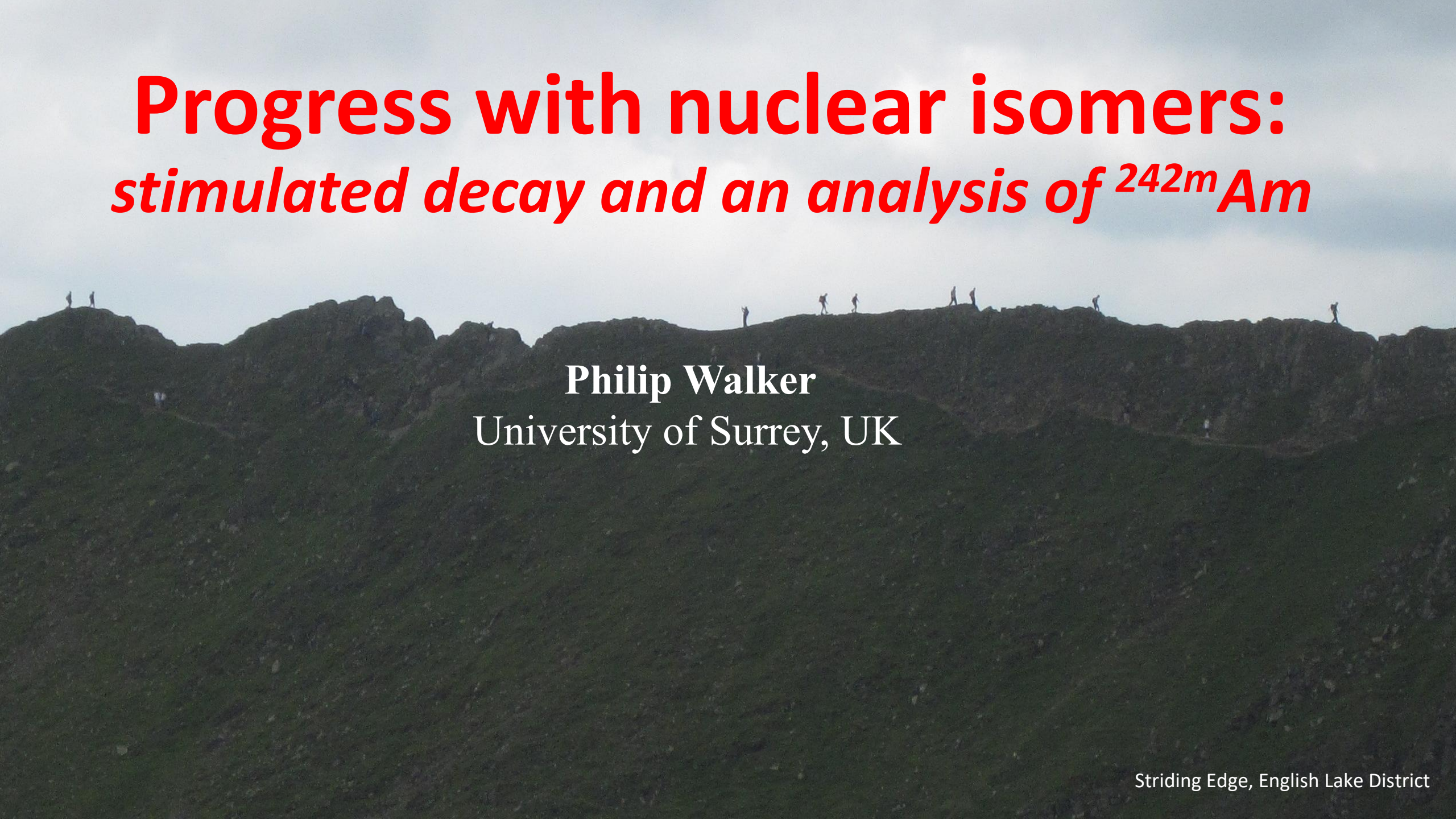
Progress with nuclear isomers:

