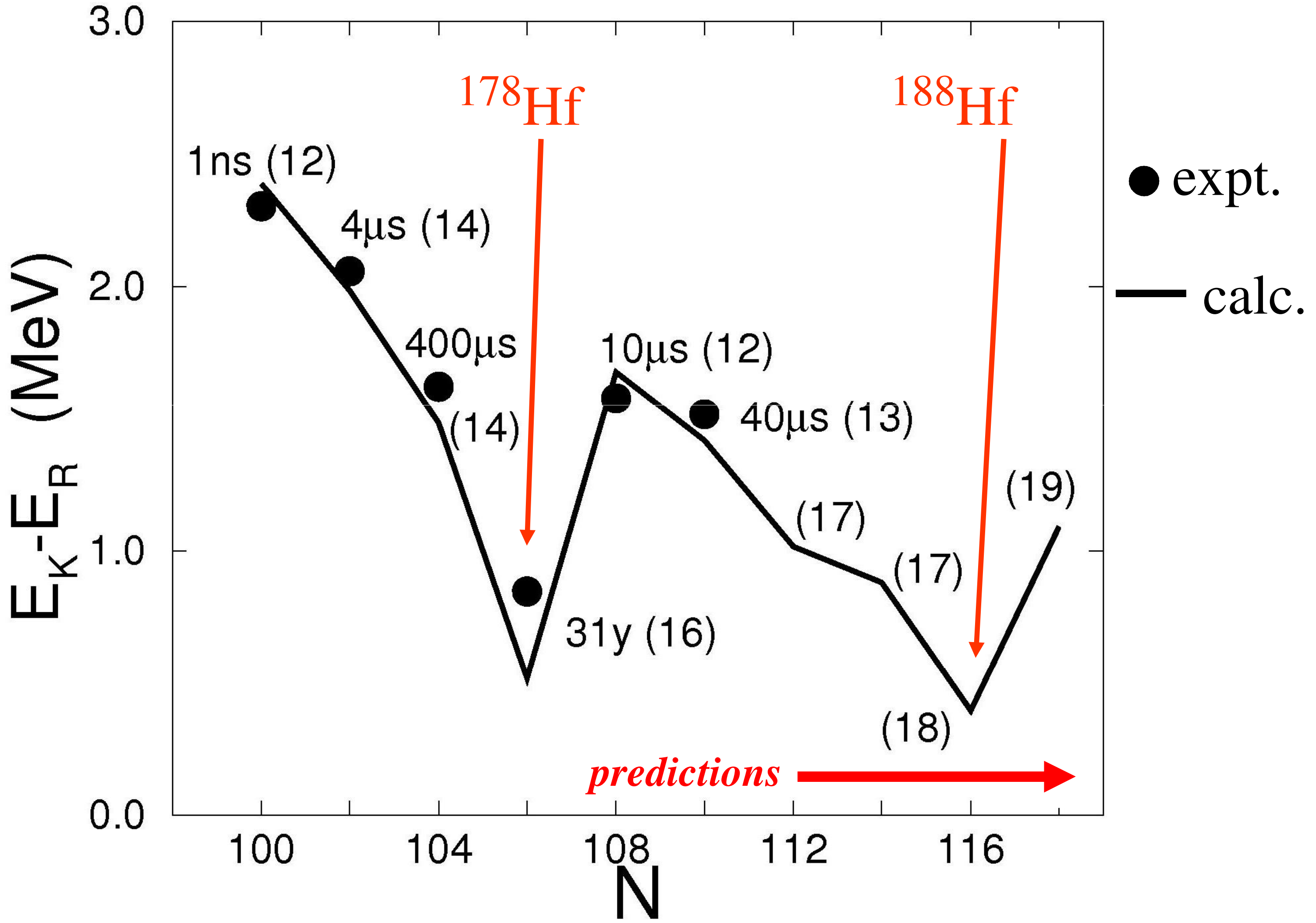


Walker, Acta Phys. Pol. B36 (2005) 1055 (Zakopane School, 2004)

