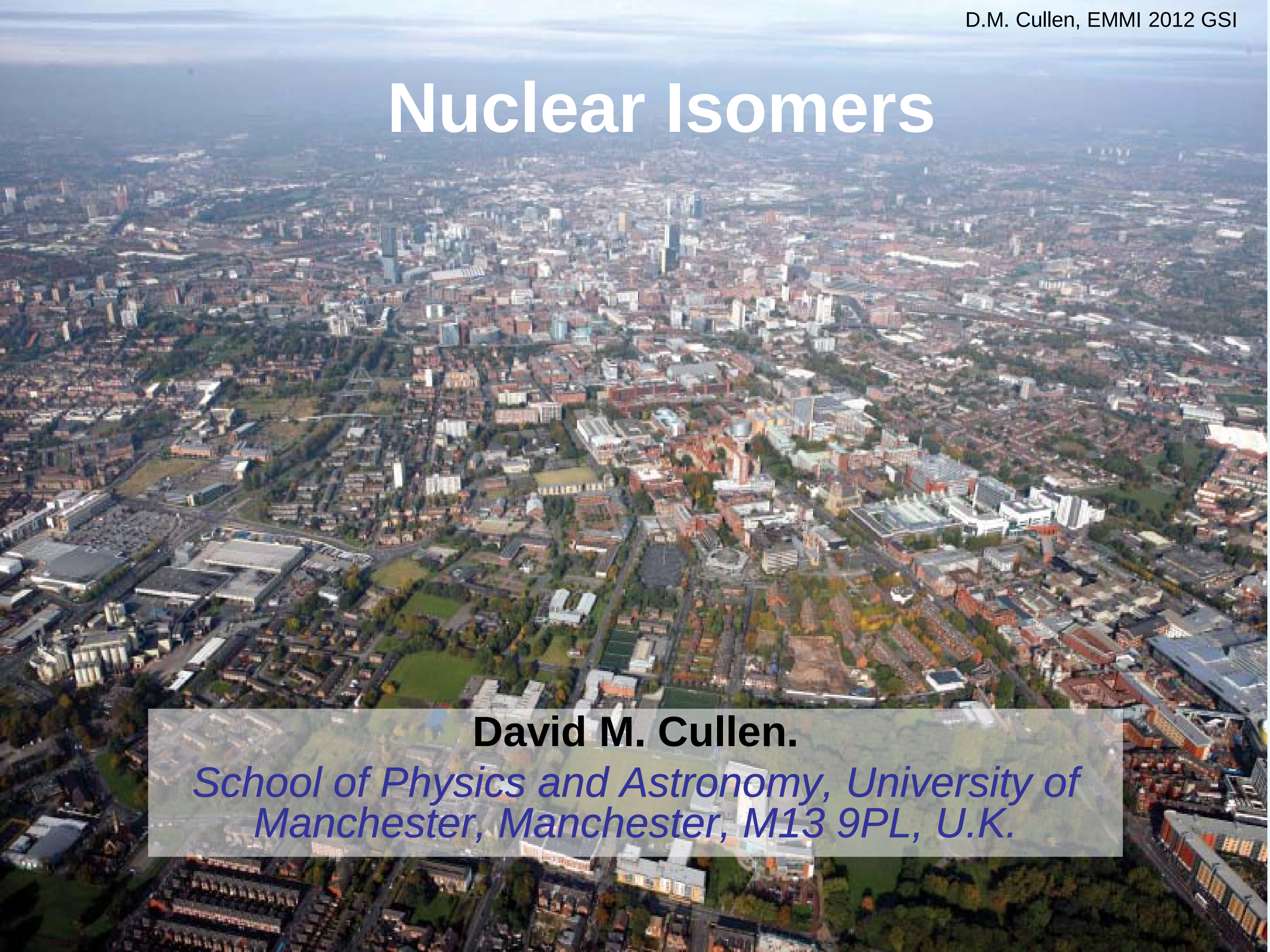

Nuclear Isomers

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Overview

The how, why, what, when and where of isomers...

1. *Why* isomers exist
2. *How* and *When* they decay ($t_{1/2}$)

What are isomers?

Term comes from *chemical isomers*.

molecules with the same molecular formula, but different arrangements of atoms.

1. Same constituent particles
2. but in different physical configuration
3. Energies are ~eV.

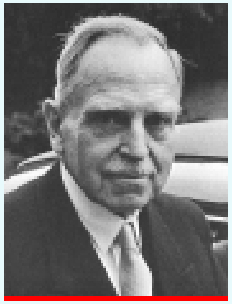
Nuclear *isomers*.

Nuclear isomers within same nucleus (N,Z) but different orbital arrangement of nucleons

1. Same constituent nucleons
2. but in different orbital configuration
3. Energies are ~ eV - MeV.

What are isomers?

1917: **predicted** by 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."



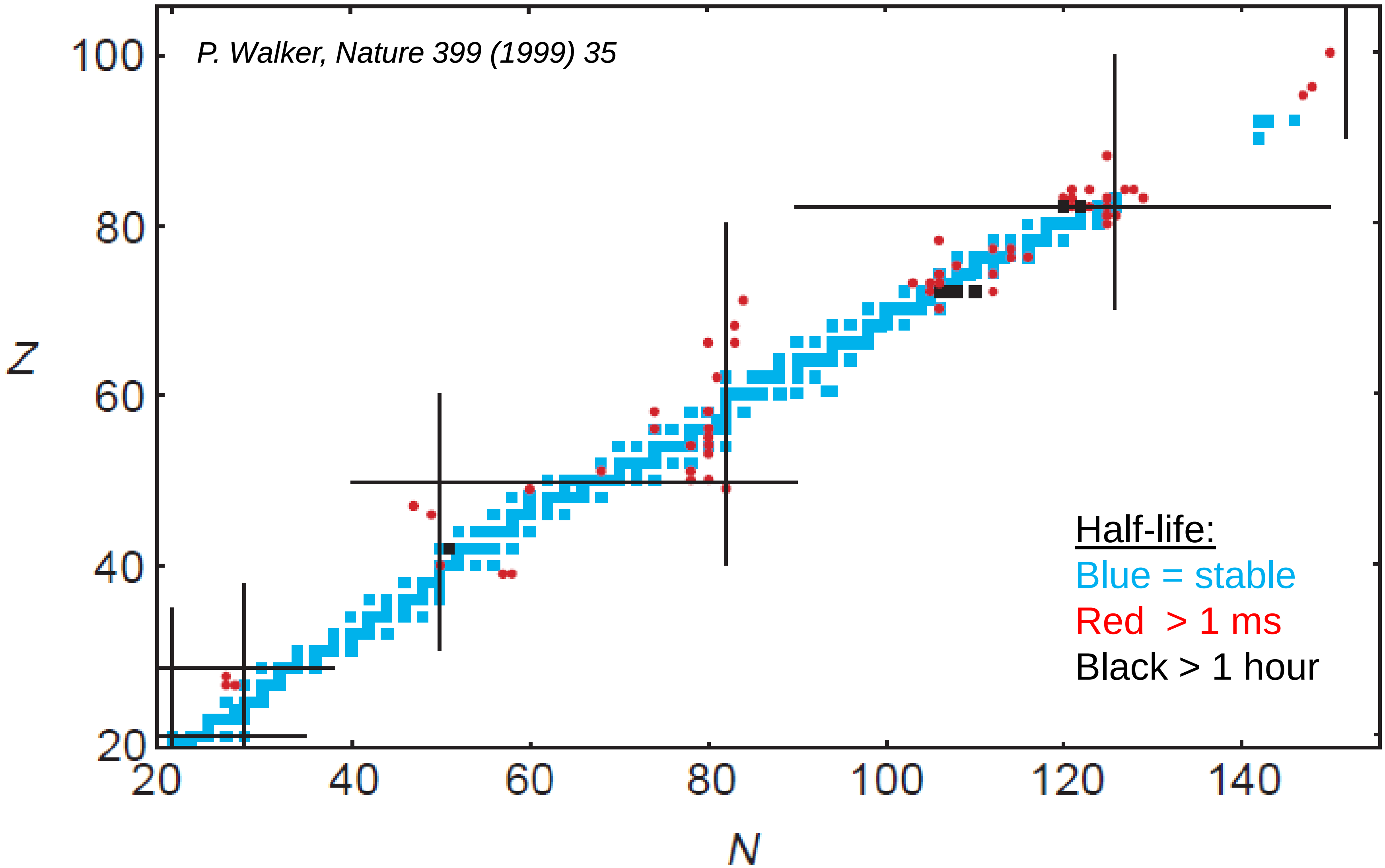
1921: uranium-X isomers **observed** by Hahn

1936*: isomers **explained** as spin traps by von Weizsäcker, Naturwissenshaften 24 (1936) 813*

Excited nuclear states with long half-lives > 1 ns

Where do isomers exist?

Where do isomers exist ?



Why are isomers important?

1. At the limits of nuclear binding, isomers may be more stable than their ground states.

$^{270}_{110}$Ds α decay

6 ms isomer at 1 MeV

0.1 ms ground state

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

$^{159}_{75}$Re p decay

21 μs isomer

ground state unknown

Joss et al., Phys. Lett. B641 (2006) 34
Liu et al., Phys. Rev. C76 (2007) 034313

Why are isomers important?

2. Long isomeric half-lives can upset delicate balance in the astrophysical neutron capture / beta decay processes.

This is reflected in the chemical abundances of the elements in our universe.

