Some (more) High(ish)-Spin Nuclear Structure

Lecture 3

Deformed States and EM transition rates.

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Outline of Lectures

- 1) Overview of nuclear structure 'limits'
  - Some experimental observables, evidence for shell structure
  - Independent particle (shell) model
  - Single particle excitations and 2 particle interactions.

- 2) Low Energy Collective Modes and EM Decays in Nuclei.
  - Low-energy Quadrupole Vibrations in Nuclei
  - Rotations in even-even nuclei
  - Vibrator-rotor transitions, E-GOS curves

- 3) EM transition rates. what they mean and how you measure them
  - Deformed Shell Model: the Nilsson Model, K-isomers
  - Definitions of B(ML) etc. ; Weisskopf estimates etc.
  - Transition quadrupole moments (Qo)
  - Electronic coincidences;
  - Doppler Shift methods (RDM, DSAM)
  - Yrast trap isomers
  - Magnetic moments and g-factors

Unpaired Particles in Deformed Nuclei: The Nilsson Model

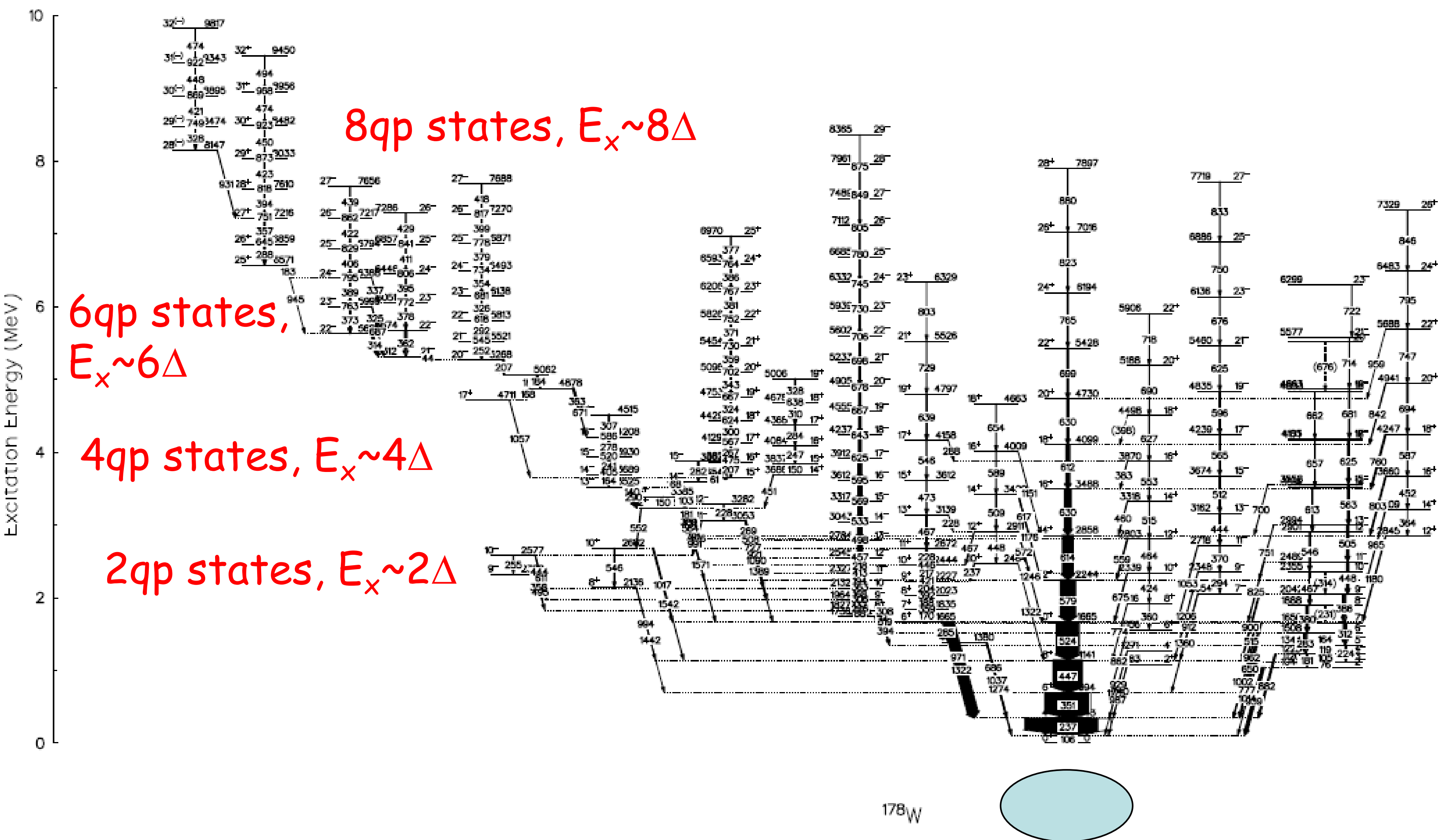
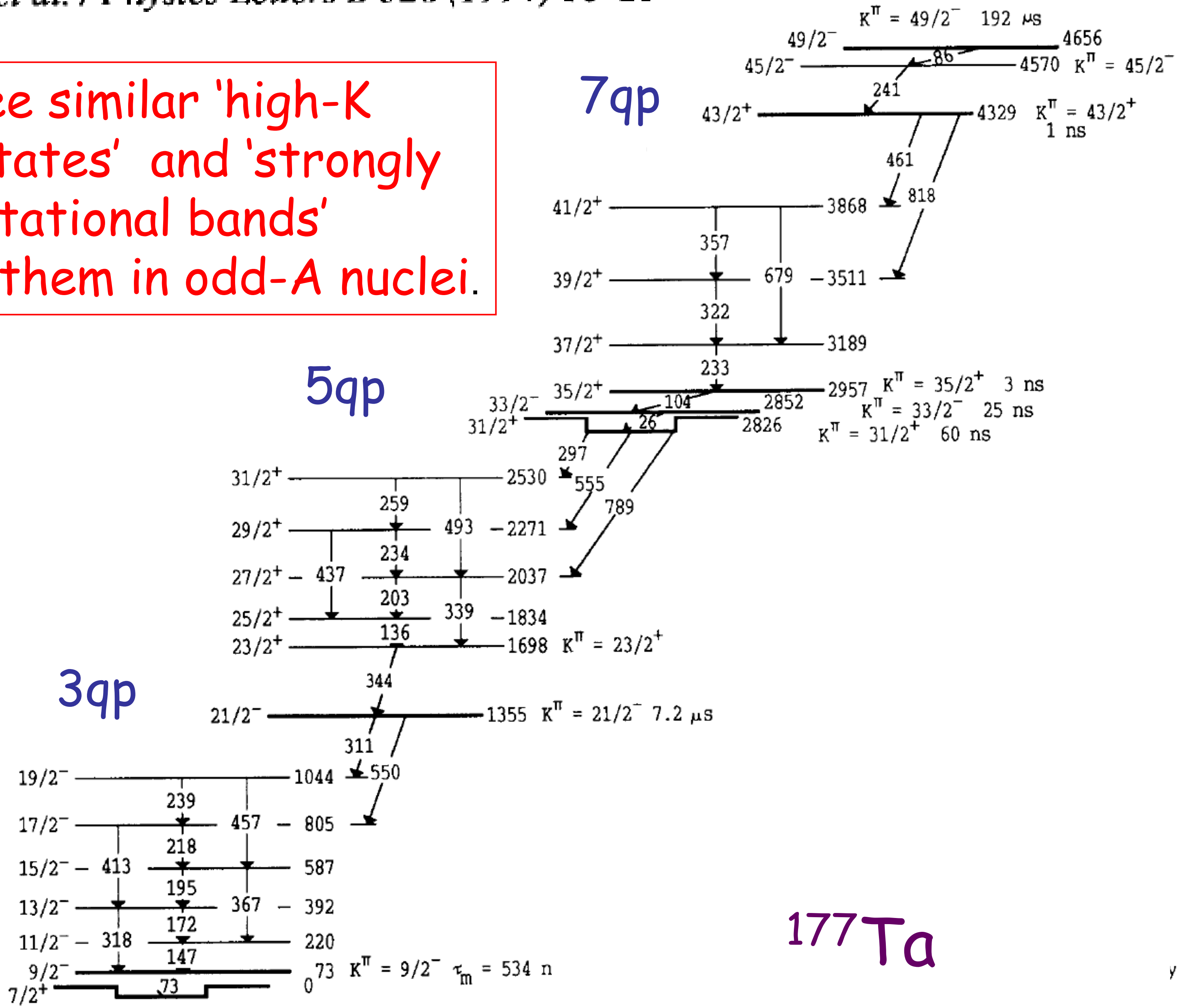


Figure 2.21: Partial decay scheme for ^{178}W showing 0, 2, 4, 6 and 8 quasi-particle structures [9].

C.S.Purry et al., Nucl. Phys. A632 (1998) p229

M. Dasgupta et al. / Physics Letters B 328 (1994) 16–21

We also see similar 'high-K isomeric states' and 'strongly coupled rotational bands' built upon them in odd-A nuclei.



Some of these 'isomers' can be VERY long lived, e.g.. E_x~1 MeV β-decaying K-'driven' isomer in ^{177}Lu.

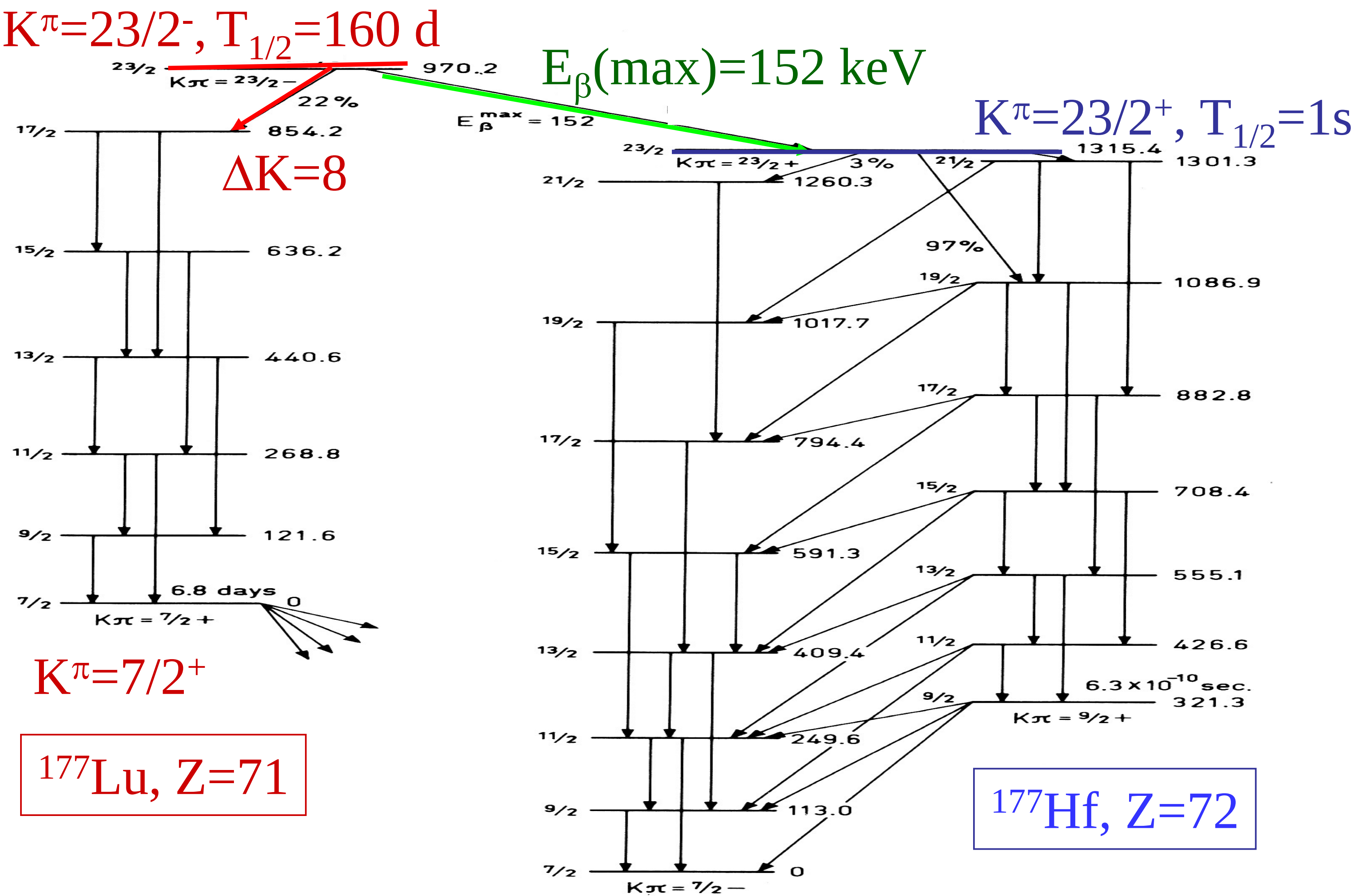
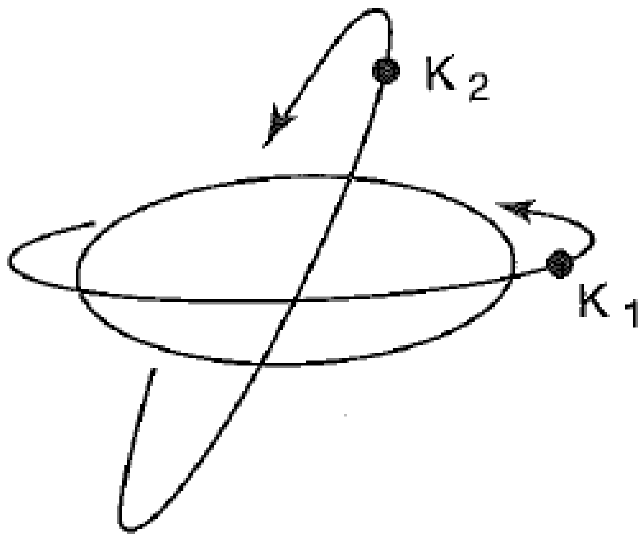
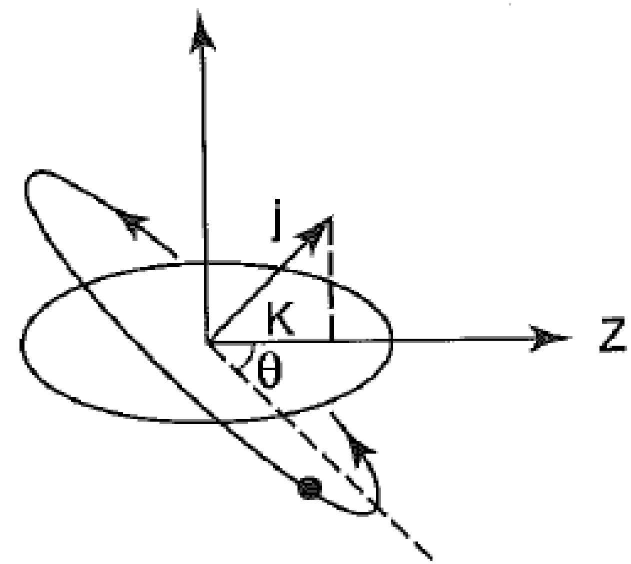


Figure 4-16 Decay scheme for ^{177}Lu^m. The data are taken from A. J. Haverfield, F. M. Bernthal, and J. M. Hollander, *Nuclear Phys.* **A94**, 337 (1967), which also includes results of previous investigations. Additional transitions reported by F. Bernthal (private communication) have also been included. The energies in the figure are in keV, and the decay times represent half lives.

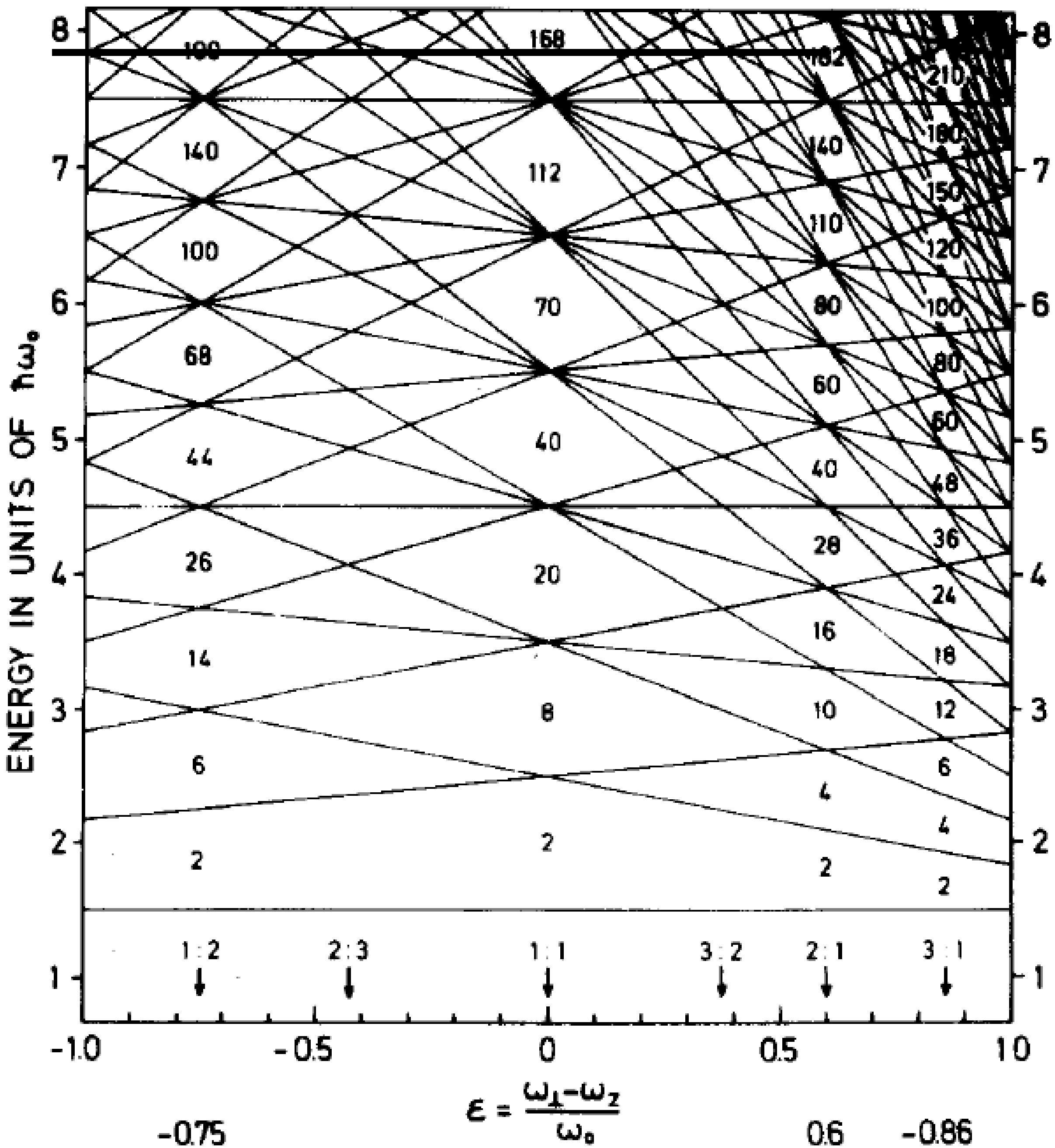
Deformed Shell Model: The Nilsson Model





sin θ ~ K / j

$$H = \frac{\mathbf{p}^2}{2m} + \frac{1}{2} m \left[\omega_x^2 (x^2 + y^2) + \omega_z^2 z^2\right] + C \mathbf{l} \cdot \mathbf{s} + D \mathbf{l}^2$$



Single particle states for an elongated spheroidal harmonic oscilator.

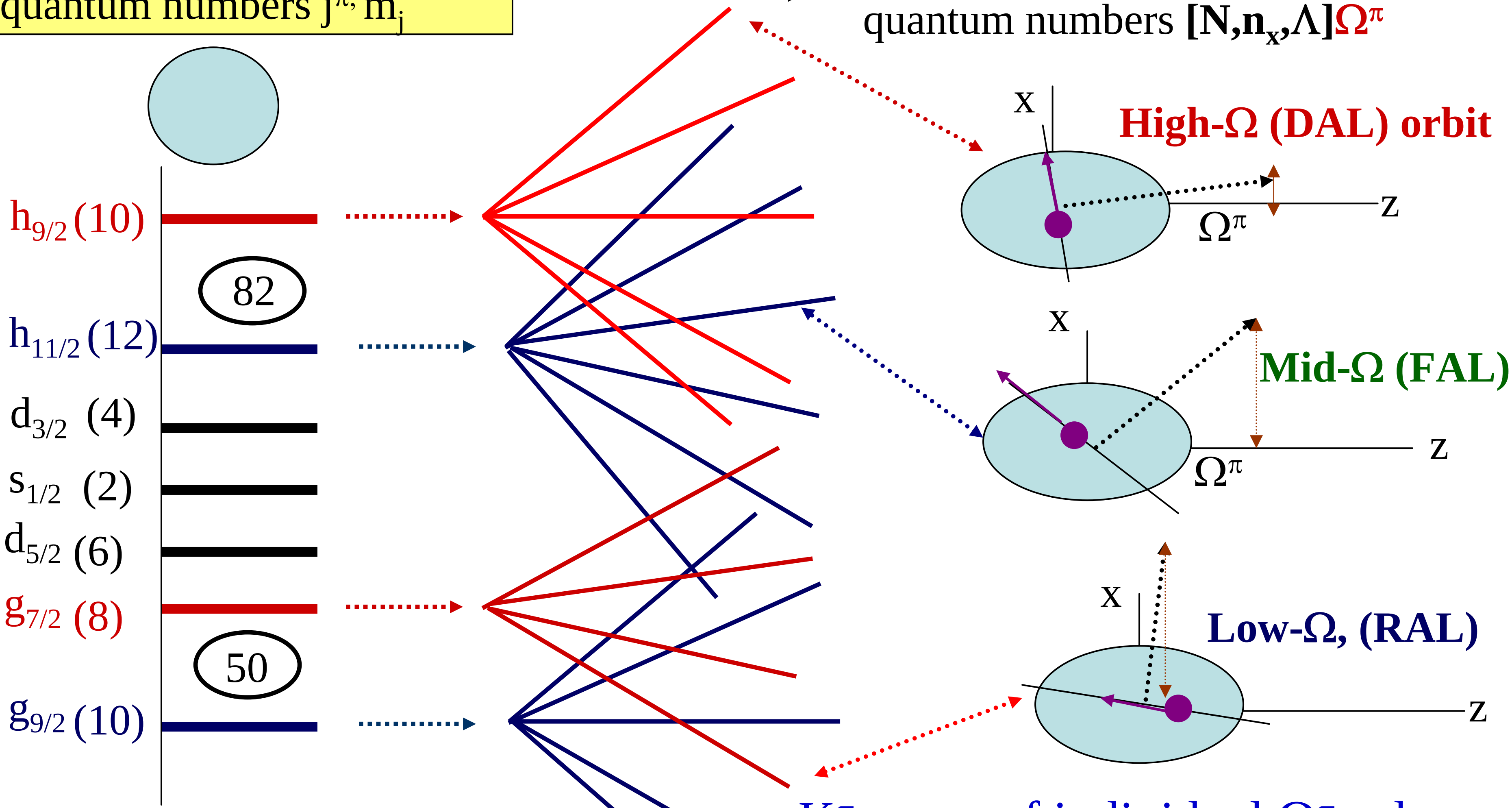
From Ragnarsson, Nilsson And Sheline, Physics Reports 45 (1978) p1

Effect of Nuclear Deformation on K-isomers

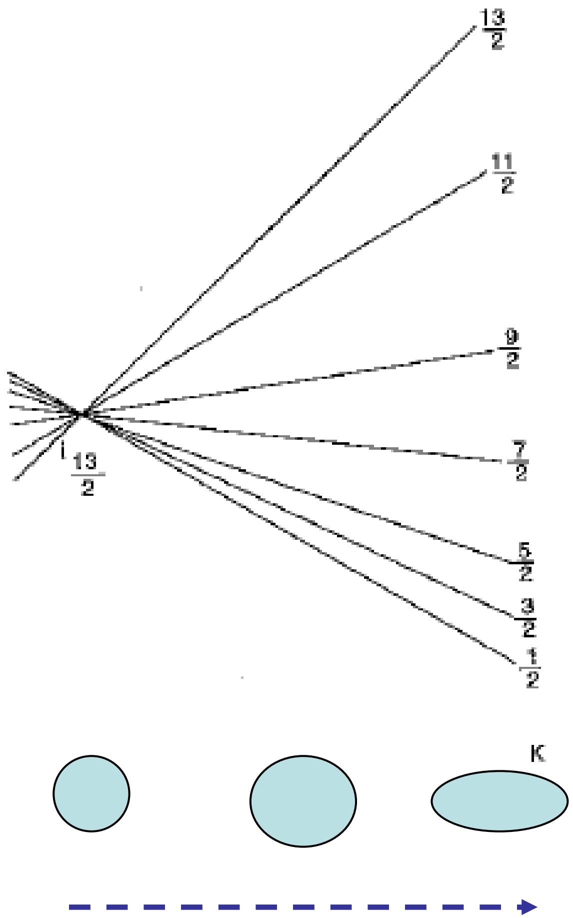
Spherical, harmon. oscilator
$H = \hbar\omega + a\,\boldsymbol{l.l} + b\,\boldsymbol{l.s}$,
quantum numbers j^{π}, m_j

Nilsson scheme: Quadrupole deformed
3-D HO. where $\hbar\omega \rightarrow \hbar\omega_x + \hbar\omega_y + \hbar\omega_z$
axial symmetry means $\omega_x = \omega_y$
quantum numbers $[N, n_x, \Lambda]\Omega^{\pi}$

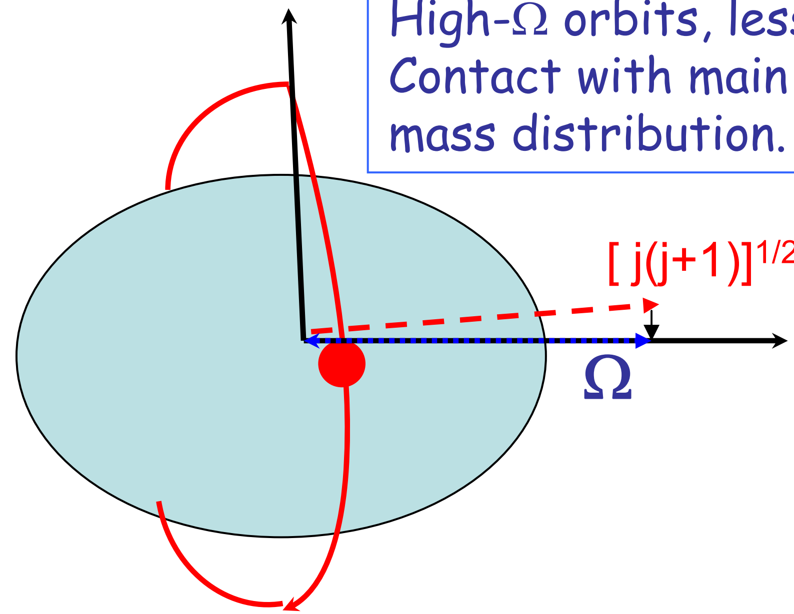
> prolate β_2



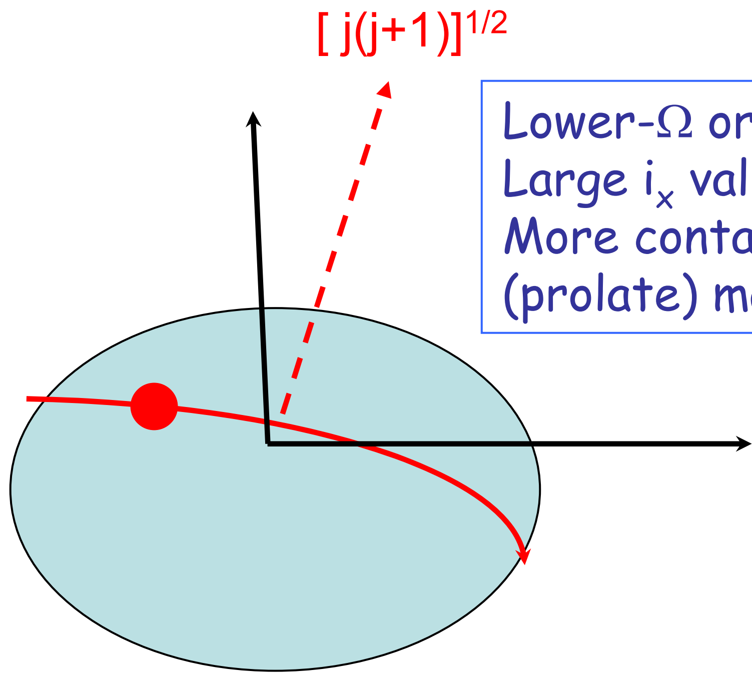
K^{π} = sum of individual Ω^{π} values.



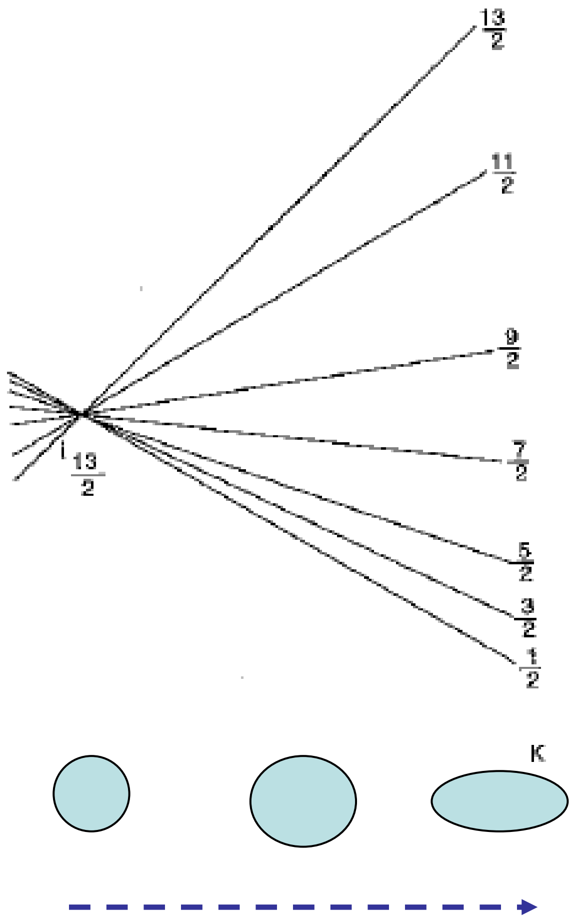
Increasing (prolate) deformation, bigger splitting.



High-Ω orbits, less Contact with main mass distribution.



Lower-Ω orbits, have Large i_x values and More contact with main (prolate) mass distribution.