stimulated decay and an analysis of ^{242m}Am

Philip Walker
University of Surrey, UK



Striding Edge, English Lake District

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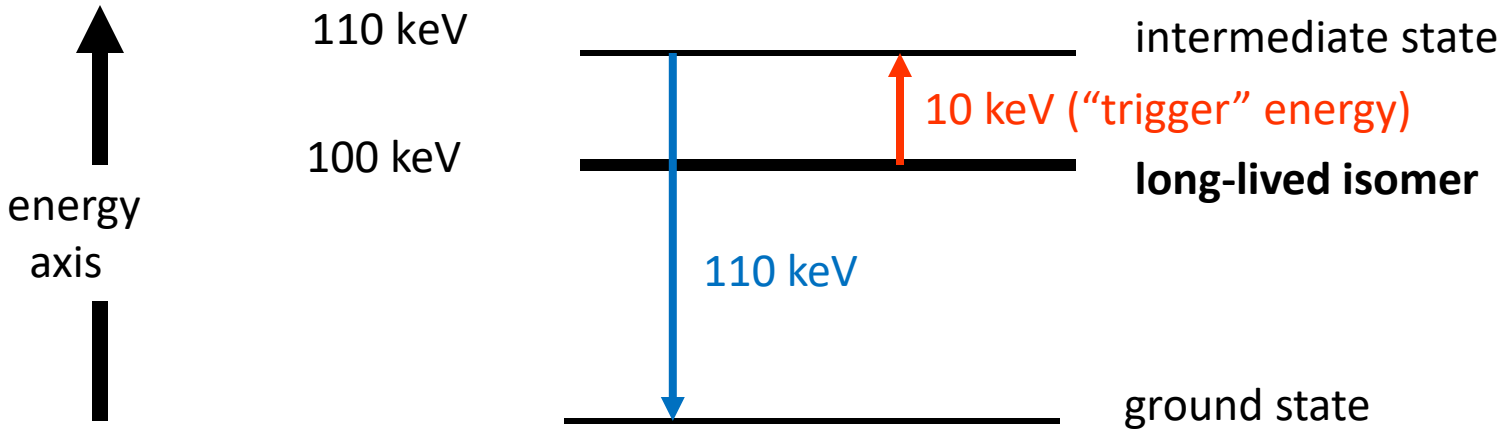
- storage and release of isomer energy
- ^{180}Ta – proof of principle
- ^{93}Mo and NEEC
- ^{242}Am and K isomerism
- K-isomer transition rates
- isomer pumping examples

Striding Edge, English Lake District

isomer manipulation

speeding up the energy release from isomers: possible development of isomer batteries and even gamma-ray lasers

conceptual picture – electromagnetic (de-)excitation

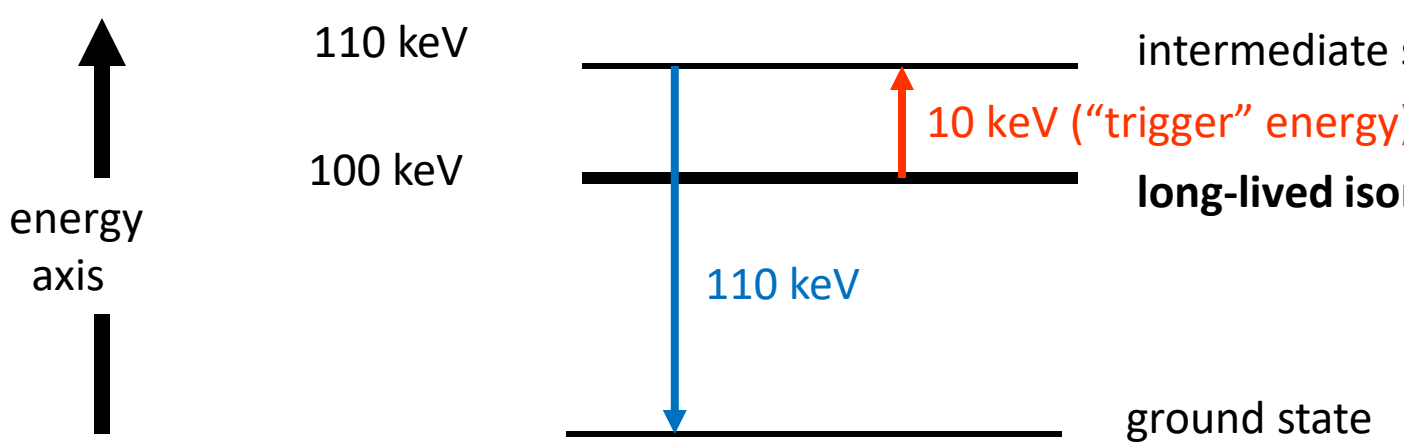


energy release ~100 keV per atom
cf. chemical energy ~ 1 eV per atom

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conceptual picture – electromagnetic (de-)excitation



laser/plasma induced

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cf. chemical energy ~ 1 eV per atom

Candidates for isomer triggering with real photons

Element	isomer energy	half-life	trigger energy	λ
^{84}Rb	464 keV	20 m	3 keV	M1/E2
^{93}Mo	2425 keV	7 h	5 keV	E2
^{129}Sb	1851 keV	18 m	10 keV	E2
^{180}Ta	77 keV	$>10^{17}$ y	1010 keV	E1
^{242}Am	49 keV	141 y	4 keV	E2