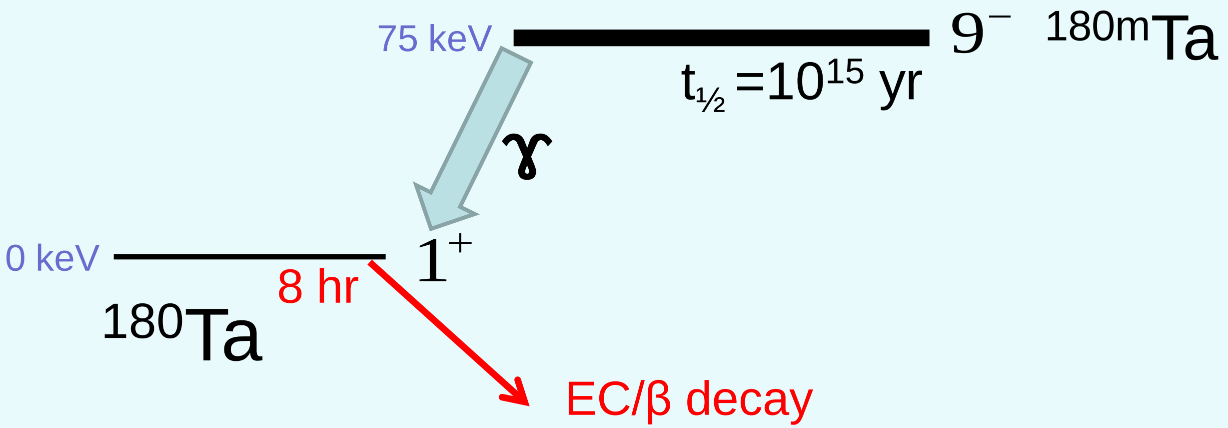
1. ^{180m}Ta 75 keV, stable (r-process waiting point)

2. ^{176m}Lu 123 keV, β^- decay, 4 h (s-process)

3. ^{26m}Al 228 keV, β^+ decay, 6 s

1. The classic very long-lived Isomer; ^{180}Ta

- Least abundant element ~ 0.012% natural Ta
- Only naturally occurring isomer on Earth
  $t_{1/2} = 10^{15}$ years (from before Earth formed!)
- Isomer affects r-process abundances
- Recent conjecture for substantial photon excitation branch from 9^- which would decrease its abundance in stellar environments



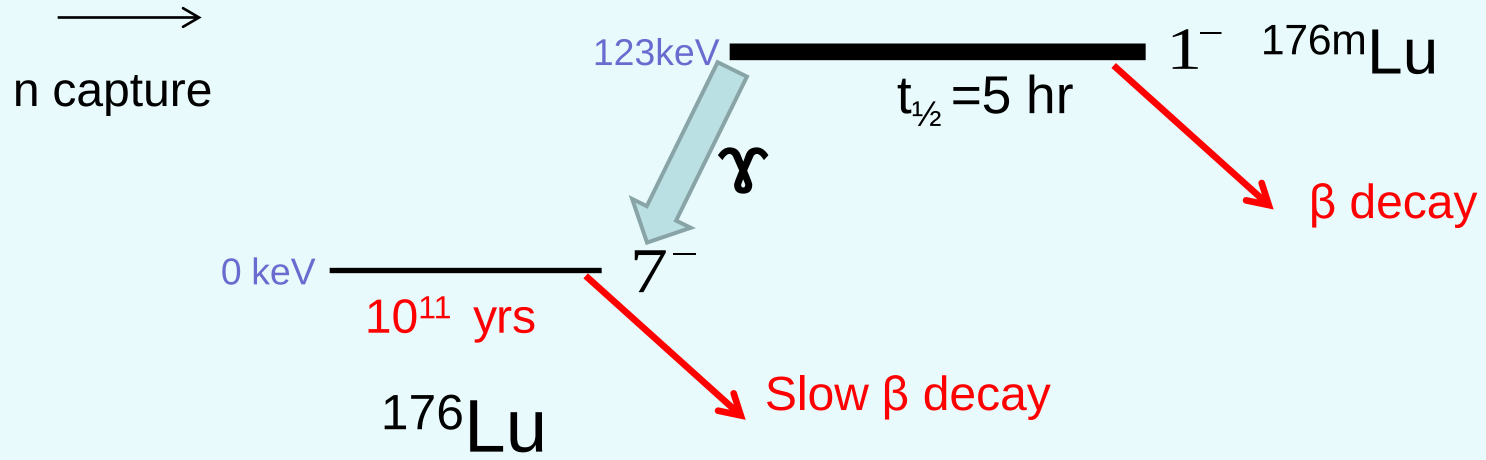
<u>Stored energy:</u>

1. 1cm^3 natural Ta → 30 KJ
2. 1cm^3 ^{180m}Ta → 300 MJ

But how to release?

2. The classic very long-lived Isomer; ^{176}Lu

- ^{176}Lu ground state is shielded from the r-process by ^{176}Yb
- Idea discussed, ^{176}Lu can be used as s-process thermometer.
- Direct population 1^- isomer from neutron capture has short half-life.

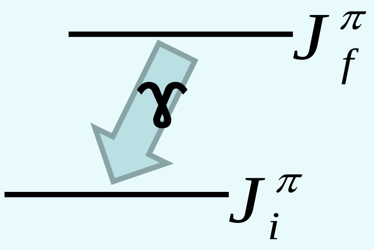


- However, photo-excitation from 1^- isomer to states which decay to ground state could increase ^{176}Lu abundance.
- and photo-excitation from ground state to the 1^- isomer would decrease ^{176}Lu abundance.
- The properties of any intermediate states controls the sensitivity of the ^{176m}Lu and ^{176}Lu to the stellar temperature.

When do isomers decay?

The Lifetimes of Isomeric States

1. ***Strong nuclear force*** dominates interactions between nucleons making up the low energy excited nuclear states.



2. **Electro-magnetic** gamma-ray decay of these states provides an accurate and sensitive probe of this structure.

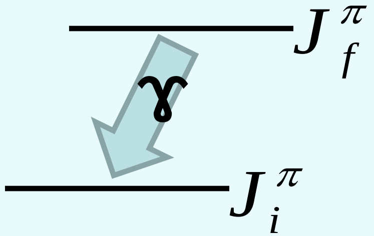
3. Comparison of the **experimental** gamma-ray **transition rates** with **theoretical** transition rates from nuclear models can give insight into the nuclear force...

The starting point is, as always, the Fermi Golden Rule.

Fermi Golden Rule (1927)

The **transition rate,** *T* for the decay of a nuclear state is given by:

$$T = \frac{2\pi}{\hbar}\left[\left\langle \psi_f^* \middle| M(\sigma L) \middle| \psi_i \right\rangle\right]^2 \rho(E)dE$$



Transition rate depends upon:

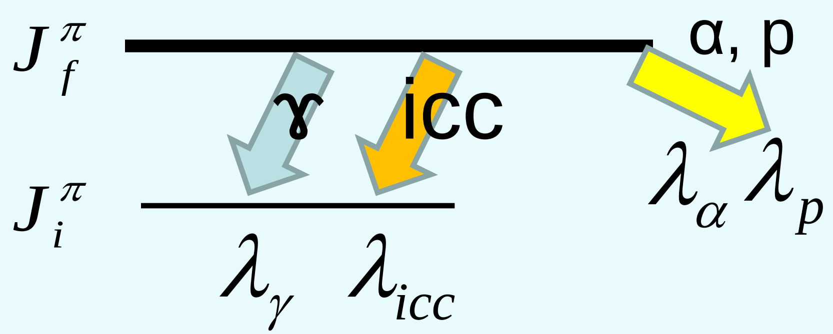
1. ***overlap*** interval between the initial Ψ_i and final Ψ_f states.

*2. M(σL) = **Operator** for decay process which turns initial into final state;*
σ = type, L=multipole order. e.g. Electric quadrupole (E2) operator.

1. *ρ(E)dE* = **Density** of final states for photon which gives transition dependence of, E^3

Transition Rates

The **transition rate** is also affected by other competing processes:



$$\lambda_f = \lambda_\gamma + \lambda_{icc} + \lambda_\alpha + \lambda_p \ldots$$

$$T_f = \frac{1}{\lambda} = \frac{1}{\lambda_\gamma + \lambda_{icc} + \lambda_\alpha + \lambda_p + \ldots}$$

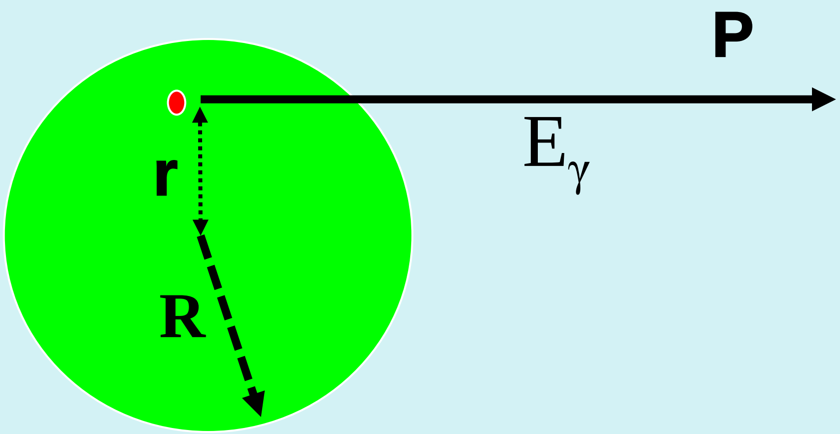
Usually the ϒ-ray branch dominates (10^{-15} – 10^{-9}) seconds unless:

1. large spin / orientation / shape change involved, or
2. low E_γ and high Z nucleus (Icc=10^9 ! for 7.8 eV in ^{229}Th).

Angular momentum removed by γ ray

γ rays have spin S = 1 ($m_z = \pm 1$ in direction of propagation).

Difficult for photon to remove orbital angular momentum.



Classical Approach:

Total angular momentum removed,

L = r x P (**P** = ħ **k**)

L=r h k (L= ℓħ, ℓ = 0, 1, 2 ...)

To even just remove 1 unit of orbital angular momentum,
(k r) must be ~1

But even k R << 1, and EM decays are **hindered** by a factor $(k\,R)^{2\ell}$ where ℓ is the orbital angular momentum removed.

Character of EM decays (σL)

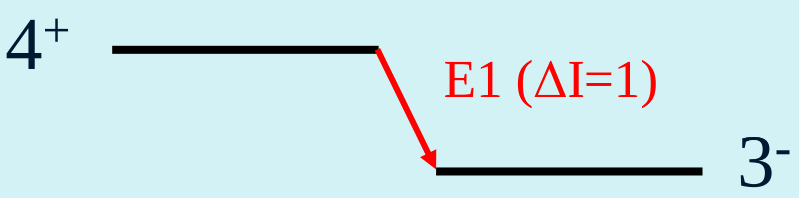
E1 Electric dipole (S=1, l=0; **<u>not</u>** hindered)
M1 Magnetic dipole (S=1, l=0; **<u>not</u>** hindered, but slower

E2 Electric quadrupole (l=1, **<u>hindered</u>** by $(kR)^2$ rel. to E1)
M2 Magnetic quadrupole ..