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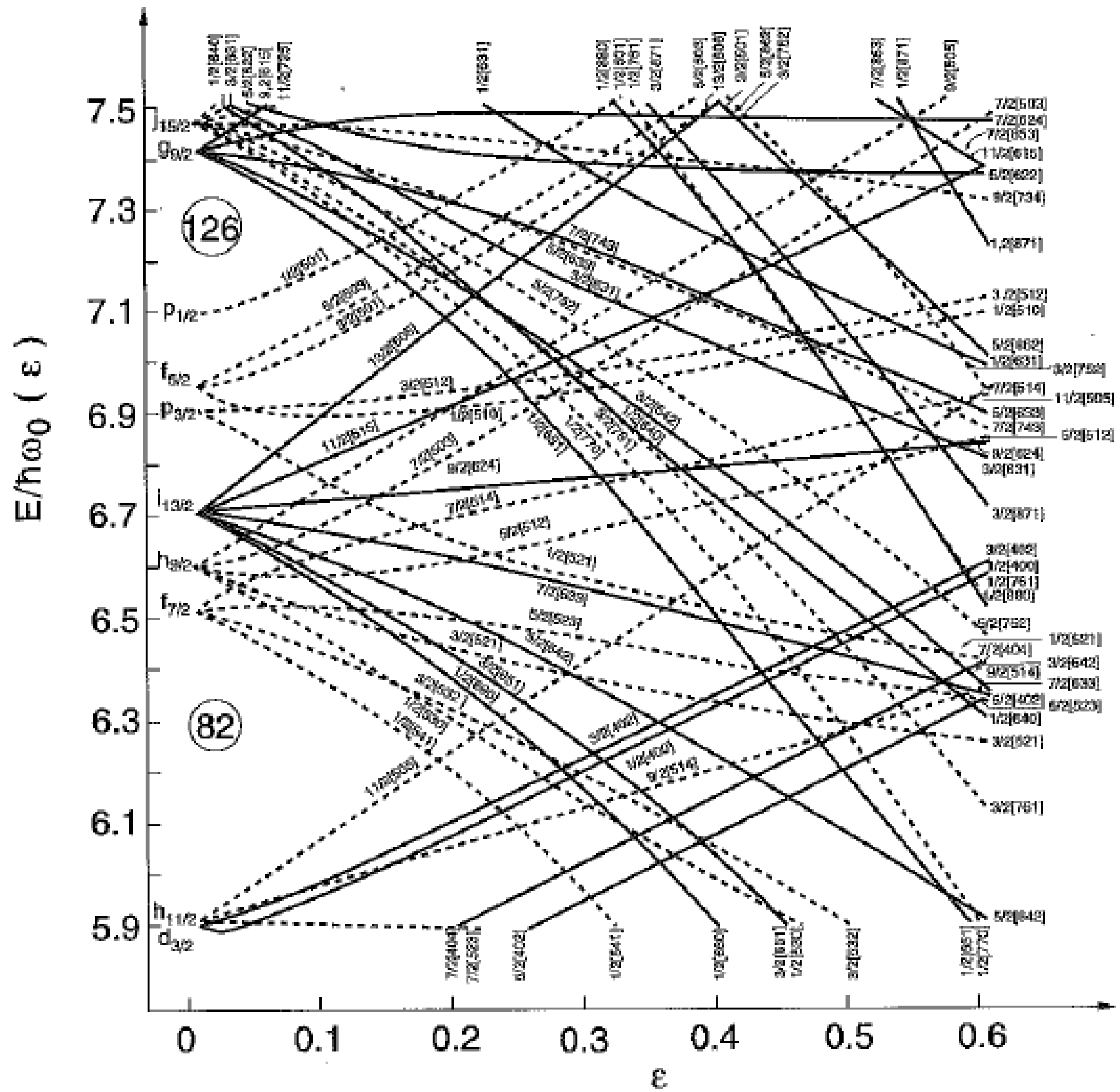
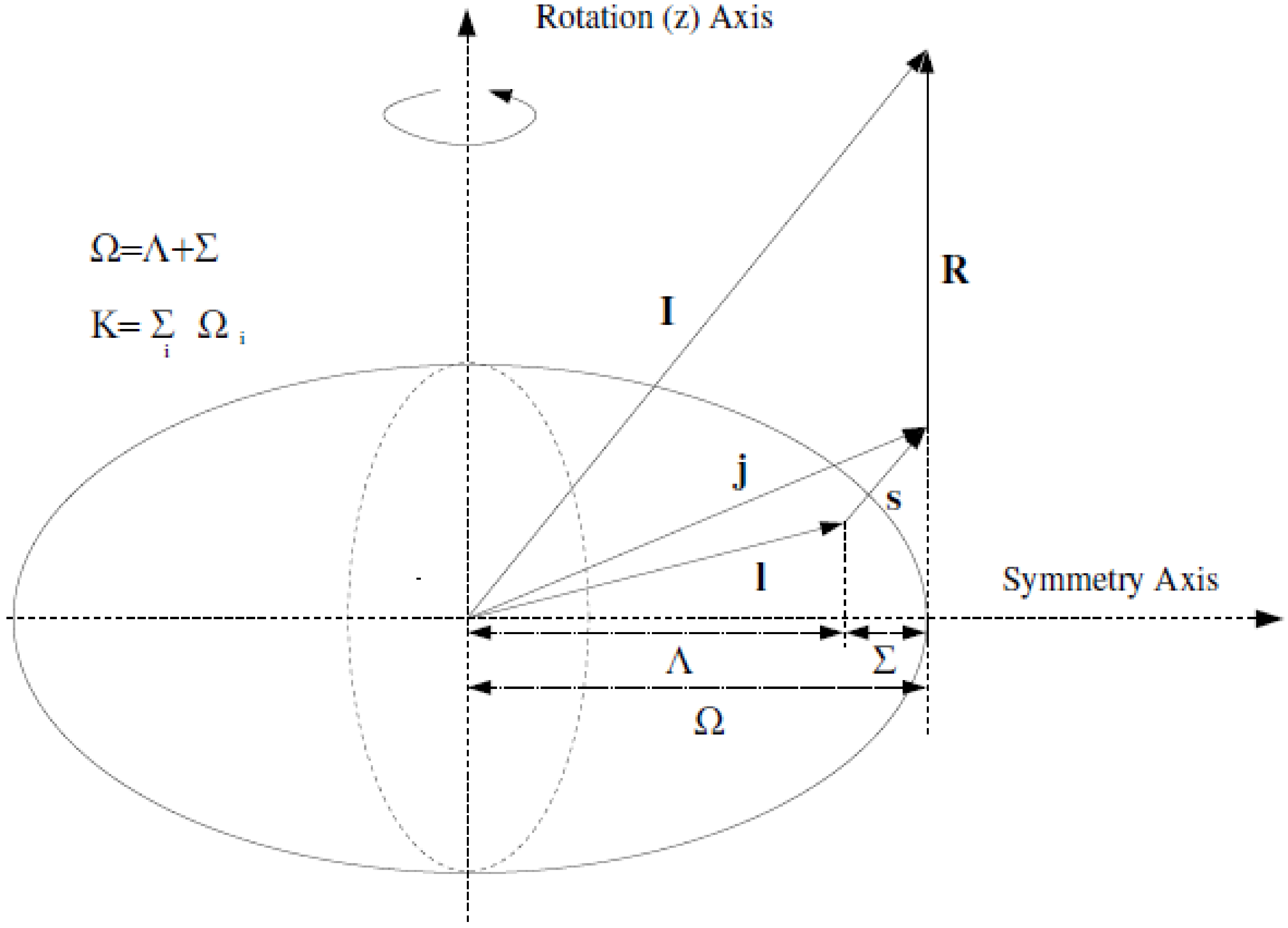
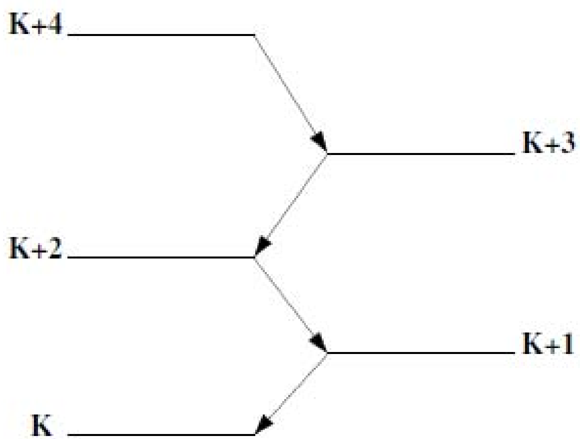
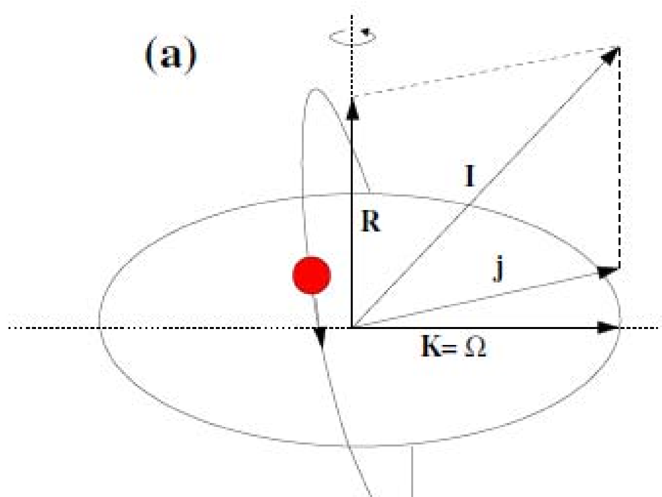


FIG. 8.4. (b) Nilsson diagram for the neutron shell 82–126. The abscissa is the deformation parameter ε, which is nearly the same as β. (Redrawn from Gustafson, 1967).

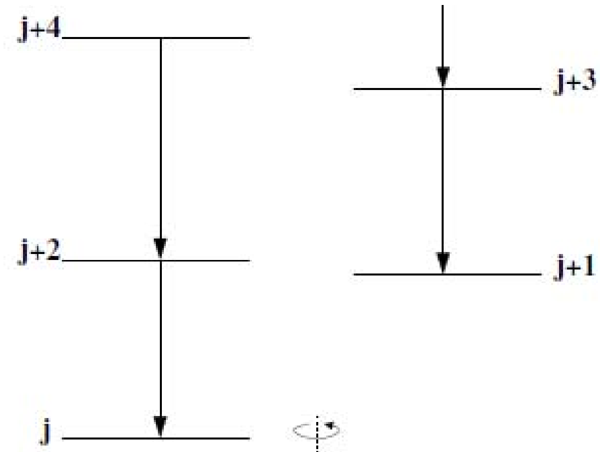

Rotation (z) Axis
Ω=Λ+Σ
K= Σ Ω
i i
I
R
j
s
l
Symmetry Axis
Λ
Σ
Ω

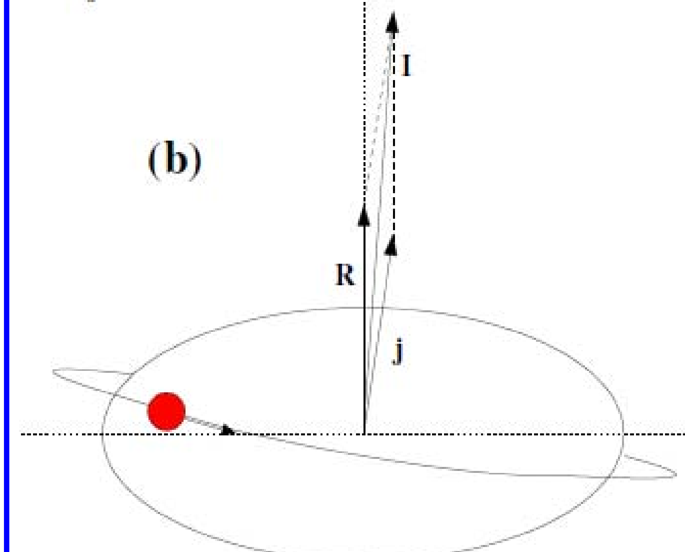
'**Strongly Coupled**' configuration.
Also called '**deformation aligned**'
Observe both 'signature partners',
Bandhead has I=K and see M1/E2
Transitions between states of I → I-1



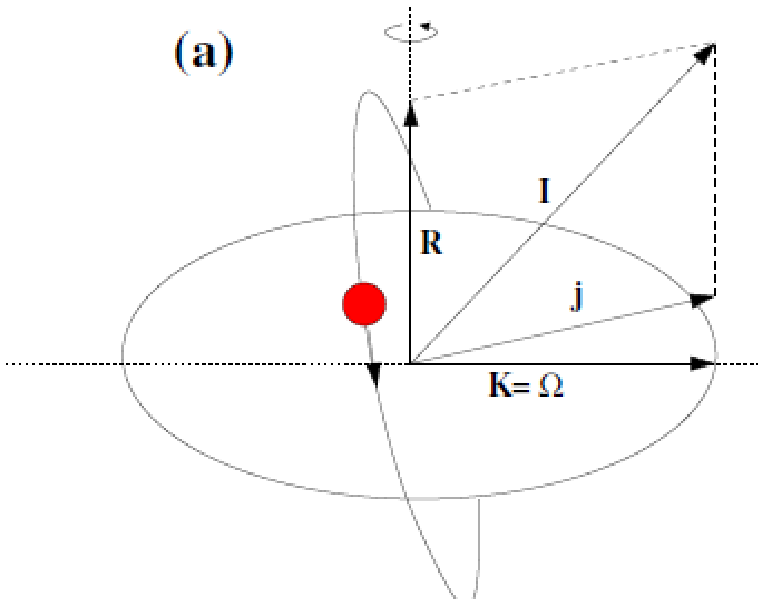


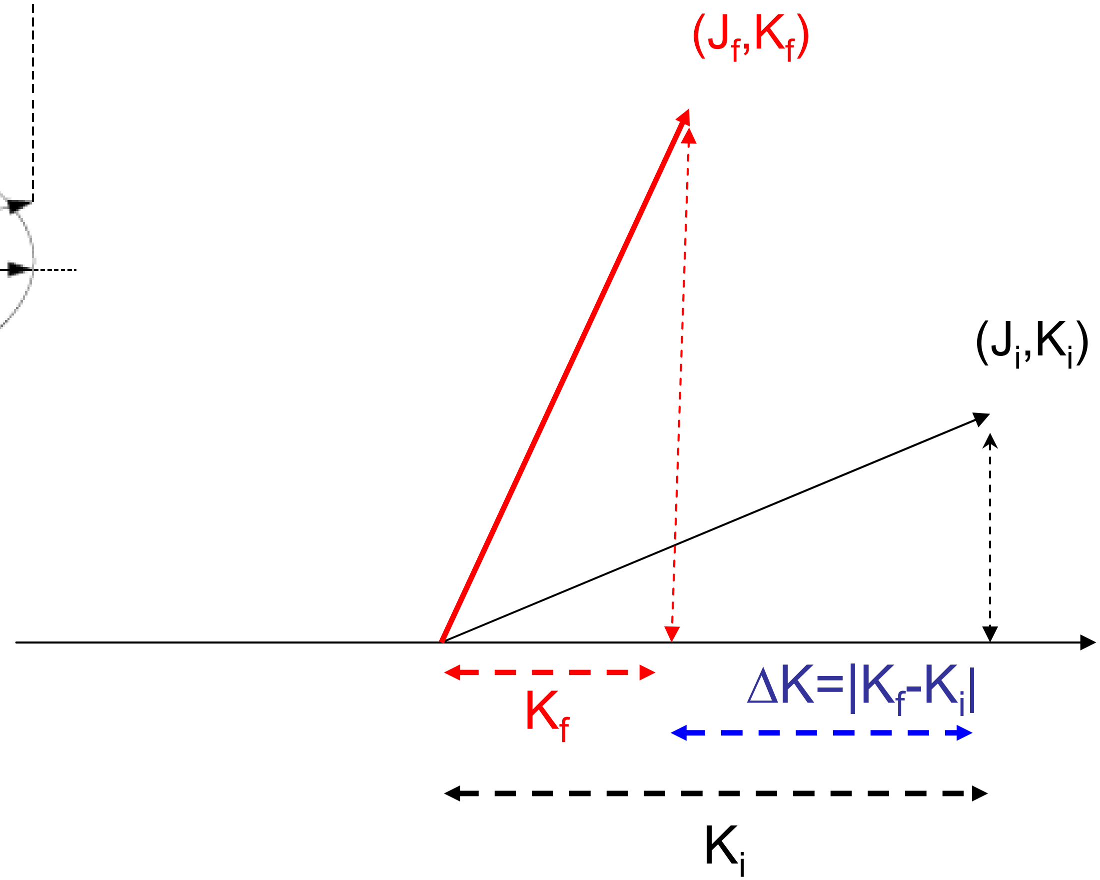
'**Weakly Coupled**' configuration.
Also called '**rotation aligned**'
Signature partners offset due to
Coriolis effects (for Ω=1/2 orbits).
Bandhead has I=j; decoupled, E2 bands
look similar to the even-even GSB.





K isomers





$$|K_i - K_f| = \Delta K \leq \lambda$$

$$\nu = \Delta K - \lambda$$

$$f_\nu = \left[\frac{T^{\gamma}_{1/2}}{T^{W}_{1/2}}\right]^{1/\nu}$$ = reduced hindrance for a K-isomeric decay transition.

'Forbiddenness' in K isomers

We can use single particle ('Weisskopf') estimates for transitions rates for a given multipolarity. (E_g (keV), $T_{1/2}$(s), Firestone and Shirley, *Table of Isotopes* (1996).

Weisskopf Estimates for $T^{1/2}$ $A = 180,\ E_\gamma = 500$ keV

$$E1 \rightarrow T_W^{1/2} = 6.76\times10^{-6} E_\gamma^{-3} A^{-2/3} \rightarrow 1.6\times10^{-15}\,s$$

$$M1 \rightarrow T_W^{1/2} = 2.20\times10^{-5} E_\gamma^{-3} \rightarrow 1.8\times10^{-13}\,s$$

$$E2 \rightarrow T_W^{1/2} = 9.52\times10^{6} E_\gamma^{-5} A^{-4/3} \rightarrow 3.0\times10^{-10}\,s$$

$$M2 \rightarrow T_W^{1/2} = 3.10\times10^{7} E_\gamma^{-5} A^{-2/3} \rightarrow 3.1\times10^{-8}\,s$$

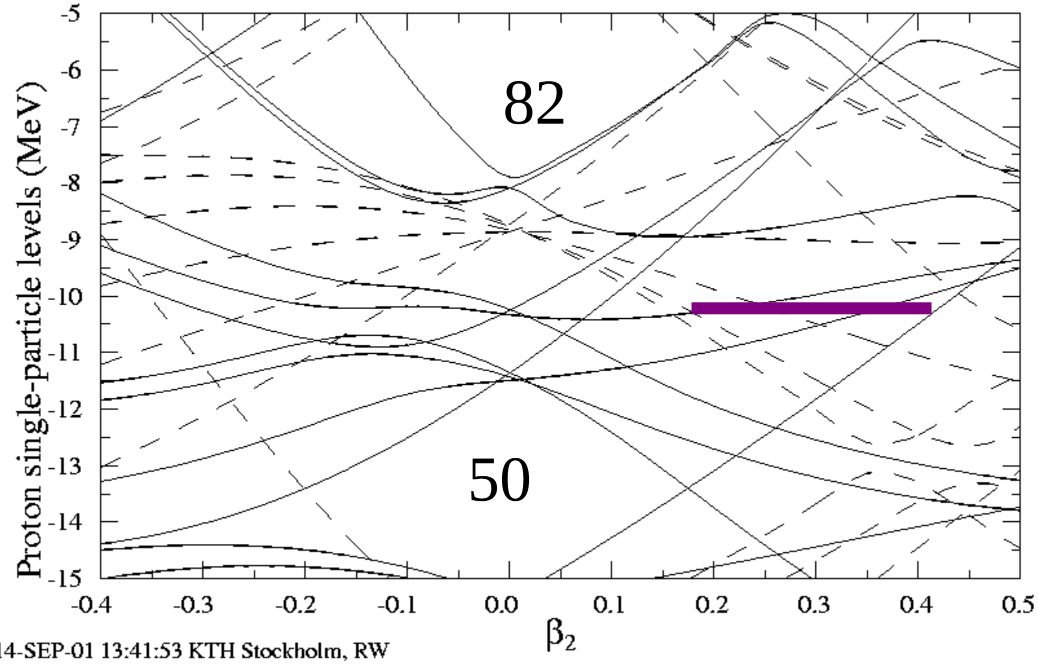
Hindrance (F) (removing dependence on multipolarity and E_γ) is defined by

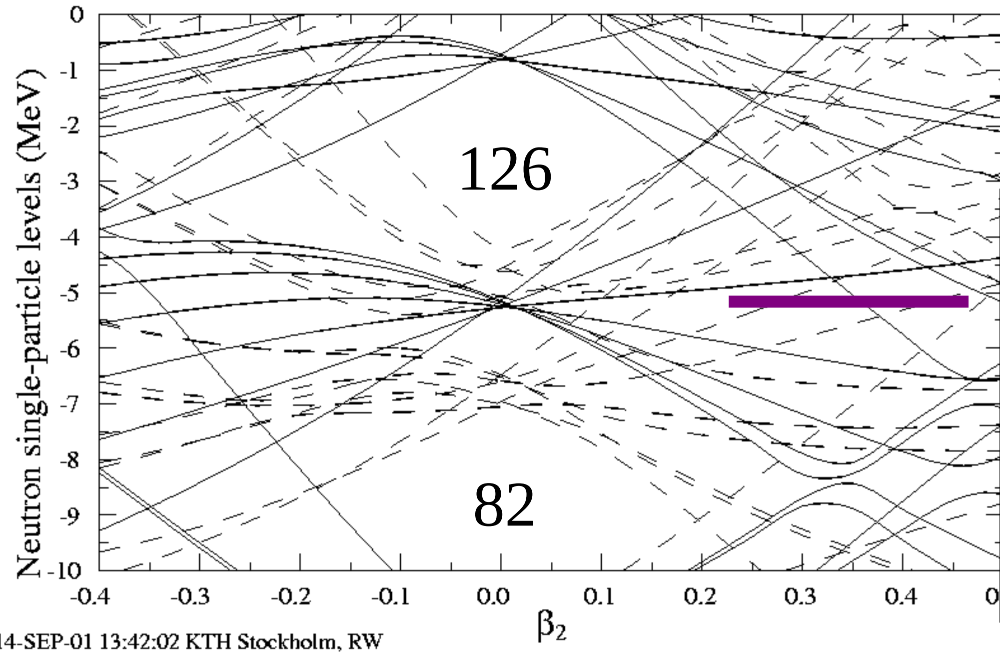
$$F = \left(\frac{T^{\gamma}_{1/2}}{T^{W}_{1/2}}\right) = \text{ratio of expt. and Weisskopf trans. rates}$$

Reduced Hindrance (f_ν) gives an estimate for the 'goodness' of K- quantum number and validity of K-selection rule (= a measure of axial symmetry).

$$f_\nu = F^{1/\nu} = \left(\frac{T^{\gamma}_{1/2}}{T^{W}_{1/2}}\right)^{1/\nu}, \quad \nu = \Delta K - \lambda$$

$f_\nu \sim 100$ typical value for 'good' K isomer (see Lobner Phys. Lett. **B26** (1968) p279)





Expect to find K-isomers in regions where high-K orbitals are at the Fermi surface.

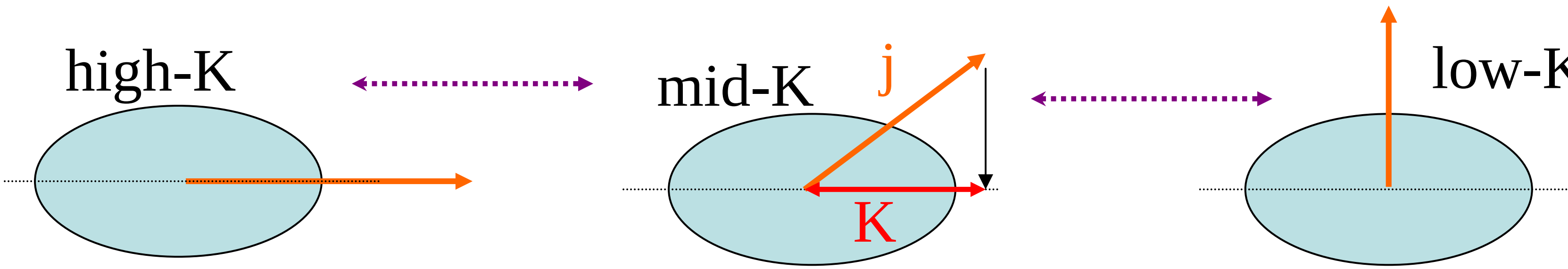
Also need large, axially symmetric deformation

($\beta_2>0.2$, $\gamma\sim0^o$)

Conditions fulfilled at A~170-190 rare-earth reg.

High-Ω single particle orbitals from eg. $i_{13/2}$ neutrons couple together to give energetically favoured states with high-K ($=\Sigma\Omega_i$).

Search for long (>100ms) K-isomers in neutron-rich(ish) A~180 nuclei.

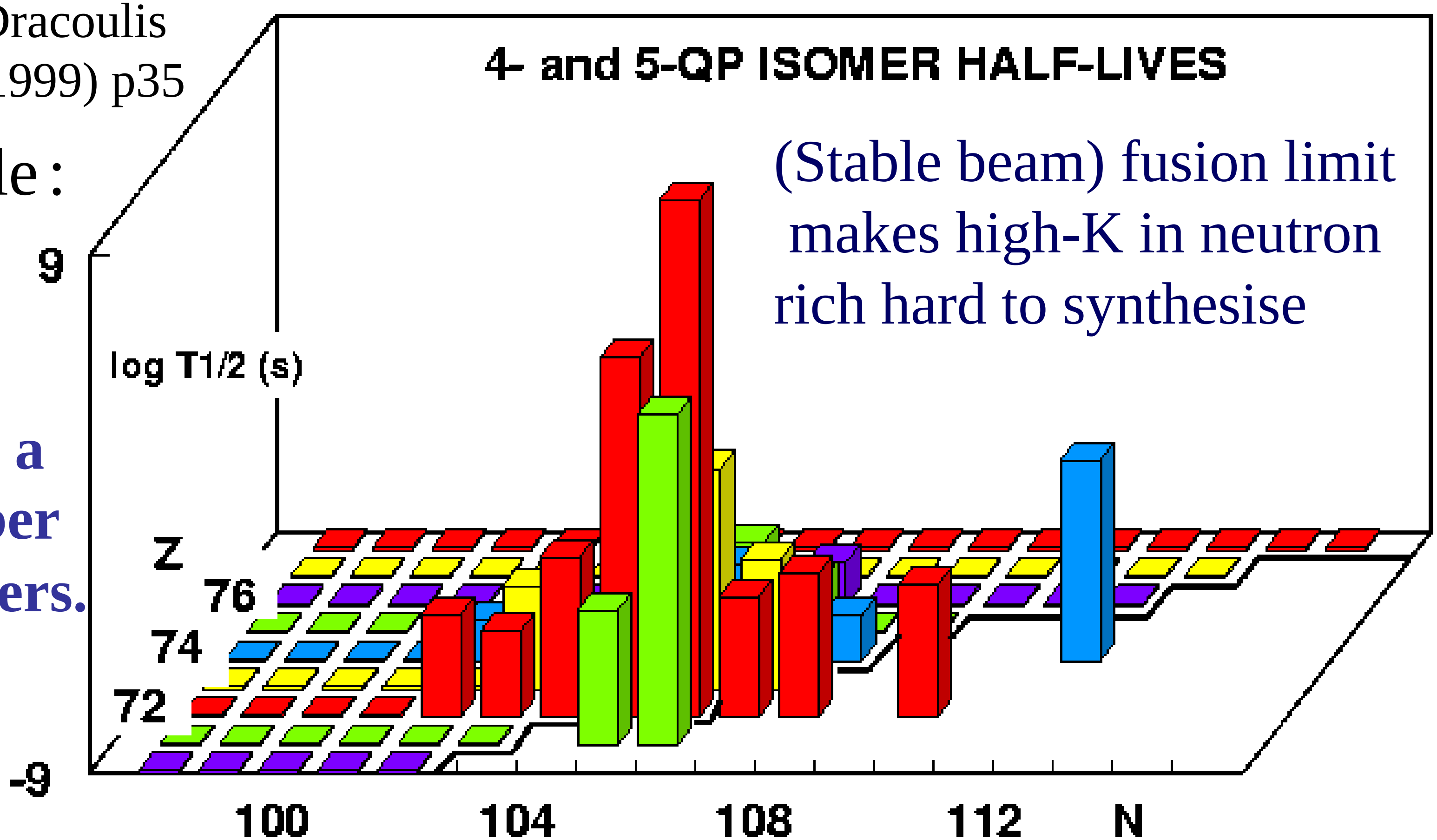


Walker and Dracoulis
Nature **399** (1999) p35

K - sel. rule:

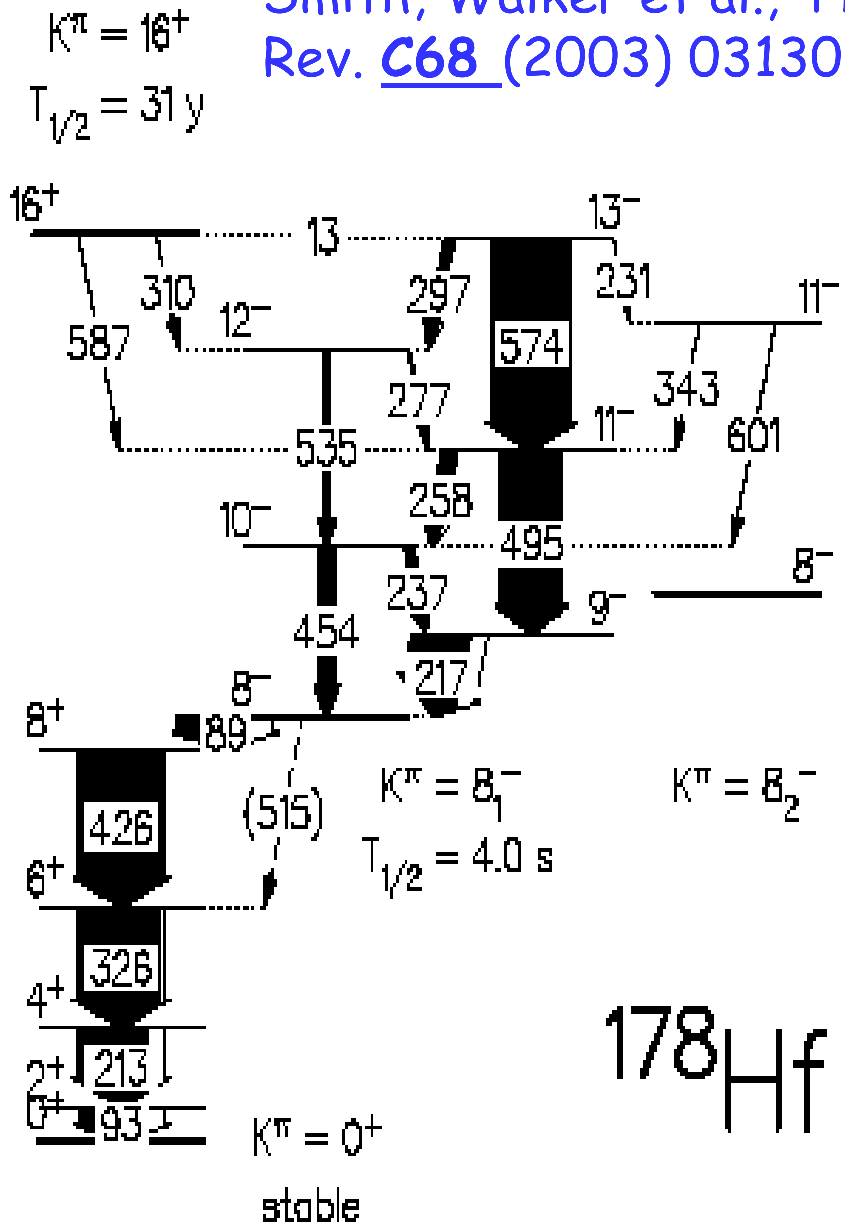
$$\Delta\lambda \geq \Delta K$$

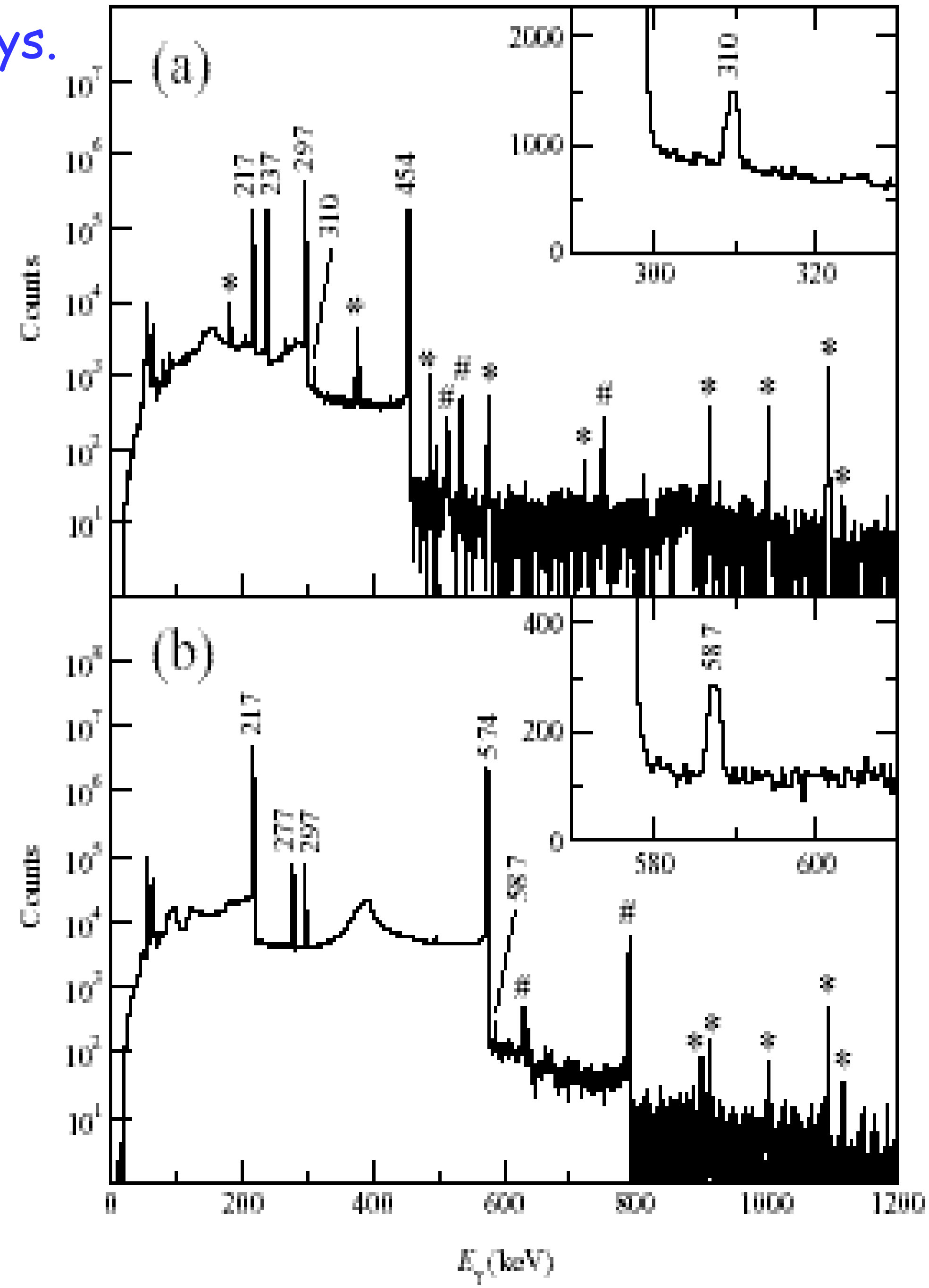
N=104 also a good number for K-isomers.