Limits to K isomerism

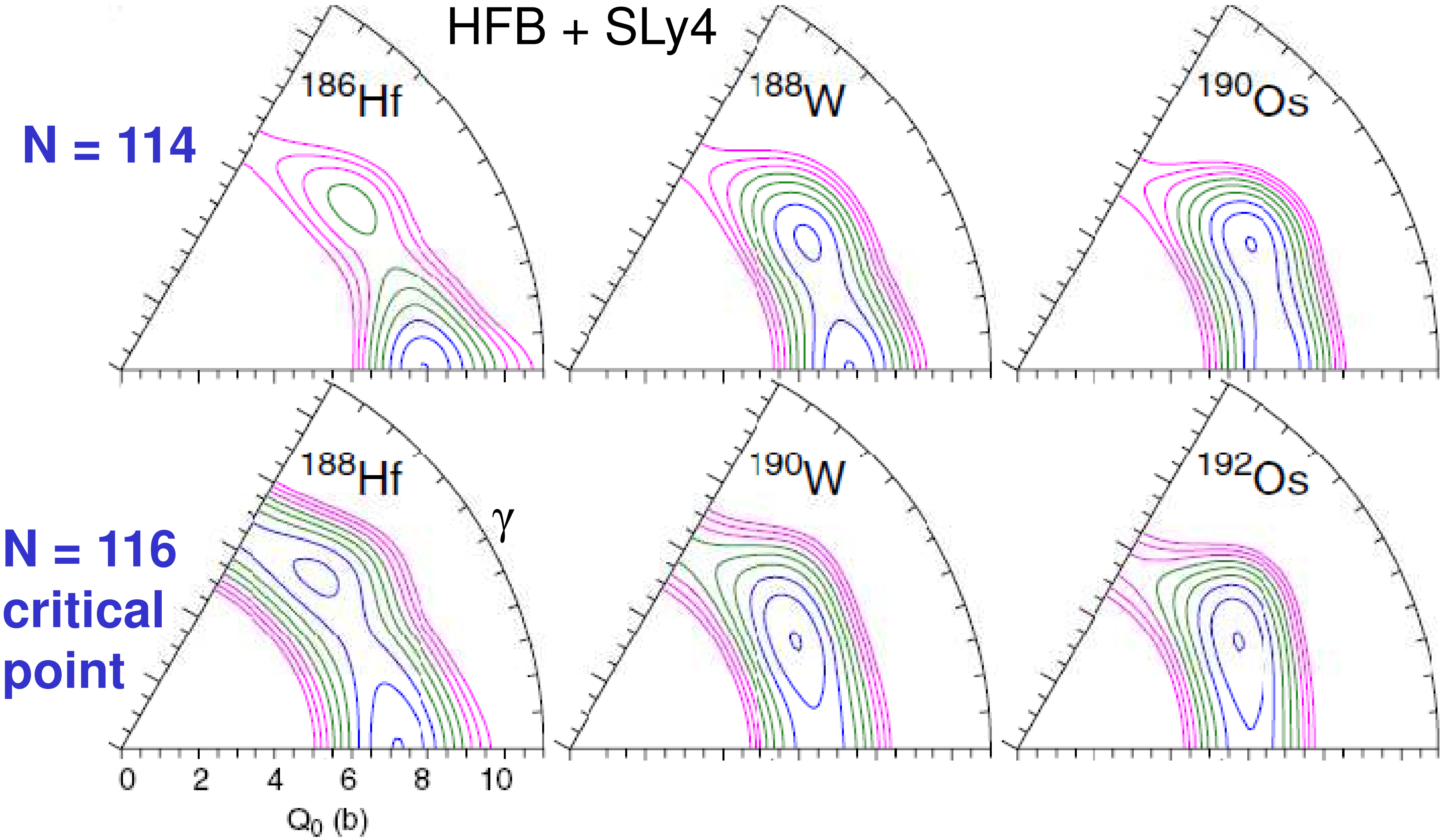
neutron-rich hafnium (Z = 72) region

hafnium (Z=72) 4-qp isomers



Walker and Dracoulis, Hyp. Int. 135 (2001) 83

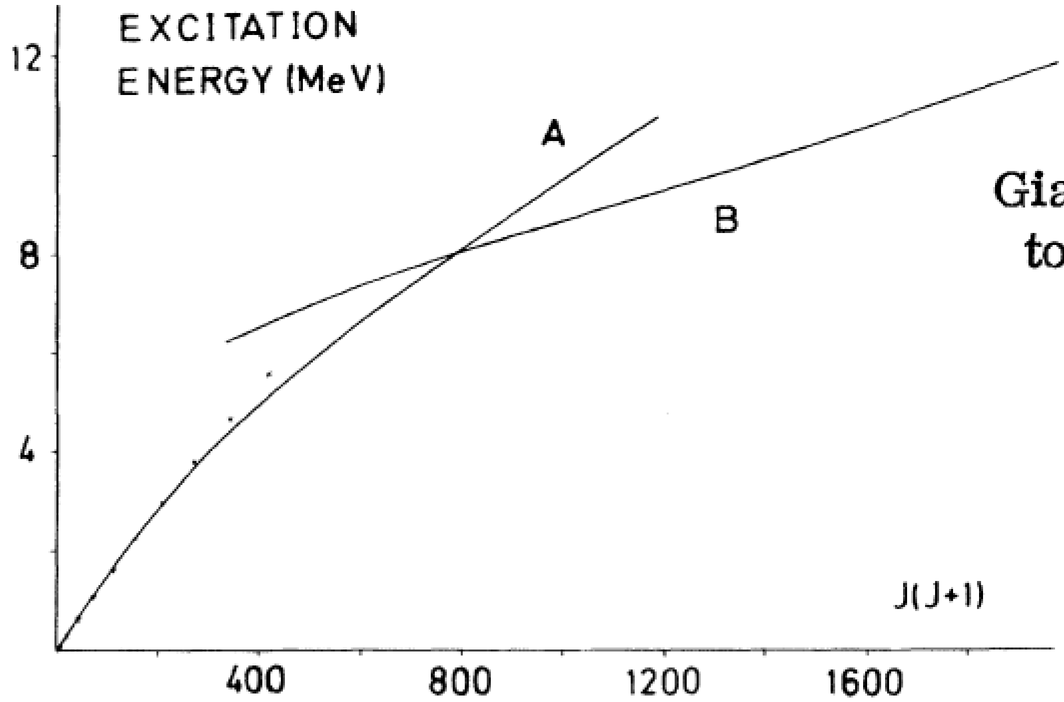
prolate-oblate shape transition (ground states)



Robledo et al., J. Phys. G36 (2009) 115104

^{180}Hf prolate → oblate *at high spin*

the original rotor of Bohr and Mottelson, 1953



Giant backbending is predicted to occur in ^{180}Hf at $J \approx 26\hbar$

prediction (HFB):
Hilton and Mang PRL43 (1979) 1979

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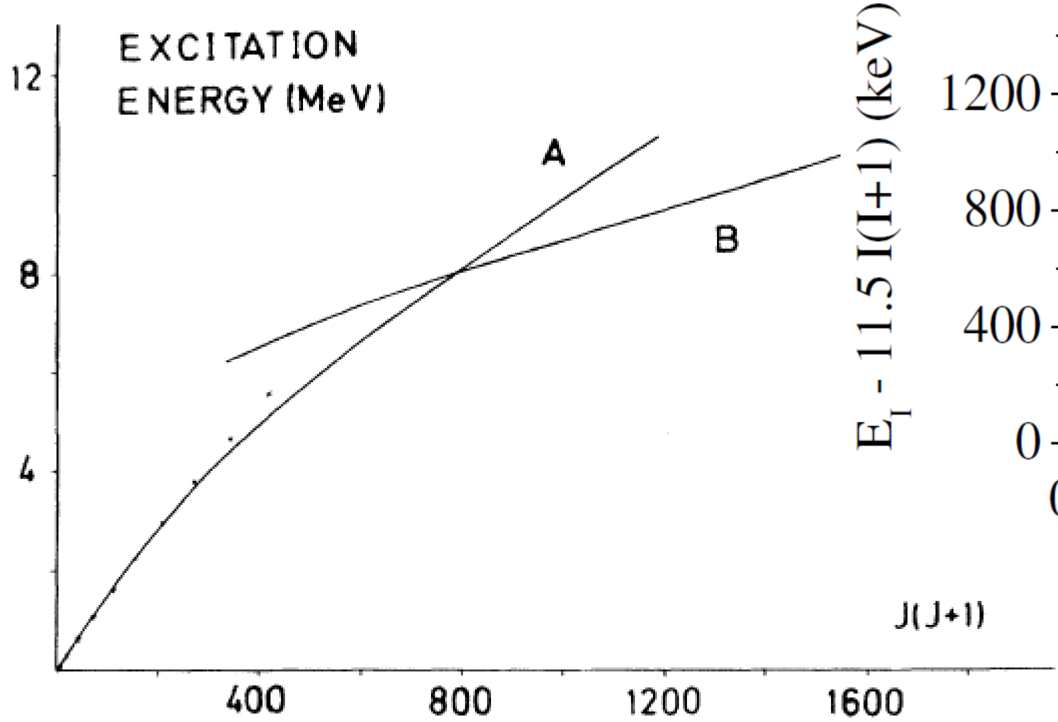