E3 Octupole (S=1, l=2; **<u>hindered</u>** by $(kR)^{2(\ell-1)}$ rel. to dipole
M3 ..

E4 Hexadecapole ...
M4 ..

<u>Consider</u> 4^+ state, it can decay to 3^- with:



1) E1 (ΔI=1) mainly
2) E3 (ΔI=1)
3) E5 (ΔI=1)

But **<u>only</u>** E1 competes due to $(kr)^{2l}$ hindrance for higher multipoles.

Evaluate γ-ray transition rates

$$\lambda = \frac{2\pi}{\hbar} \left| \int \psi^{\star} M(\sigma L) \psi \, \mathrm{d}v \right|^2 \frac{\mathrm{d}N}{\mathrm{d}E}$$

Transition operator:

$$M(EL) \sim \frac{1}{k} (kr)^L P_L(\cos\theta)$$

1. Electric dipole term:

$$r^1 P_1(\cos\theta) = r\cos\theta = z$$

(Electric dipole = *e* z)

2. Electric quadrupole term:

$$r^2 P_2(\cos\theta) = r^2 \frac{1}{2}[3\cos^2\theta - 1] = \frac{1}{2}[3z^2 - r^2]$$

(Mean value of $\langle 3z^2 - r^2 \rangle$ averaged over nucleus gave the quadrupole moment)

Single-particle Weisskopf γ ray transition rates

Matrix elements are evaluated for a **single** proton making a simple transition between two shell-model states.

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

E = transition energy in units of MeV

λ in units of s^{-1}

Weisskopf single-particle γ-ray transition rates:

Consider a **500-keV** transition in ^{229}Th:

$T_{1/2}(M1) = 9.9\times10^{-14}$ s
$T_{1/2}(M2) = 1.7\times10^{-8}$ s *** Isomeric ***
$T_{1/2}(M3) = 4.0\times10^{-3}$ s *** Isomeric ***
$T_{1/2}(M4) = 1.5\times10^{+3}$ s *** Isomeric ***

$(kr)^{2l}$ hindrance

$T_{1/2}(E1) = 1.5\times10^{-15}$ s
$T_{1/2}(E2) = 2.1\times10^{-10}$ s
$T_{1/2}(E3) = 5.0\times10^{-5}$ s *** Isomeric ***
$T_{1/2}(E4) = 16.4$ s *** Isomeric ***

Only M1, E1 and E2 have half-lives < 10^{-9} s (non-isomeric).

Weisskopf single-particle γ-ray transition rates:

Consider a **300-keV** transition in ^{229}Th:

$T_{1/2}$ (M1) = 4.6×10^{-13} s
$T_{1/2}$ (M2) = 2.2×10^{-7} s *** Isomeric ***
$T_{1/2}$ (M3) = 1.4×10^{-1} s *** Isomeric ***
$T_{1/2}$ (M4) = 149228 s *** Isomeric ***

$(kr)^{2l}$ hindrance

$T_{1/2}$ (E1) = 6.9×10^{-15} s
$T_{1/2}$ (E2) = 2.8×10^{-9} s *** Isomeric ***
$T_{1/2}$ (E3) = 1.8×10^{-3} s *** Isomeric ***
$T_{1/2}$ (E4) = 1630.97 s *** Isomeric ***

Only M1 and E1 have half-lives < 10^{-9} s (non-isomeric).

Weisskopf single-particle γ-ray transition rates:

Consider a **150-keV** transition in ^{229}Th:

$T_{1/2}$ (M1) = 3.7×10^{-12} s
$T_{1/2}$ (M2) = 7.0×10^{-6} s *** Isomeric ***
$T_{1/2}$ (M3) = 18.10 s *** Isomeric ***
$T_{1/2}$ (M4) = $7.6 \times 10^{+7}$ s *** Isomeric ***

$(kr)^{2l}$ hindrance

$T_{1/2}$ (E1) = 5.5×10^{-14} s
$T_{1/2}$ (E2) = 8.9×10^{-8} s *** Isomeric ***
$T_{1/2}$ (E3) = 0.2275 s *** Isomeric ***
$T_{1/2}$ (E4) = $8.3 \times 10^{+5}$ s *** Isomeric ***

Only M1 and E1 have half-lives < 10^{-9} s (non isomeric).

Weisskopf single-particle γ-ray transition rates:

Consider a **10-keV** transition in ^{229}Th:

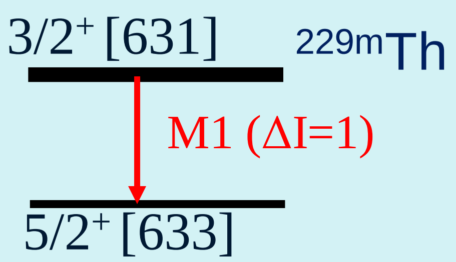
$T_{1/2}$(M1) = 1.2×10^{-8} s *** Isomeric ***
$T_{1/2}$(M2) = 5.29 s *** Isomeric ***
$T_{1/2}$(M3) = $3.1\times10^{+9}$ s *** Isomeric ***
$T_{1/2}$(M4) = $2.9\times10^{+18}$ s *** Isomeric ***

$(kr)^{2l}$ hindrance

$T_{1/2}$(E1) = 1.8×10^{-10} s
$T_{1/2}$(E2) = 0.0677 s *** Isomeric ***
$T_{1/2}$(E3) = $3.9\times10^{+7}$ s *** Isomeric ***
$T_{1/2}$(E4) = $3.2\times10^{+16}$ s *** Isomeric ***

Only E1 has half-life < 10^{-9} s (non-isomeric).

Weisskopf single-particle γ-ray transition rates:



Consider a **7.6-eV** transition in ^{229}Th:

$T_{1/2}$ (M1) = 28.2 s *** Isomeric ***
$T_{1/2}$ (M2) = $2.1\times10^{+16}$ s *** Isomeric ***
$T_{1/2}$ (M3) = $2.1\times10^{+31}$ s *** Isomeric ***
$T_{1/2}$ (M4) = ∞ s *** Isomeric ***

$(kr)^{2l}$ hindrance

$T_{1/2}$ (E1) = 0.42 s *** Isomeric ***
$T_{1/2}$ (E2) = $2.7\times10^{+14}$ s *** Isomeric ***
$T_{1/2}$ (E3) = $2.7\times10^{+29}$ s *** Isomeric ***
$T_{1/2}$ (E4) = ∞ s *** Isomeric ***

Every possible EM multipole decay is isomeric!

Why do isomers exist?

Why do isomers exist?

So far we've discussed how in EM decay, large half-lives arise due to **differences** or **non-overlap** between initial and final state.

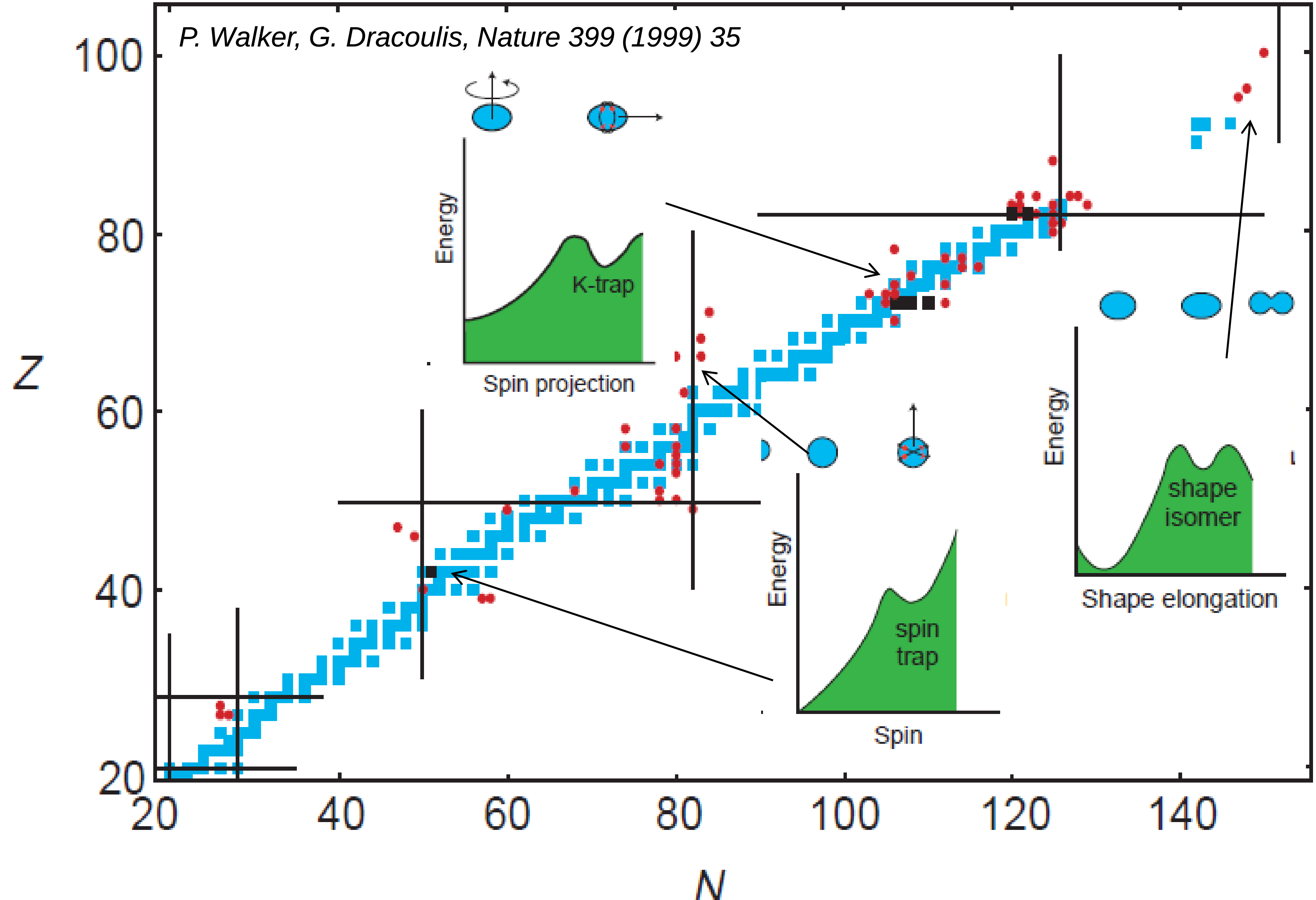
$$T = \frac{2\pi}{\hbar}\left[\langle \psi_f^* | M(\sigma L) | \psi_i \rangle\right]^2 \rho(E) dE$$

We generally classify isomers based upon 3 mechanisms:

1. **Shape-trap**
   - Difficulty changing **shape** to match the states to which it decays.
2. **Spin-trap**
   - difficulty changing **spin** to match the states to which it decays.
3. **K-Trap**
   - Difficulty changing their spin **orientation** relative to axis of symmetry to match the states to which it decays.