(Stable beam) fusion limit makes high-K in neutron rich hard to synthesise

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





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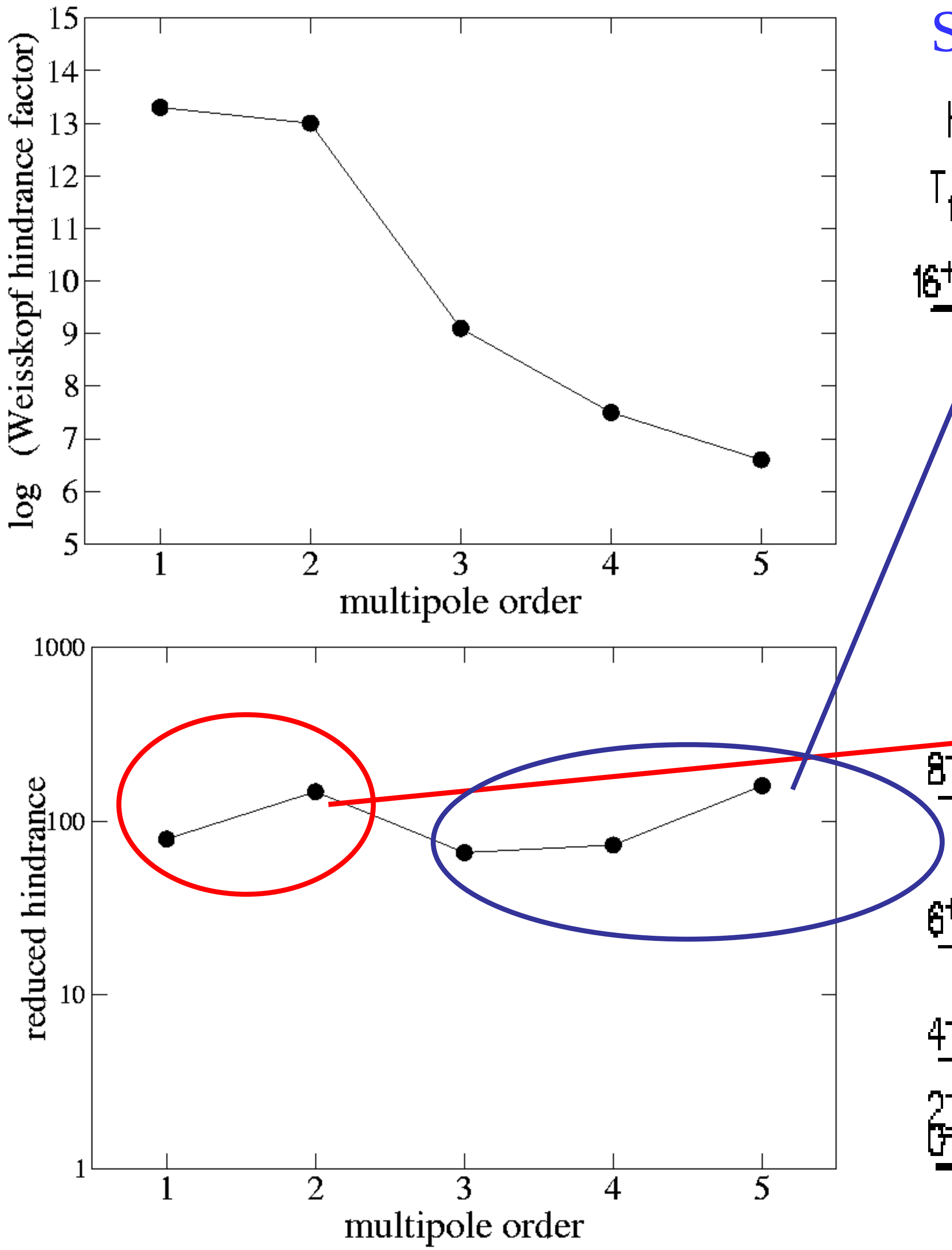
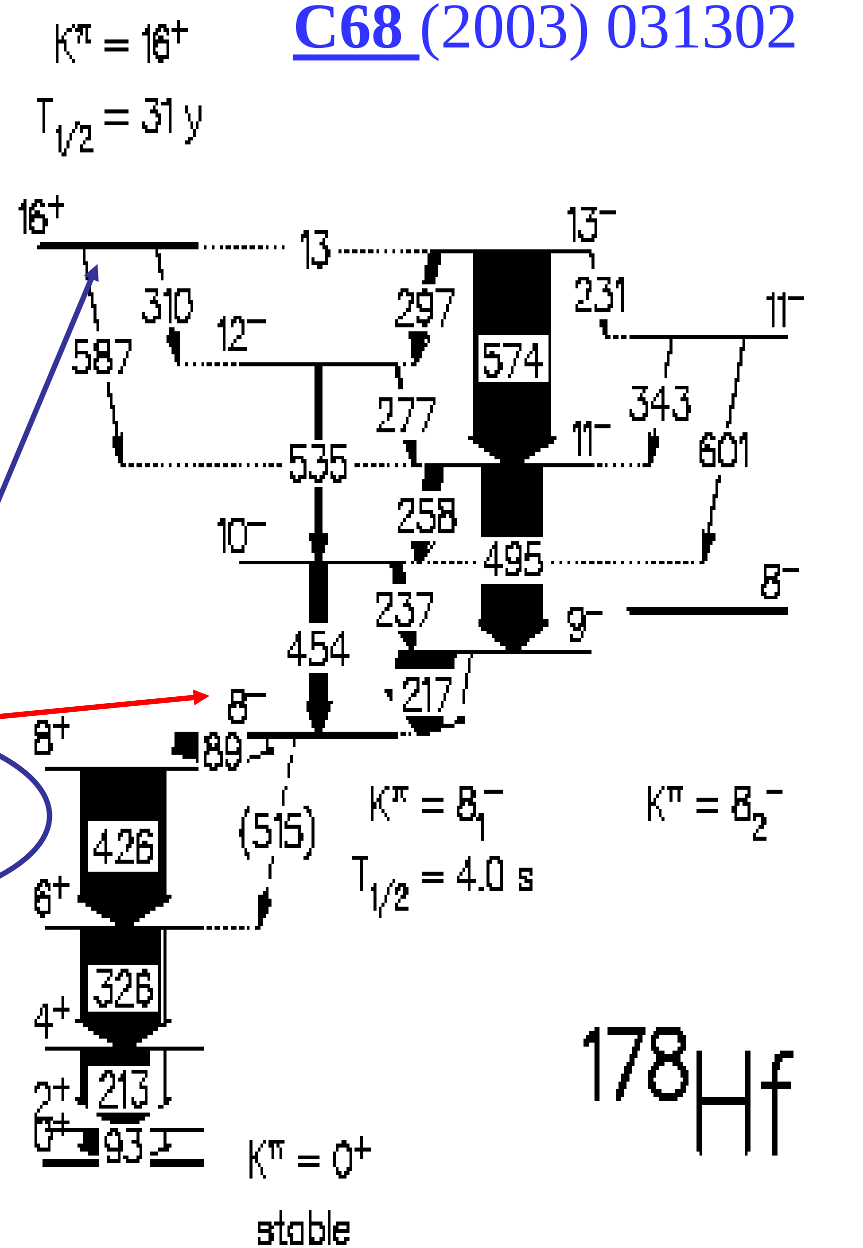
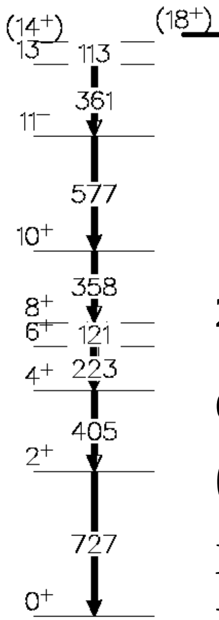




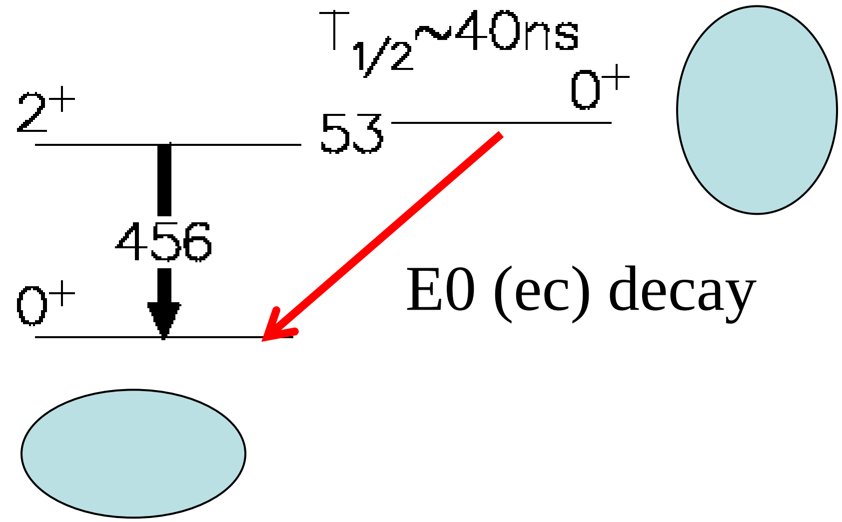


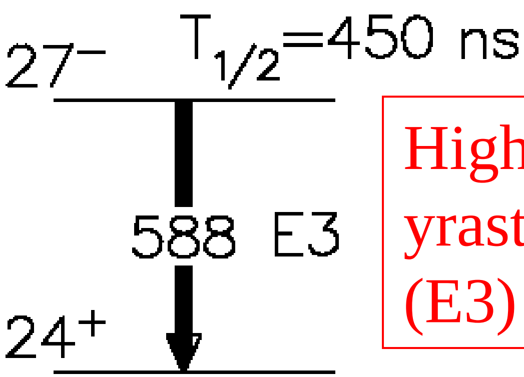
$T_{1/2}$=41 secs

α–decay to states in ^{208}Pb.

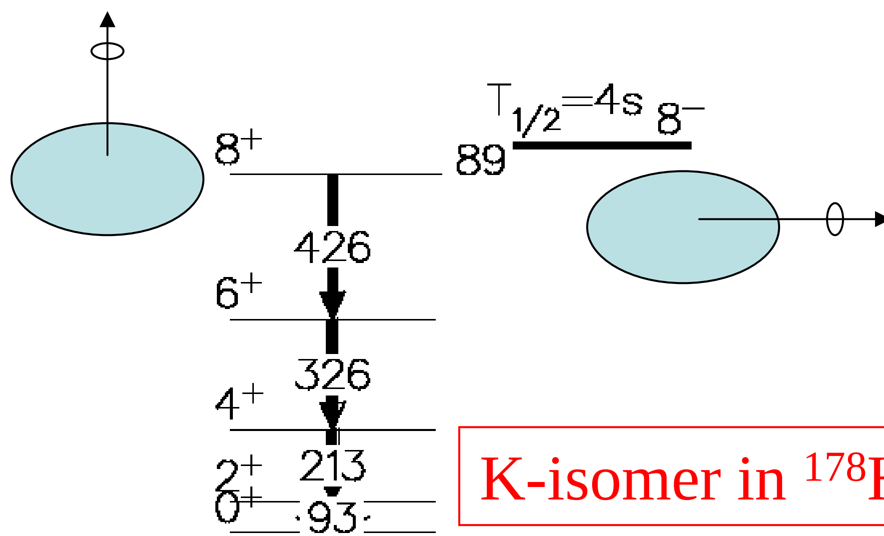
^{212}Po, high-spin α-decaying yrast trap. (also proton decaying isomers, e.g, ^{53}Co PL**B33** (1970) 281ff.

^{74}Kr, shape isomer



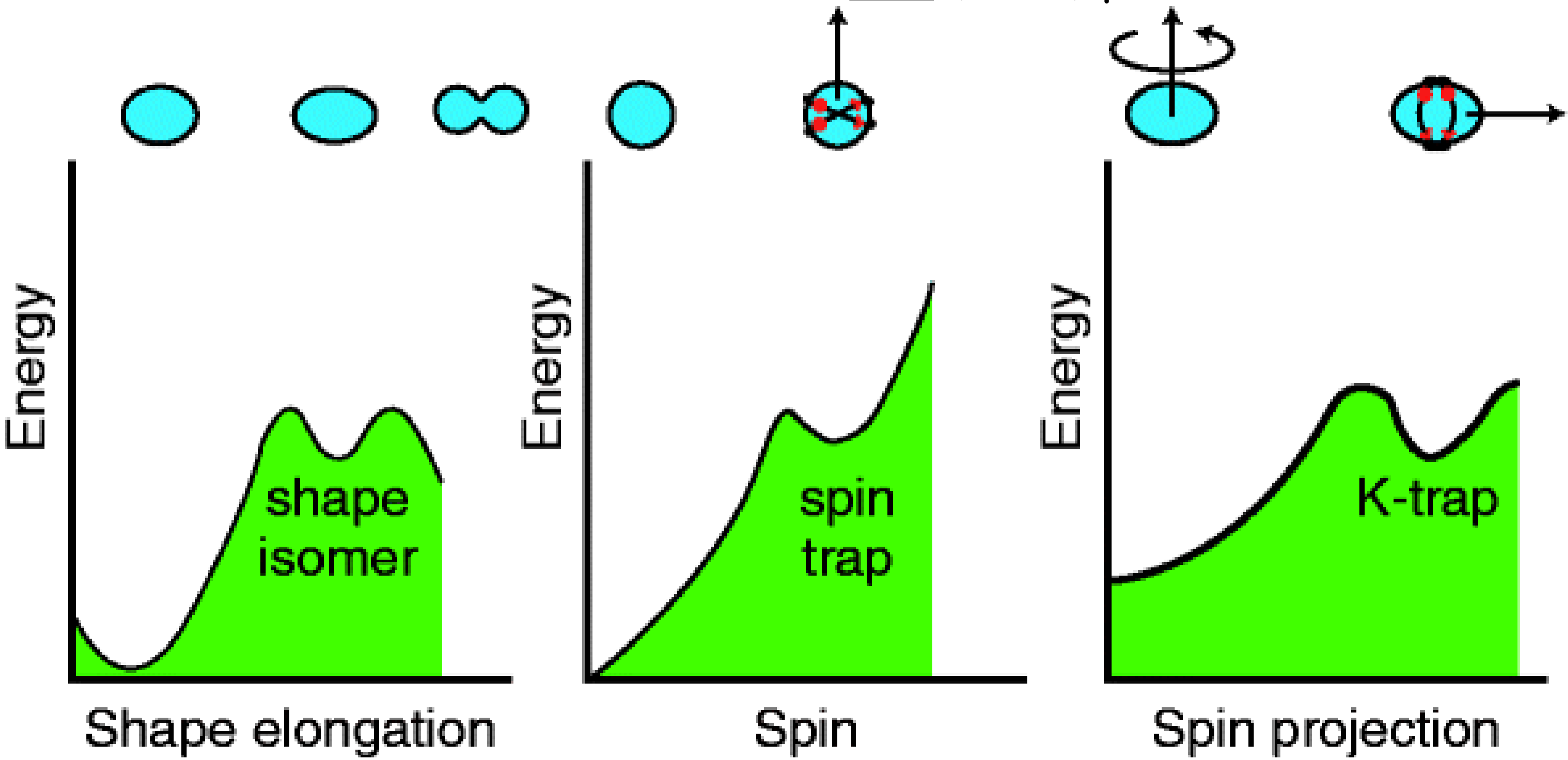


High-spin, yrast-trap (E3) in ^{212}Fr



K-isomer in ^{178}Hf

P.M.Walker and G.D.Dracoulis. Nature, **399** (1999) p35



What about EM transition rates between low-energy states in nuclei ?

EM Transition Rates

Classically, the average power radiated by an EM multipole field is given by

$$P(\sigma L) = \frac{2(L+1)c}{\varepsilon_0 L[(2L+1)!!]^2}\left(\frac{\omega}{c}\right)^{2L+2}[m(\sigma L)]^2$$

m(σL) is the time-varying electric or magnetic multipole moment.
ω is the (circular) frequency of the EM field

For a quantized (nuclear) system, the decay probability is determined by the MATRIX ELEMENT of the EM MULTIPOLE OPERATOR, where

$$m_{fi}(\sigma L) = \int \psi_f^* m(\sigma L)\psi_i dv$$ i..e, integrated over the nuclear volume.

We can then get the general expression for the probability per unit time for gamma-ray emission, $\lambda(\sigma L)$, from:

$$\lambda(\sigma L) = \frac{1}{\tau} = \frac{P(\sigma L)}{\hbar\omega} = \frac{2(L+1)}{\varepsilon_0 \hbar L[(2L+1)!!]^2}\left(\frac{\omega}{c}\right)^{2L+1}[m_{fi}(\sigma l)]^2$$

(see Introductory Nuclear Physics, K.S. Krane (1988) p330).

$$T_{fi}(\lambda L) = \frac{8\pi(L+1)}{\hbar L\left((2L+1)!!\right)^2}\left(\frac{E_\gamma}{\hbar c}\right)^{2L+1} B(\lambda L : J_i \rightarrow J_f) \qquad (5.0.3)$$

where $B(\lambda L : J_i \rightarrow J_f)$ is called the *reduced matrix element*.

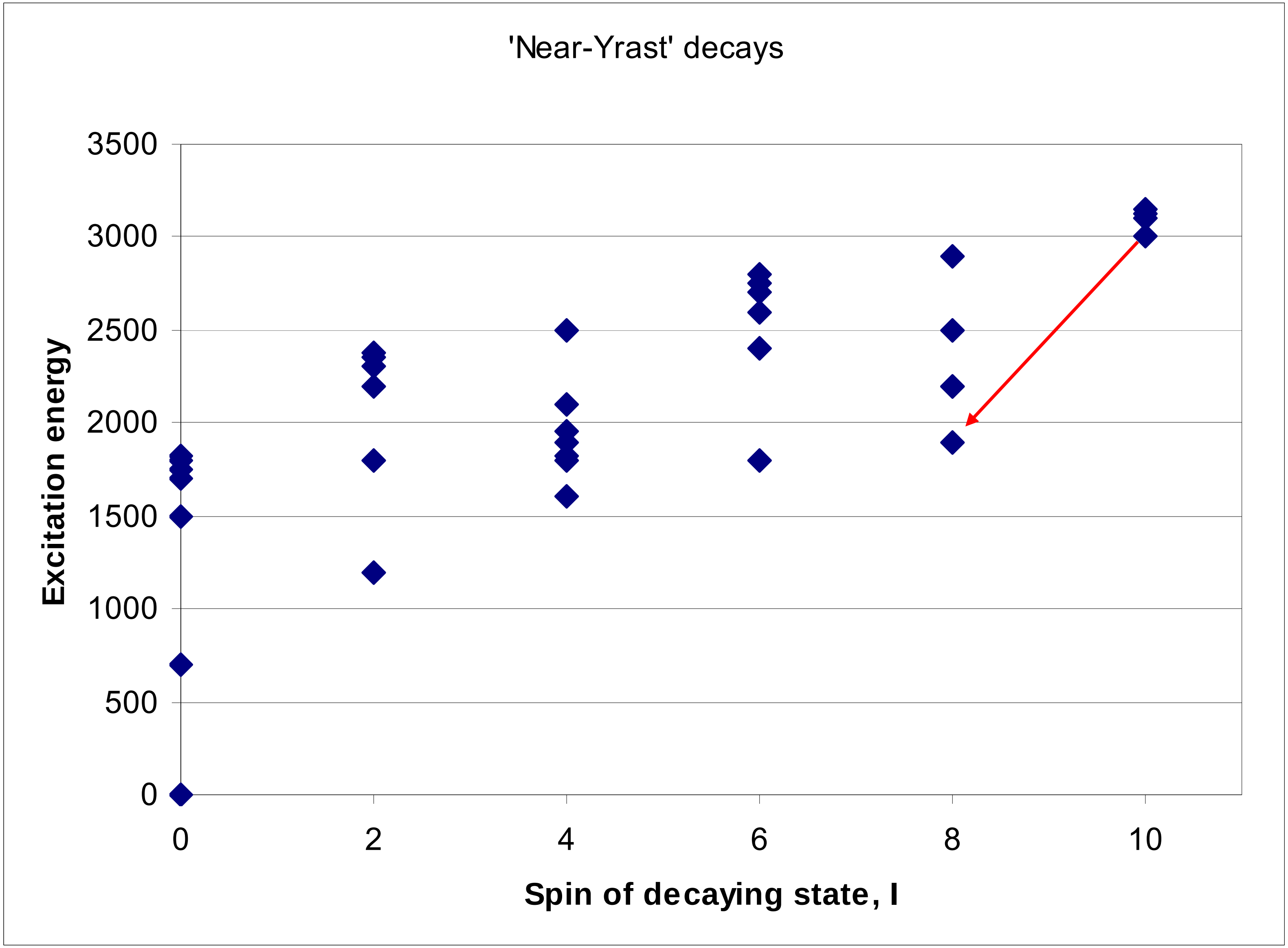
Measuring the lifetime (decay probability) of a nuclear state thus gives a value for the $B(\lambda L : J_i \rightarrow J_f)$.

For lifetimes, τ in units of seconds where the transition *probability* per unit second, $T = \frac{1}{\tau}$, (E_γ in MeV),

Multipolarity	Electric Transition Rate (s^{-1})	Magnetic Transition Rate (s^{-1})
1	$1.587 \times 10^{15}\ E_\gamma^3\ B(E1)$	$1.779 \times 10^{13}\ E_\gamma^3\ B(M1)$
2	$1.223 \times 10^{9}\ E_\gamma^5\ B(E2)$	$1.371 \times 10^{7}\ E_\gamma^5\ B(M2)$
3	$5.689 \times 10^{2}\ E_\gamma^7\ B(E3)$	$6.387 \times 10^{0}\ E_\gamma^7\ B(M3)$
4	$1.649 \times 10^{-4}\ E_\gamma^9\ B(E4)$	$1.889 \times 10^{-6}\ E_\gamma^9\ B(M4)$
5	$3.451 \times 10^{-11}\ E_\gamma^{11}\ B(E5)$	$3.868 \times 10^{-13}\ E_\gamma^{11}\ B(M5)$

Table 2.2: Transition probabilities $T(s^{-1})$ expressed by $B(EL)$ in $(e^2(fm)^{2L})$ and $B(ML)$ in $(\frac{e\hbar}{2mc}(fm)^{2L-2})$. E_γ is the γ-ray energy, in MeV. (Taken from ref [69]).

The EM transition rate depends on $E\gamma^{2\lambda+1}$,, the highest energy transitions for the lowest λ are (generally) favoured.
This results in the preferential population of yrast and near-yrast states.



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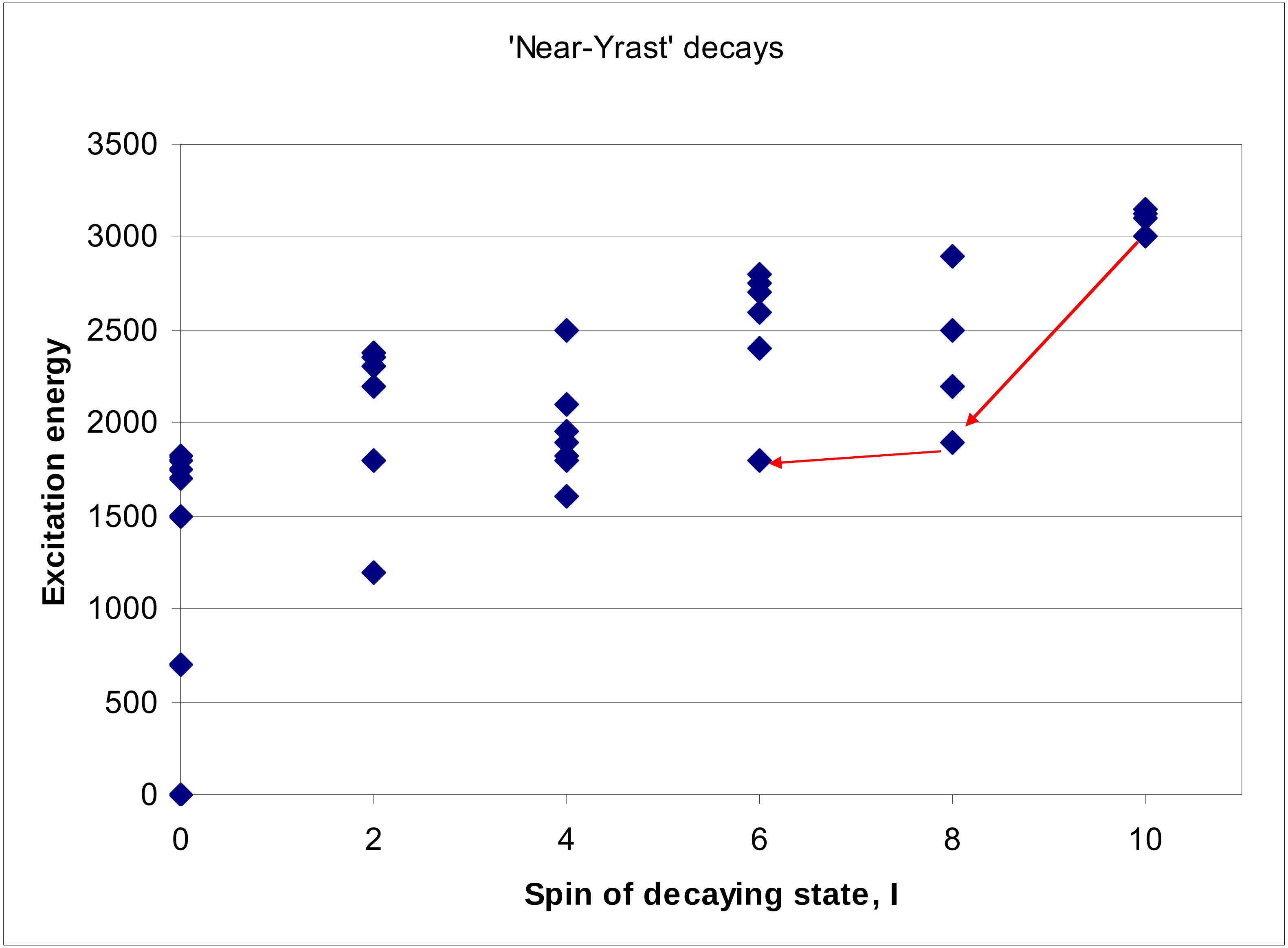

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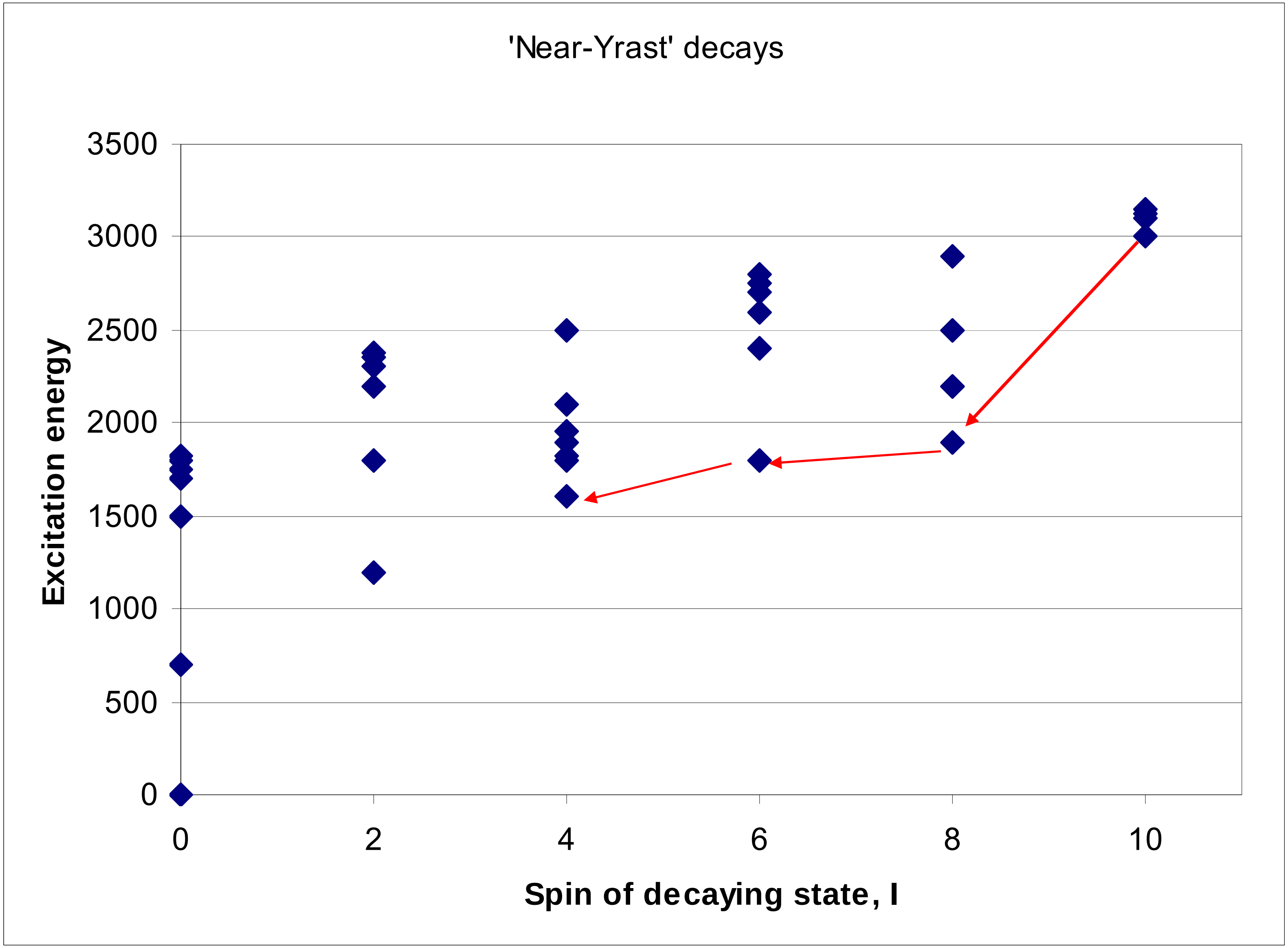

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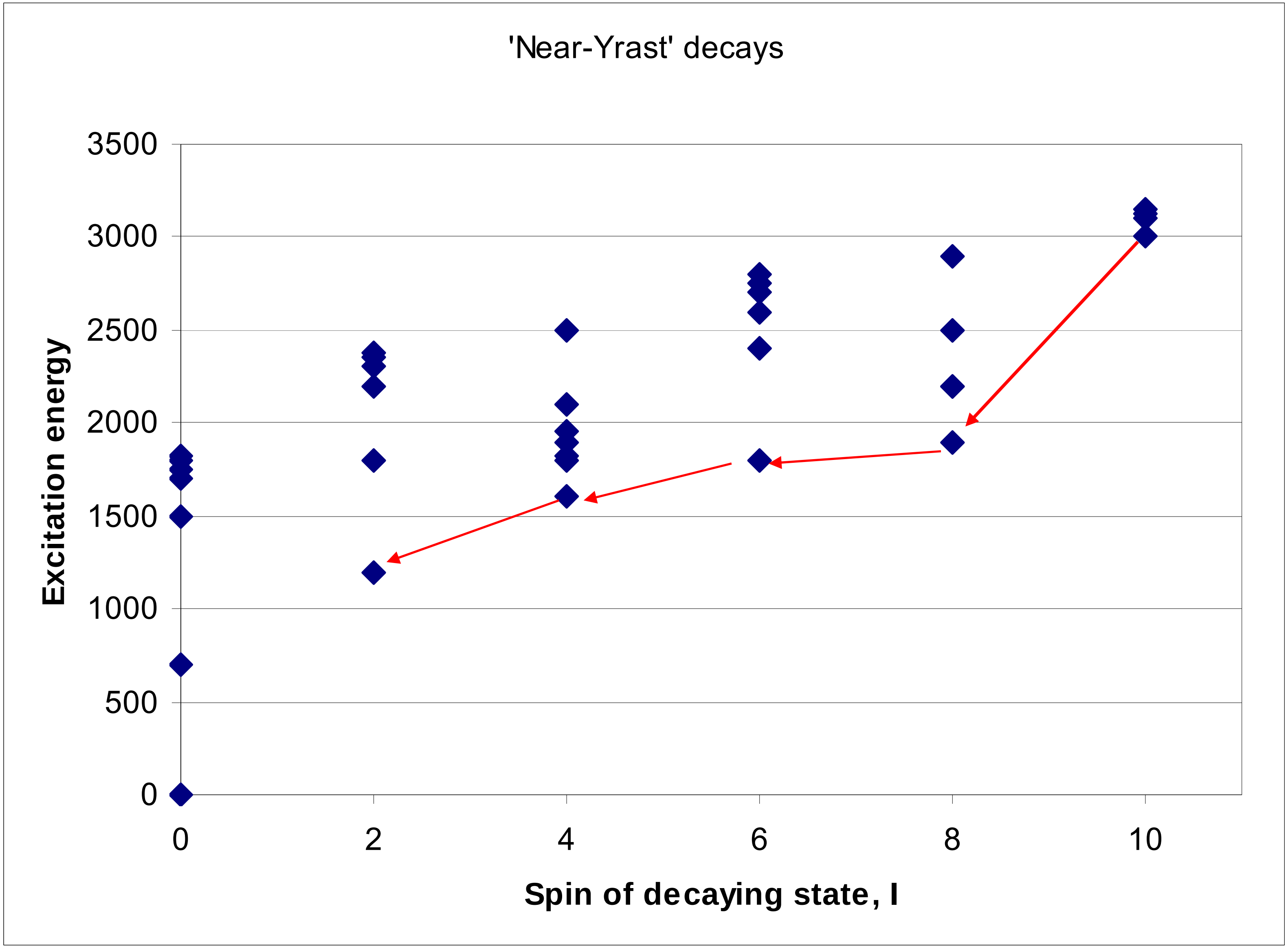