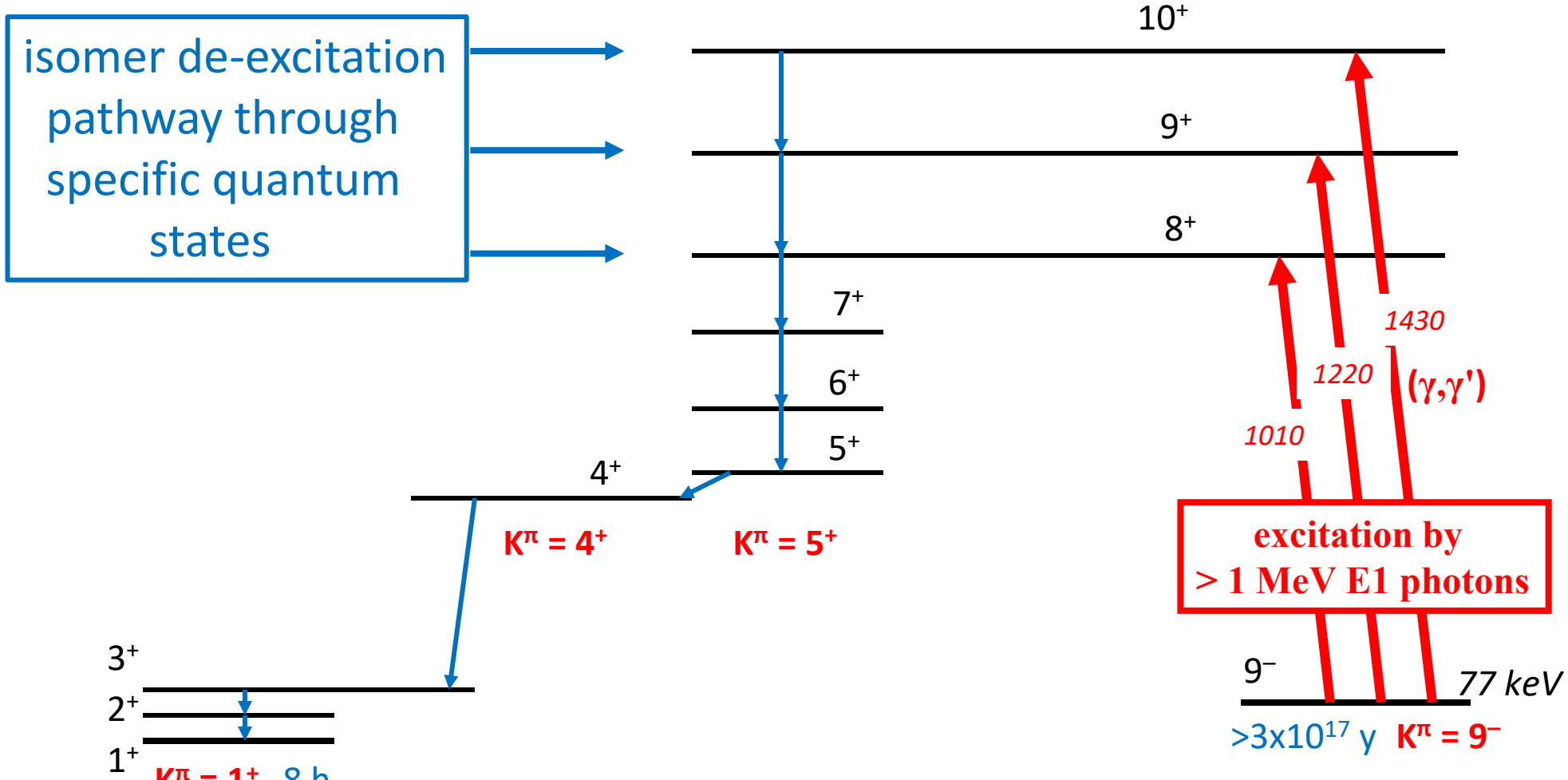
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^{180}Ta isomer photoexcitation and decay

0.012% of natural tantalum

nature's only "stable" isomer



isomer energy: 76.79(55) keV
Nesterenko et al. PRC106(2022)024310
isomer half-life: >2.9x10^{17} y
Arnquist et al. PRL134(2023)152501