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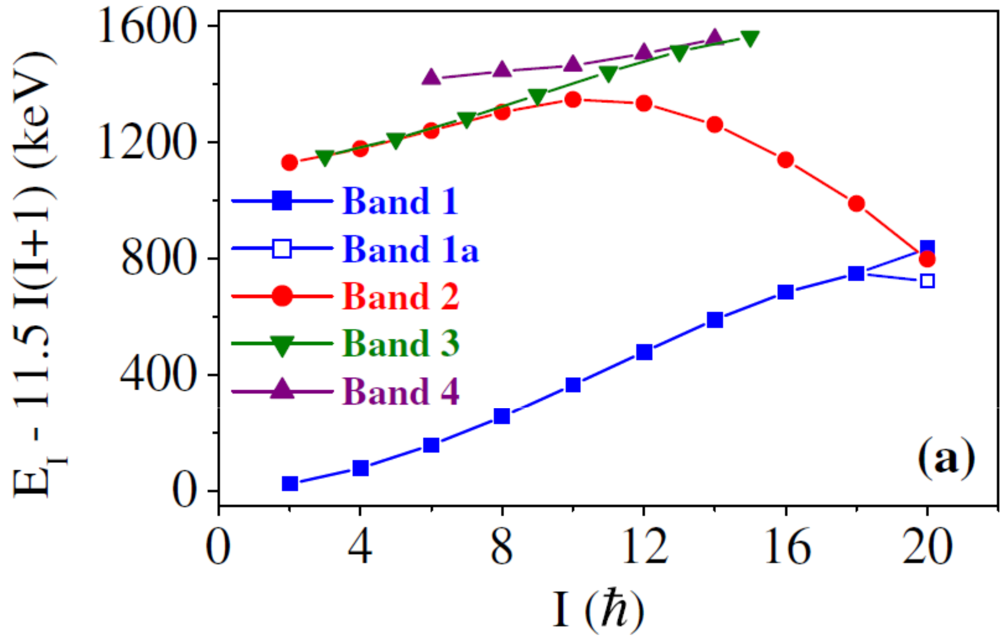
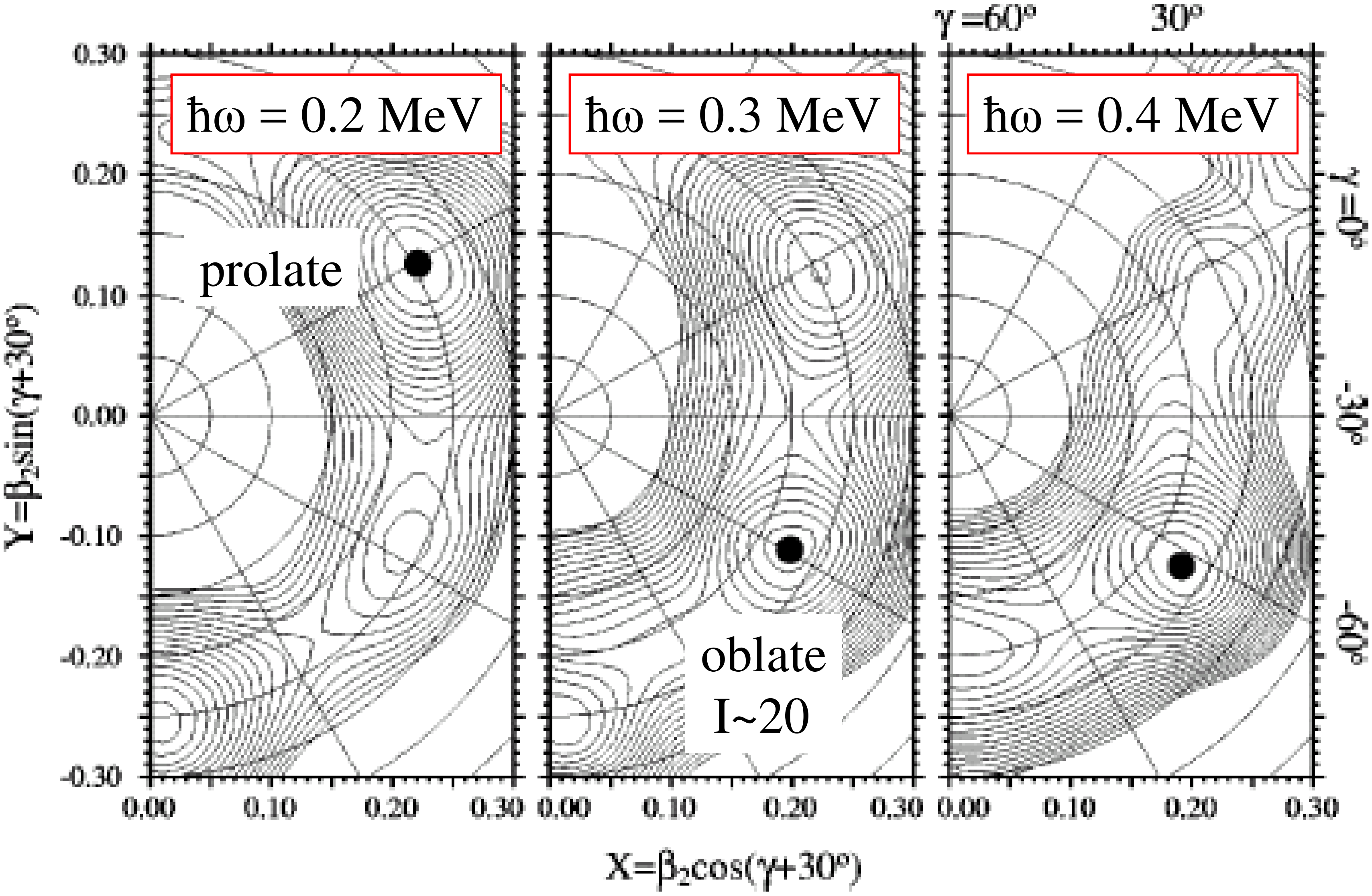