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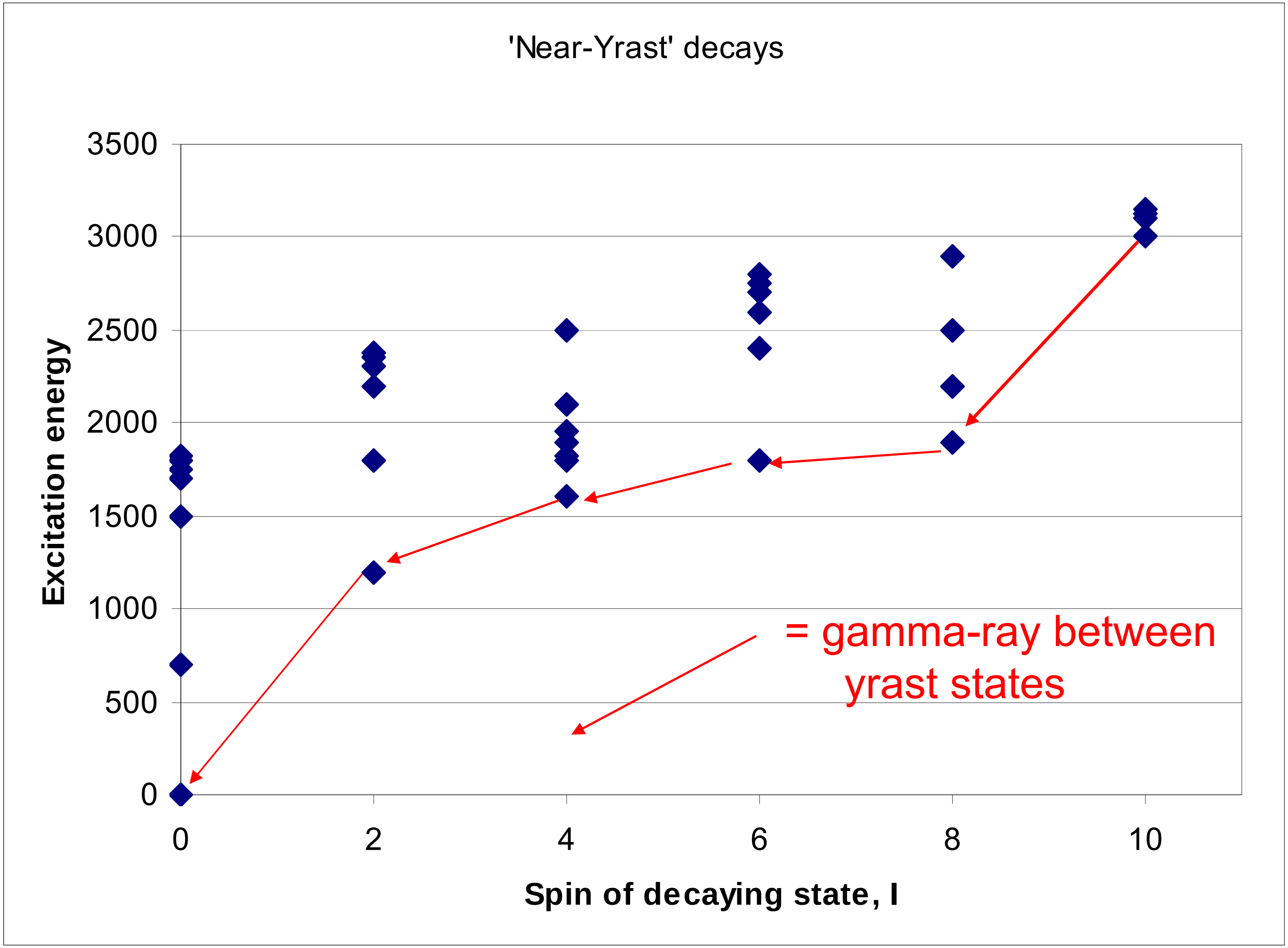
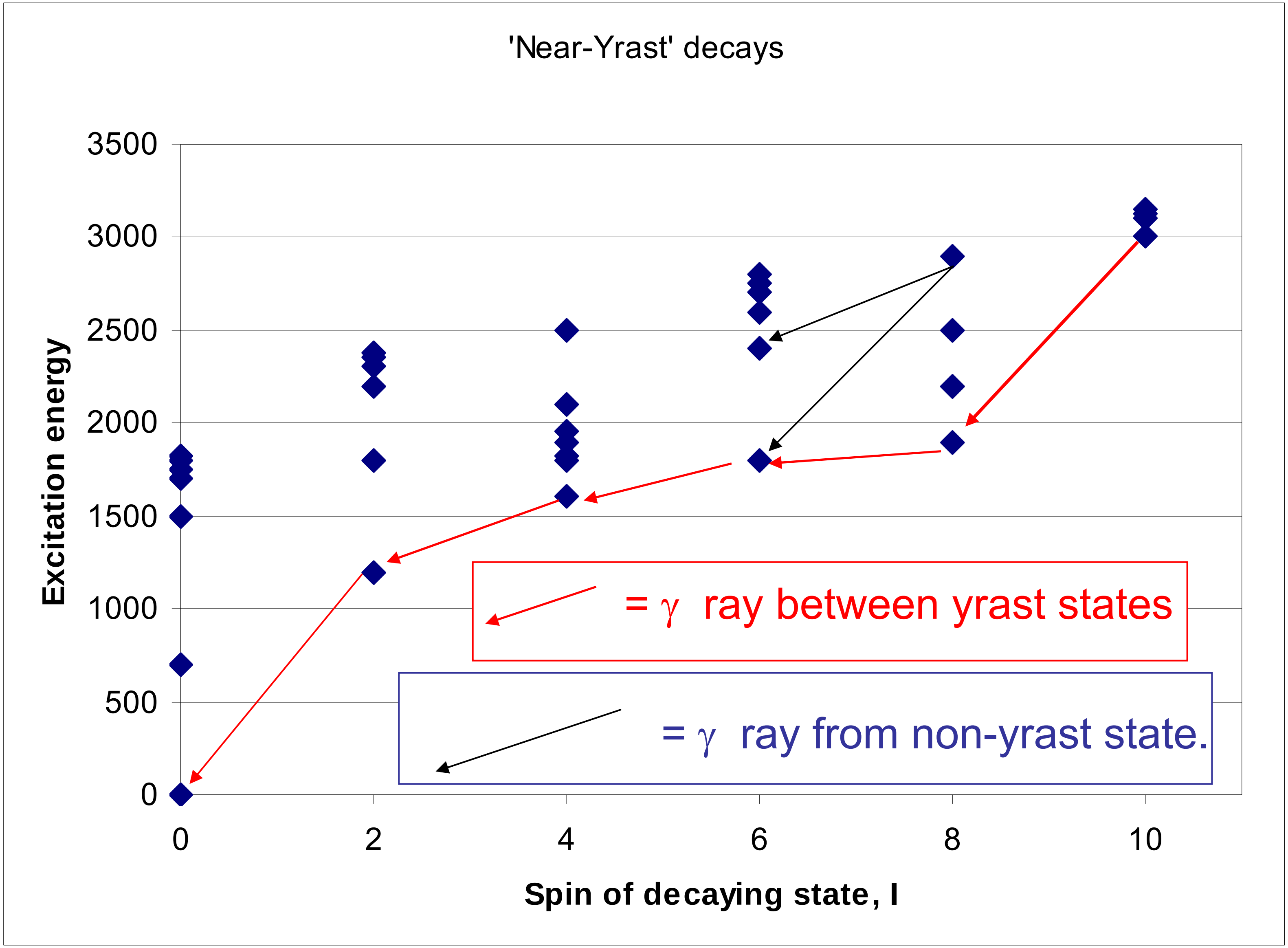


The EM transition rate depends on $E\gamma^{2\lambda+1}$, (for E2 decays E_γ^5)
Thus, the highest energy transitions for the lowest λ are usually favoured.
Non-yrast states decay to yrast ones (unless very different wfs , K-isomers)



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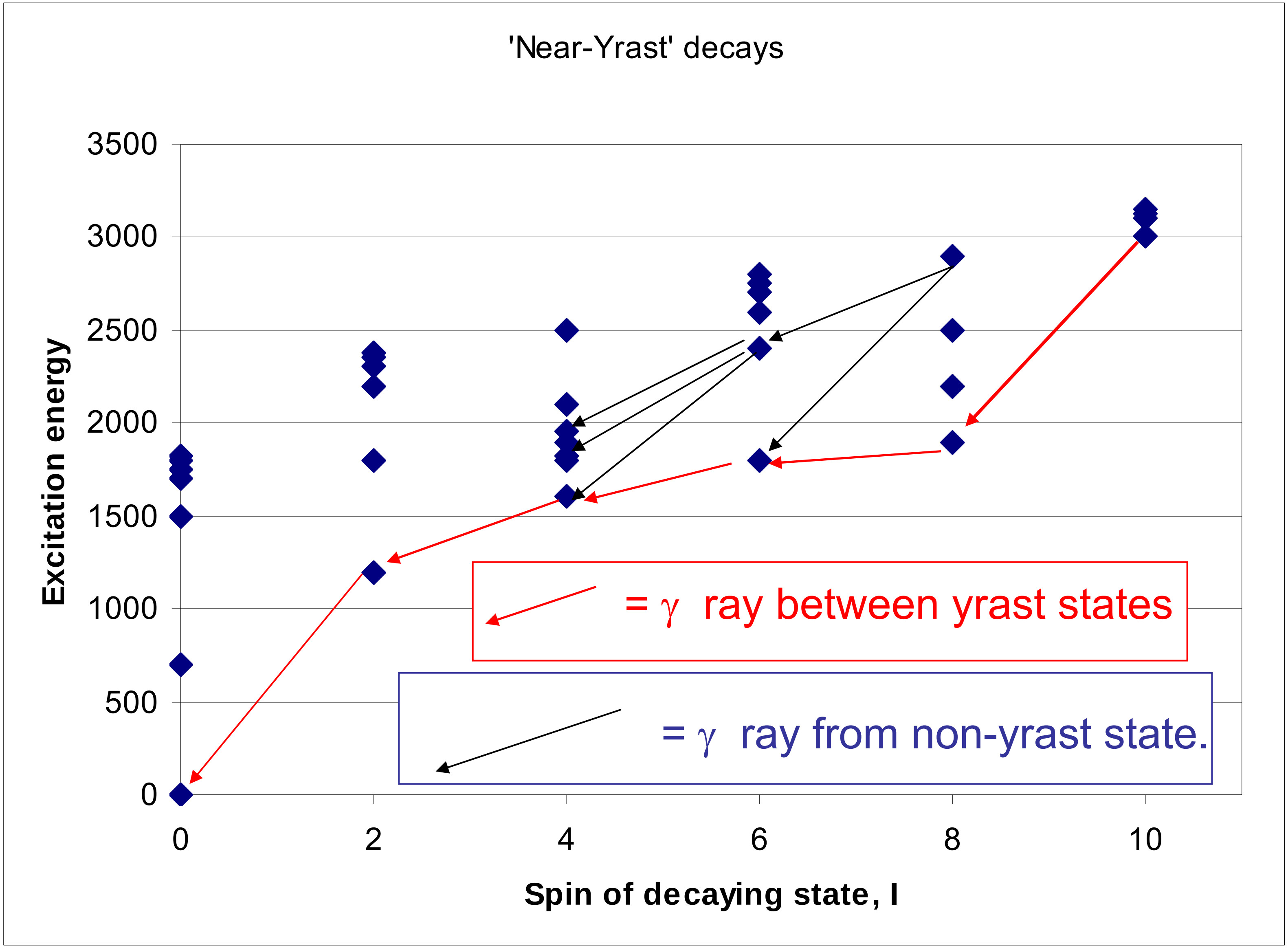

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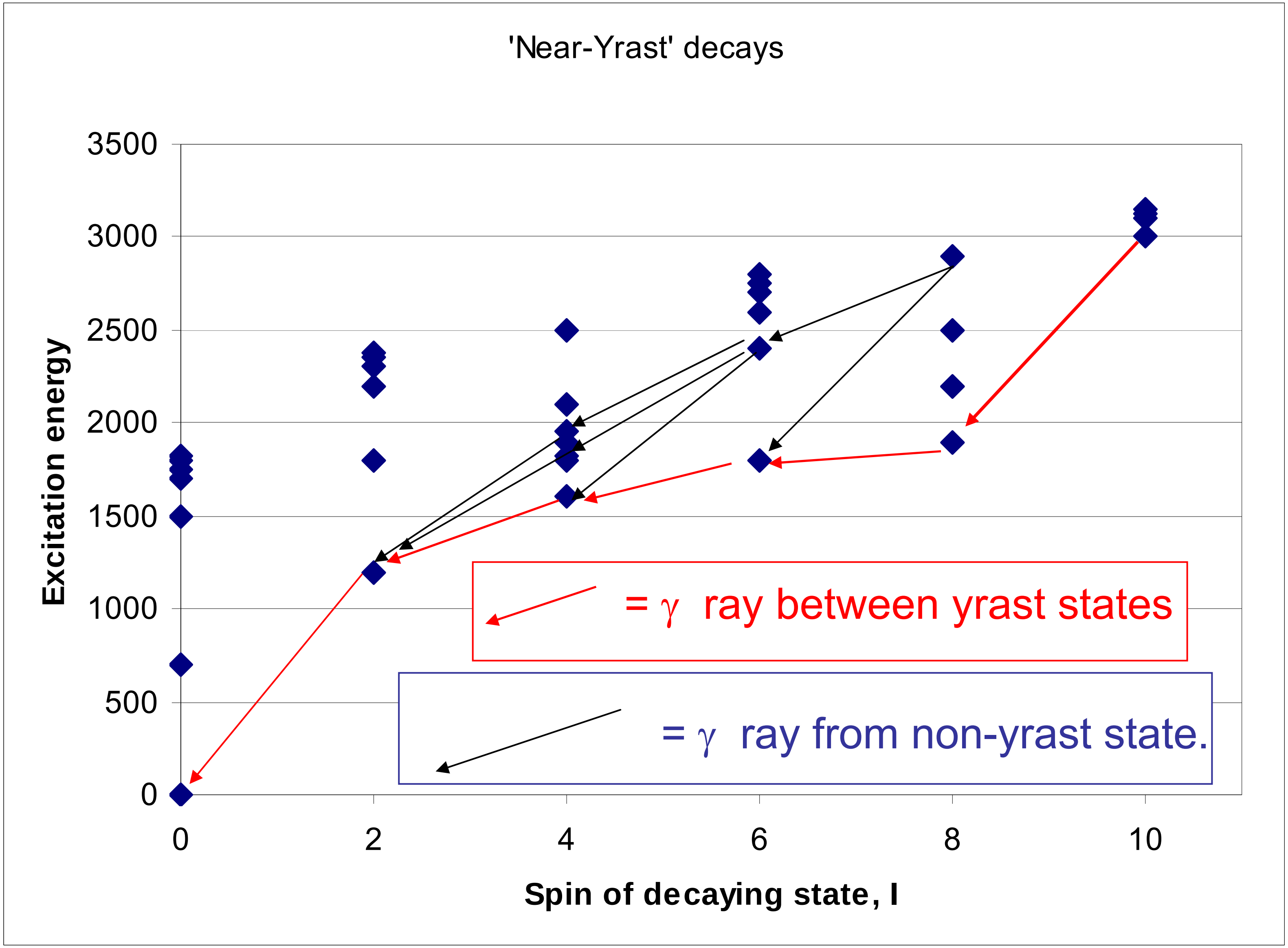
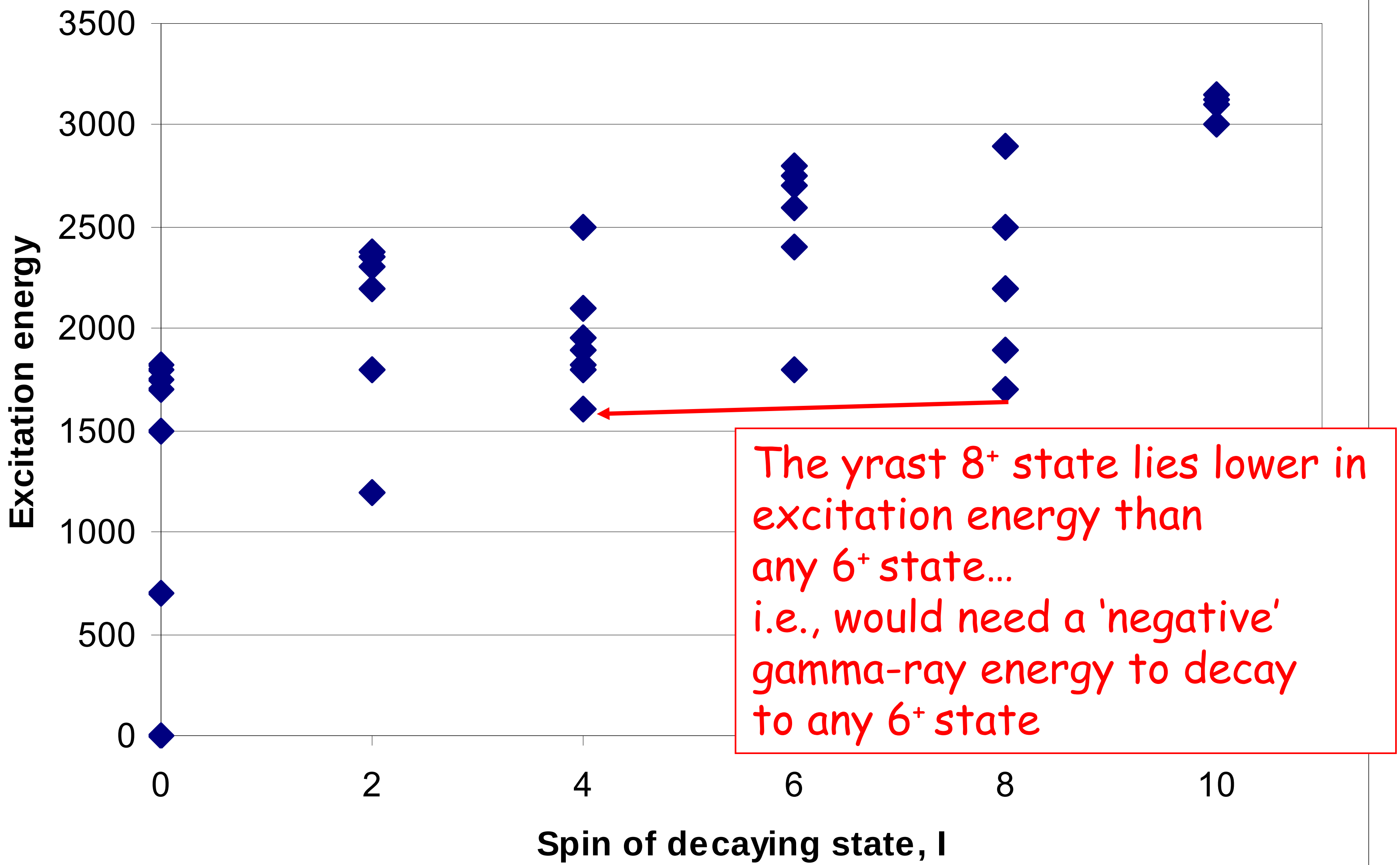
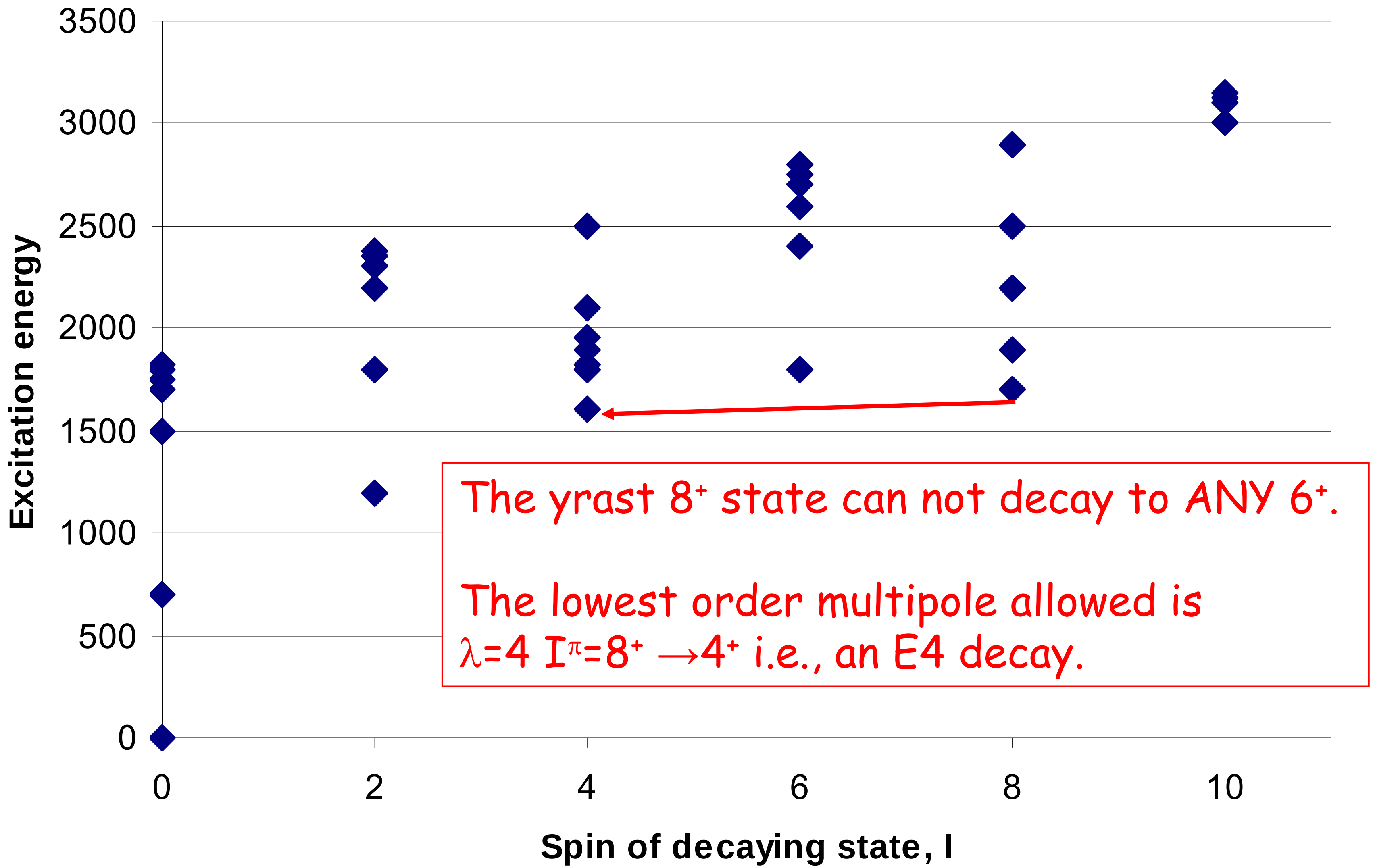


Yrast Traps


3500
3000
2500
2000
1500
1000
500
0
Excitation energy
0
2
4
6
8
10
Spin of decaying state, I
The yrast 8+ state lies lower in excitation energy than any 6+ state…
i.e., would need a 'negative' gamma-ray energy to decay to any 6+ state

Yrast Traps


3500
3000
2500
2000
1500
1000
500
0
Excitation energy
0
2
4
6
8
10
Spin of decaying state, I
The yrast 8^+ state can not decay to ANY 6^+.
The lowest order multipole allowed is
$\lambda=4$ $I^\pi=8^+ \rightarrow 4^+$ i.e., an E4 decay.

Weisskopf Single Particle Estimates:

These are 'yardstick' estimates for the speed of electromagnetic decays for a given electromagnetic multipole.

They depend on the size of the nucleus (i.e., *A*) and the energy of the photon (E_γ^{2L+1})

They estimates using of the transition rate for spherically symmetric proton orbitals for nuclei of radius $r=r_0A^{1/3}$.

Multipolarity	Electric Transition Rate (s^{-1})	Magnetic Transition Rate (s^{-1})
1	$1.0 \times 10^{14} A^{2/3} E_\gamma^3$	$3.1 \times 10^{13} E_\gamma^3$
2	$7.3 \times 10^{7} A^{4/3} E_\gamma^5$	$2.2 \times 10^{7} A^{2/3} E_\gamma^5$
3	$3.4 \times 10^{1} A^{2} E_\gamma^7$	$1.0 \times 10^{1} A^{4/3} E_\gamma^7$
4	$1.1 \times 10^{-5} A^{8/3} E_\gamma^9$	$3.3 \times 10^{-6} A^{2} E_\gamma^9$
5	$2.4 \times 10^{-12} A^{10/3} E_\gamma^{11}$	$7.4 \times 10^{-13} A^{8/3} E_\gamma^{11}$

Table 2.3: Single-particle Weisskopf transition probability estimates as a function of the atomic mass measured in atomic mass units A and the γ-ray energy E_γ in MeV.

$$B_{sp}(EL) = \frac{1.2^{2L}}{4\pi} \left(\frac{3}{L+3} \right)^2 A^{\frac{2L}{3}} e^2 fm^{2L} \tag{2.15}$$

$$B_{sp}(ML) = \frac{10}{\pi} 1.2^{2L-2} \left(\frac{3}{L+3} \right)^2 A^{2L-2} 2 \left(\frac{e\hbar}{2Mc} \right)^2 fm^{2L-2} \tag{2.16}$$

Weisskopf Estimates

τ_{sp} for 1Wu at $A \sim 100$ and E_g = 200 keV

M1 2.2ps	M2 4.1μs	M3 36 s	M4 43Ms
E1 5.8 fs	E2 92 ns	E3 0.2s	E4 66Ms

i.e., lowest multipole decays are favoured….but need to conserve angular momentum so need at least $\lambda = I_i - I_f$ for decay to be allowed.

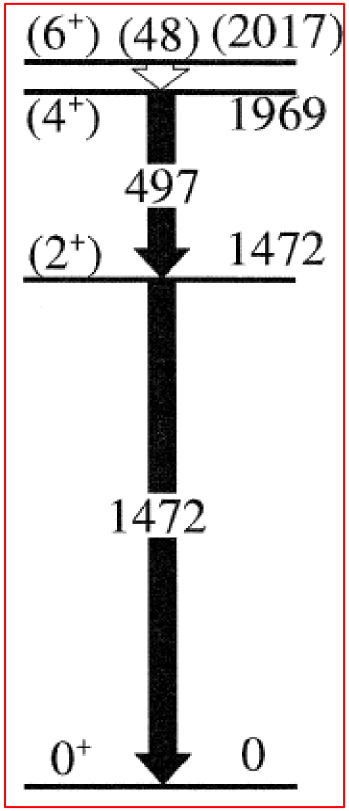
Note, for low E_γ and high-l, internal conversion also competes/dominates.

EM Selection Rules and their Effects on Decays

- Allows decays have:

$$\left|I_i - I_f\right| \le \lambda \le \left|I_i - I_f\right|$$

e.g., decays from $I^\pi = 6^+$ to $I^\pi = 4^+$ are allowed to proceed with photons carrying angular momentum of $\lambda = 2,3,4,5,6,7,8,9$ and $10\,\hbar$.



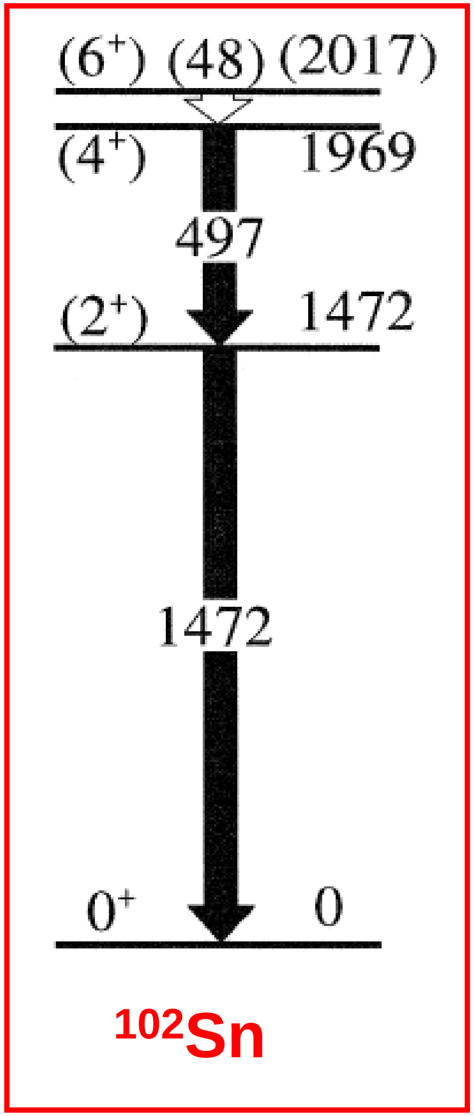
e.g., $^{102}Sn_{52}$

Why do we only observe the E2 decays ?

Are the other allowed decays present ?

Need also to conserve parity between intial and final states, thus, here the transition can not change the parity.

This adds a further restriction : Allowed decays now restricted to E2, E4, E6, E8 and E10 ; and M3, M5, M7, M9

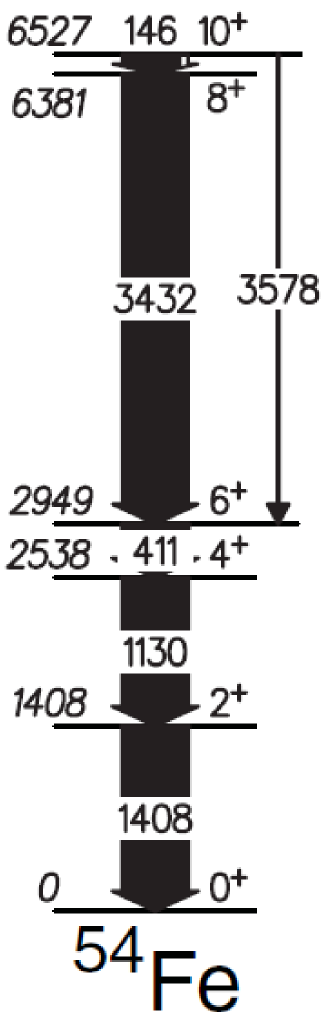


E_γ	E2 (1Wu)	M3 (1Wu)	E4 (1Wu)
48 ($6^+ \rightarrow 4^+$)	112μs	782,822 s	2.5E+14s
555 ($6^+ \rightarrow 2^+$)			66,912s
497 ($4^+ \rightarrow 2^+$)	0.9ns	61ms	180,692s
1969 ($4^+ \rightarrow 2^+$)			751ms

Conclusion, in general see a cascade of (stretched) E2 decays in near-magic even-even nuclei.

What about core breaking?

We can have cases where low-energy (~100 keV) E2 decays competing with high-energy (~4 MeV) E4 transitions across magic shell closures, e.g. $^{54}Fe_{28}$.



Z=26; N=28 case.