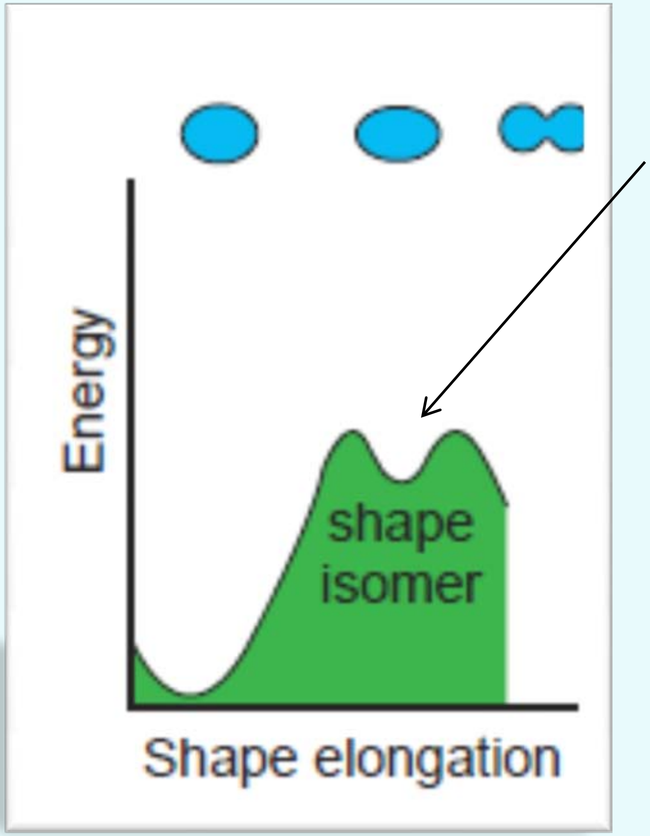
The exact situation depends upon the detailed shell structure of the neutron and proton orbits in each nucleus.

Three Isomer Types



D.M. Cullen, EMMI 2012 GSI

1. Shape Isomers



Secondary minimum in energy at large deformation supported by large Coulomb repulsion in heavy nuclei.

- The so called **"Fission isomers"**

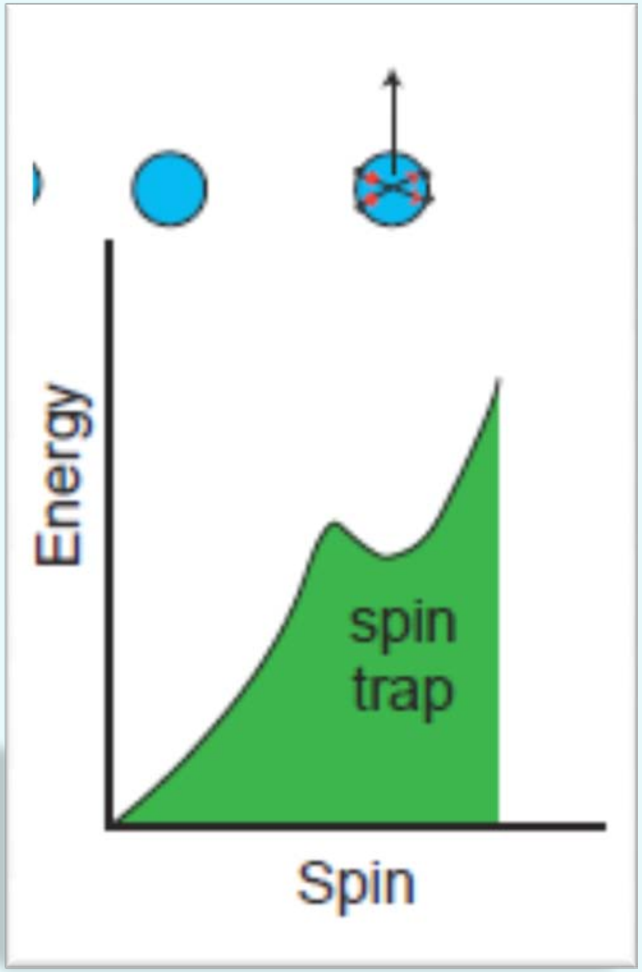
- ^{242}Am   2.2 MeV Isomer with 2:1 axis ratio
- Fissions with 14 ms half-life
- Longest half-life for fission isomer

For some fission isomers, γ-ray decay back to ground state **competes** with fission into two lighter nuclei.

*Isomerism results from large difference in **shape** of initial (deformed) and final (spherical) states.*

Other examples are the prolate – oblate shape coexistence in the Hg / Pb nuclei.

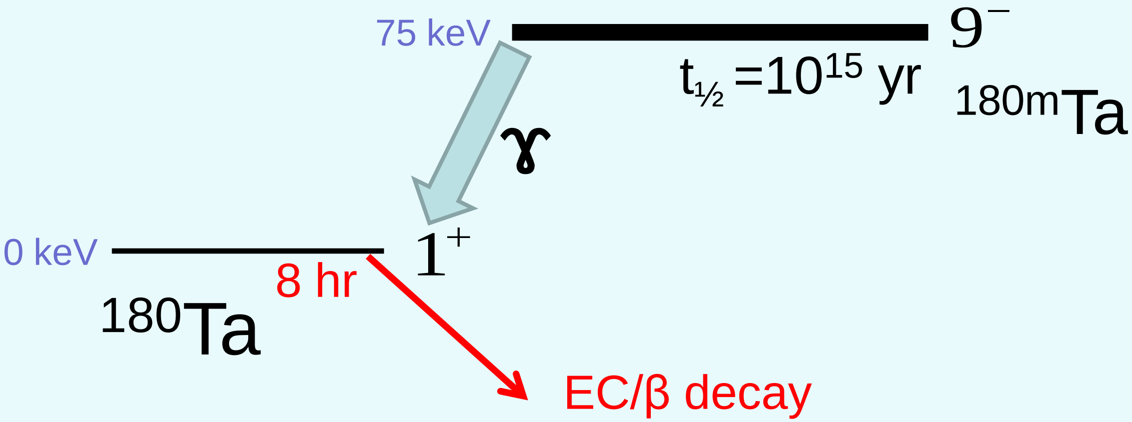
2. Spin-trap Isomers



Common form of isomer:

Existence due to inability of EM decays to meet angular momentum selection rules

- High multipolarity, low energy, M8 transition ($9^- \rightarrow 1^+$) results in 10^{15} year half-life.



*Isomerism results from large difference in **angular momentum** between initial (9^-) and final state (1^+).*

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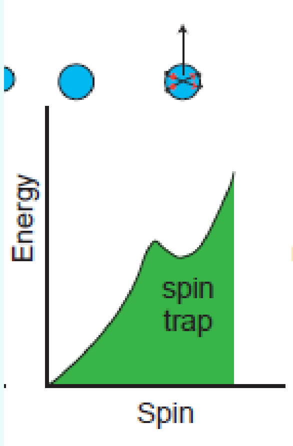
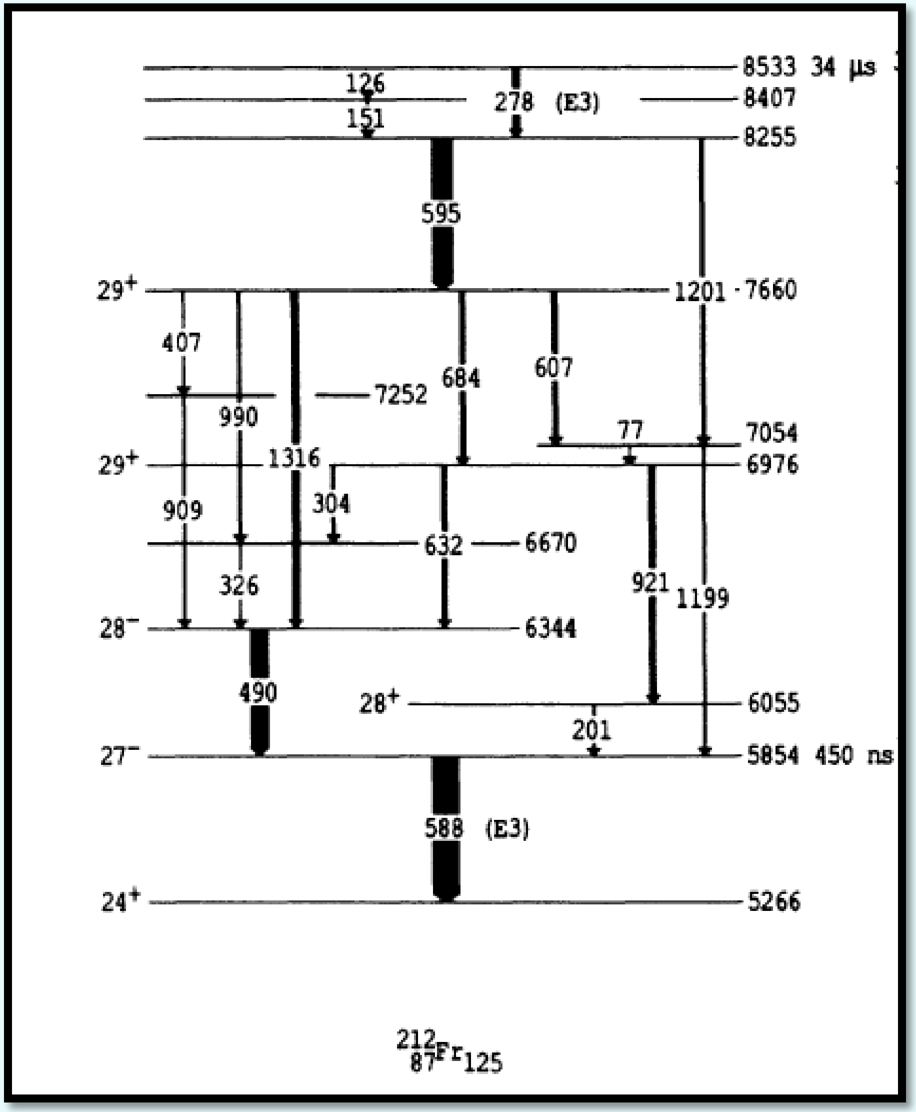
2. Spin-trap Isomers