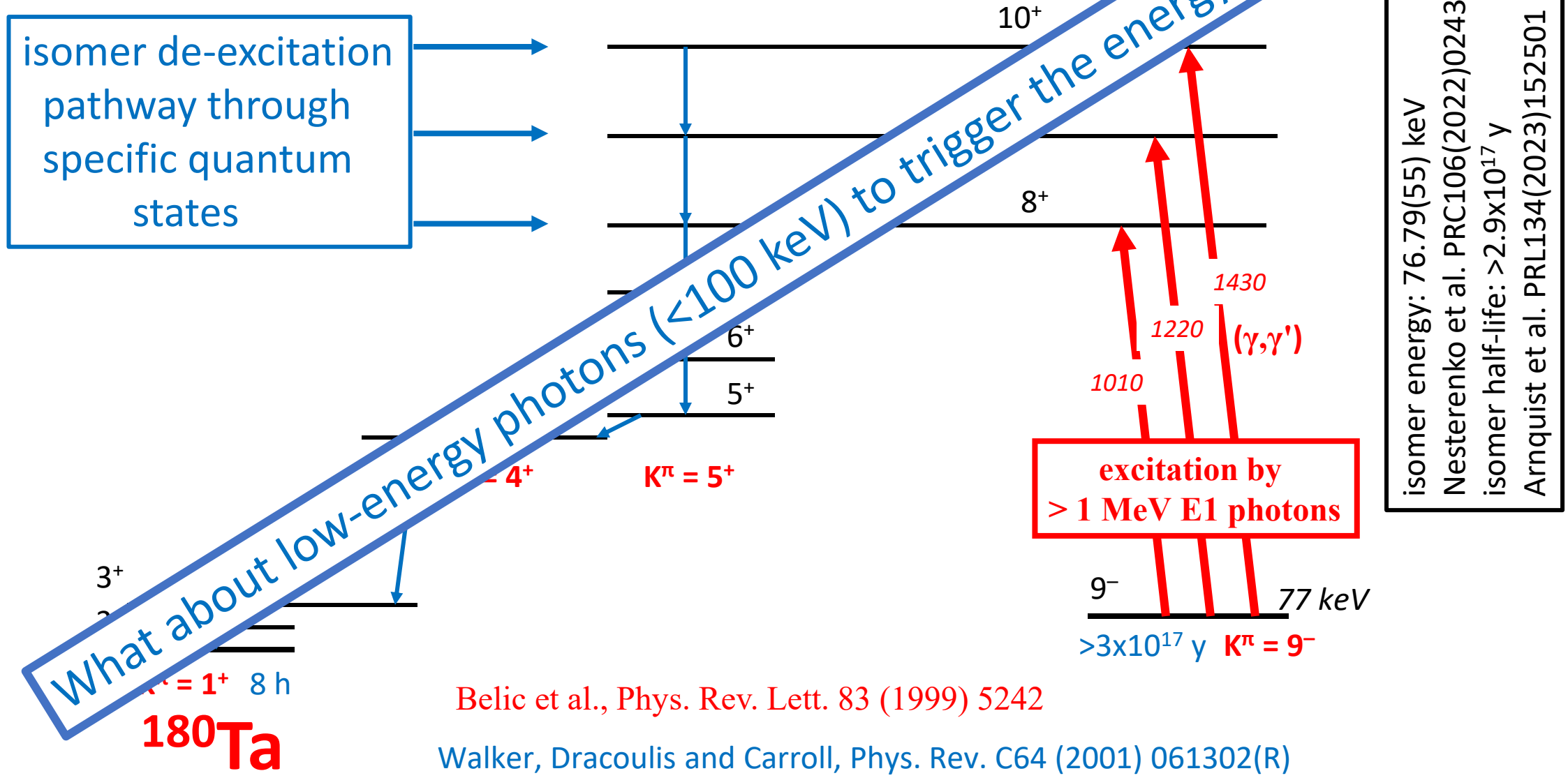
Belic et al., Phys. Rev. Lett. 83 (1999) 5242

Walker, Dracoulis and Carroll, Phys. Rev. C64 (2001) 061302(R)

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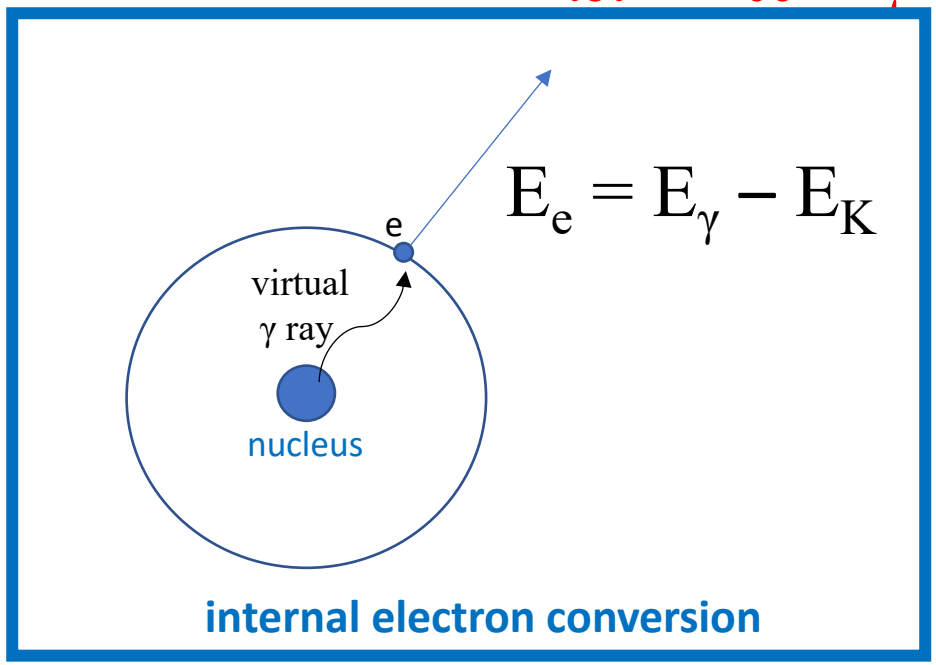