- 2 proton holes in $f_{7/2}$ shell.
- Maximum spin in simple valence space is $I^{\pi}=6^{+}$.
- i.e., $(\pi f_{7/2})^{-2}$ configuration coupled to $I^{\pi}= 6^{+}$

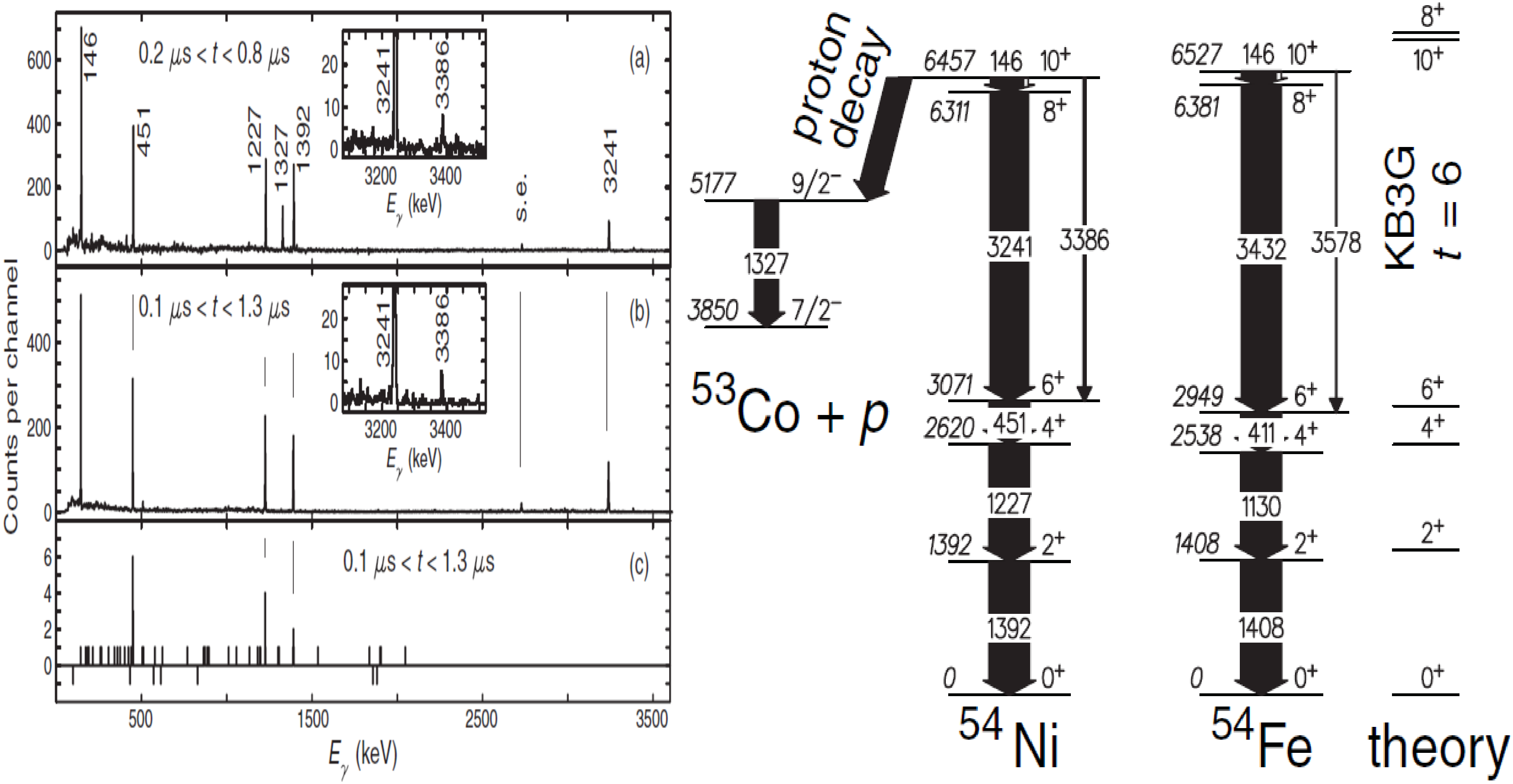
Additional spin requires exciting (pairs) of nucleons across the N or Z=28 shell closures into the $f_{5/2}$ shell.

E_{γ}	E2 (1Wu)	M3 (1Wu)	E4 (1Wu)
146 keV ($10^{+}\rightarrow8^{+}$)	1.01μs	613s	20.9E+6s
3578 keV ($10^{+}\rightarrow6^{+}$)			6.5ms

PHYSICAL REVIEW C **78**, 021301(R) (2008)

Isospin symmetry and proton decay: Identification of the 10^+ isomer in ^{54}Ni

D. Rudolph,[1] R. Hoischen,[1,2] M. Hellström,[1] S. Pietri,[3] Zs. Podolyák,[3] P. H. Regan,[3] A. B. Garnsworthy,[3,4] S. J. Steer,[3] F. Becker,[2,*] P. Bednarczyk,[2,5] L. Cáceres,[2,6] P. Doornenbal,[2,7,†] J. Gerl,[2] M. Górska,[2] J. Grębosz,[2,5] I. Kojouharov,[2] N. Kurz,[2] W. Prokopowicz,[2,5] H. Schaffner,[2] H. J. Wollersheim,[2] L.-L. Andersson,[1] L. Atanasova,[8] D. L. Balabanski,[8,9] M. A. Bentley,[10] A. Blazhev,[7] C. Brandau,[2,3] J. R. Brown,[10] C. Fahlander,[1] E. K. Johansson,[1] A. Jungclaus,[6] and S. M. Lenzi[11]



Physics Letters B 672 (2009) 116–119

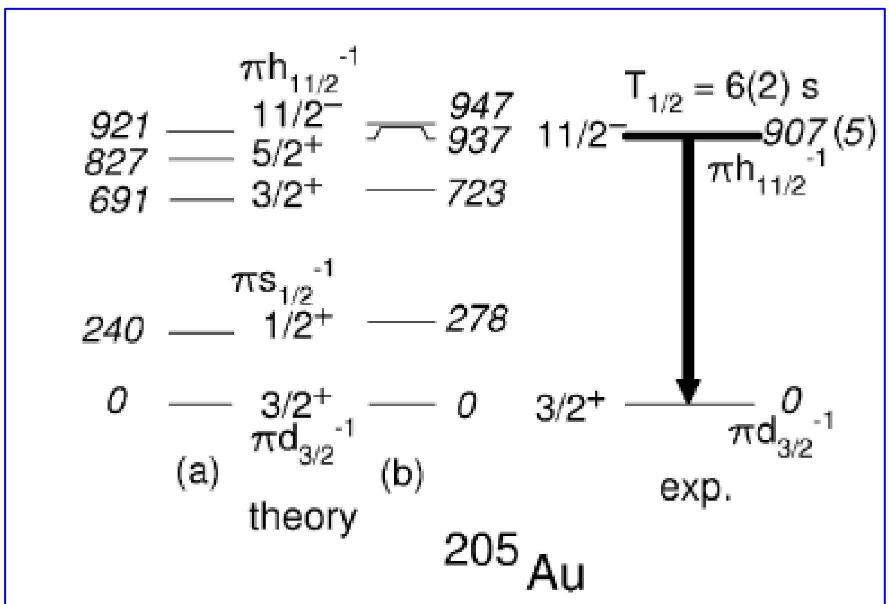
Contents lists available at ScienceDirect

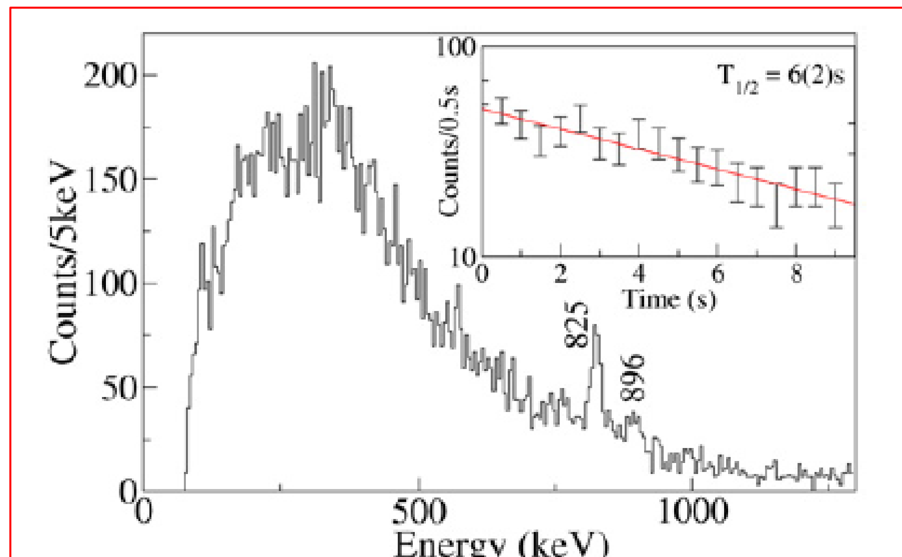
Physics Letters B

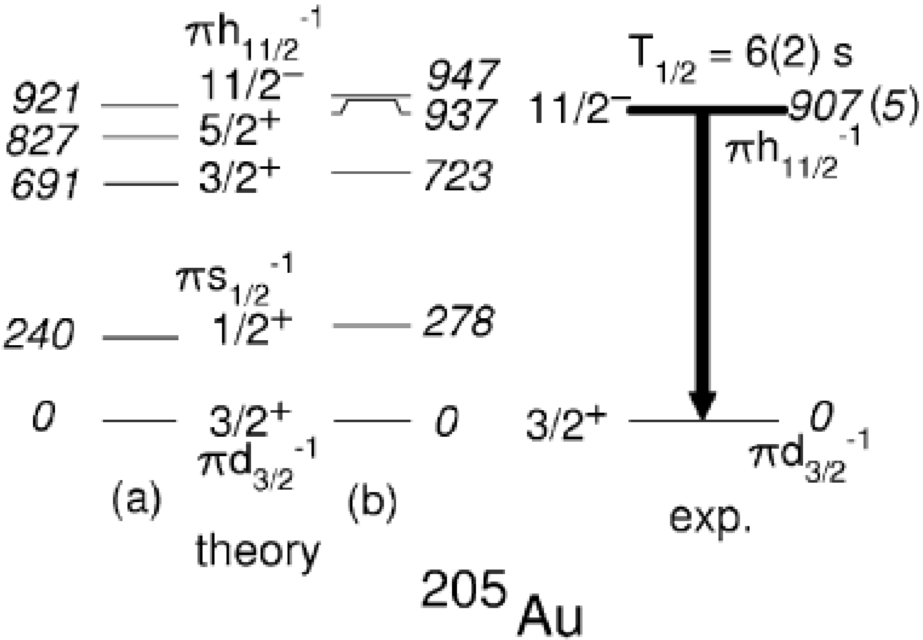
www.elsevier.com/locate/physletb

Proton–hole excitation in the closed shell nucleus ^{205}Au

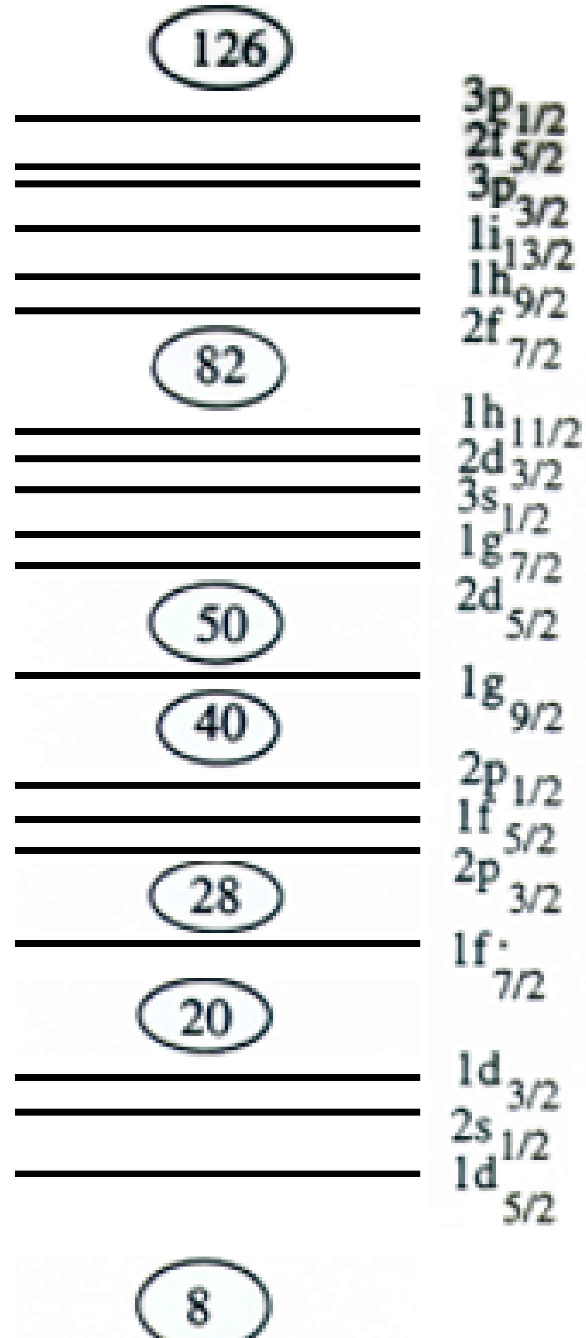
Zs. Podolyák [a,*], G.F. Farrelly [a], P.H. Regan [a], A.B. Garnsworthy [a], S.J. Steer [a], M. Górska [b], J. Benlliure [c], E. Casarejos [c], S. Pietri [a], J. Gerl [b], H.J. Wollersheim [b], R. Kumar [d], F. Molina [e], A. Algora [e,f], N. Alkhomashi [a], G. Benzoni [g], A. Blazhev [h], P. Boutachkov [b], A.M. Bruce [i], L. Caceres [b,j], I.J. Cullen [a], A.M. Denis Bacelar [i], P. Doornenbal [b], M.E. Estevez [c], Y. Fujita [k], W. Gelletly [a], H. Geissel [b], H. Grawe [b], J. Grębosz [b,l], R. Hoischen [m,b], I. Kojouharov [b], S. Lalkovski [i], Z. Liu [a], K.H. Maier [n,l], C. Mihai [o], D. Mücher [h], B. Rubio [e], H. Schaffner [b], A. Tamii [k], S. Tashenov [b], J.J. Valiente-Dobón [p], P.M. Walker [a], P.J. Woods [q]





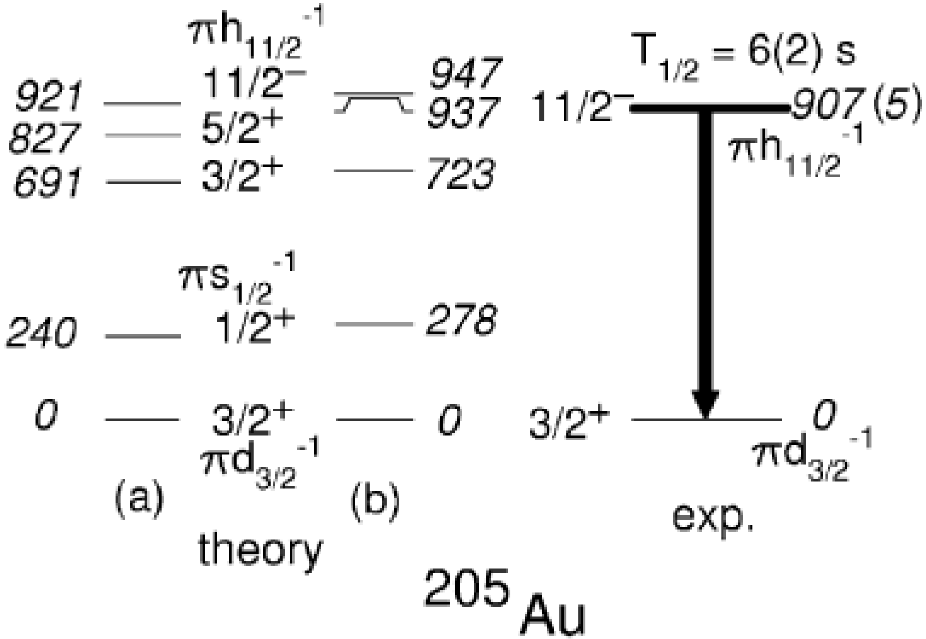


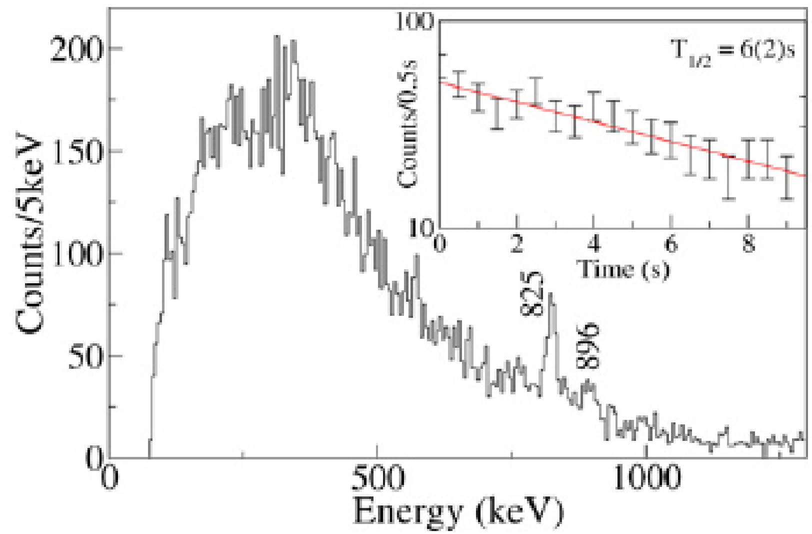
$\pi h_{11/2}^{-1}$
921 11/2⁻ 947
827 5/2⁺ 937
691 3/2⁺ 723
$\pi s_{1/2}^{-1}$
240 1/2⁺ 278
0 3/2⁺ 0
$\pi d_{3/2}^{-1}$
(a) (b)
theory
$T_{1/2}$ = 6(2) s
11/2⁻ 907(5)
$\pi h_{11/2}^{-1}$
3/2⁺ 0
$\pi d_{3/2}^{-1}$
exp.
^{205}Au



126
$3p_{1/2}$
$2f_{5/2}$
$3p_{3/2}$
$1i_{13/2}$
$1h_{9/2}$
$2f_{7/2}$
82
$1h_{11/2}$
$2d_{3/2}$
$3s_{1/2}$
$1g_{7/2}$
$2d_{5/2}$
50
$1g_{9/2}$
40
$2p_{1/2}$
$1f_{5/2}$
$2p_{3/2}$
28
$1f_{7/2}$
20
$1d_{3/2}$
$2s_{1/2}$
$1d_{5/2}$
8

Podolyak et al., Phys. Lett. **B672** (2009) 116





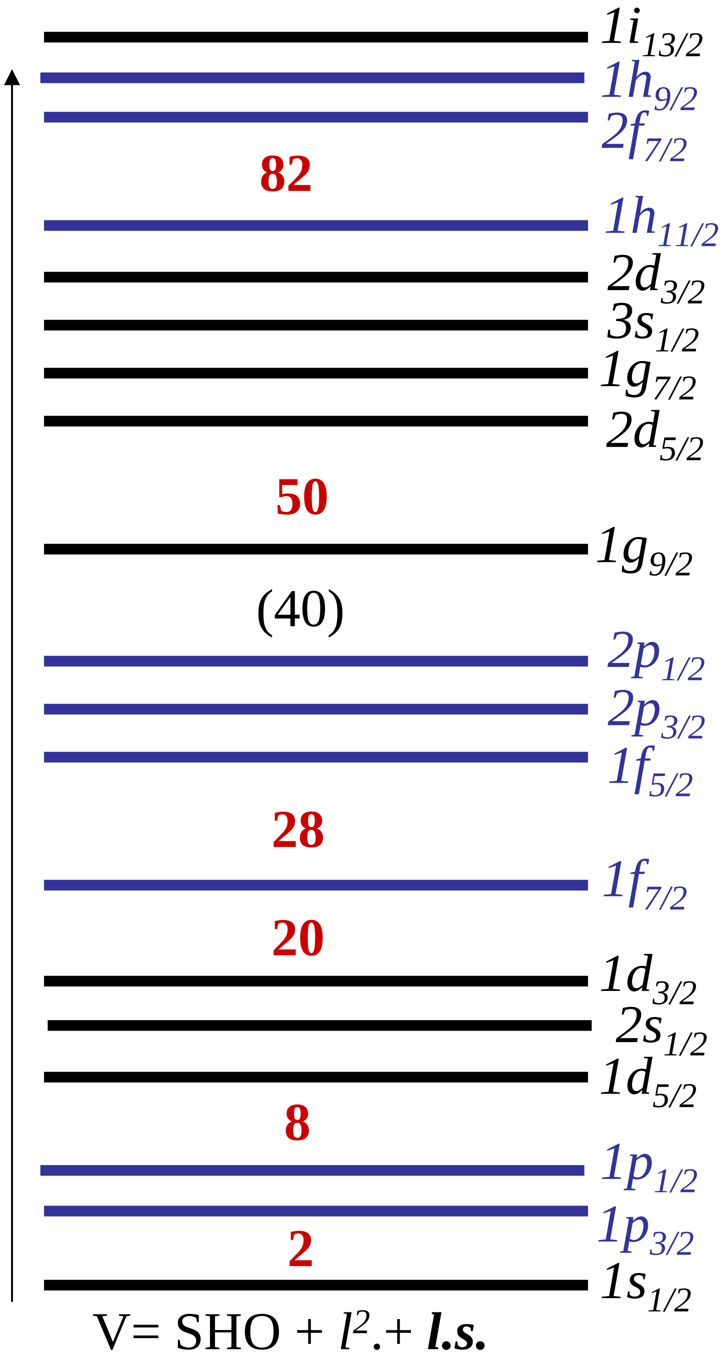
N=126 ; Z=79. Odd, single proton transition;
$h_{11/2} \rightarrow d_{3/2}$ state (holes in Z=82 shell).

Selection rule says lowest multipole decay allowed is λ=11/2 - 3/2 = 4.
Change of parity means lowest must transition be M4.

1Wu 907 keV M4 in ^{205}Au has $T_{1/2}$= 8secs.

‘Pure’ single particle (proton) transition from $11/2^-$ state to $3/2^+$ state.

(note, decay here is observed following INTERNAL CONVERSION).
These competing decays (to gamma emission) are often observed in isomeric decays



ASIDE:
Why are E1 s isomeric?

E1s often observed with decay probabilities Of $10^{-5} \rightarrow 10^{-9}$ Wu

E1 single particle decays need to proceed between orbitals which have $\Delta l = 1$ and change parity, e.g.,

$f_{7/2}$ and $d_{5/2}$

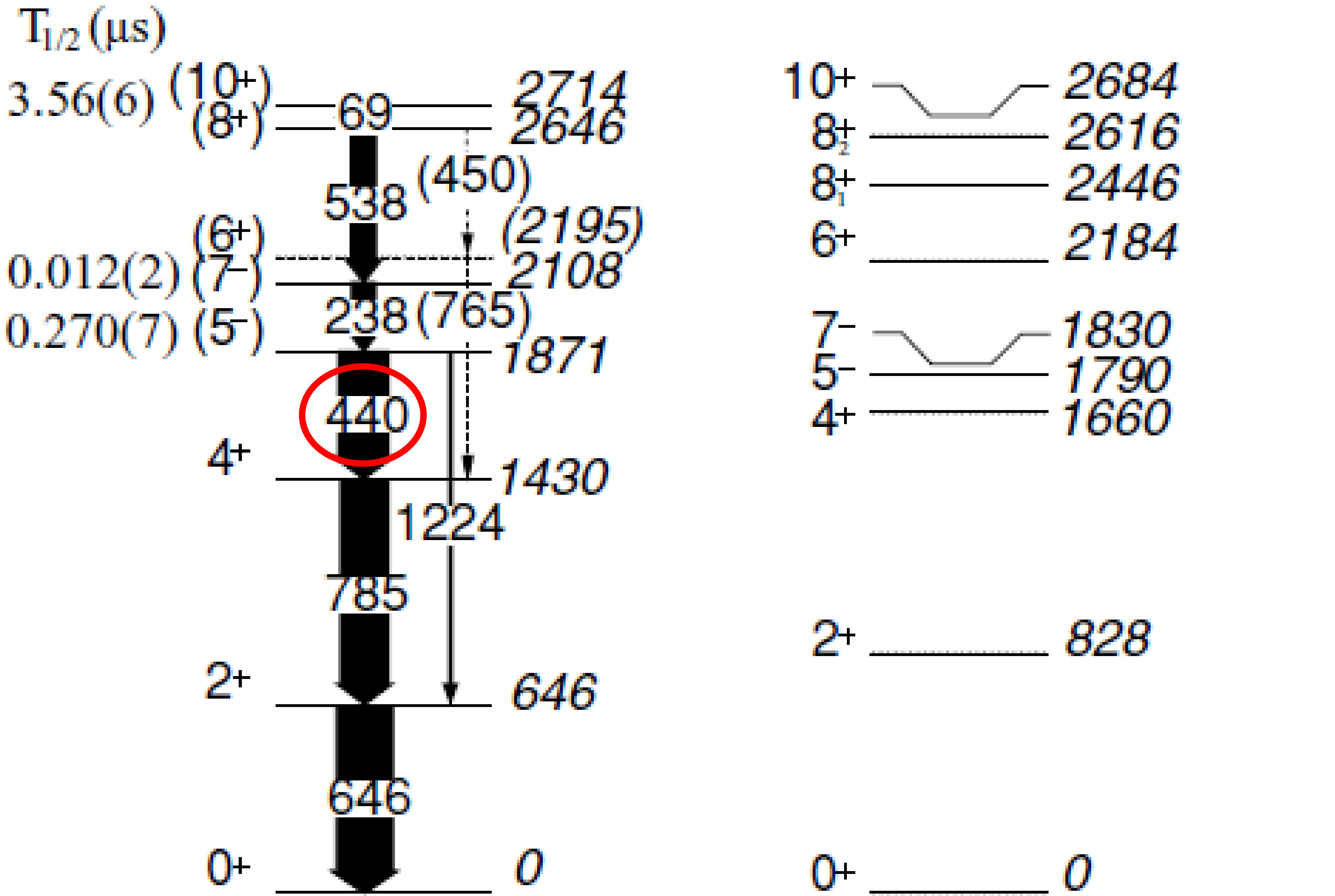
or $g_{9/2}$ and $f_{7/2}$

or $h_{11/2}$ and $g_{9/2}$

or $i_{13/2}$ and $h_{11/2}$

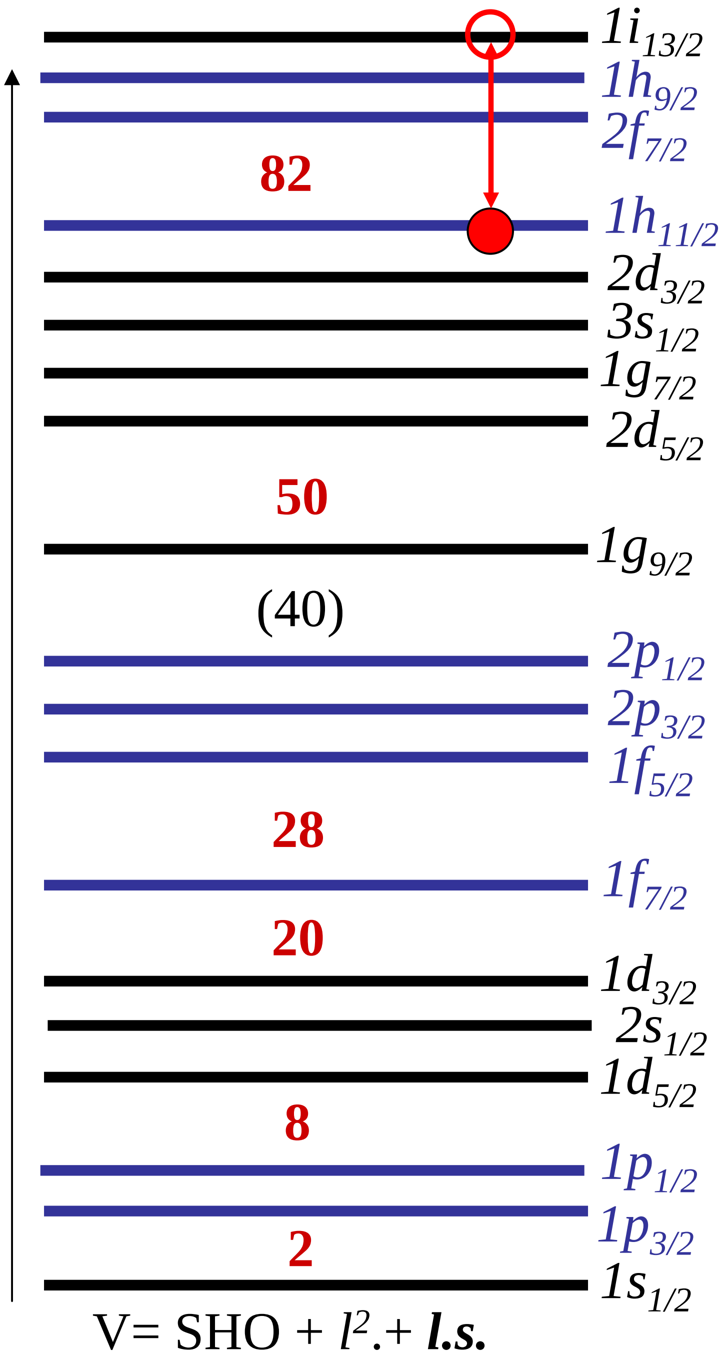
or $p_{3/2}$ and $d_{5/2}$

BUT these orbitals are along way from each other in terms of energy in the mean-field single particle spectrum.



e.g., ^{128}Cd, isomeric 440 keV E1 decay.
1 Wu 440 keV E1 should have ~4×10^{-15}s;
Actually has ~300 ns (i.e hindered by ~10^{8} !!)

L. Cáceres,[1,2,*] M. Górska,[1]
PHYSICAL REVIEW C **79**, 011301(R) (2009)



Why are E1 s isomeric?

E1 single particle decays need to proceed between orbitals which have Delta L=1 and change parity, e.g.,

What about typical 2-particle configs. e.g.,

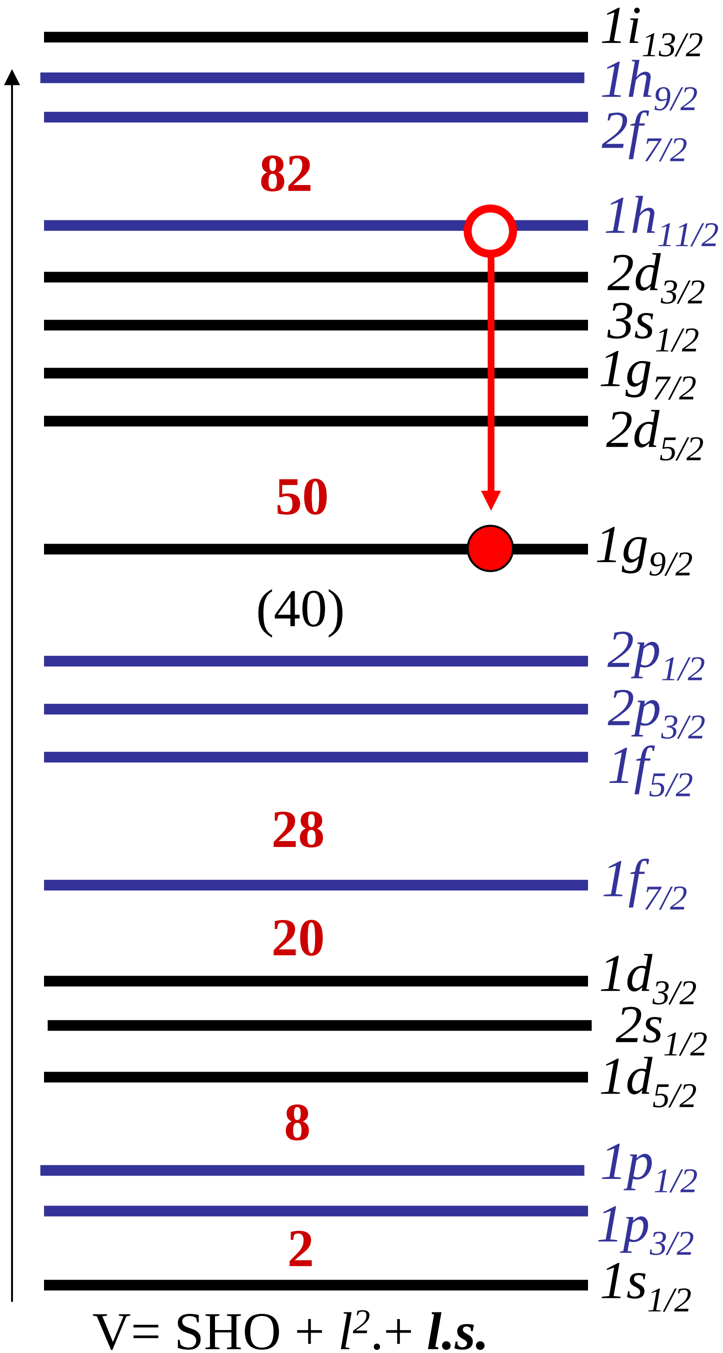
$I^{\pi}=5^{-}$ from mostly $(h_{11/2})^{-1}$ x $(s_{1/2})^{-1}$

$I^{\pi}=4^{+}$ from mostly $(d_{3/2})_{-}^{1}$ x $(s_{1/2})^{-1}$

No E1 'allowed' between such orbitals.

E1 occur due to (very) small fractions of the wavefunction from orbitals in higher shells.

Small overlap wavefunction in multipole Matrix element causes 'slow' E1s



Why are E1 s isomeric?