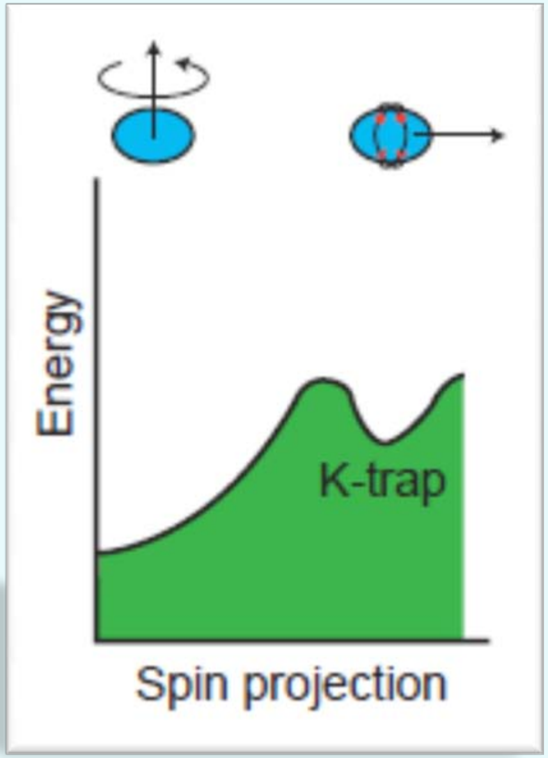




Spin-trap isomers are also known to exist at very high excitation energy in *near spherical* nuclei.

e.g. an 8.4 MeV, spin 34 isomer in ^{212}Fr with 34 μs half-life.

3. K-trap Isomers



K-isomers are a form of spin-trap isomer

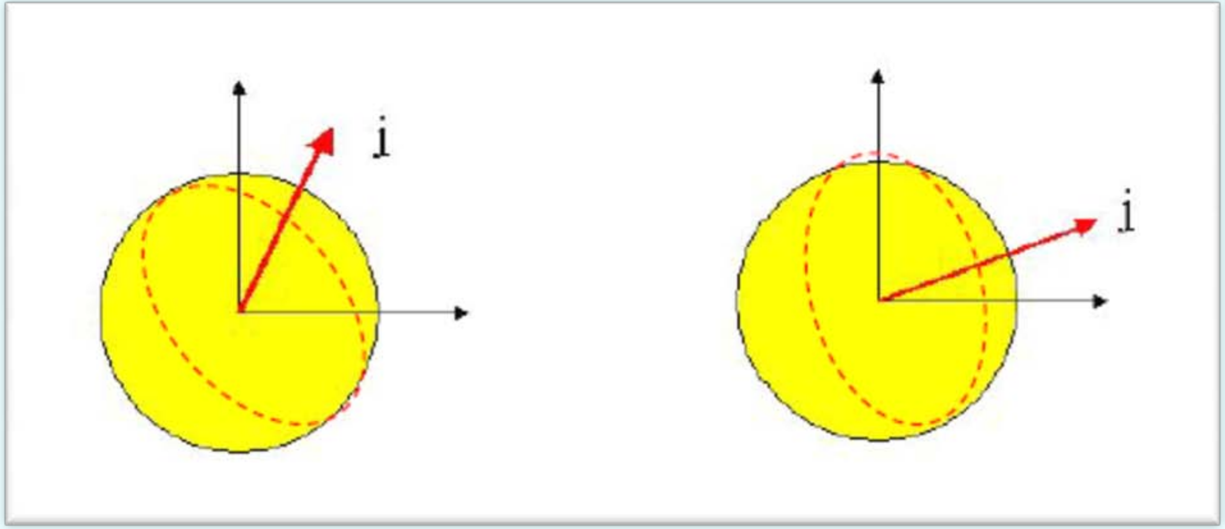
K-isomers only exist in mid-shell axially symmetric *deformed* nuclei

Existence depends not only on *magnitude* of spin (I=K) but on its *orientation*.

Isomerism results from difference in ***orientation*** *of angular momentum between initial and final states.*

3. K-trap or K Isomers

Orientation of nuclear orbits



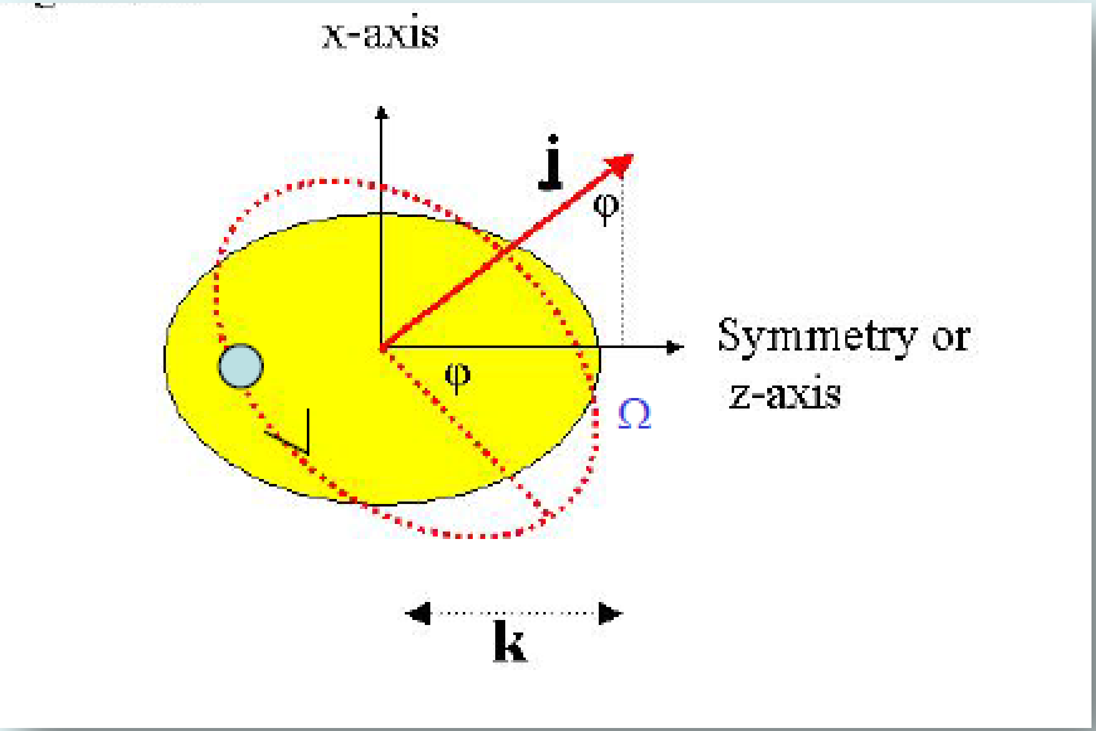
In a spherical nucleus the energy of an orbit does not depend on its **orientation** relative to the nuclear symmetry axis.

We have *nlj* quantum numbers.

3. K-Isomers

In a deformed nucleus, the energy of states are **strongly** dependent on

1. the orientation of the orbit
2. its overlap with the core.



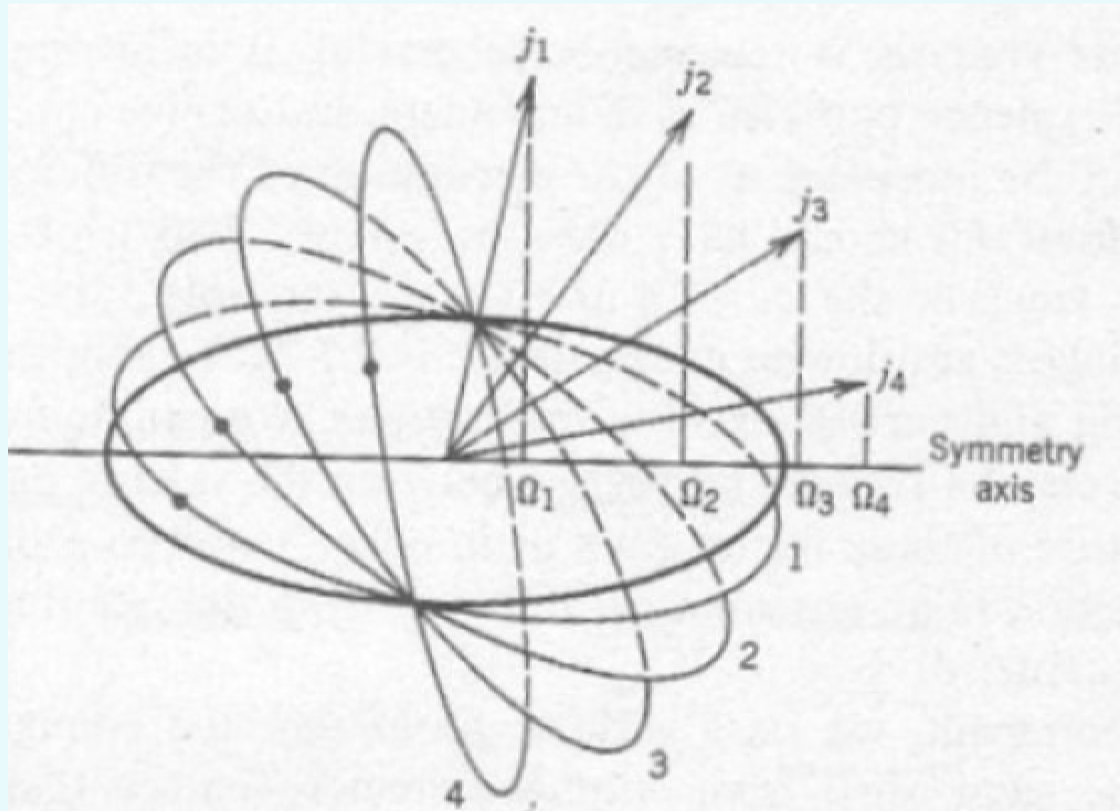
The **orientation** of an orbit is specified by magnetic sub-state of the nucleon or its projection, K, of the **total** intrinsic angular momentum onto the symmetry axis.