experiment (Gammasphere at ANL):
Tandel et al. PRL101 (2008) 182503

total Routhian surfaces (TRS): ^{182}Hf

Xu, Walker and Wyss, Phys. Rev. C62 (2000) 014301



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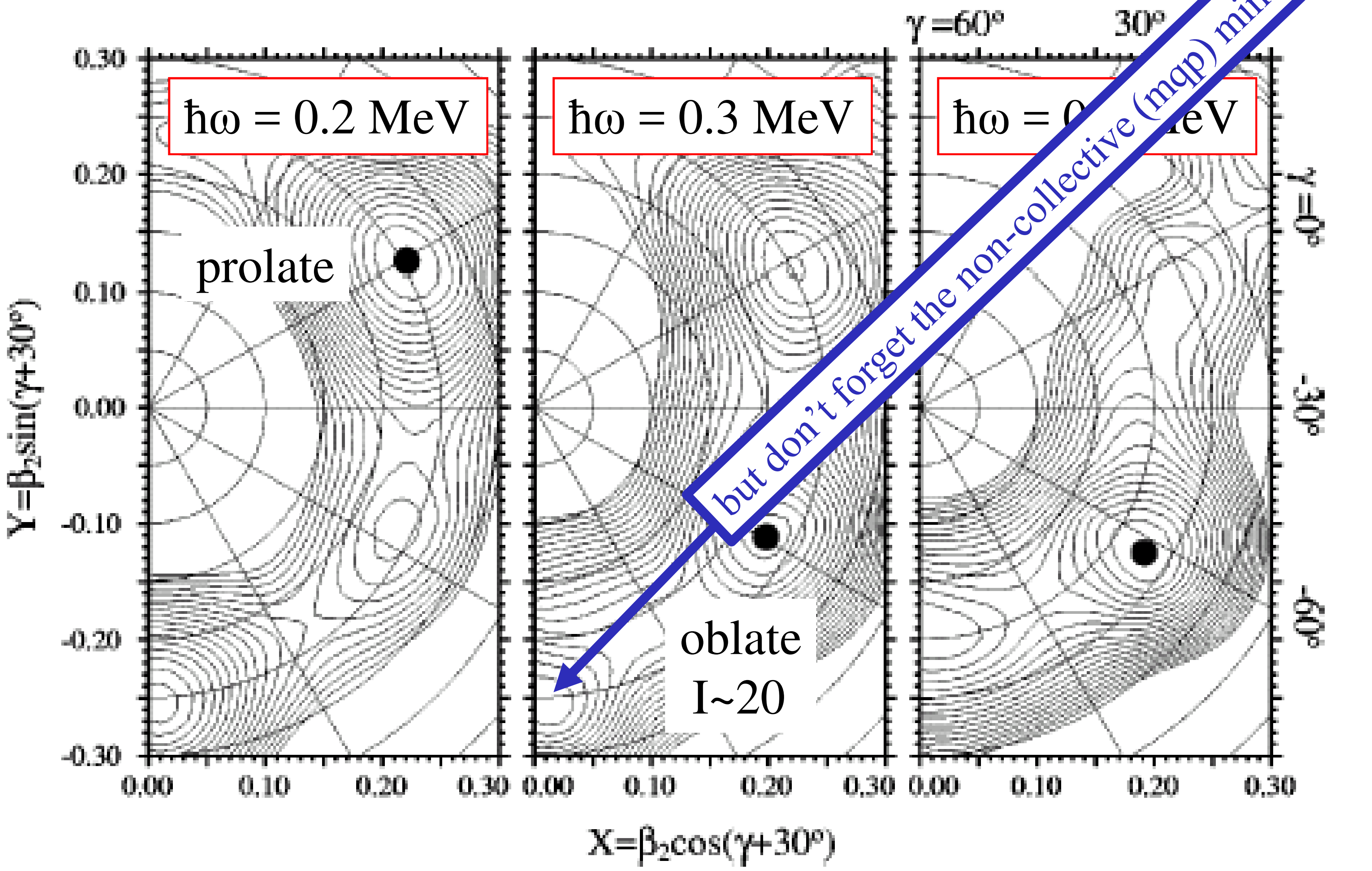
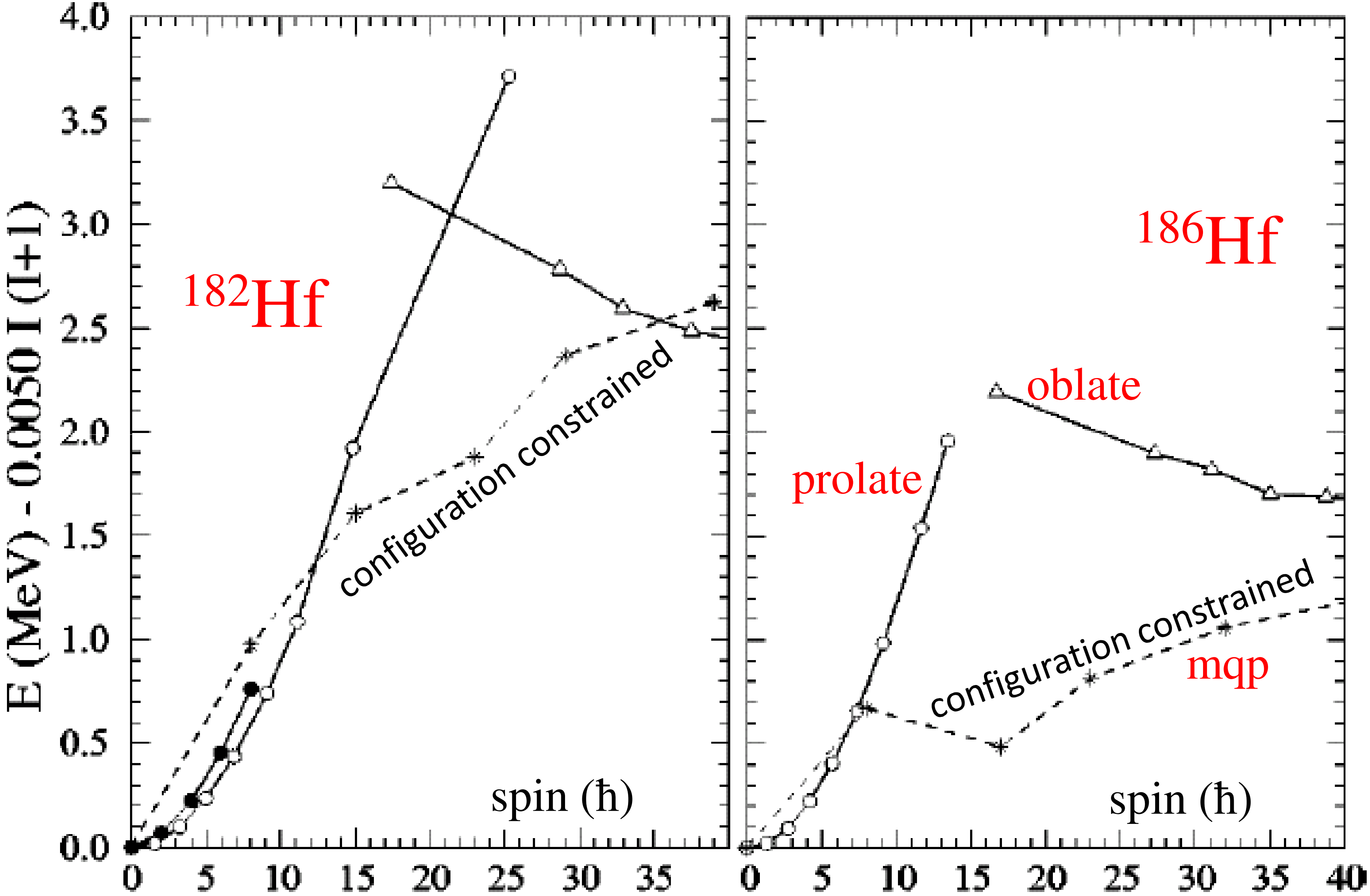
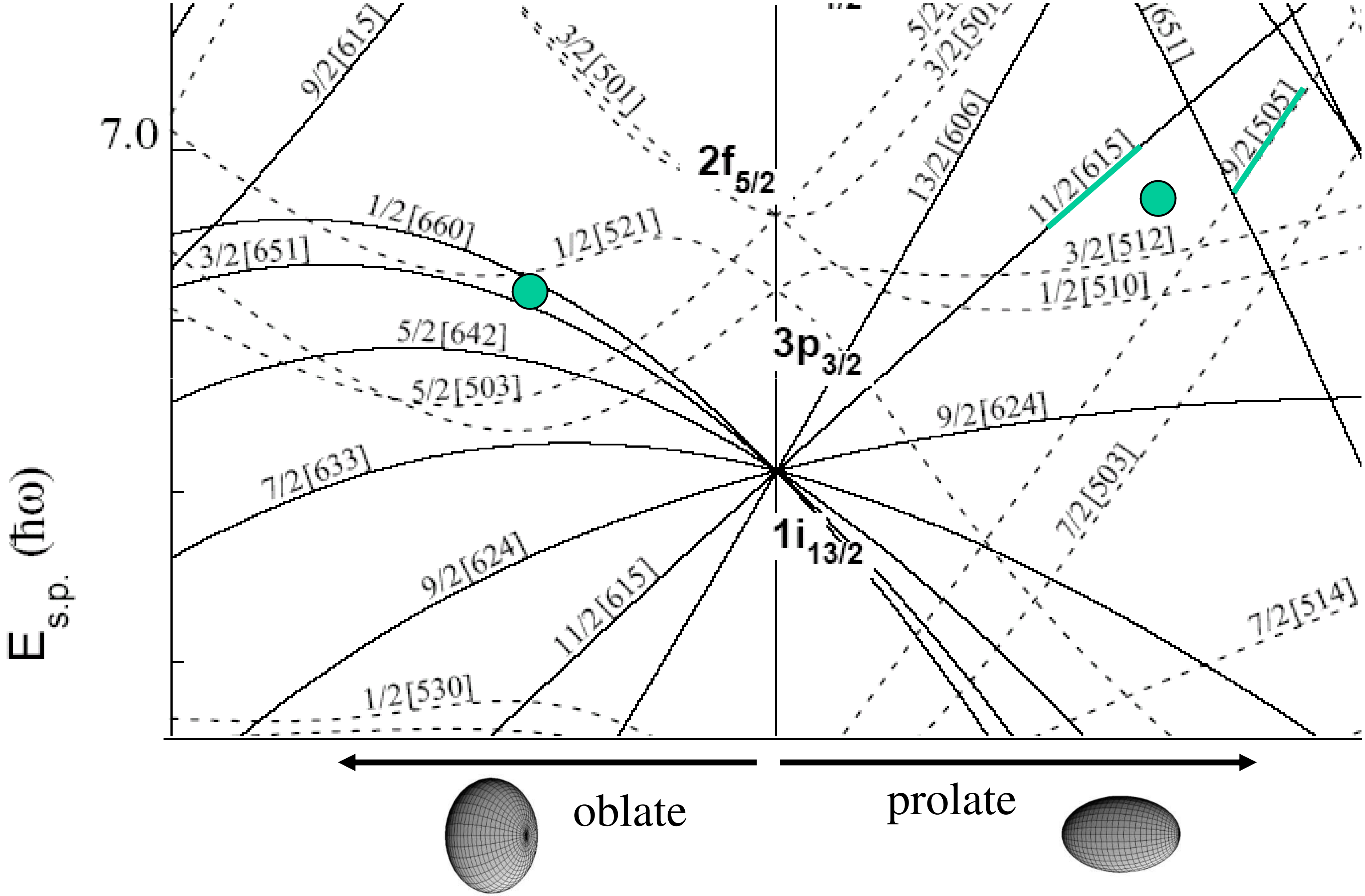


TRS calculations

Xu, Walker and Wyss, Phys. Rev. C62 (2000) 014301



Nilsson single-particle diagram ● N = 116 (^{188}Hf, ^{190}W, ^{192}Os)