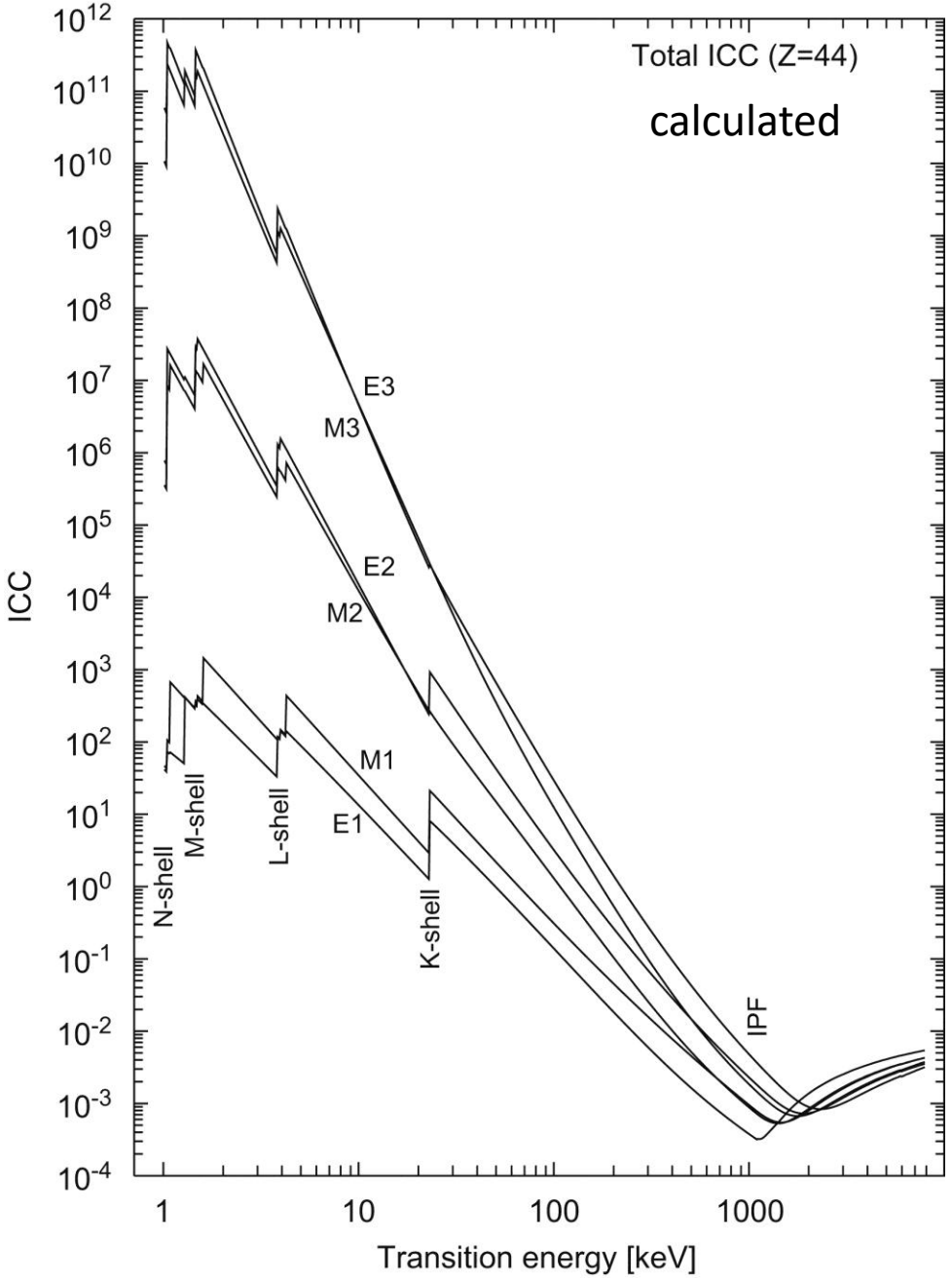
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Internal conversion

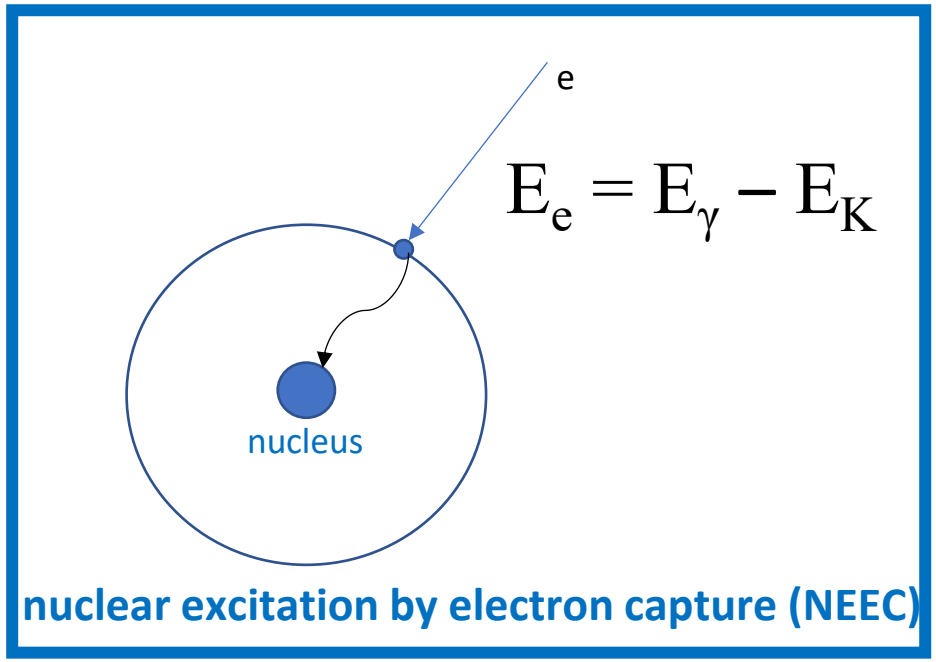
$$ICC = \alpha_{tot} = I_{ce} / I_{\gamma}$$