We use the $[N\ n_z\ \lambda]\Omega$ quantum numbers.

3. K-Isomers

The High-K Isomer

Where there is more than one single particle, then quantum number, **K**, is used to denote the **total** intrinsic angular momentum projection onto the symmetry axis,



$$K = \sum_i \Omega_i = \Omega_1 + \Omega_2 + \Omega_2 + \ldots$$

As $\underline{J} = \underline{j}_1 + \underline{j}_2 + \ldots$

3. K-trap Isomers

K-isomers exist in mid-shell axially symmetric *deformed* nuclei and generally when upper orbits of shell are being filled (high-Ω components), e.g. N~100-106 Hf nuclei

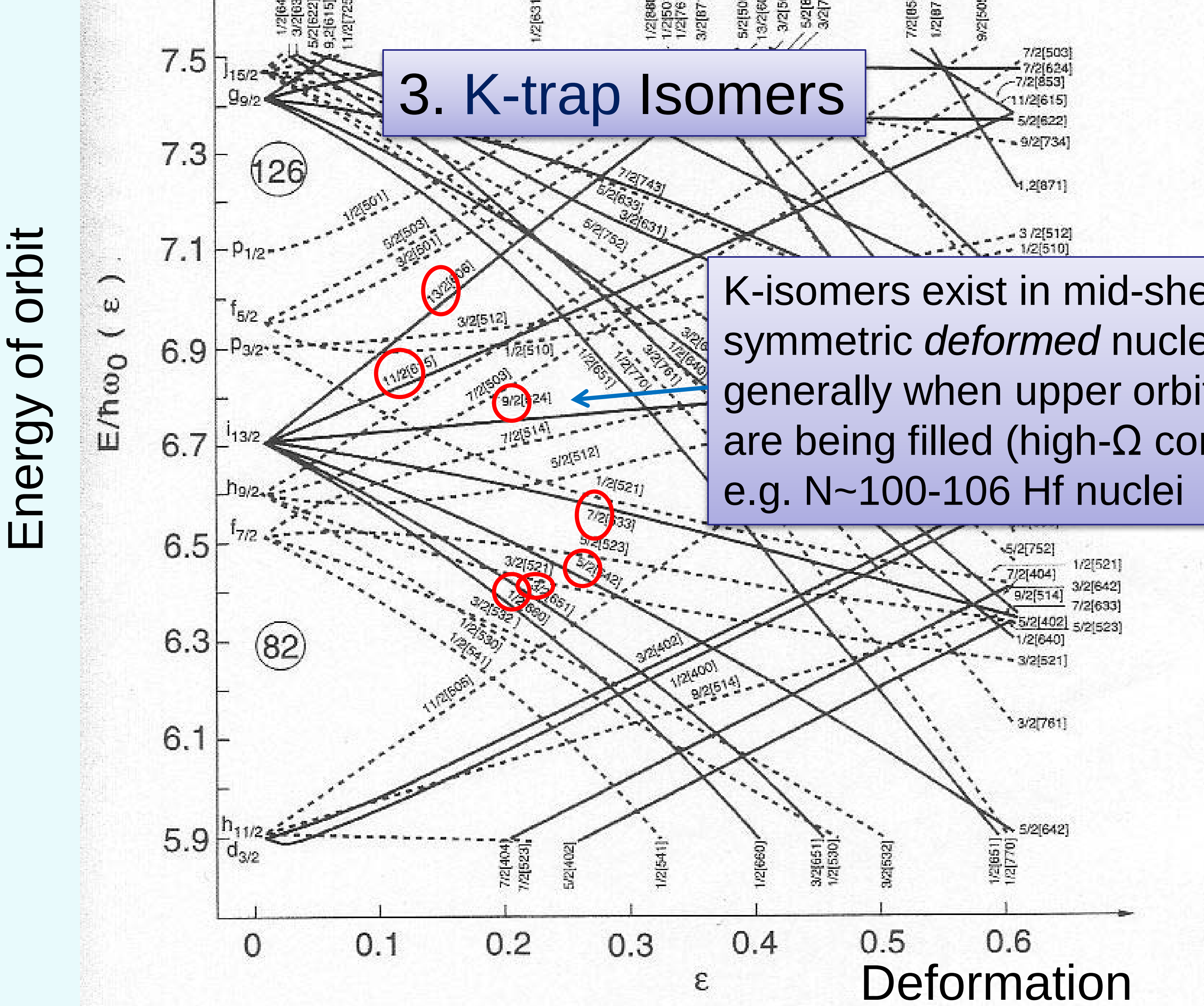
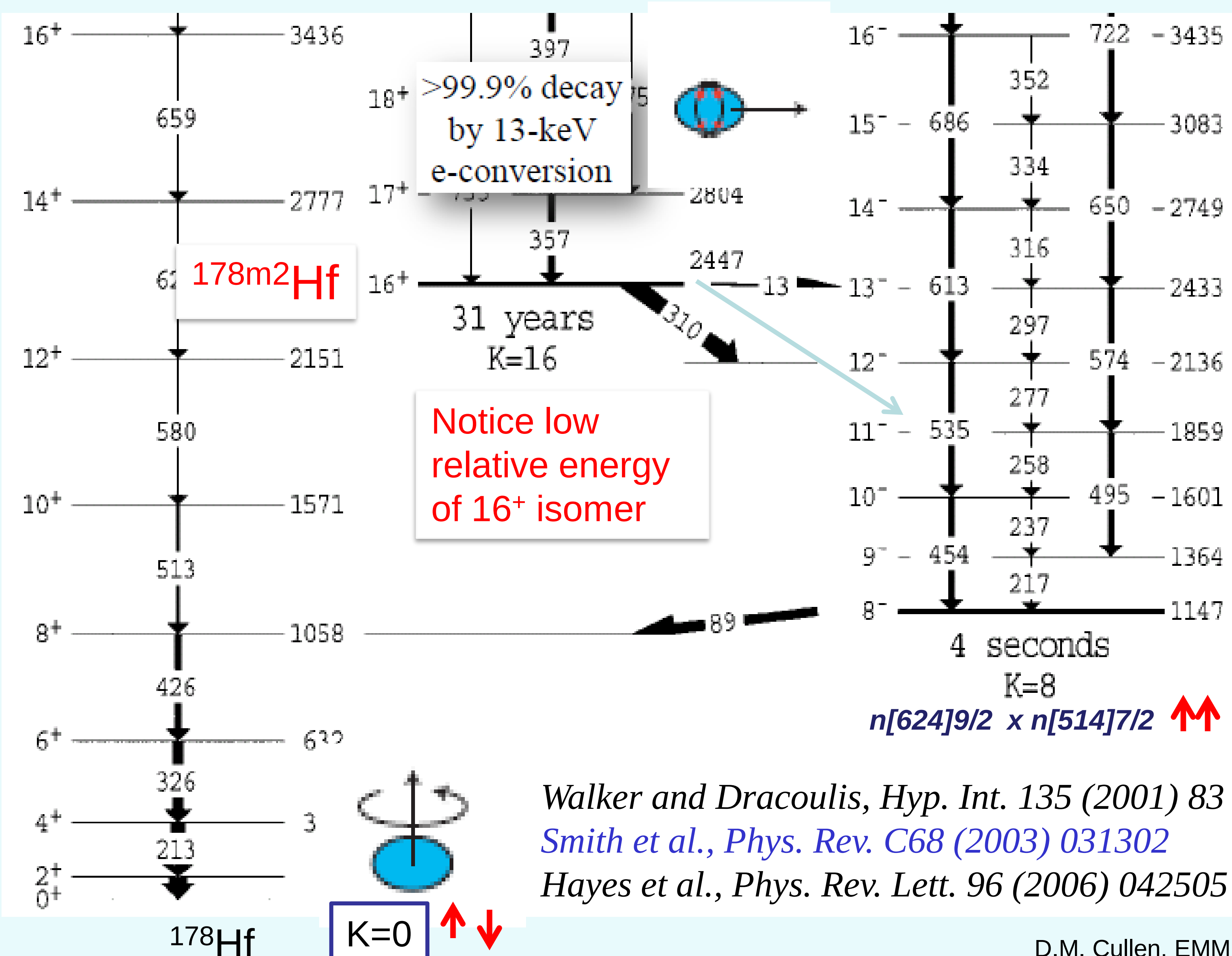


FIG. 8.4. (b) Nilsson diagram for the neutron shell 82–126. The abscissa is the deformation parameter ε, which is nearly the same as β. (Redrawn from Gustafson, 1967).

The classic long-lived Isomer; $^{178}Hf_{106}$



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

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

Hayes et al., Phys. Rev. Lett. 96 (2006) 042505

K-trap Isomers

K-Selection rule.