E1s often observed with decay probabilities Of $10^{-5} \rightarrow 10^{-8}$ Wu

E1 single particle decays need to proceed between orbitals which have Delta L=1 and change parity, e.g.,

$f_{7/2}$ and $d_{5/2}$

or $g_{9/2}$ and $f_{7/2}$

or $h_{11/2}$ and $g_{9/2}$

or $p_{3/2}$ and $d_{5/2}$

BUT these orbitals are along way from each other in terms of energy in the mean-field single particle spectrum.

Measurements of EM Transition Rates

Rep. Prog. Phys., Vol. 42, 1979.

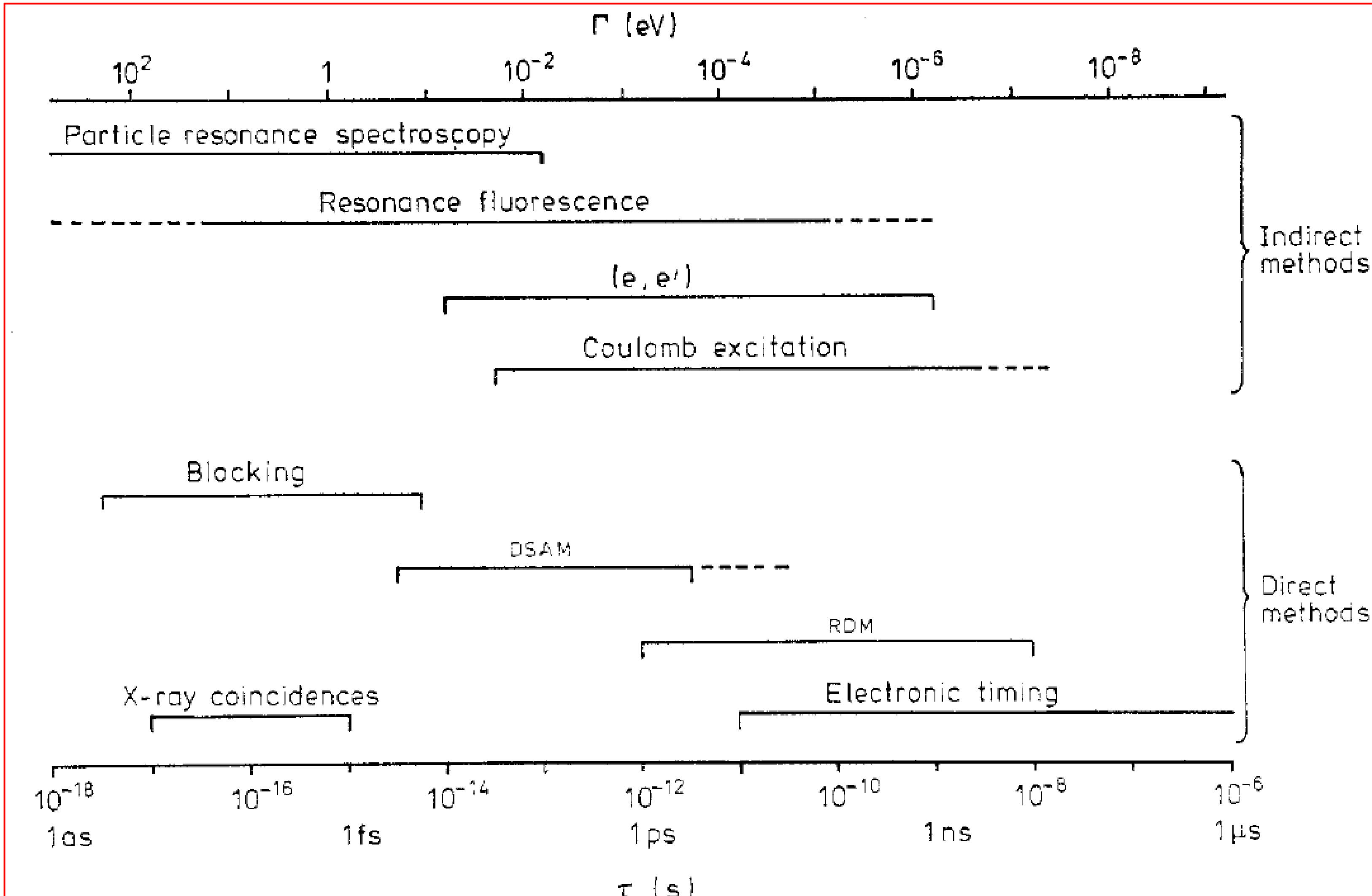
The measurement of the lifetimes of excited nuclear states

PJ NOLAN† and JF SHARPEY-SCHAFER‡

$$\Gamma\tau = \hbar.$$

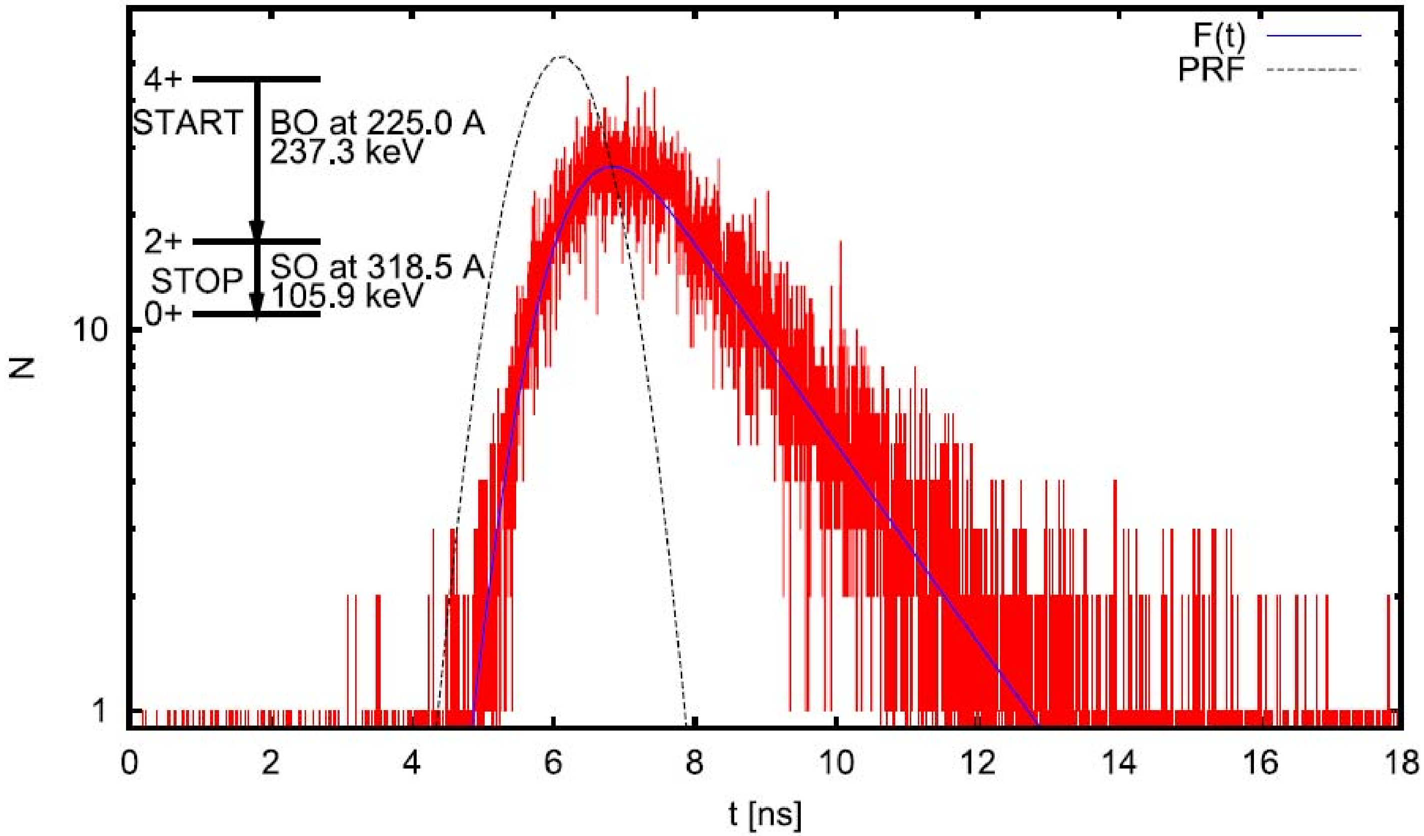
$$\Gamma \propto |\langle \psi_f | \hat{O}_{decay} | \psi_i \rangle|^2$$

$$\Gamma_{total} = \sum_j \Gamma_j.$$



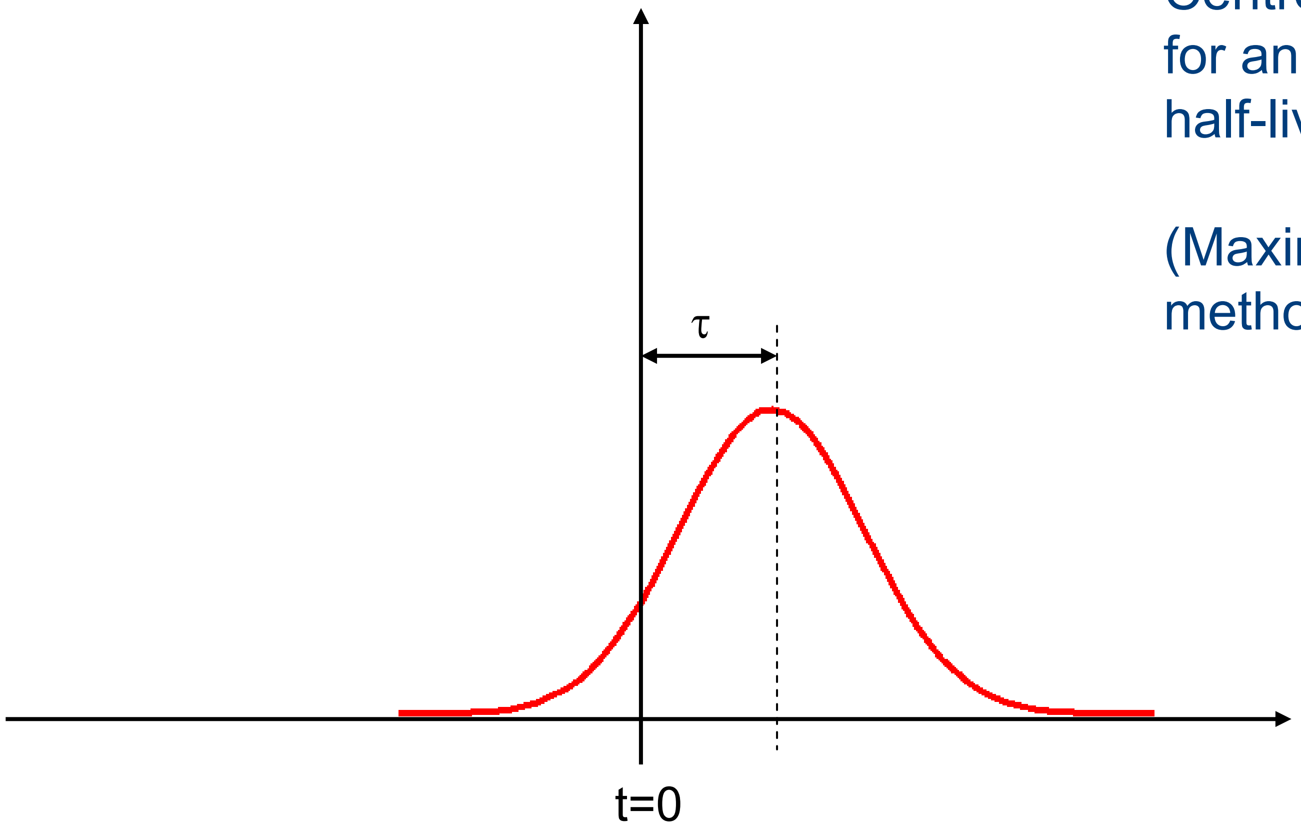
Fast-timing Techniques

M. Rudigier et al. / Nuclear Physics A 847 (2010) 89–100



Gaussian-exponential convolution to account for timing resolution

Fast-timing Techniques

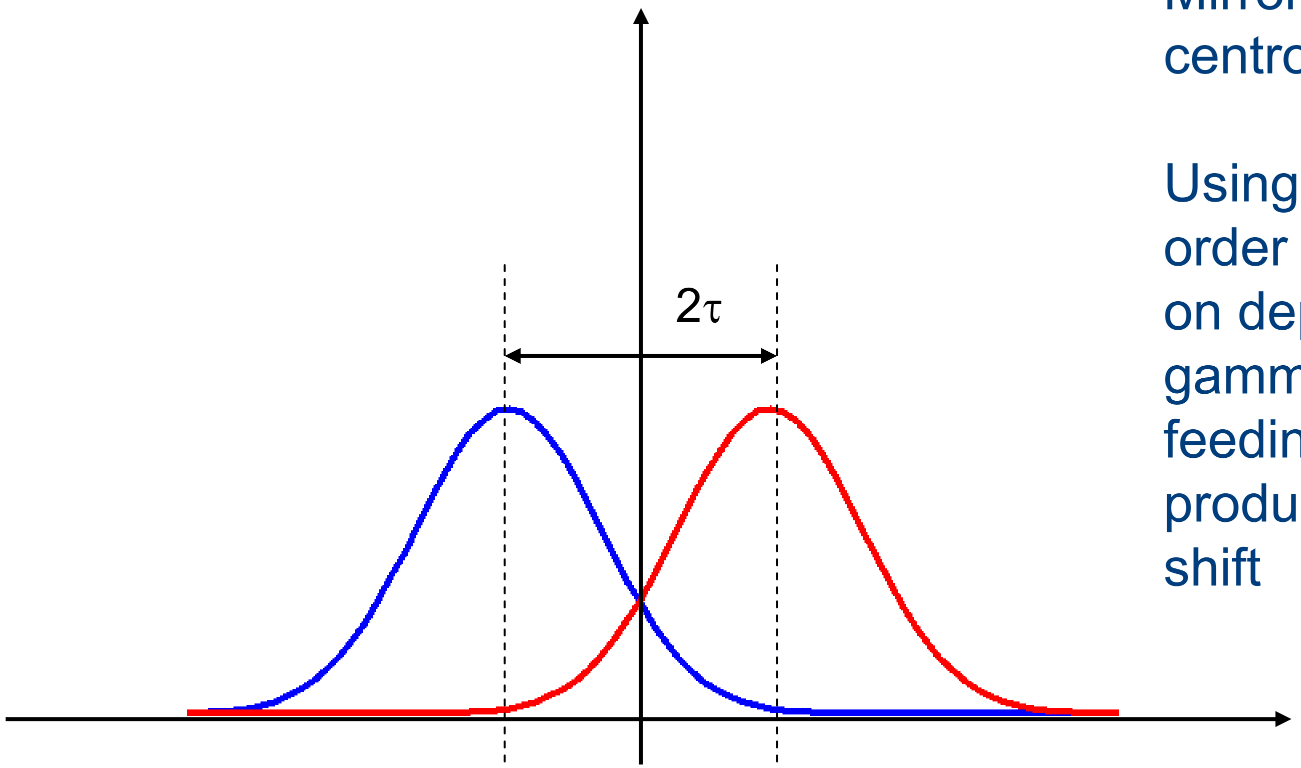


Centroid shift method for an analysis of short half-lives

(Maximum likelihood method)

Difference between the centroid of observed time spectrum and the prompt response give lifetime, τ

Fast-timing Techniques

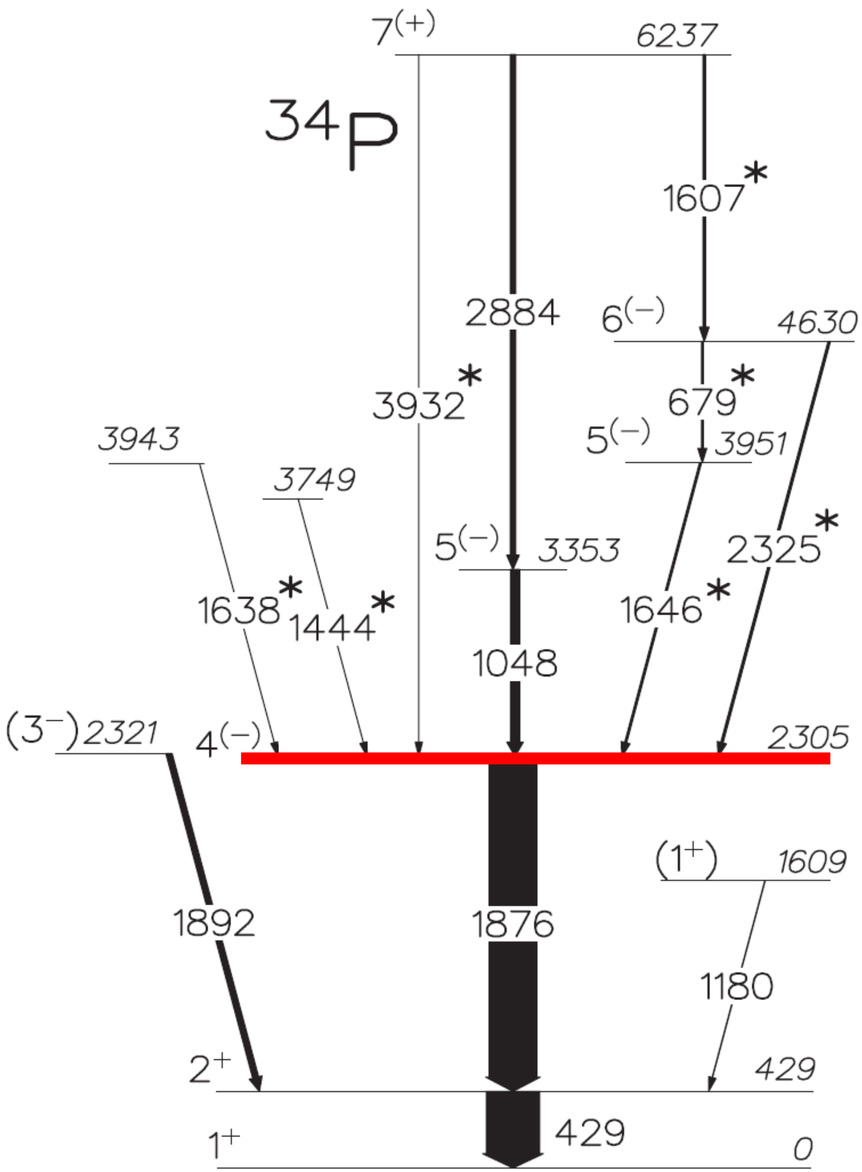


Mirror-symmetric centroid shift method.

Using reversed gate order (e.g. start TAC on depopulating gamma, stop on feeding gamma) produces opposite shift

Removes the need to know where the prompt distribution is and other problems to do with the prompt response of the detectors

An example, 'fast-timing' in ^{34}P.



P. C. BENDER *et al.* PHYSICAL REVIEW C **80**, 014302 (2009)

R. CHAKRABARTI *et al* PHYSICAL REVIEW C **80**, 034326 (2009)

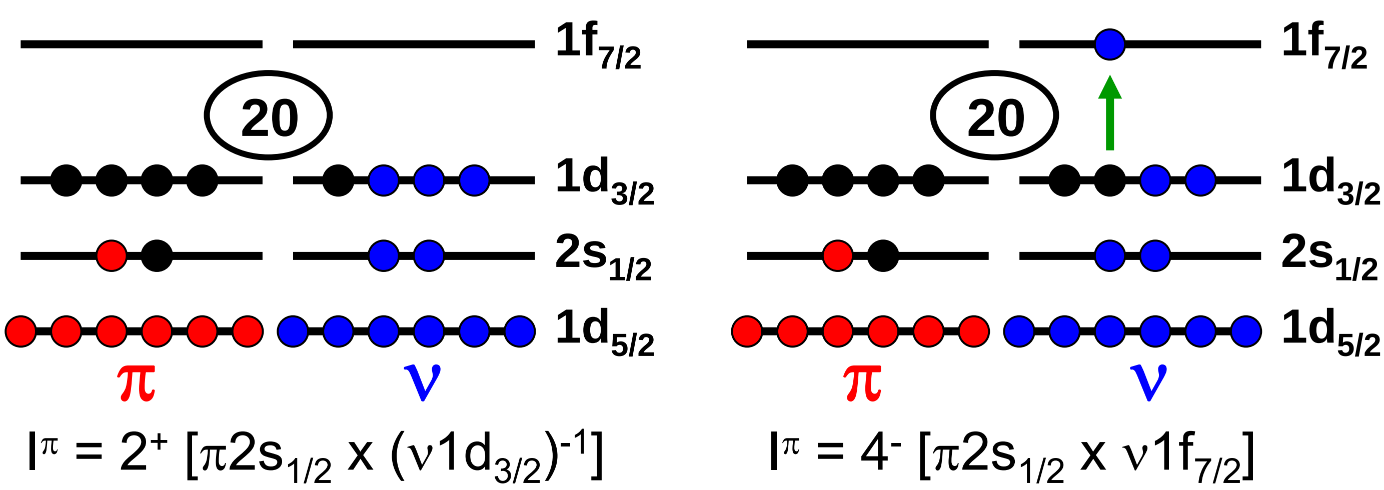
- Recent study of ^{34}P identified low-lying $I^{\pi}=4^{-}$ state at E=2305 keV.
- $I^{\pi}=4^{-} \rightarrow 2^{+}$ transition can proceed by M2 and/or E3.
- Aim of experiment is to measure precision lifetime for 2305 keV state and obtain B(M2) and B(E3) values.
- Previous studies limit half-life to 0.3 ns < $t_{1/2}$ < 2.5ns

Physics….which orbitals are involved?

- Theoretical (shell model) predictions suggest 2^+ state based primarily on $[\pi 2s_{1/2} \times (\nu 1d_{3/2})^{-1}]$ configuration and 4^- state based primarily on $[\pi 2s_{1/2} \times \nu 1f_{7/2}]$ configuration.

- Thus expect transition to go mainly via $f_{7/2} \rightarrow d_{3/2}$, M2 transition.

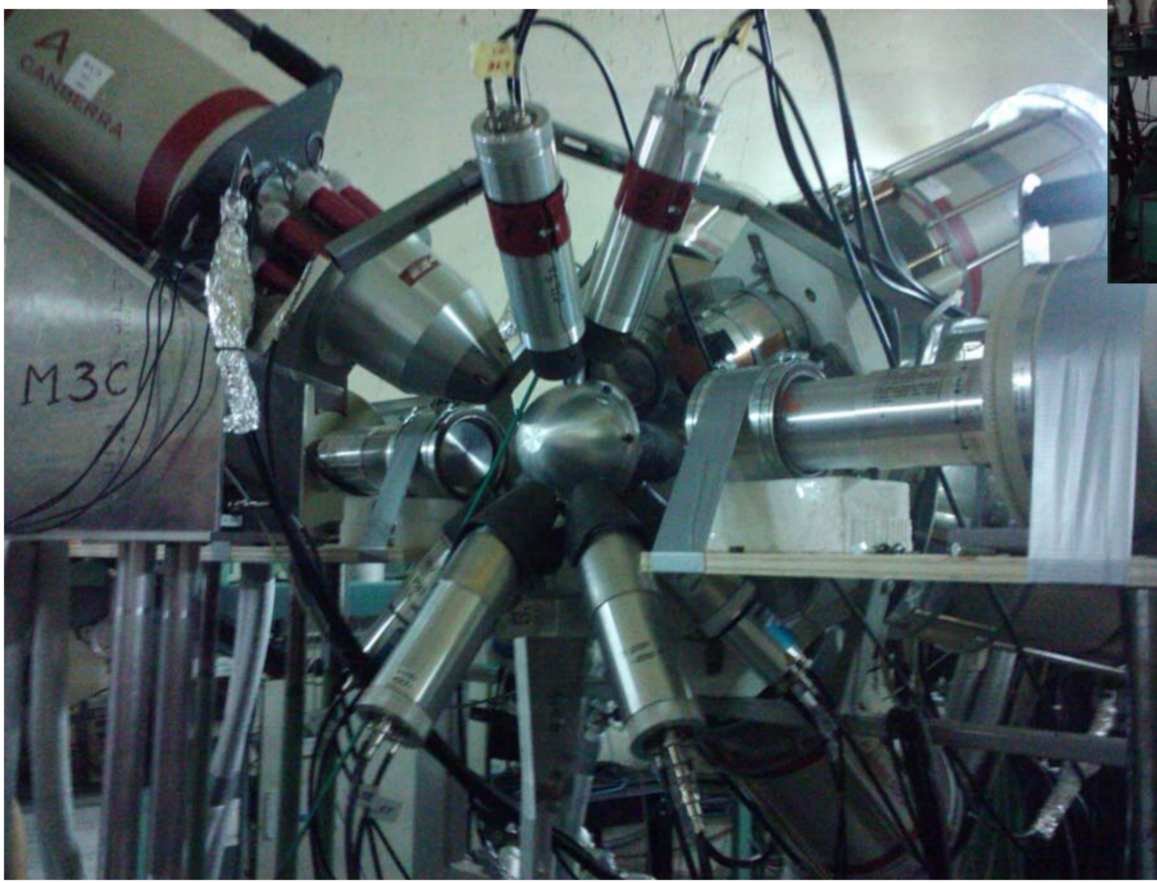
- Different admixtures in 2^+ and 4^- states may also allow some E3 components (e.g., from, $f_{7/2} \rightarrow s_{1/2}$) in the decay.



Experiment to Measure Yrast 4^- Lifetime in ^{34}P

$^{18}O(^{18}O,pn)^{34}P$ fusion-evaporation at 36 MeV $\sigma \sim 5 - 10$ mb

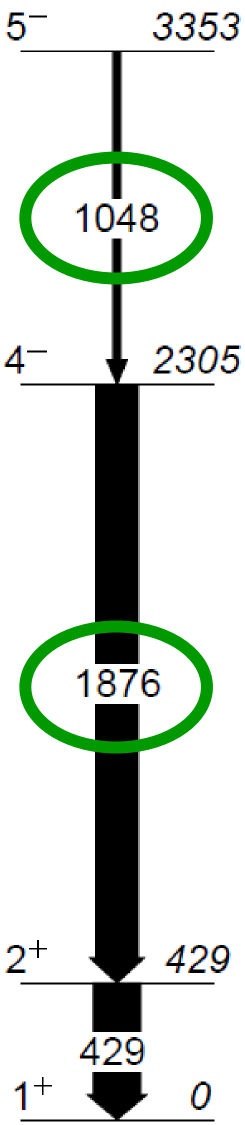
50mg/cm^2 $Ta_2{}^{18}O$ enriched foil; ^{18}O Beam from Bucharest Tandem (~20pnA)



Array 8 HPGe (unsuppressed) and 7 $LaBr_3$:Ce detectors

-3 (2"x2") cylindrical
-2 (1"x1.5") conical
-2 (1.5"x1.5") cylindrical

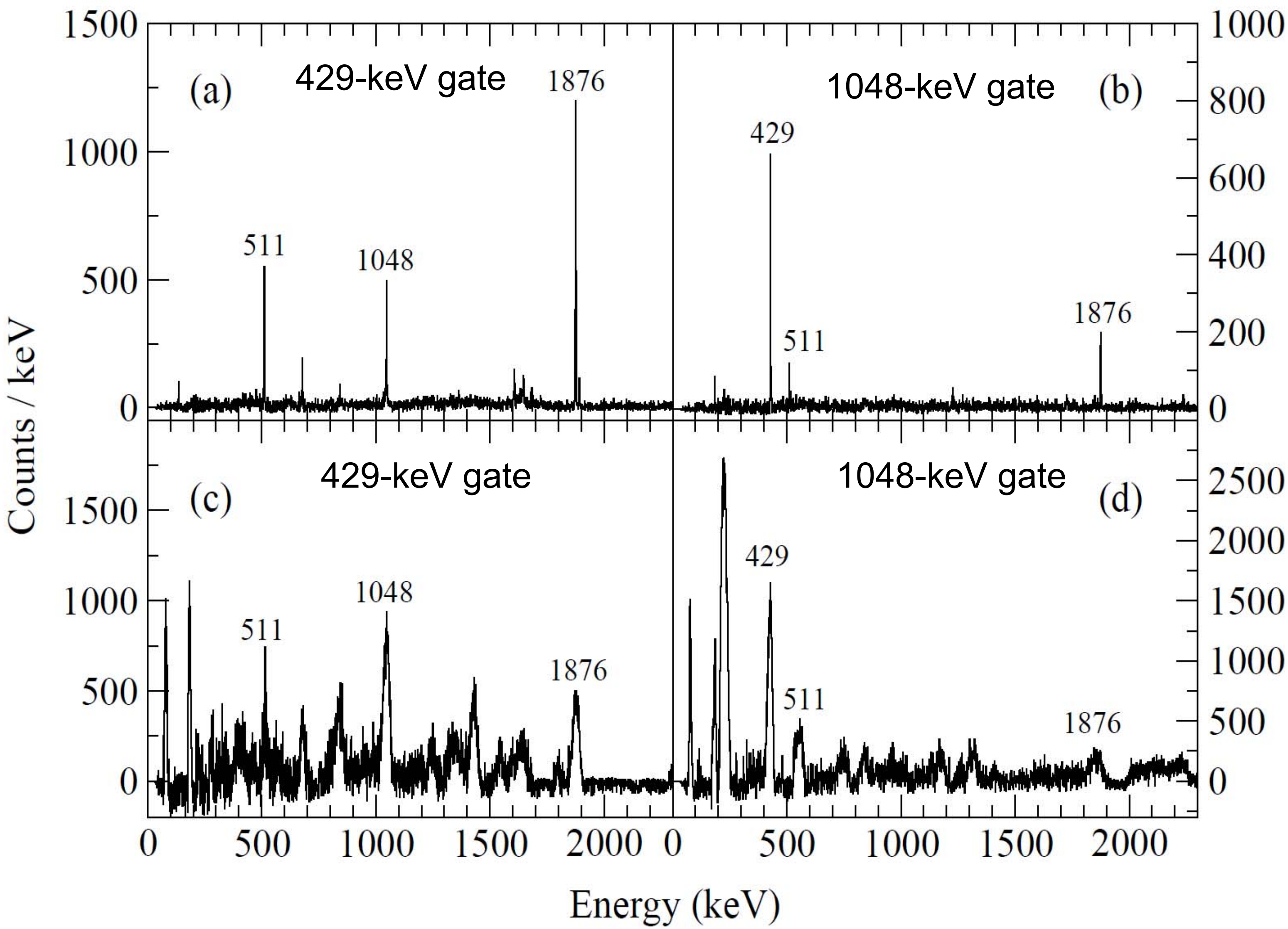
Ge-Gated Time differences

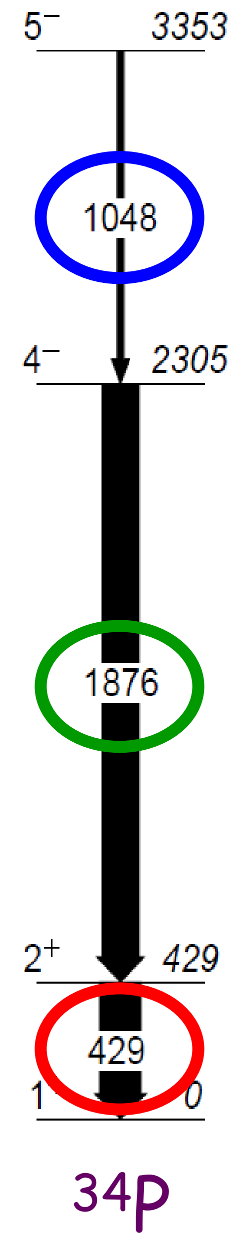


Gates in $LaBr_3$ detectors to observe time difference and obtain lifetime for state

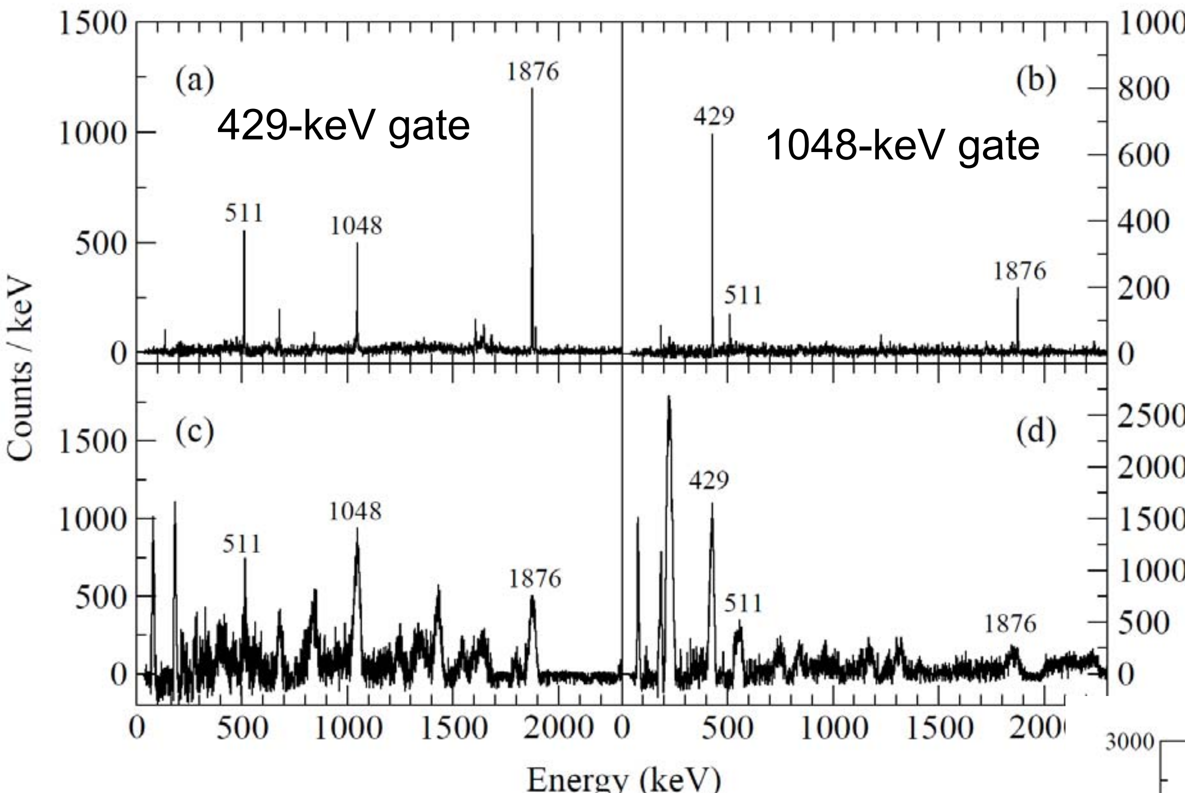
Ideally, we want to measure the time difference between transitions directly feeding and depopulating the state of interest (4^-)

Gamma-ray energy coincidences 'locate' transitions above and below the state of interest....