Kibédi et al.
Nucl. Inst. Meth.
A589 (2008) 202

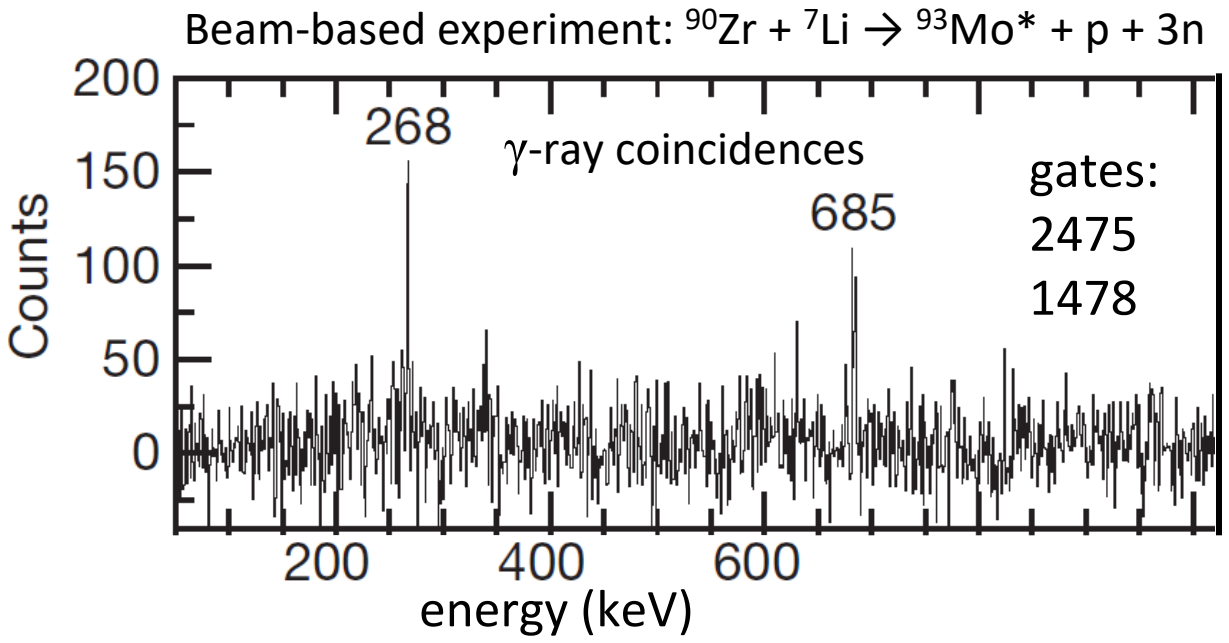
Inverse of internal conversion:
nuclear excitation by electron capture - NEEC