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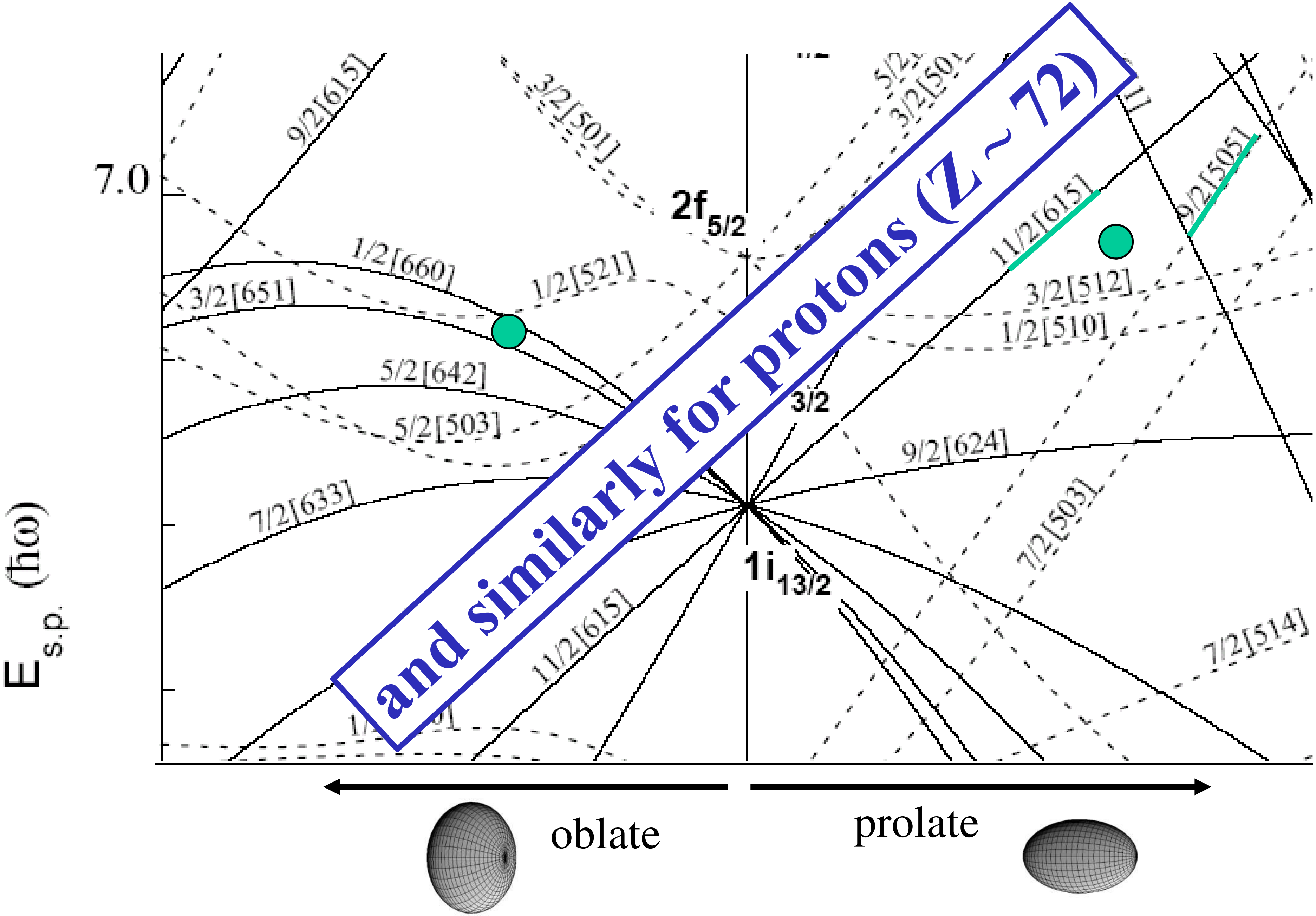
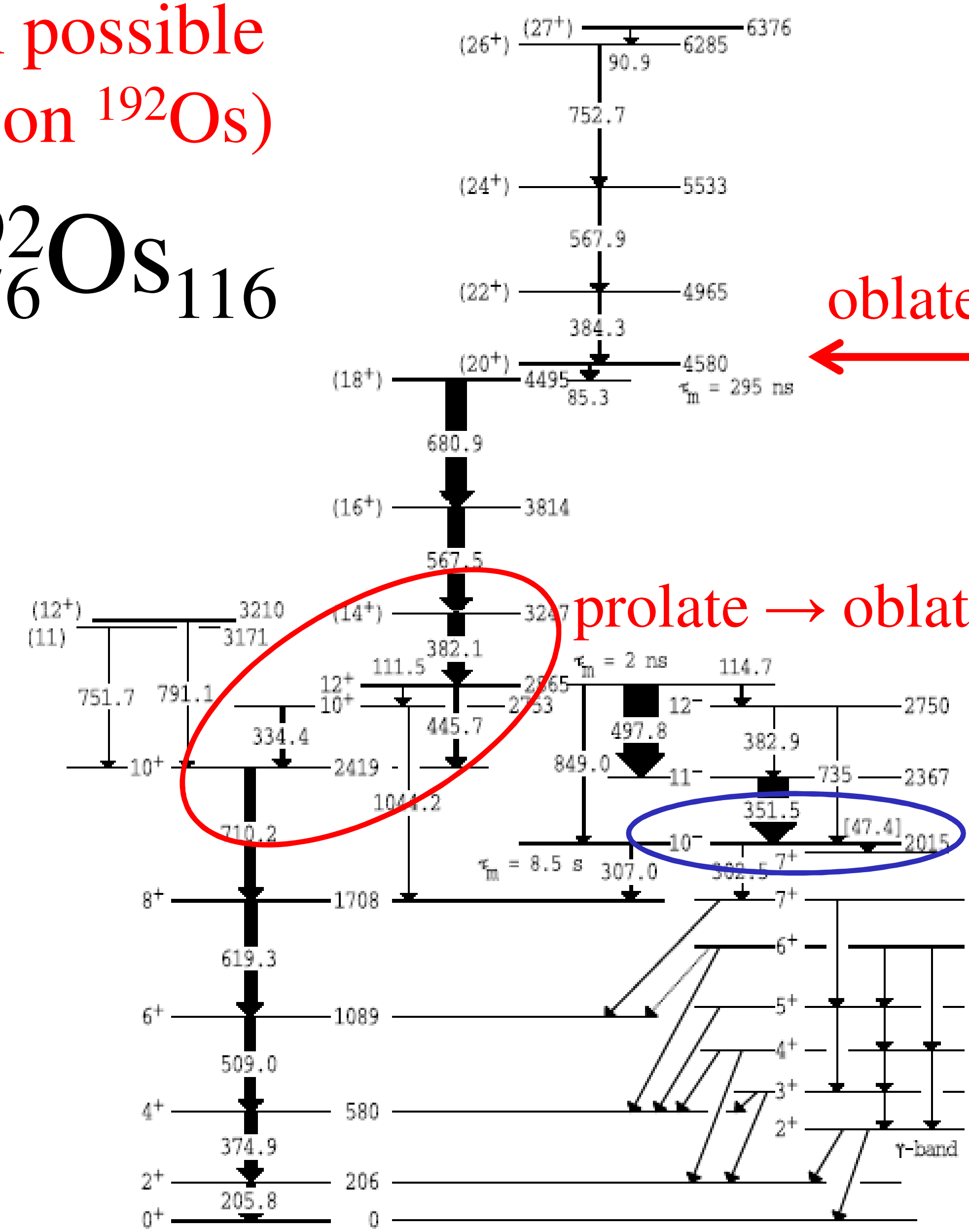


Spins > 20 ħ possible
(^{136}Xe on ^{192}Os)