The multipolarity of the decay radiation from the isomer, λ must be greater than or equal to the change in the K-value between the initial and final states.

e.g. $^{180}Hf_{108}$

1.1 MeV, K=8 isomer, $t_{1/2}$=5.5 hr.

n[624]9/2 x n[514]7/2 ↑↑

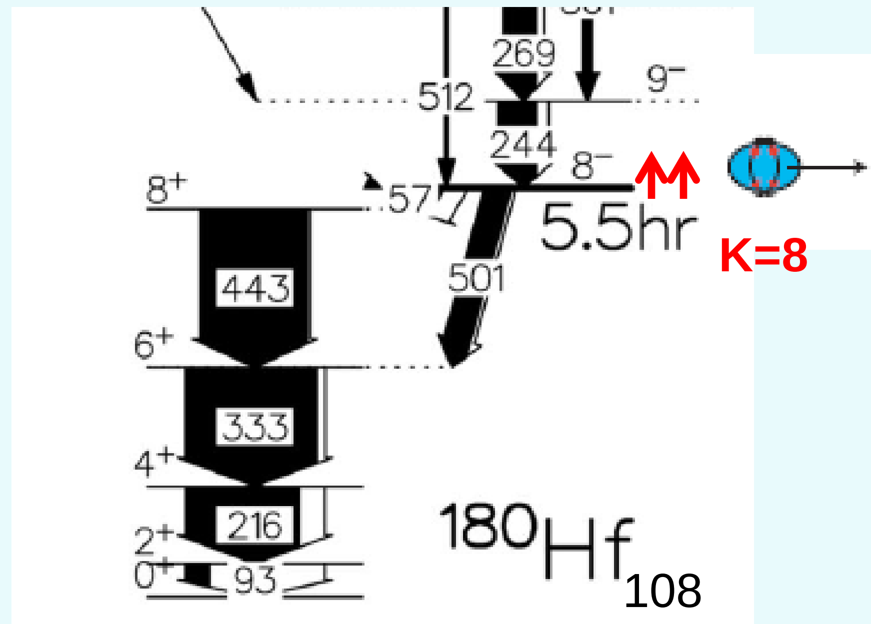
- nuclear ground state has K=0
  (fully paired even-even nucleus)

-i.e. Needs ΔK=8 transition!

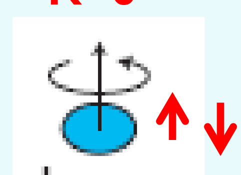
-Actually decays via hindered

λ=1 ΔK=8 57-keV transition

λ=2 ΔK=8 501-keV transition



K=0



Löbner's empirical rule (1965)

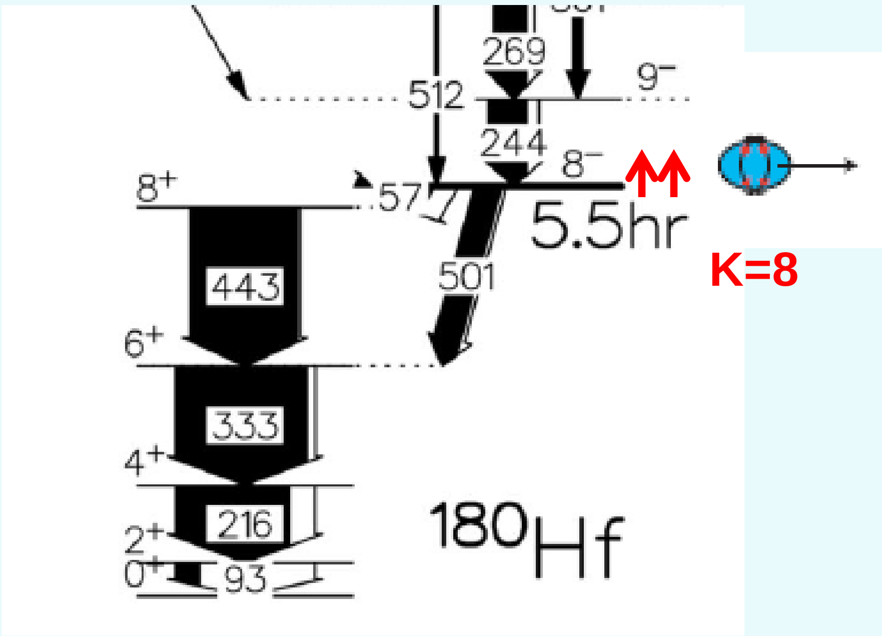
Define a degree of K-forbiddenness, $\nu = \Delta K - \lambda$

For every degree of K-forbiddenness, ν, transition will be hindered by factor of 100 over single-particle rate.

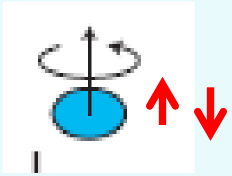
<u>e.g. For ^{180}Hf, Löbner suggests:</u>

- 57-keV transition (λ=1 ΔK=8, ν =7)
  Weisskopf, $T_{1/2}(E1) = 1.2\times10^{-12}$ s
  delayed by 100^7 or 10^{14} gives
  $T_{1/2}$(E1)=1200s or <u>20 mins</u>

- 501-keV transition (λ=2 ΔK=8 , ν =6)
  Weisskopf, $T_{1/2}(M2) = 2.0\times10^{-8}$ s
  delayed by 100^6 = 10^{12} gives
  $T_{1/2}$(M2)=2000s = <u>33 mins</u>



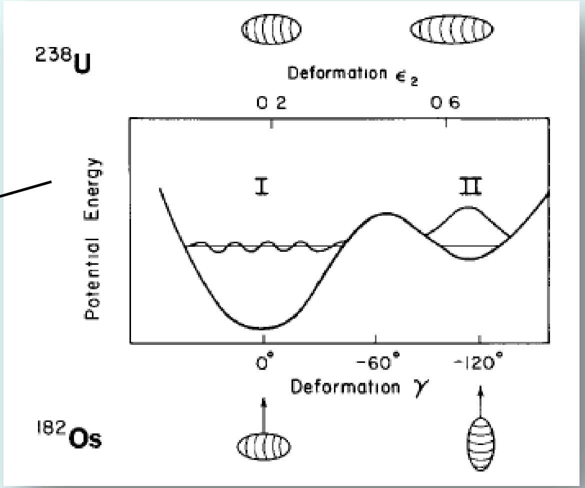
K=0



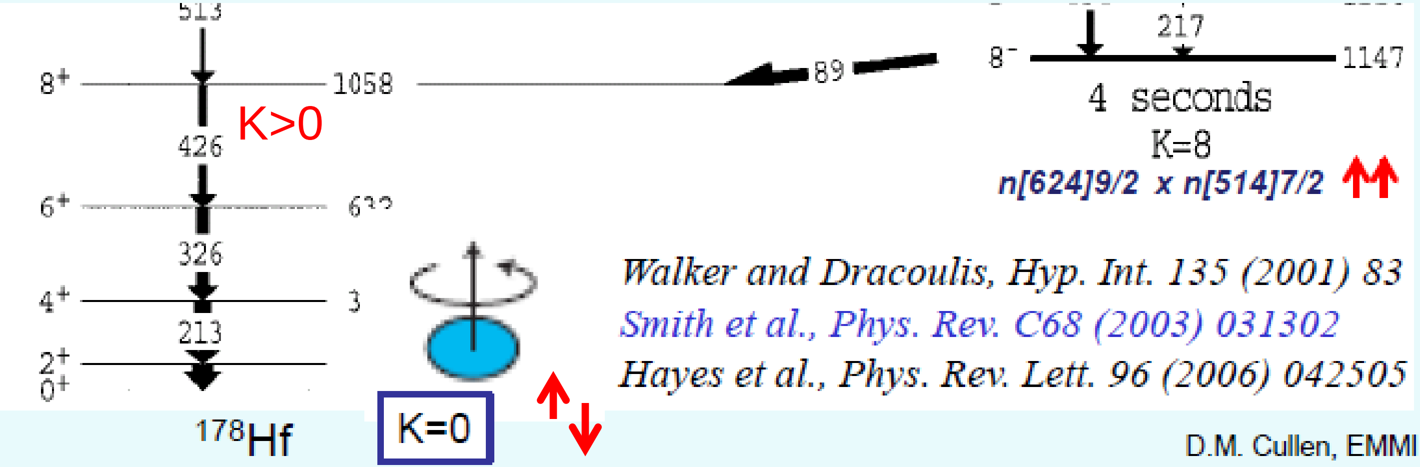
Löbner's gives reasonable estimates for lifetimes

So the K-Selection rule appears to hold. However, there are certain exceptions:

1. Gamma softness (tunnelling through γ plane / reorientation of intrinsic nuclear spin) ^{182}Os. NPA 485 (88) 136.



2. K-mixing through Coriolis force, where ground-state band has non-zero K components which mix with the K-isomer wavefuntion and enhance the decay.



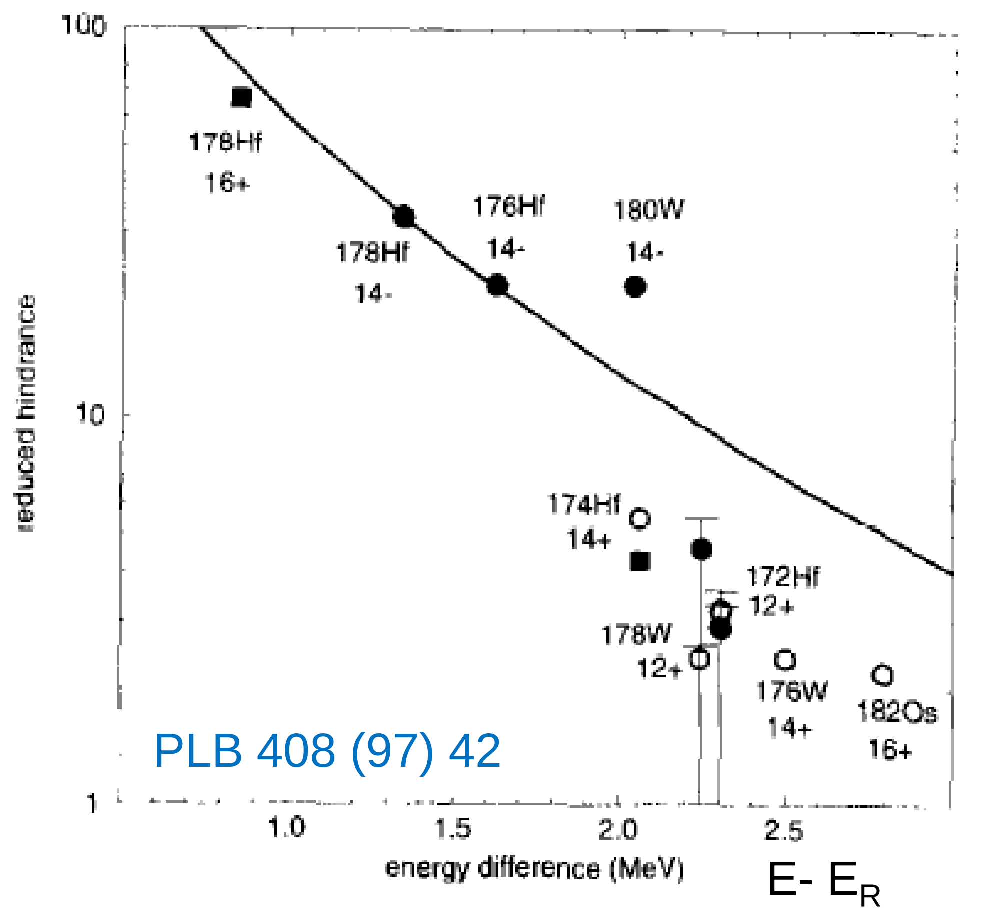
Breakdown of the K-Selection rule.