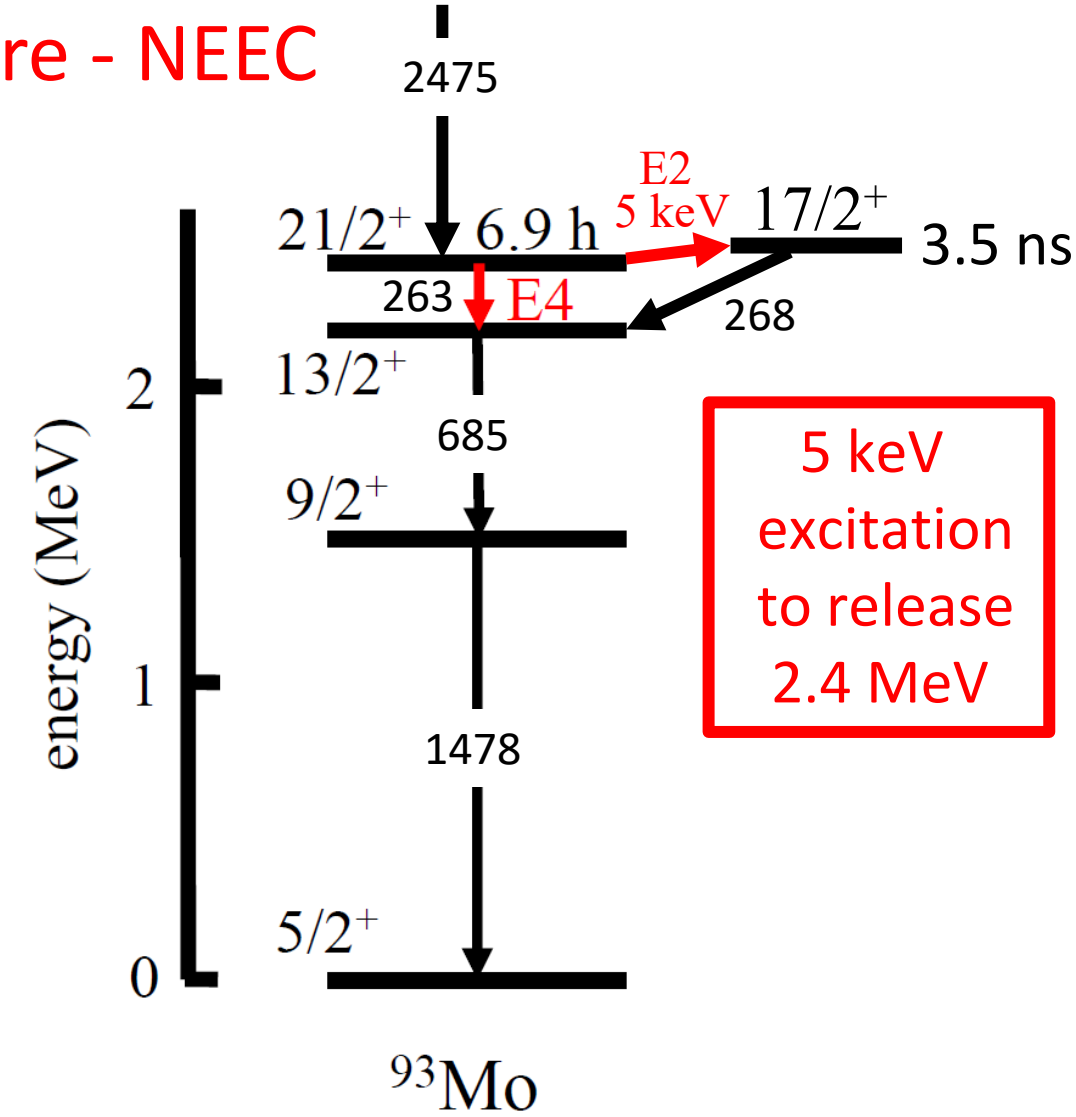


trigger rate = NEEC probability x gamma rate

Inverse of internal conversion: nuclear excitation by electron capture - NEEC

first observation of NEEC
Gammasphere@Argonne National Lab





5 keV excitation to release 2.4 MeV

Chiara et al., Nature 554 (2018) 216

Inverse of internal conversion: nuclear excitation by electron capture - NEEC

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Gammasphere

too strong by 10^9?!