$^{192}_{76}\mathrm{Os}_{116}$

Dracoulis et al. Phys. Lett. B720 (2013) 330
(Gammasphere data)



oblate ← 200 ns isomer 20 ħ

prolate → oblate bandcrossing

high-K isomer
6 s, 10 ħ

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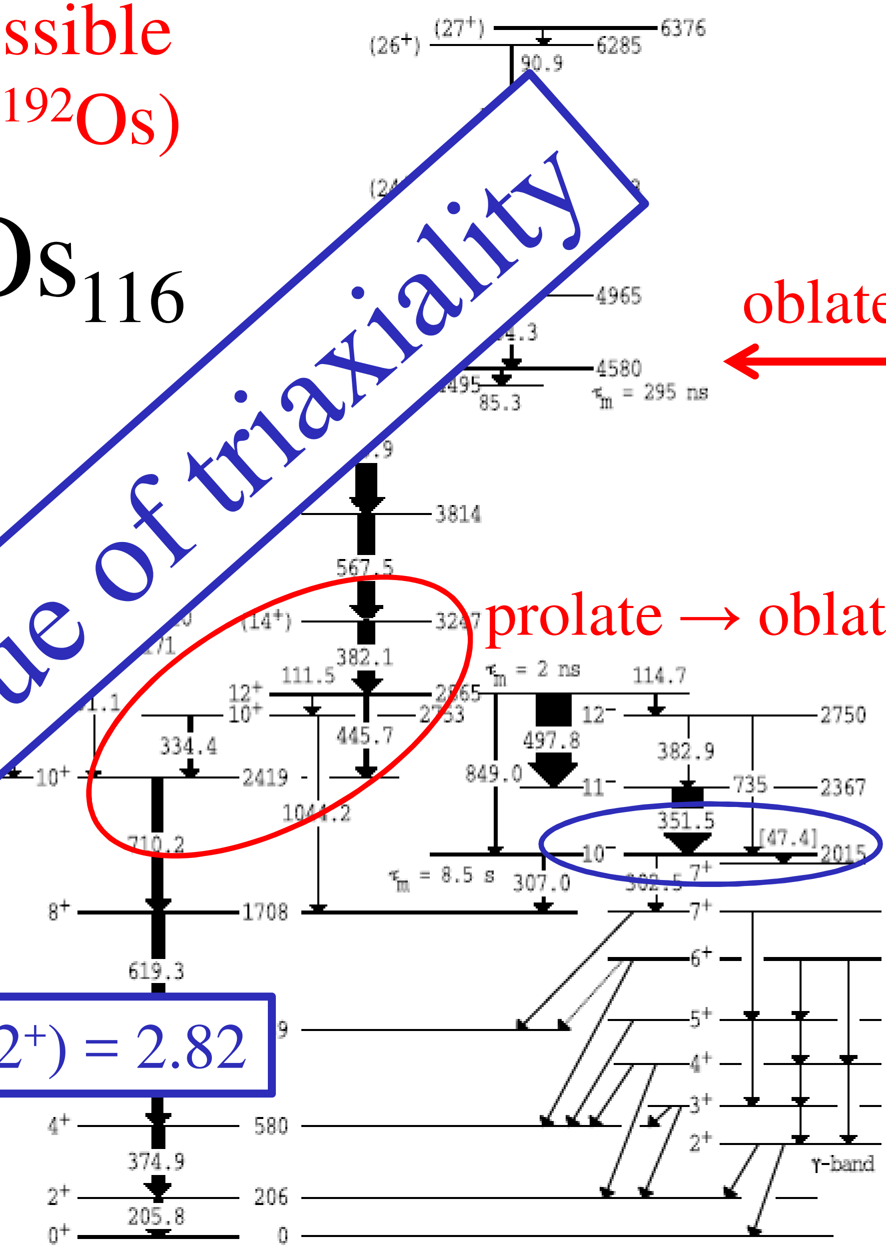
(^{136}Xe on ^{192}Os)

$^{192}_{76}Os_{116}$



issue of triaxiality

oblate ← 200 ns isomer 20 ħ

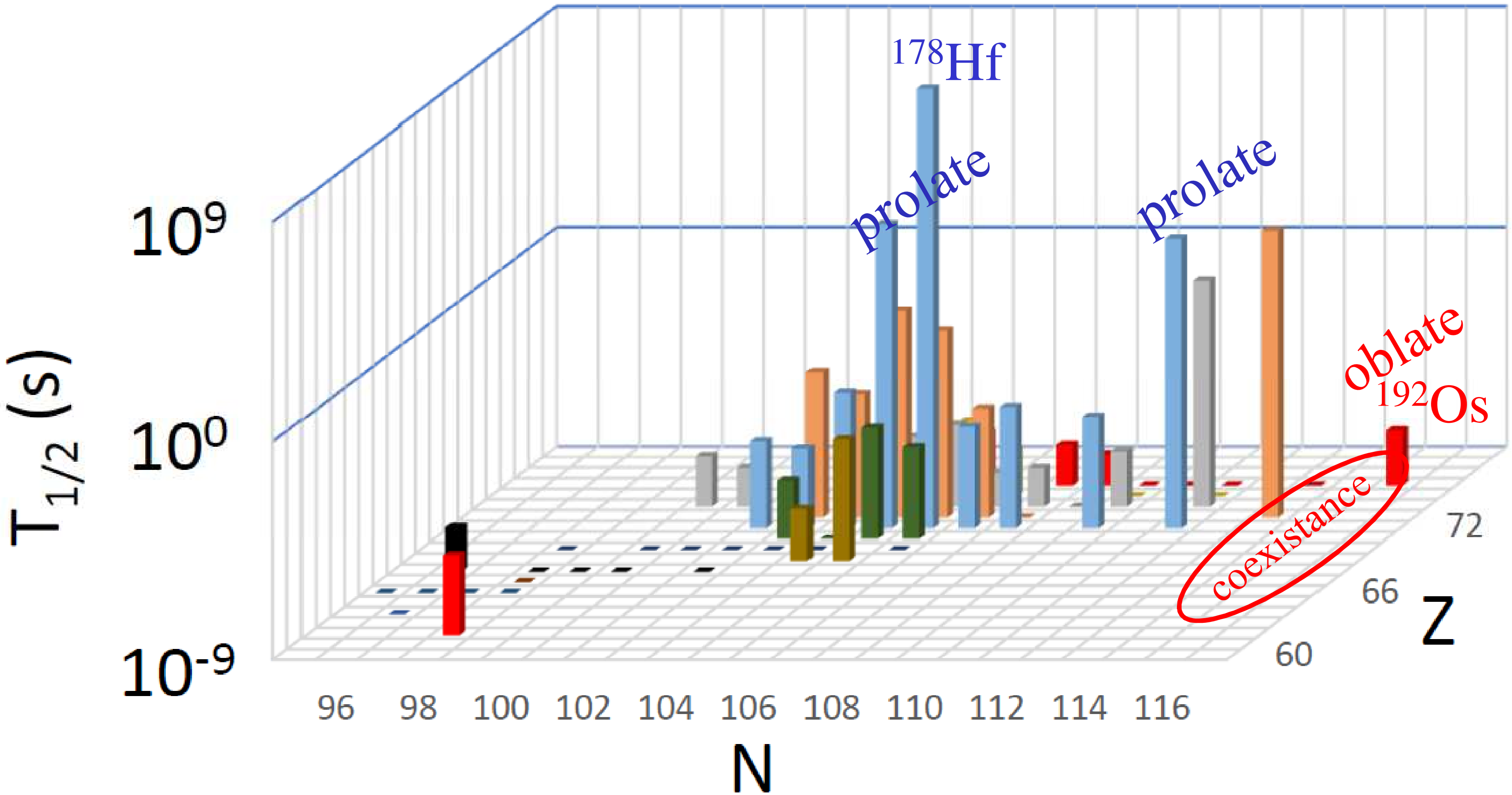
prolate → oblate bandcrossing

high-K isomer 6 s, 10 ħ

E(4+)/E(2+) = 2.82

Dracoulis et al. Phys. Lett. B720 (2013) 330 (Gammasphere data)

A~180 isomers with at least 2 broken pairs



Walker, Prog. Part. Nucl. Phys. to be published

Summary – high-K isomers

superheavy nuclei – extra stability
A~190 neutron-rich – long-lived isomers, oblate coexistance
future challenges – n-rich Hf, Ta data, isomer manipulation