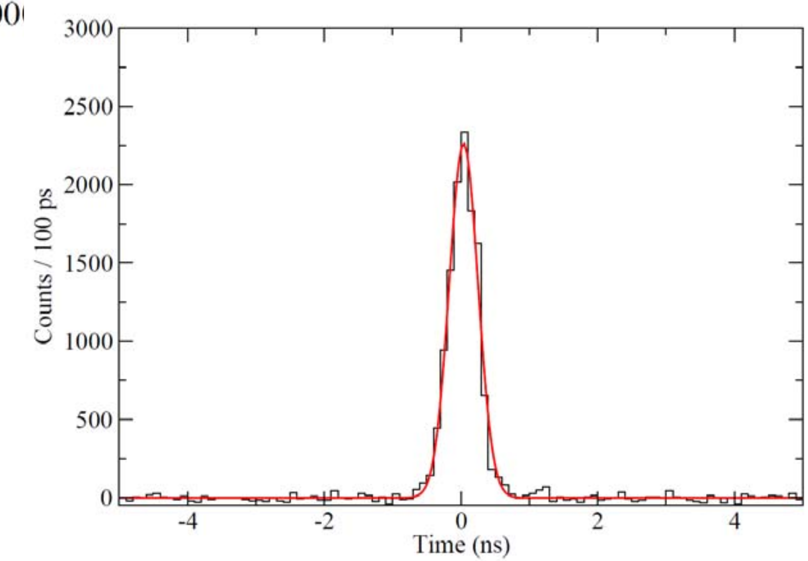


Ungated LaBr$_3$ Time difference

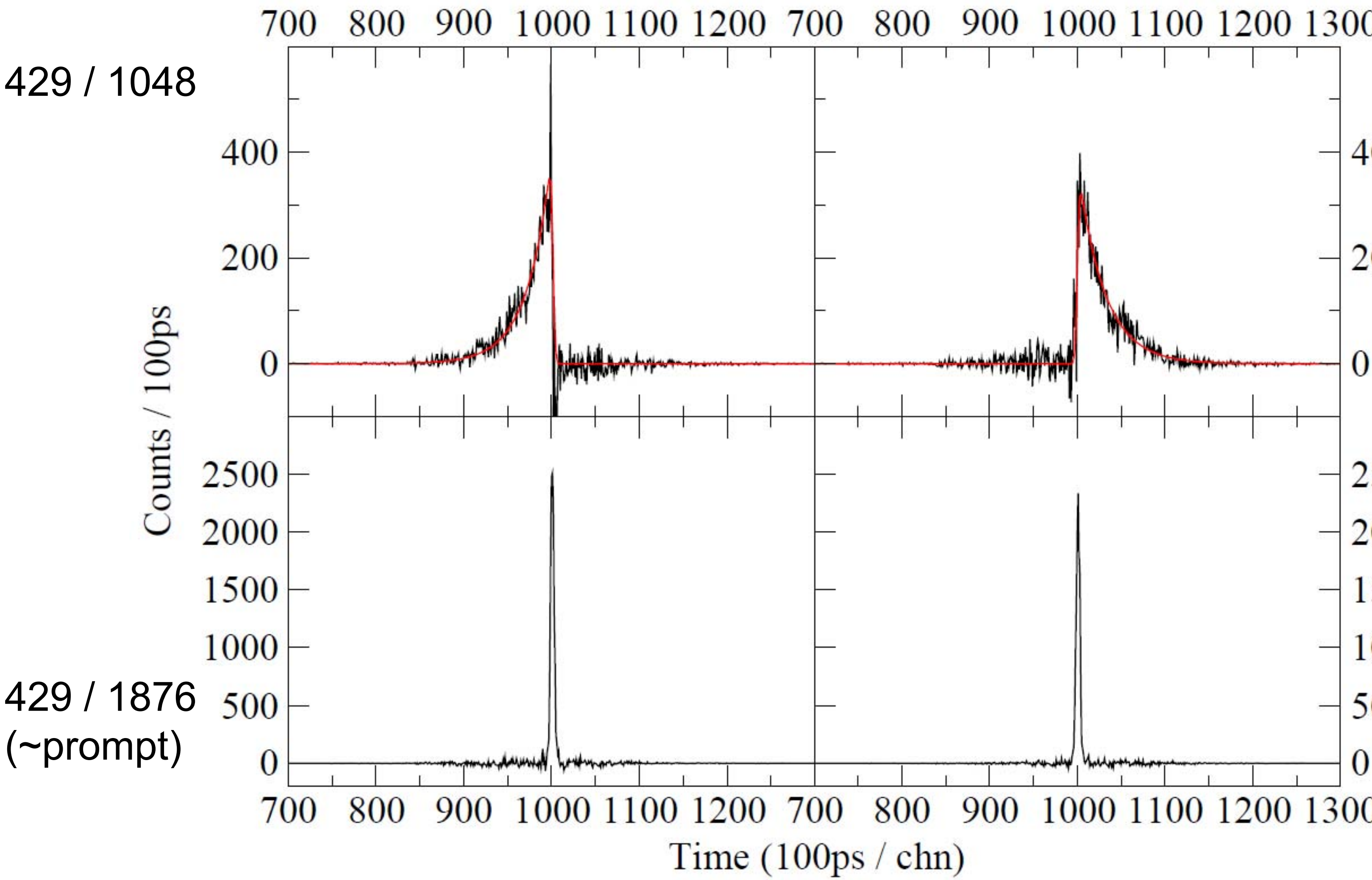


The LaBr$_3$-LaBr$_3$ coincidences were relatively clean where it counts so try without the Ge gate…

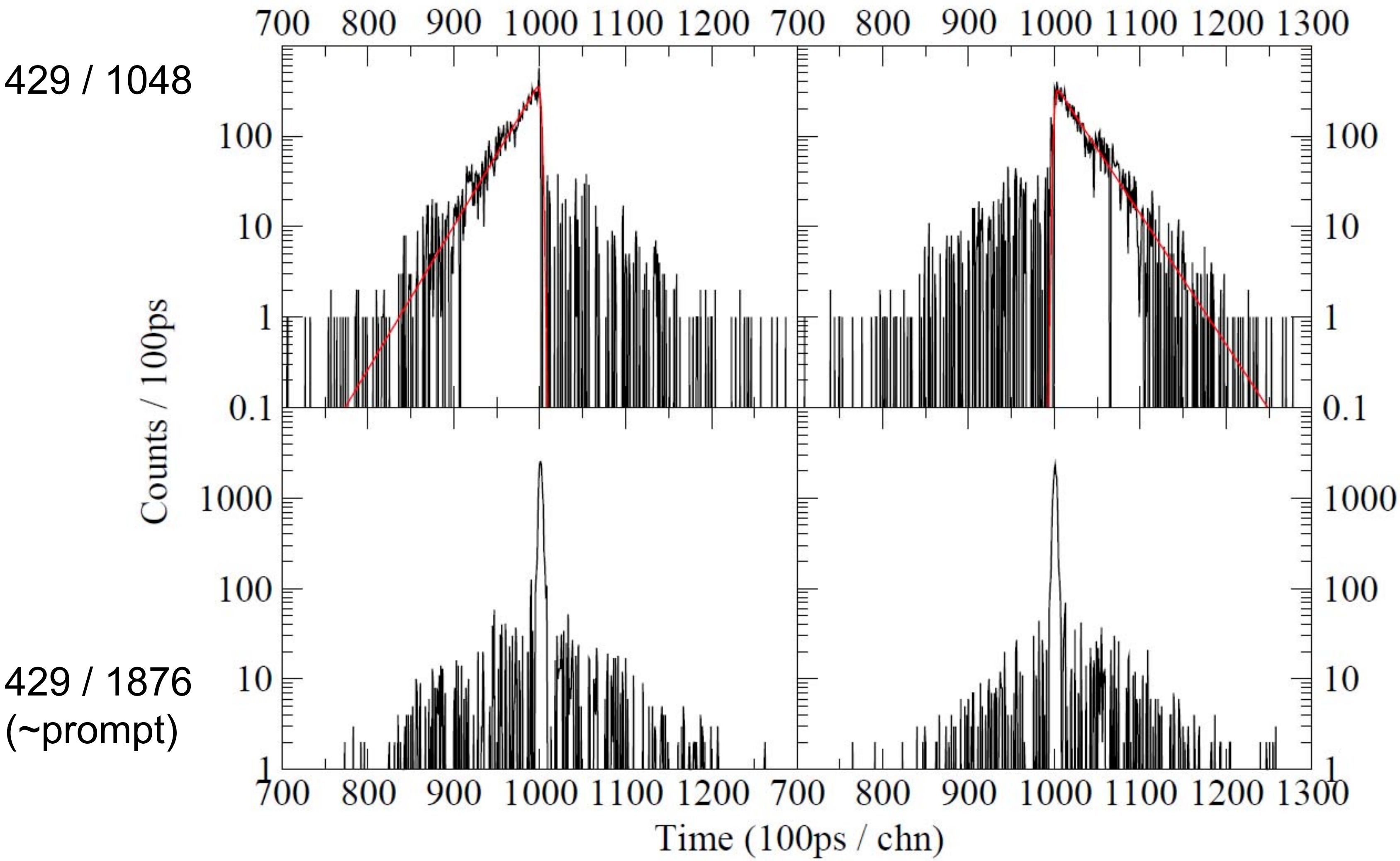
e.g. The 1876-429-keV time difference is ^{34}P. Should show prompt distribution as half-life of 2^+ is short.
FWHM = 470(10) ps



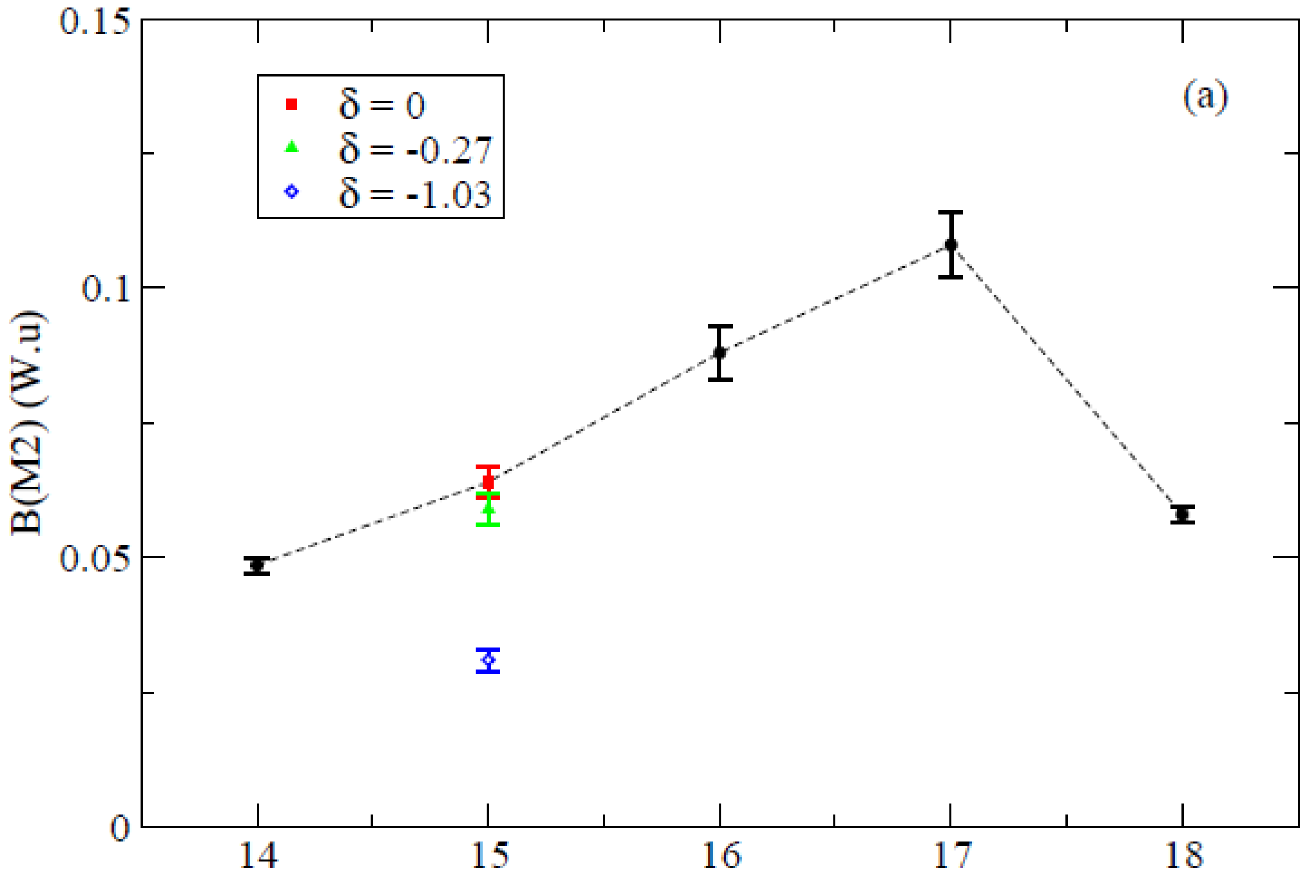
Result: $T_{1/2}$ ($I^{\pi}=4^{-}$) in ^{34}P= 2.0(1) ns



Results: $T_{1/2}$ = 2.0(1)ns



Discussion: *M2* Strengths



- Experimental B(M2) and Mixing ratios from N=19 nuclei approaching the island of inversion.

What about 'faster' transitions..
i.e. < ~10 ps ?

Collective Model B(E2), B(M1) values ?

The reduced in-band transition probabilities[1] are given by,

$$B(E2; I_i K \rightarrow I_f K) = \frac{5}{16\pi} e^2 Q_o^2 | < I_i 2 K 0 | I_f K > |^2$$

$$B(E2; I_i K \rightarrow I_f K) = \frac{5}{16\pi} e^2 Q_o^2 | < I_i 1 K 0 | I_f K > |^2 \qquad (2.4.56)$$

$$B(M1; I_i K \rightarrow I_f K) = \frac{3}{4\pi} e^2 | < I_i 1 K 0 | I_f K > |^2 (g_K - g_R)^2 K^2$$

where Q_o is the intrinsic quadrupole moment and g_K and g_R are the intrinsic and rotational gyromagnetic ratios respectively. The relevant Clebsch-Gordon coefficients[2] are given below.

$$E2(\Delta I = 2) = \left[\frac{3(I-K)(I-K-1)(I+K)(I+K-1)}{(2I-2)(2I-1)I(2I+1)} \right]^{1/2}$$

$$E2(\Delta I = 1) = -K \left[\frac{3(I-K)(I+K)}{(I-1)I(2I+1)(I+1)} \right]^{1/2} \qquad (2.4.57)$$

$$M1(\Delta I = 1) = - \left[\frac{(I-K)(I+K)}{I(2I+1)} \right]^{1/2}$$

[1] K.E.G. Löbner in, The Electromagnetic Interaction in Nuclear Spectroscopy, W.D. Hamilton (Ed), North-Holland (1975) Chapter 5

[2] The Theory of Atomic Spectra, Condon and Shortley (1935) reprinted (1963) p76-77

THE MEASUREMENT OF SHORT NUCLEAR LIFETIMES[1]

By A. Z. Schwarzschild and E. K. Warburton
Brookhaven National Laboratory, Upton, New York[2]

Annual Review of Nuclear Science (1968) **18** p265-290

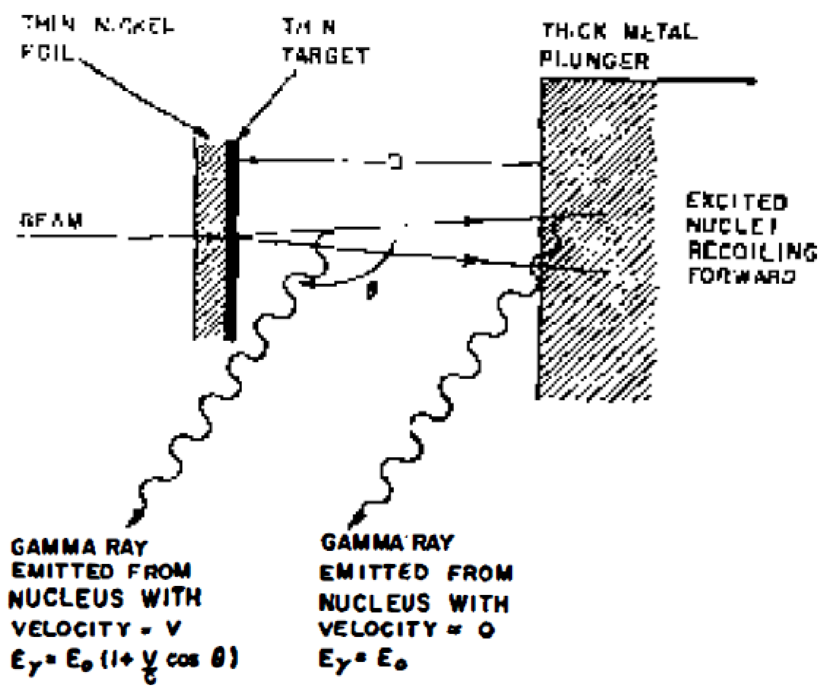
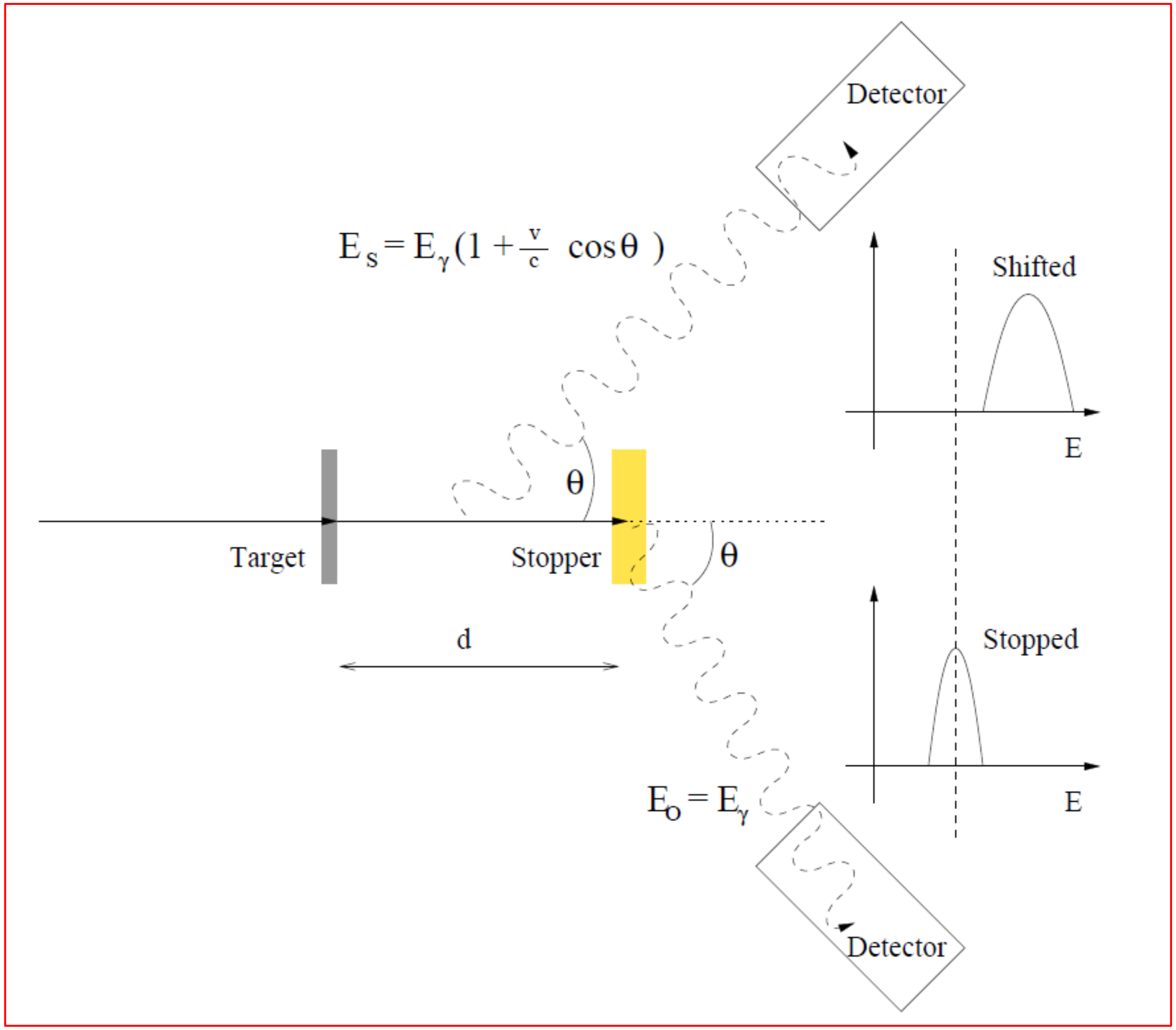


Fig. 5. Recoil method of measuring lifetimes of excited states.



$$E_0 = E_0$$

$$E_S = E_0\left(\frac{\sqrt{1-\beta^2}}{1-\beta\cos\theta}\right)$$

$$E_S \approx E_0(1+\beta\cos\theta)$$

$$I_0 = N_0 \exp\left(\frac{-d}{v\tau}\right)$$

$$I_S = N_0\left(1 - \exp\left(\frac{-d}{v\tau}\right)\right)$$

$$R = \frac{I_0}{I_0 + I_S} = \exp\left(\frac{-d}{v\tau}\right)$$

$$\tau = \frac{-d}{v\ln(R)}$$

$$B(E2) = \frac{1}{1.225\times10^9 E_\gamma^5 \tau(1+\alpha)},$$

$$B(E2) = \frac{5}{16\pi} e^2 Q_t^2 |\langle J_i K 20 | J_f K\rangle|^2,$$

$$Q_t \approx \frac{3}{\sqrt{5\pi}} Z R_0^2 \beta_2 (1 + 0.16\beta_2),$$

PHYSICAL REVIEW C **76**, 064302 (2007)

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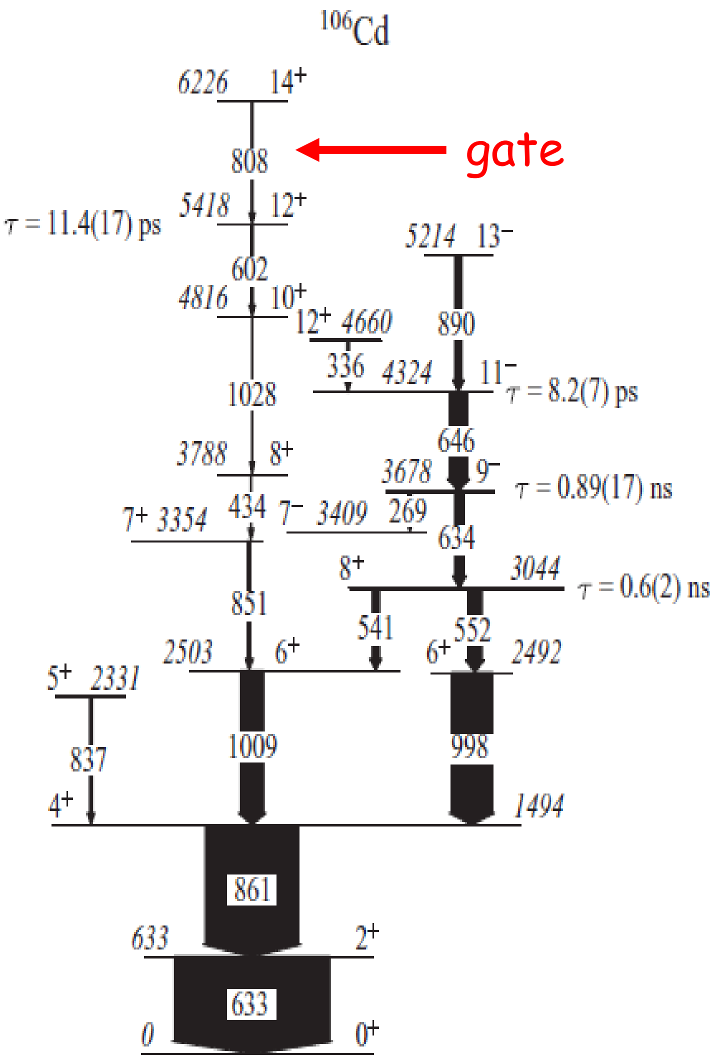

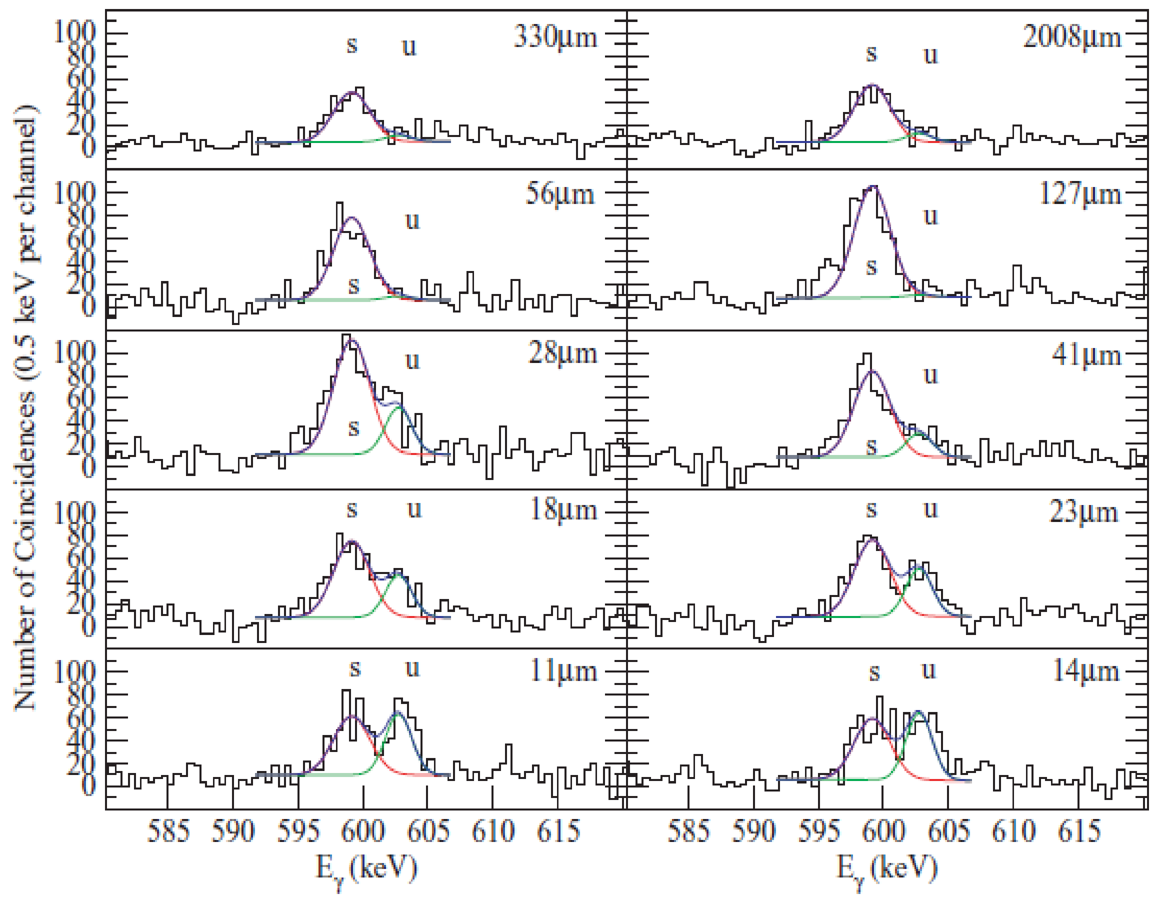

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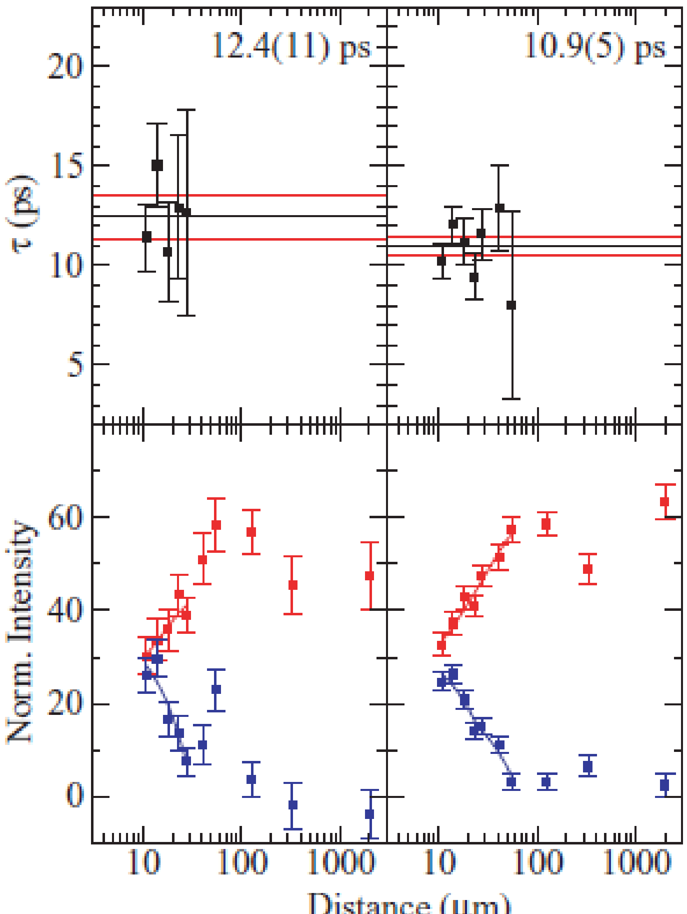
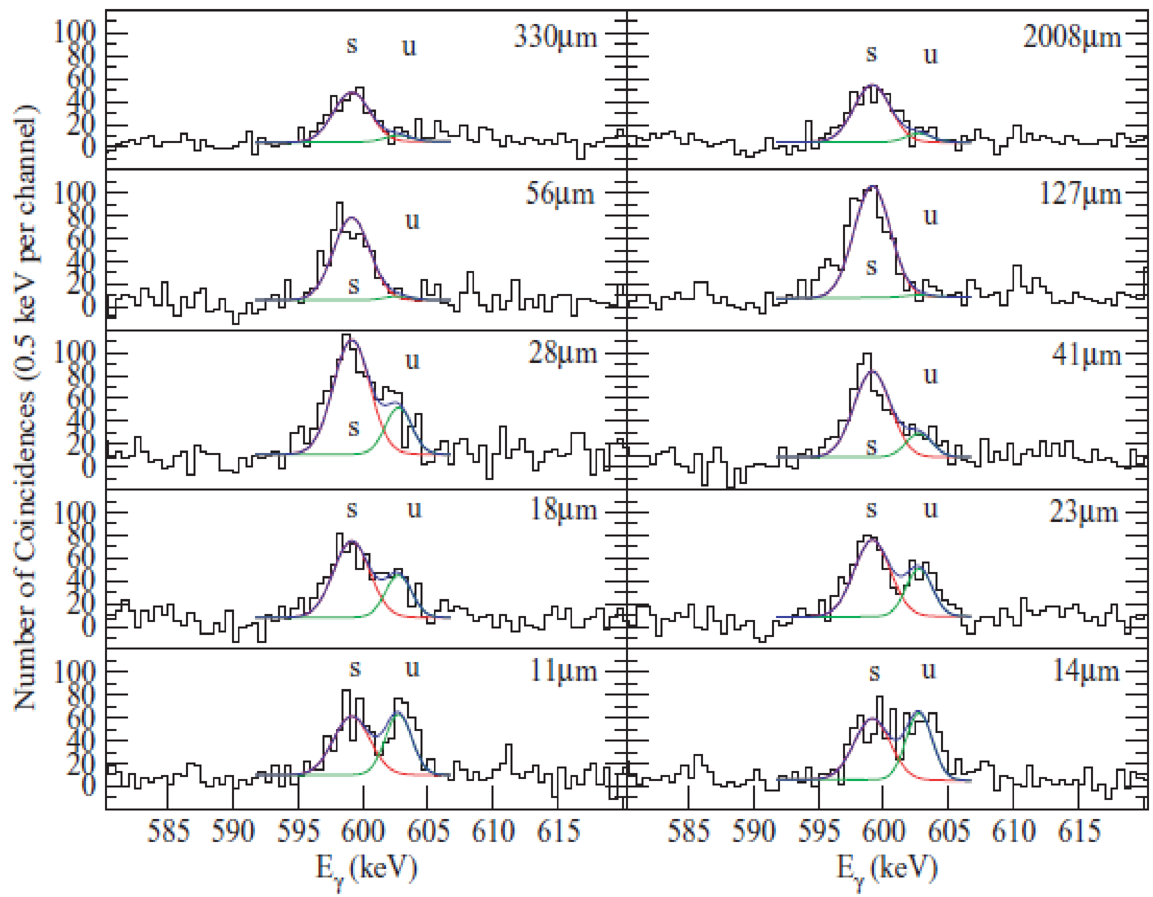
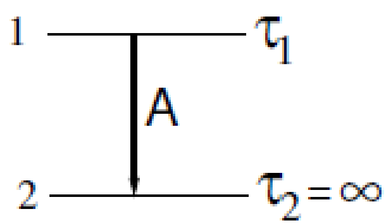




$$\tau = \frac{I_U}{v \frac{dI_s}{dx}}$$

ASIDE: Multistep cascades, need to account for decay lifetimes of states feeding the state of interest…..need to account for the Bateman Equations.