3. Statistical K-mixing at high excitation energy / level density.

   Characterise this by excitation energy above yrast rotational states, $E – E_R$.

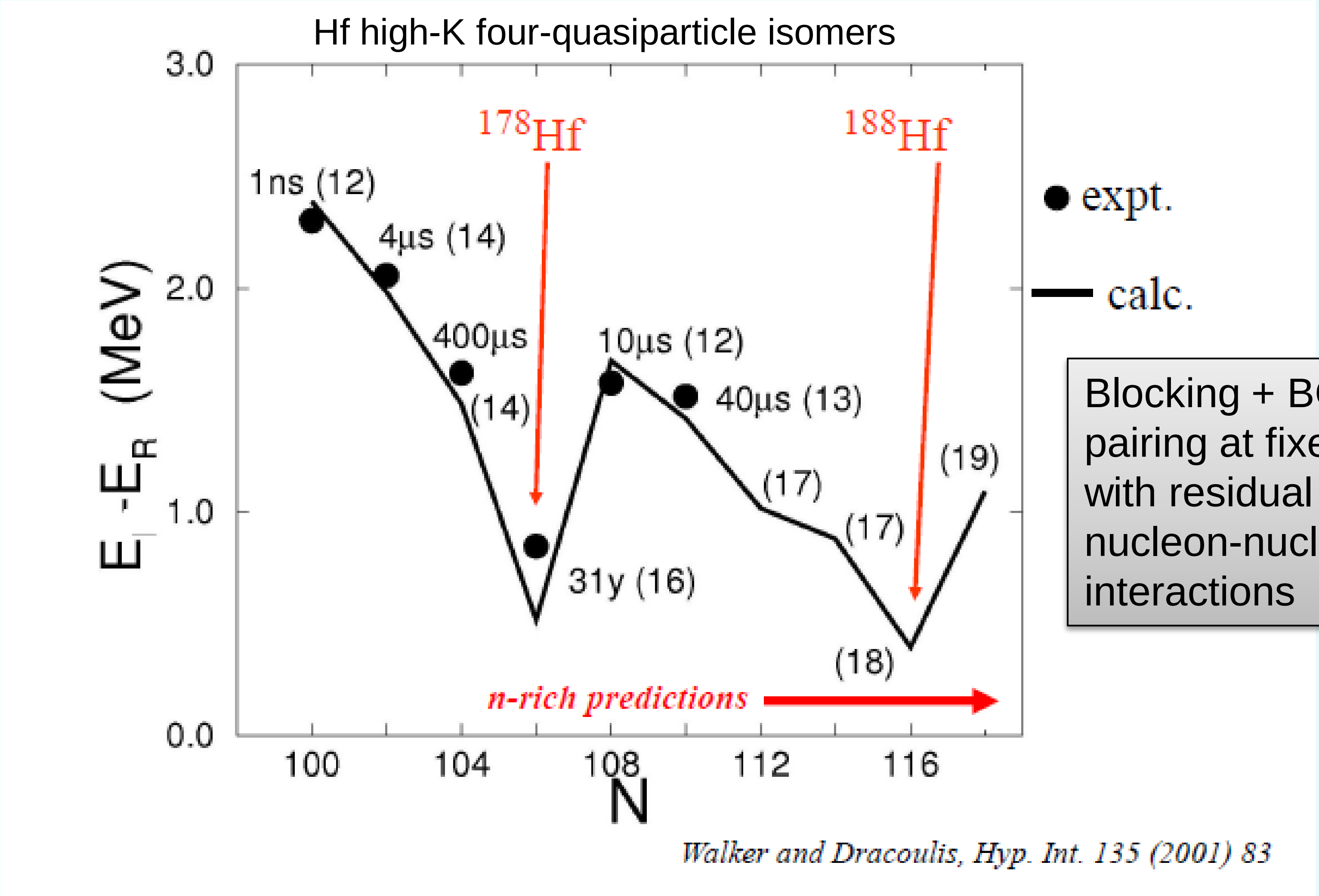
   At higher excitation energy, the density of states increases as ~ $E^{1/2}$

   The number of high-K states provide **additional** paths for the isomer to decay to and **reduce** the isomer lifetime.



PLB 408 (97) 42

Excitation energy of isomeric states

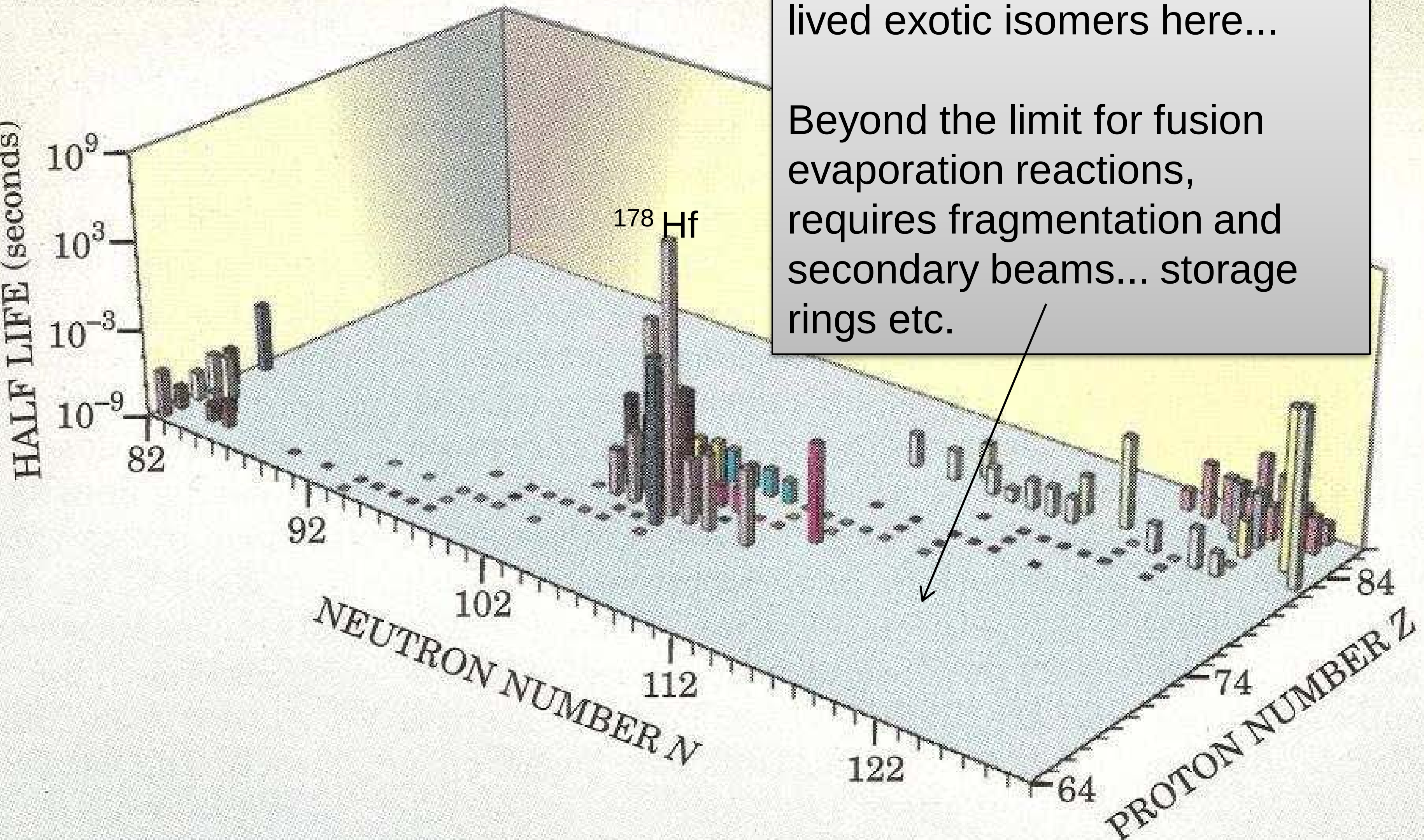


Blocking + BCS pairing at fixed shape with residual nucleon-nucleon interactions

Note:

1. Low-energy isomers should have the longest lifetimes!
2. In Mass 180 region, they should be found in the n-rich nuclei...

Mass 180 Isomers (spin + K traps can reinforce isomerism)



Predictions for many very long lived exotic isomers here...

Beyond the limit for fusion evaporation reactions, requires fragmentation and secondary beams... storage rings etc.

Walker and Carroll, Physics Today (June 2005) 39

Experimental techniques for Isomer Detection

1. Recoil shadow (delayed)
2. Recoil-Isomer tagging (prompt and delayed)
3. Ion-Traps (delayed)
4. Schottky Mass measurements (delayed)
5. Many other techniques at this meeting...
6. ...

Summary and Future

- Hopefully I've given a flavour for the *how*, *why*, *when* and *where* of isomers!
- A *variety* of isomeric states can exist in nuclei
- These affects don't always occur alone and can reinforce each other, e.g. the long lived Hf K and spin-trap isomers.
- The longest or most hindered isomers are often those with the lowest excitation energy.
- Calculations with BCS blocking and residual interactions show that many new isomers are just "*waiting*" to be discovered !

The End...