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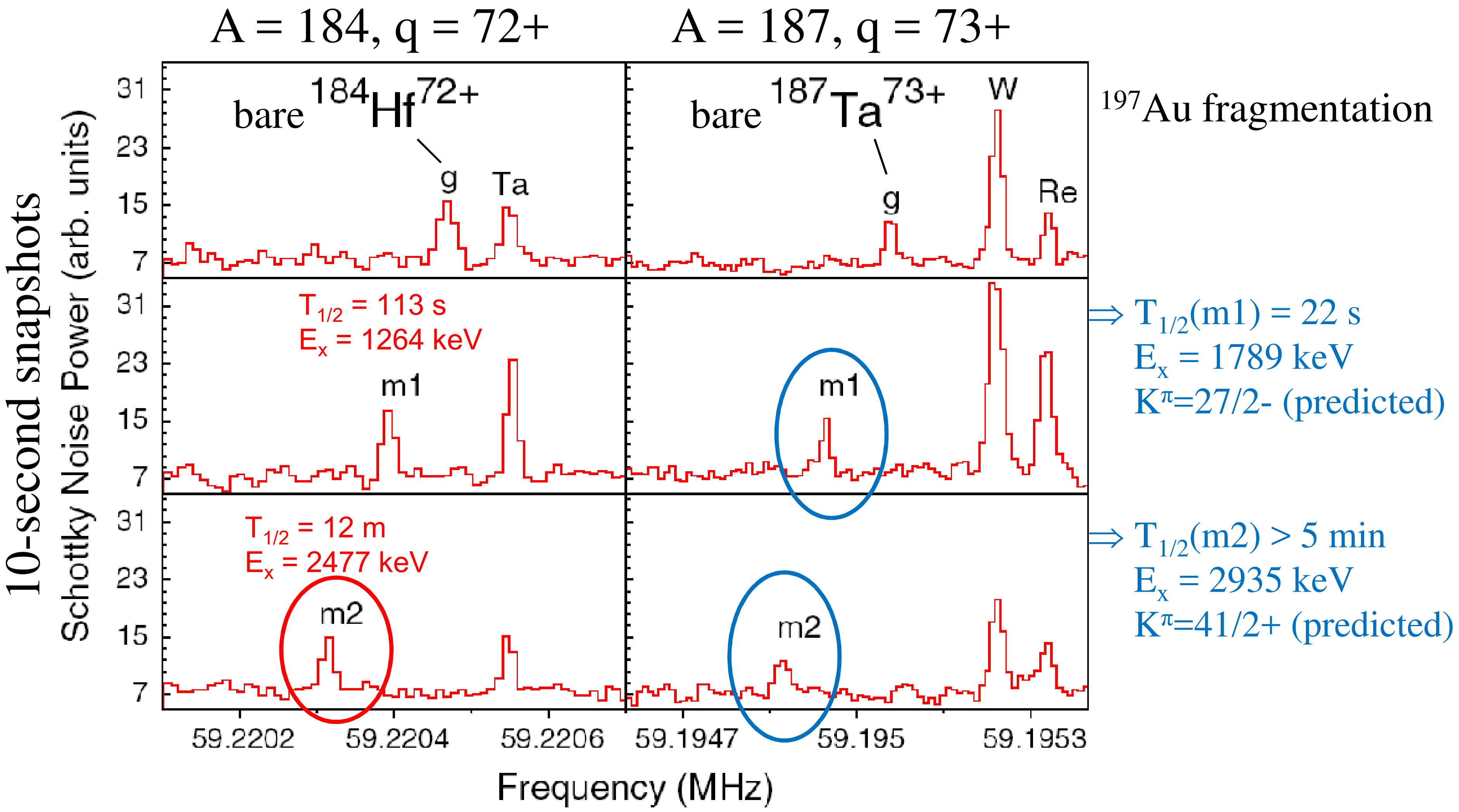
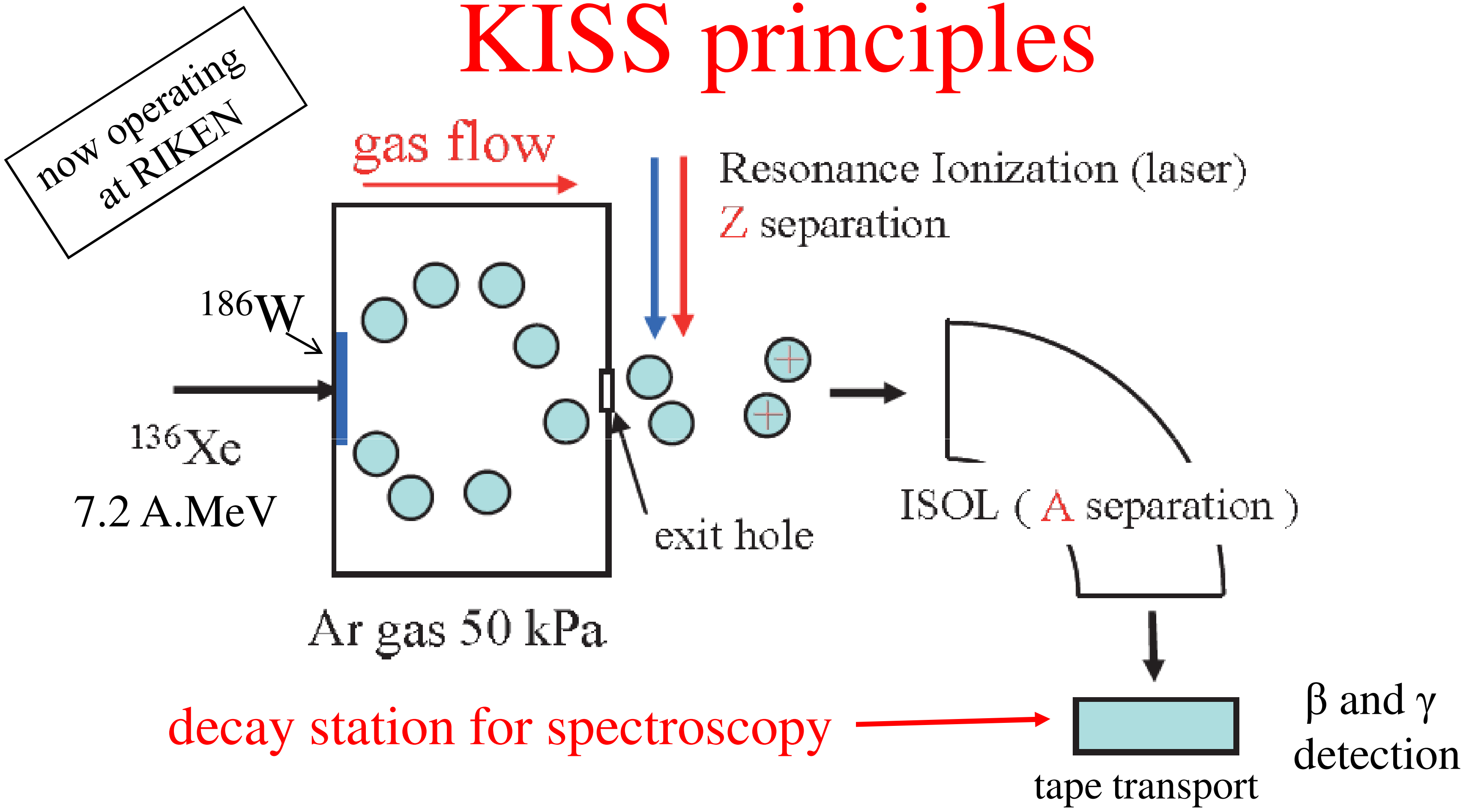
Yuri Litvinov (GSI)
Filip Kondev (Argonne)
George Dracoulis (ANU)
Yoshikazu Hirayama (KEK)

^{184}Hf and ^{187}Ta isomers seen in the ESR at GSI



Reed et al., Phys. Rev. Lett. 105 (2010) 172501; Phys. Rev. C86 (2012) 054321 new experimental programme at the KEK Isotope Separation System