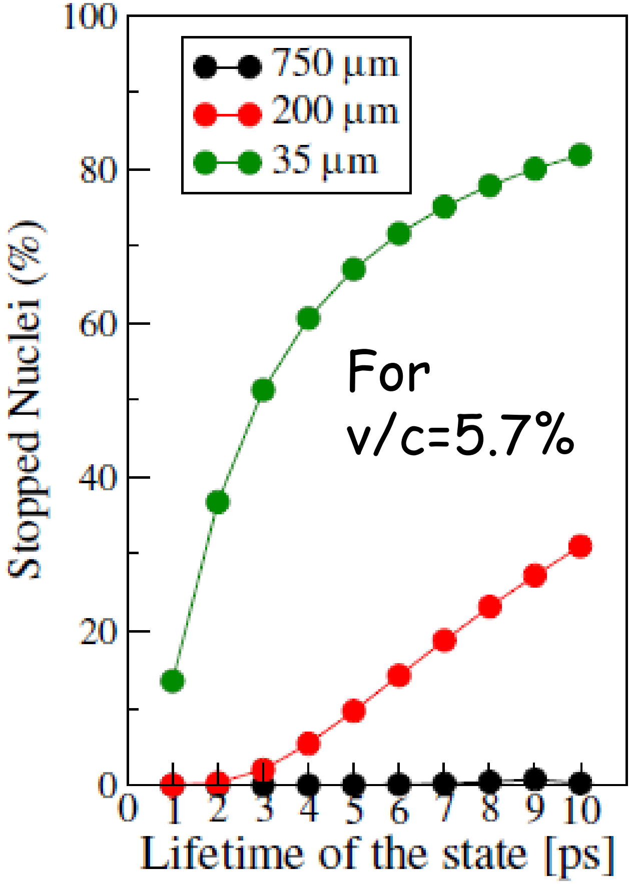
$$TOF = \frac{d}{v}$$



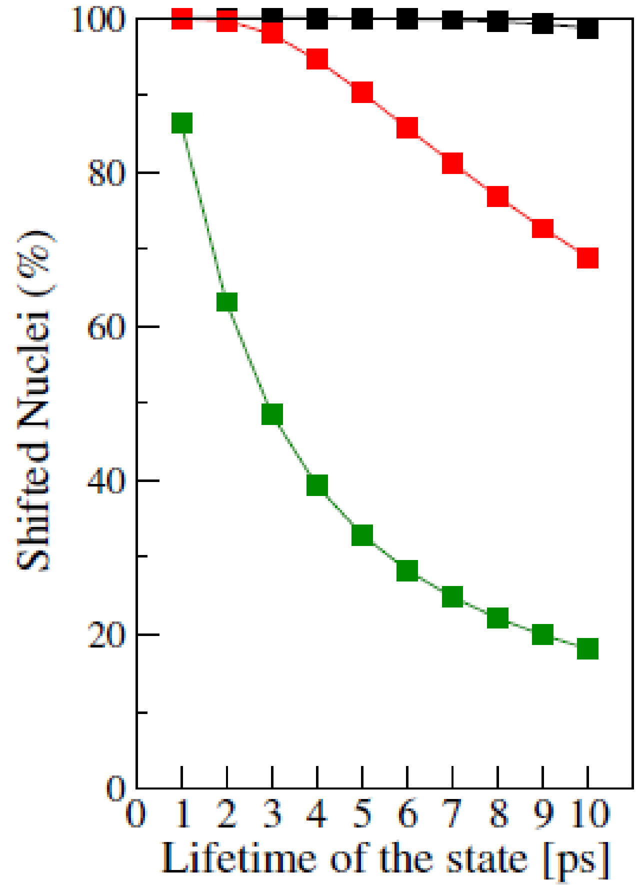
(a)

(a) Single decay

$$N_u(t) = N_0 e^{\frac{-t}{\tau}}$$

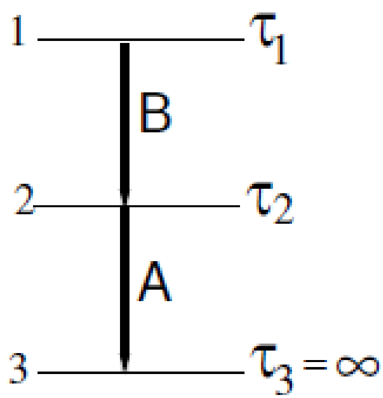


$$N_s(t) = N_0 - N_u(t) = N_0[1 - e^{\frac{-t}{\tau}}]$$

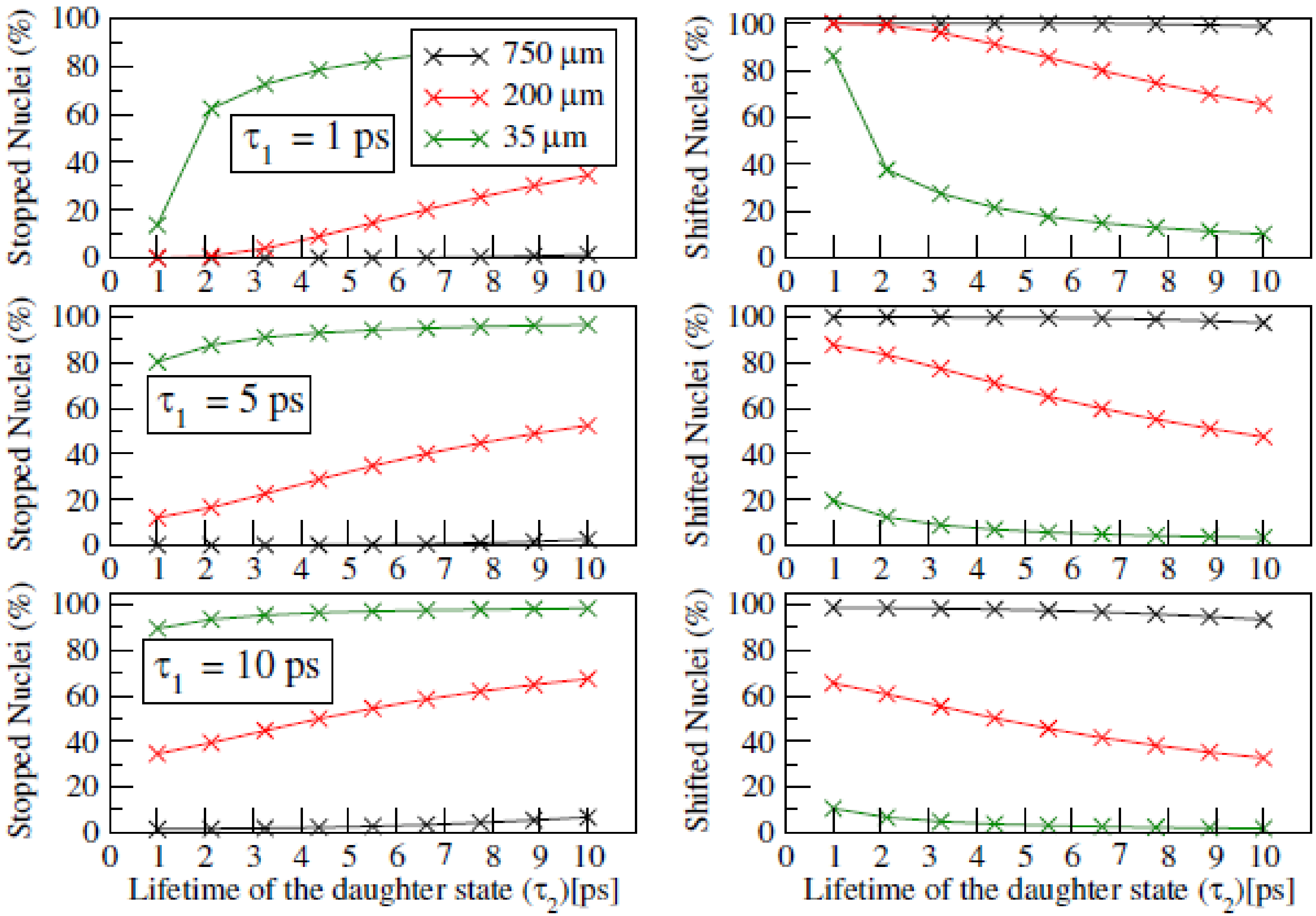


(b)

For v/c=5.7%



(a) Two-step decay

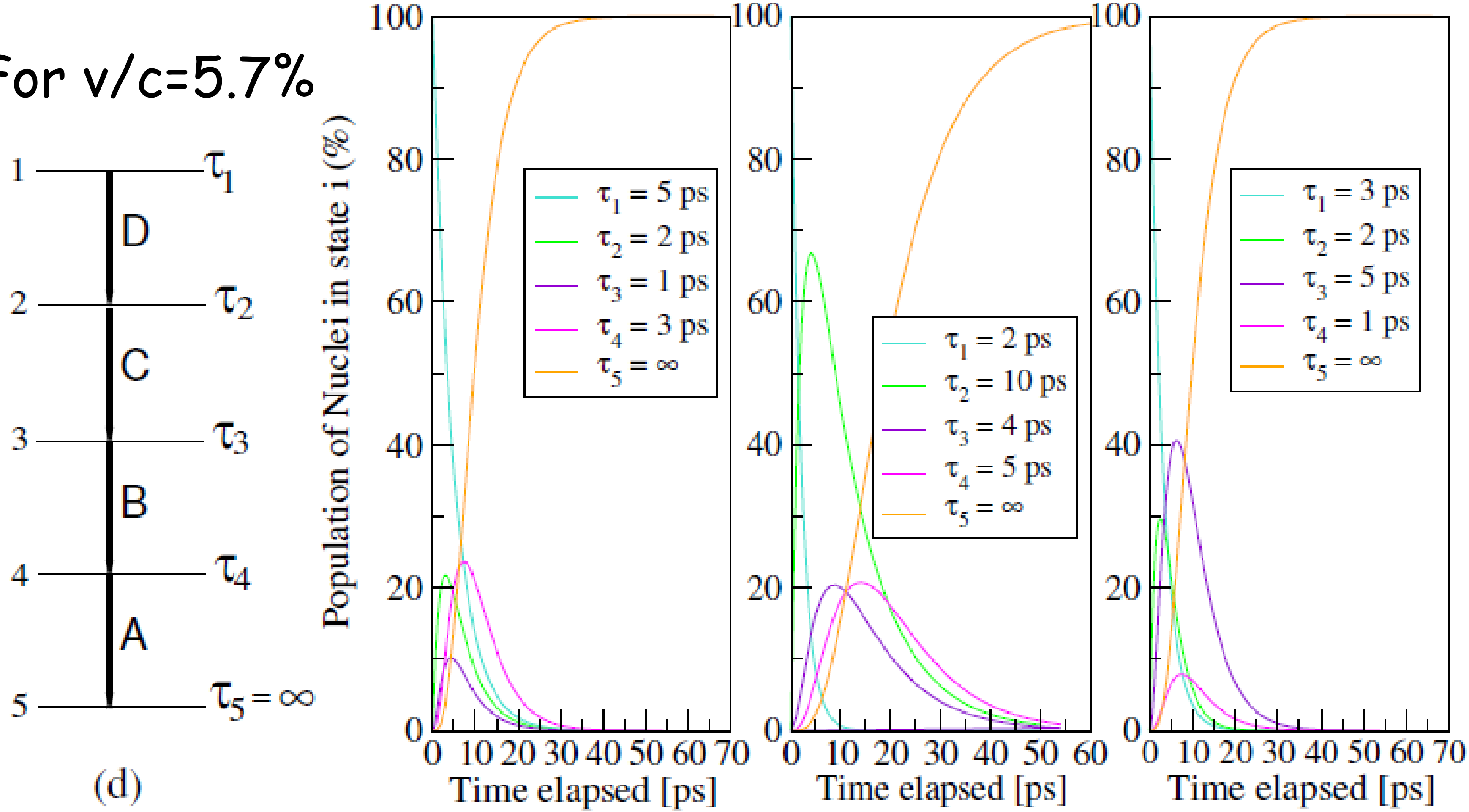


(b)

$$\frac{dN_2(t)}{dt} = \lambda_1 N_1(t) - \lambda_2 N_2(t)$$

ASIDE: Multistep cascades, need to account for decay lifetimes of states feeding the state of interest…..need to account for the Bateman Equations.

For v/c=5.7%

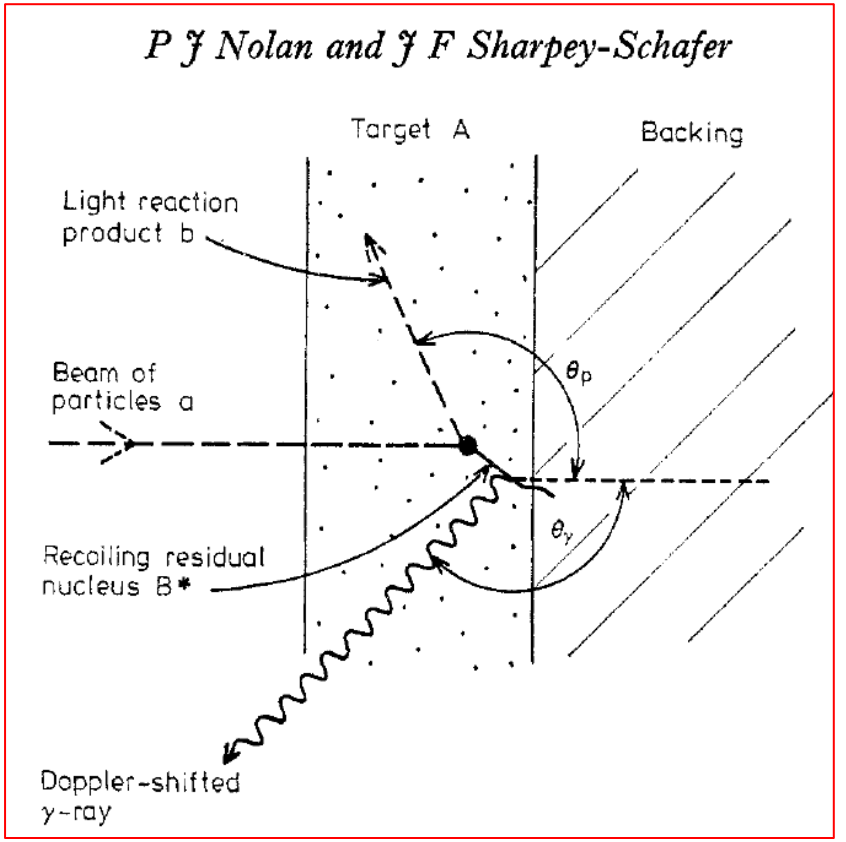


(a) Four-step decay (b)

This can be accounted for by using the 'differential decay curve method' by gating on the Doppler shifted component of the direct feeding gamma-ray to the state of interest, see G. Bohm et al., Nucl. Inst. Meth. Phys. Res. **A329** (1993) 248.

If the lifetime to be measured is so short that all of the states decay in flight, the RDM reaches a limit.

To measure even shorter half-lives (<1ps).
In this case, make the 'gap' distance zero !! i.e., have nucleus slow to do stop in a backing.

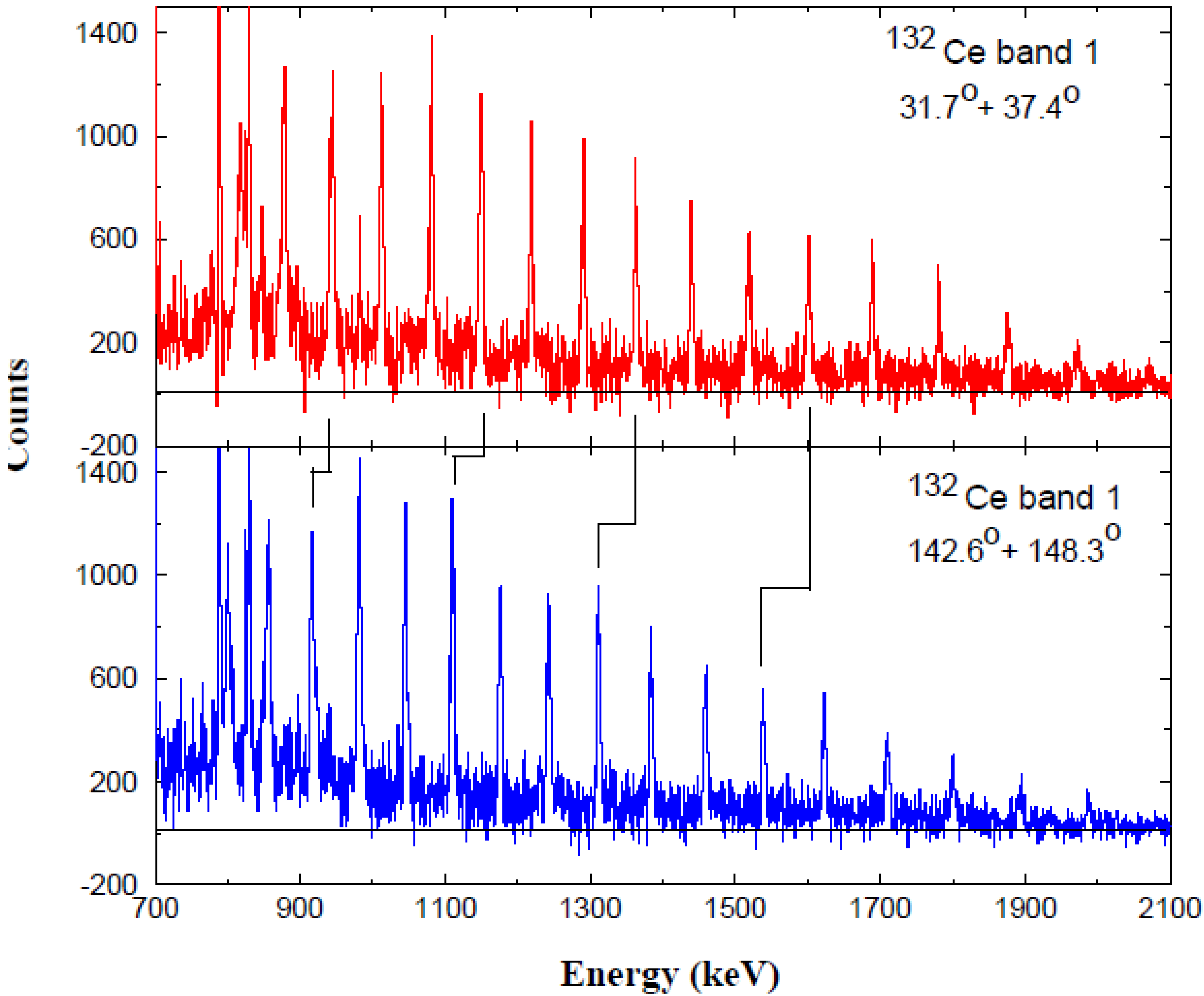


We can use the quantity
$F(\tau) = (v_s / v_{max})$.

$E_s(v,\theta) = E_0(1+{}^{v}/_{c} \cos(\theta))$

Measuring the centroid energy of the Doppler shifted line gives the **average** value for the quantity E_s (and this v) when transition was emitted.

The ratio of vs divided by the maximum possible recoil velocity (at t=0) is the quantity, $F(\tau)$ = fractional Doppler shift.



132 Ce band 1
31.7° + 37.4°
132 Ce band 1
142.6° + 148.3°
Counts
Energy (keV)
1400
1000
600
200
-200
700
900
1100
1300
1500
1700
1900
2100

In the rotational model,

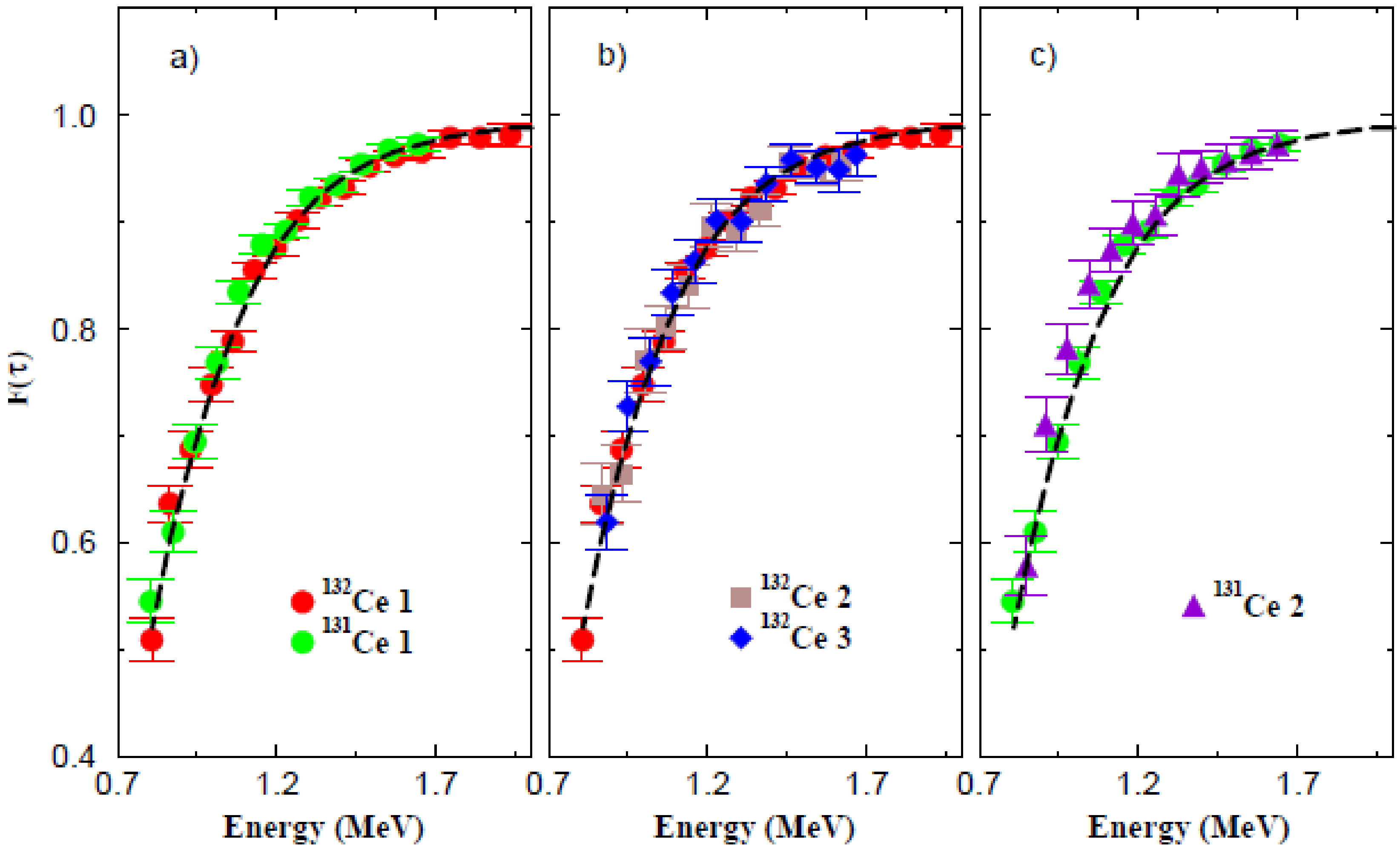
$$\frac{1}{\tau} = 1.223 E_\gamma^5 \frac{5}{16} Q_o^2 | < J_i K 20 | J_f K > |^2$$

where the CG coefficient is given by,

$$< J_i K 20 | J_f K >= \sqrt{\frac{3(J-K)(J-K-1)(J+K)(J+K-1)}{(2J-2)(2J-1)J(2J+1)}}$$

Thus, measuring τ and knowing the transition energy, we can obtain a value for Q_0

$$Q_0 = \frac{3}{\sqrt{5\pi}} Z R^2 \beta_2 \left(1 + \frac{1}{8}\sqrt{\frac{5}{\pi}}\beta_2 \ldots\right)$$



If we can assume a constant quadrupole moment for a rotational band (Qo), and we know the transition energies for the band, correcting for the feeding using the Bateman equations, we can construct 'theoretical' F(τ) curves for bands of fixed Qo values

Intrinsic Quadrupole Moment of the Superdeformed Band in ^{152}Dy

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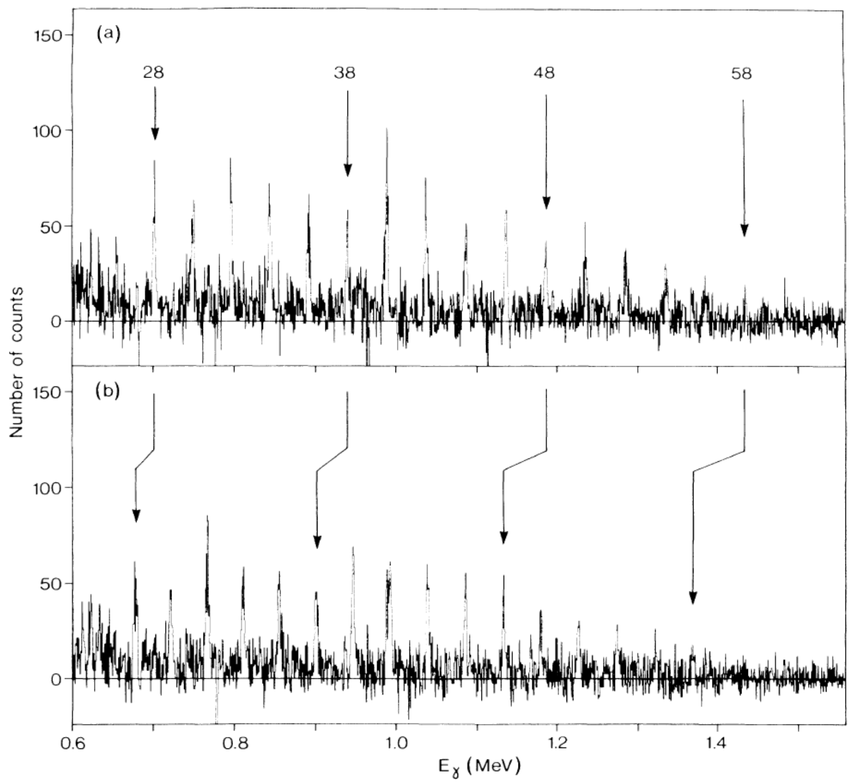
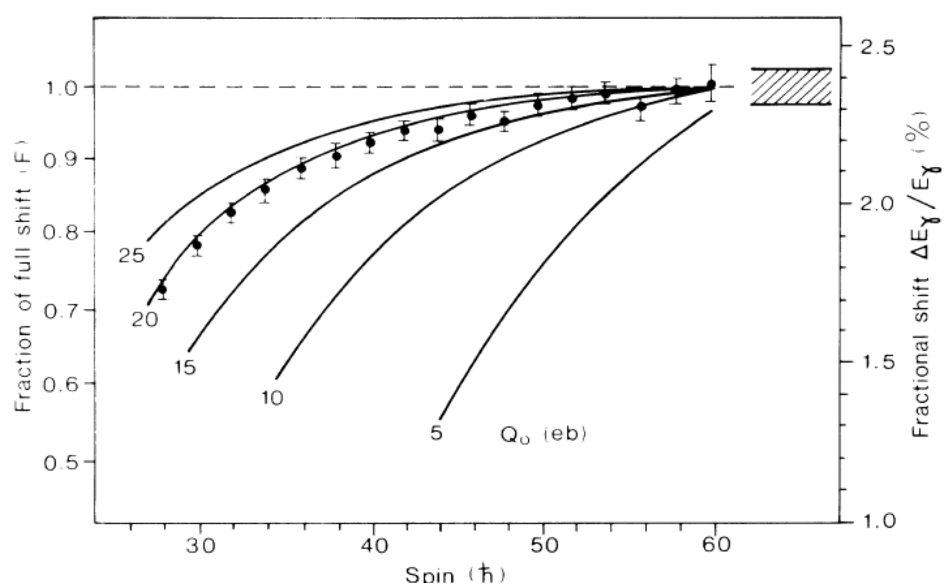
(Received 9 February 1987; revised manuscript received 3 June 1987)





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Magnetic Moment of the 6^+ Isomeric State of ^{134}Te†

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(Received 4 March 1976)

The inherent alignment of the prompt fission fragments was used to measure the g factor of the 6^+ isomeric state of ^{134}Te by the time-differential perturbed angular-correlation method. The experimental result $g_{exp} = 0.846 \pm 0.025$ is close to effective g factors of $g_{7/2}$ protons in nuclei with 82 neutrons. The deviation from the Schmidt value is discussed in terms of the polarization of the $^{132}_{50}Sn_{82}$ core by the $g_{7/2}$ protons.

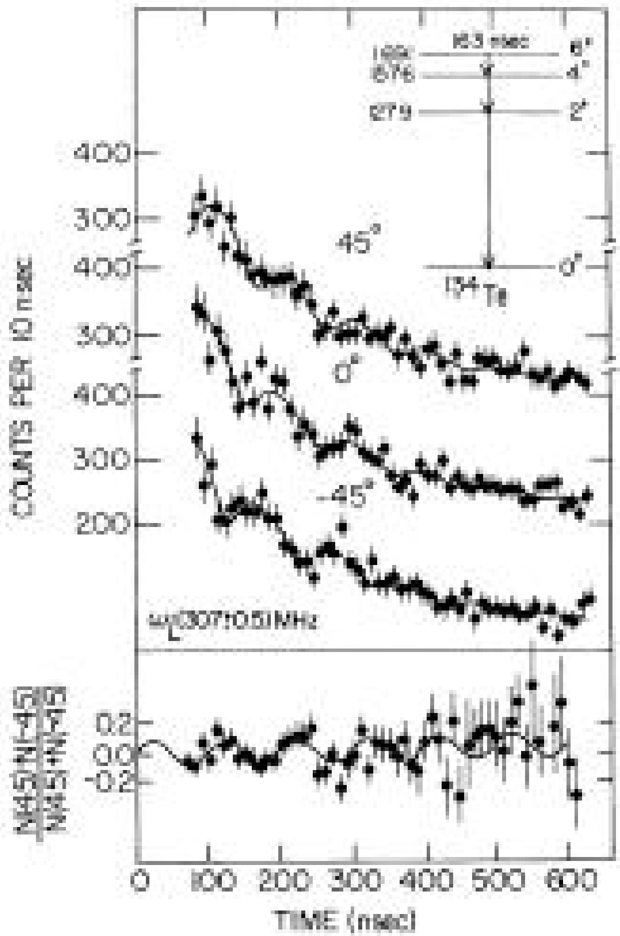

FIG. 2. Time spectra of the 115.3-keV radiation of ^{134}Te at three angles with respect to the fission direction. Normalized differences between the intensities at 45° and −45° are given in the lower part of the figure. The solid lines were obtained by a least-squares fit to the data. The decay scheme of ^{134}Te as determined in Refs. 3, 4, and 5 is also shown.

classically $\boldsymbol{\mu} = \boldsymbol{I} \times \boldsymbol{A}$

magnetic moment reflects size of current loop (i.e. ang. mom. of state) and direction/sign of current (i.e., π or ν config.)

$g = \mu / I$, can use **‘Schmidt model’** to give estimates for what the g-factors should be for pure spherical orbits.

Can measure g directly from ‘twisting’ effect of putting magnetic dipole moment, μ, in a magnetic field, B. Nucleus precesses with the Larmor frequency, $\omega_L = g\mu_N B$