KISS principles

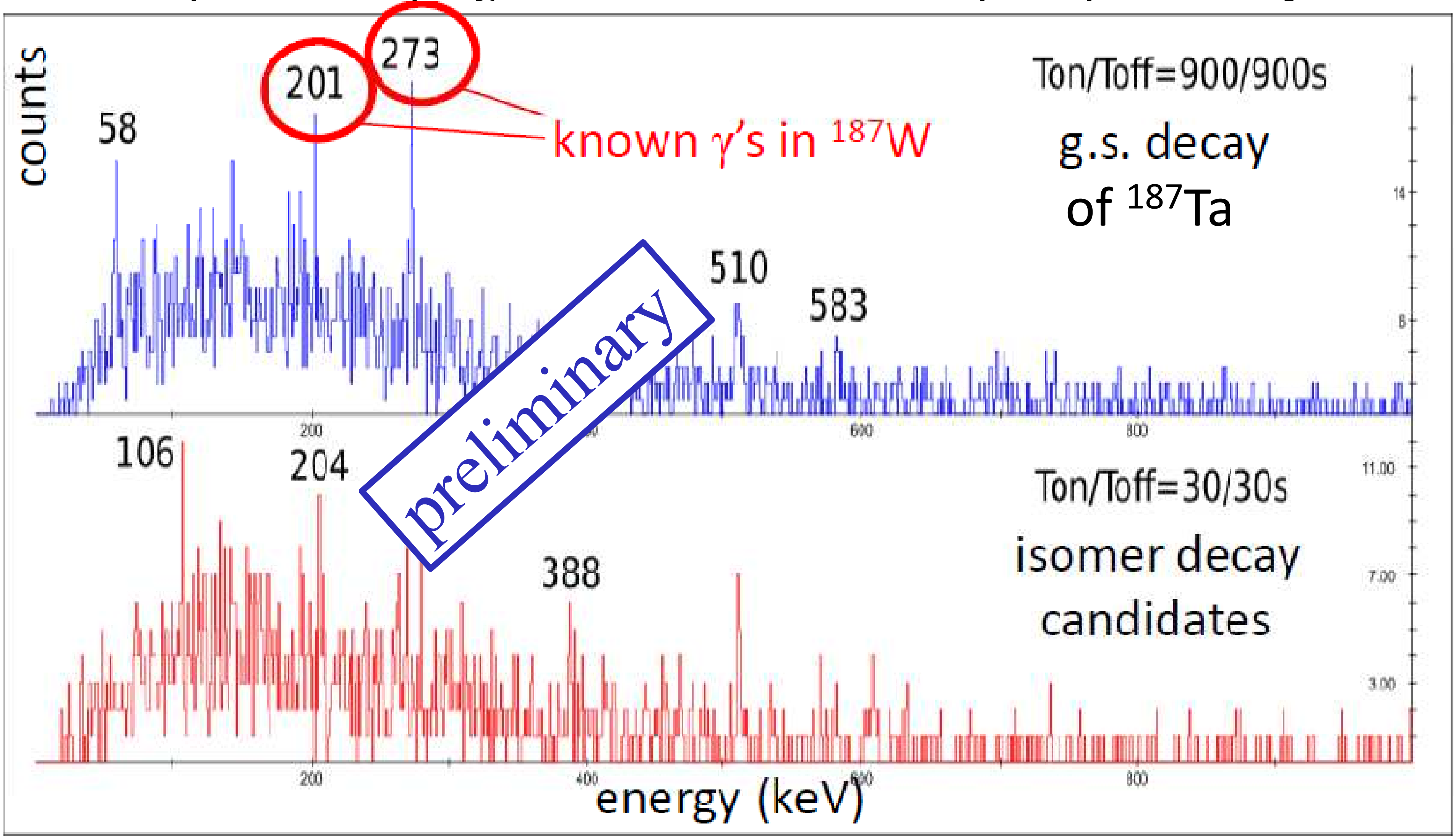


decay station for spectroscopy

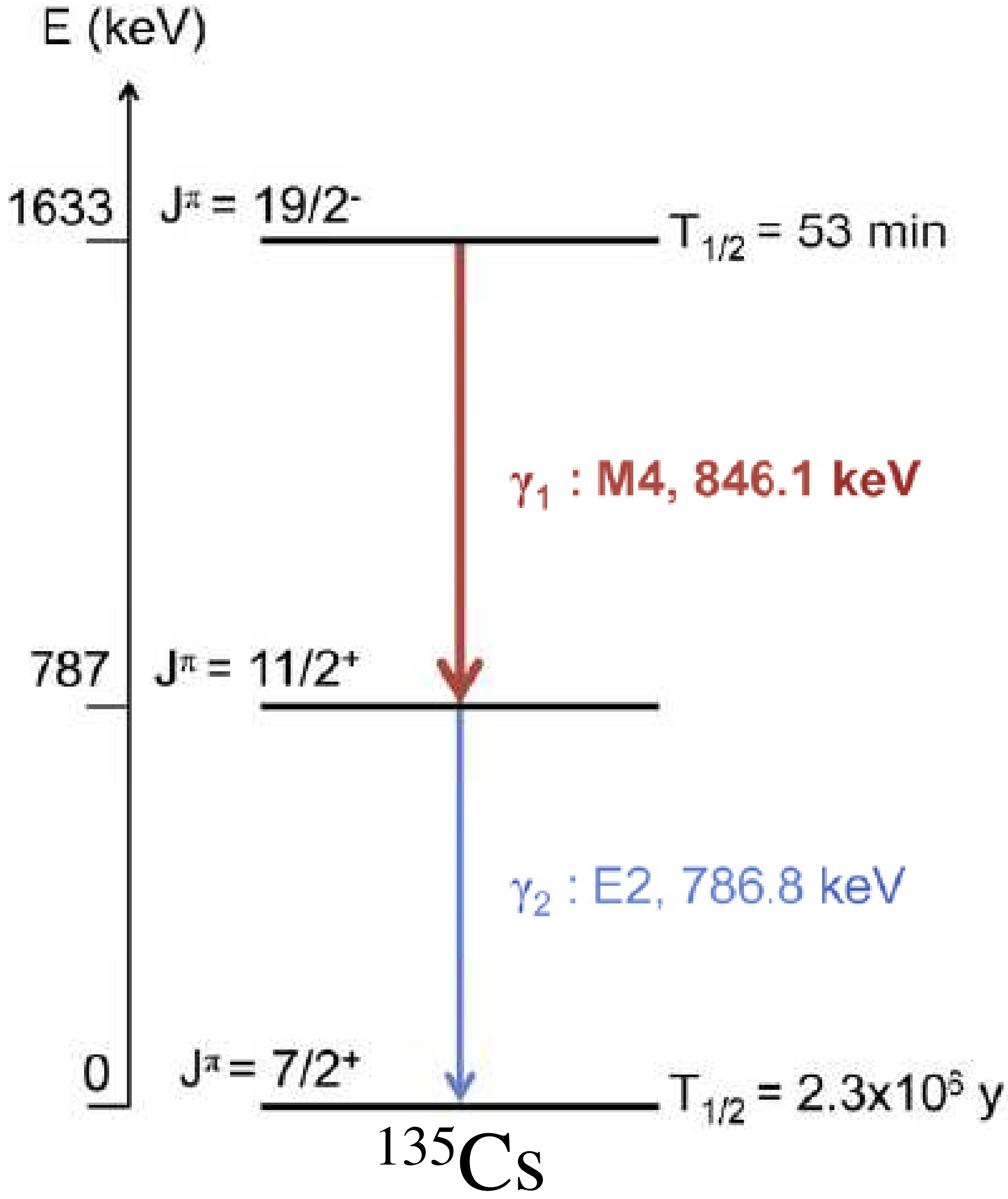
separation time ≈500 ms

from Jeong et al., KEK Report 2010-2;
see also Hirayama et al., Phys. Rev. C96 (2017) 014307

new experimental programme at the KEK Isotope Separation System



see also Hirayama et al., Phys. Rev. C96 (2017) 014307



possibility of coherent γ-ray emission from a Bose-Einstein condensate of ^{135}Cs isomers at 100 nK

Margumi, Walker & Renzoni, Phys. Lett. B777 (2018) 281