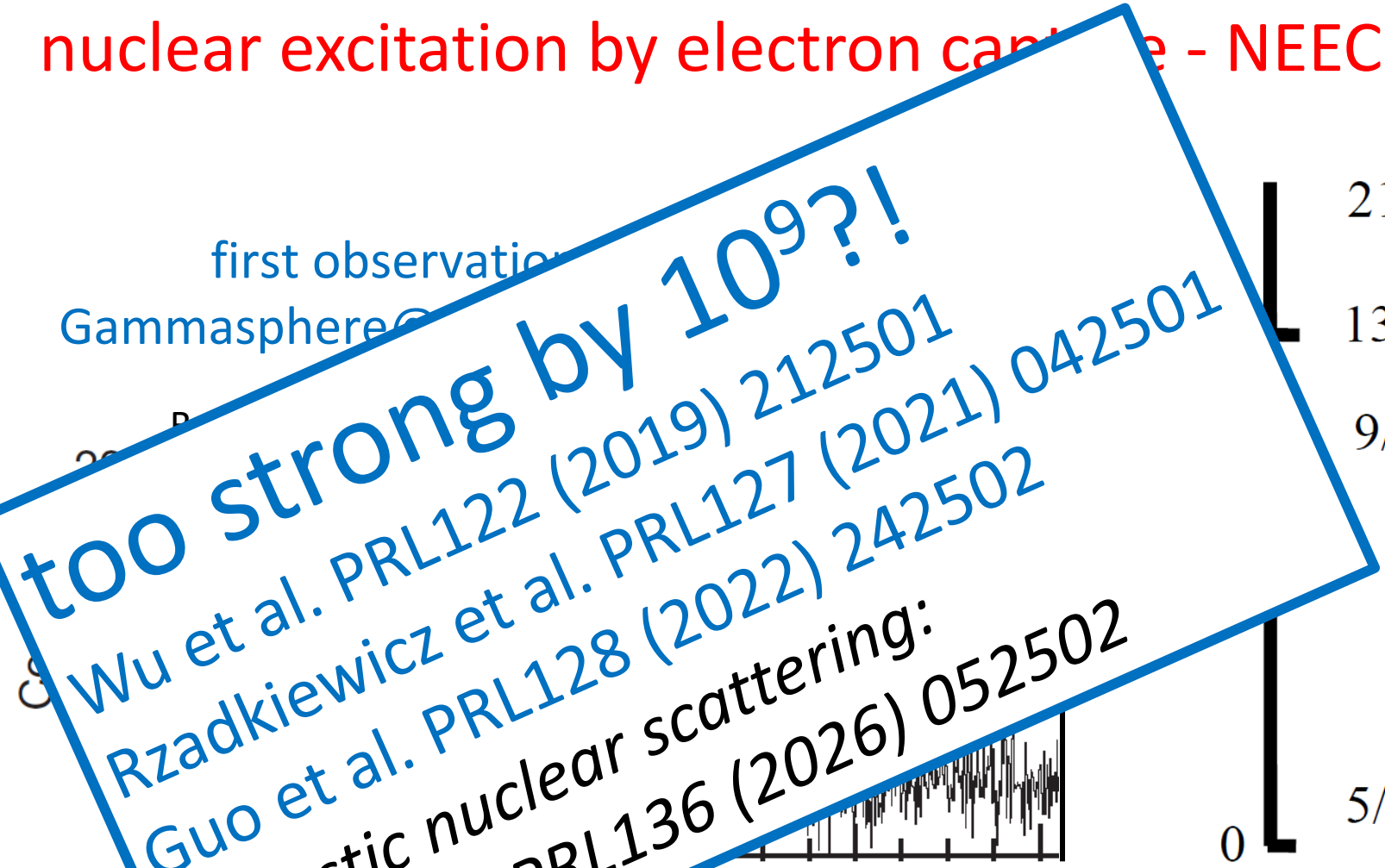
Wu et al. PRL122 (2019) 212501

Rzadkiewicz et al. PRL127 (2021) 042501

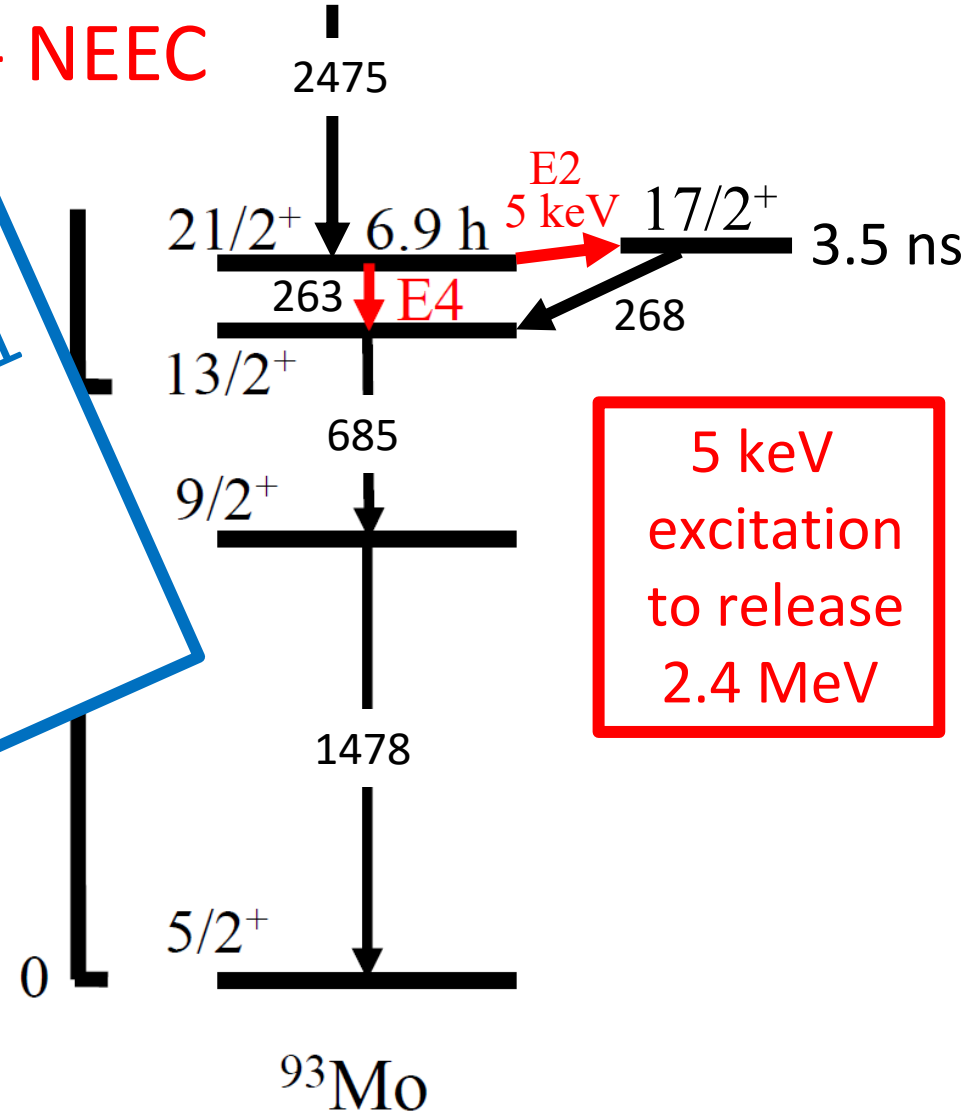
Guo et al. PRL128 (2022) 242502

Inelastic nuclear scattering:

Ding et al. PRL136 (2026) 052502



... et al., Nature 554 (2018) 216



5 keV excitation to release 2.4 MeV

Inverse of internal conversion: nuclear excitation by electron capture -

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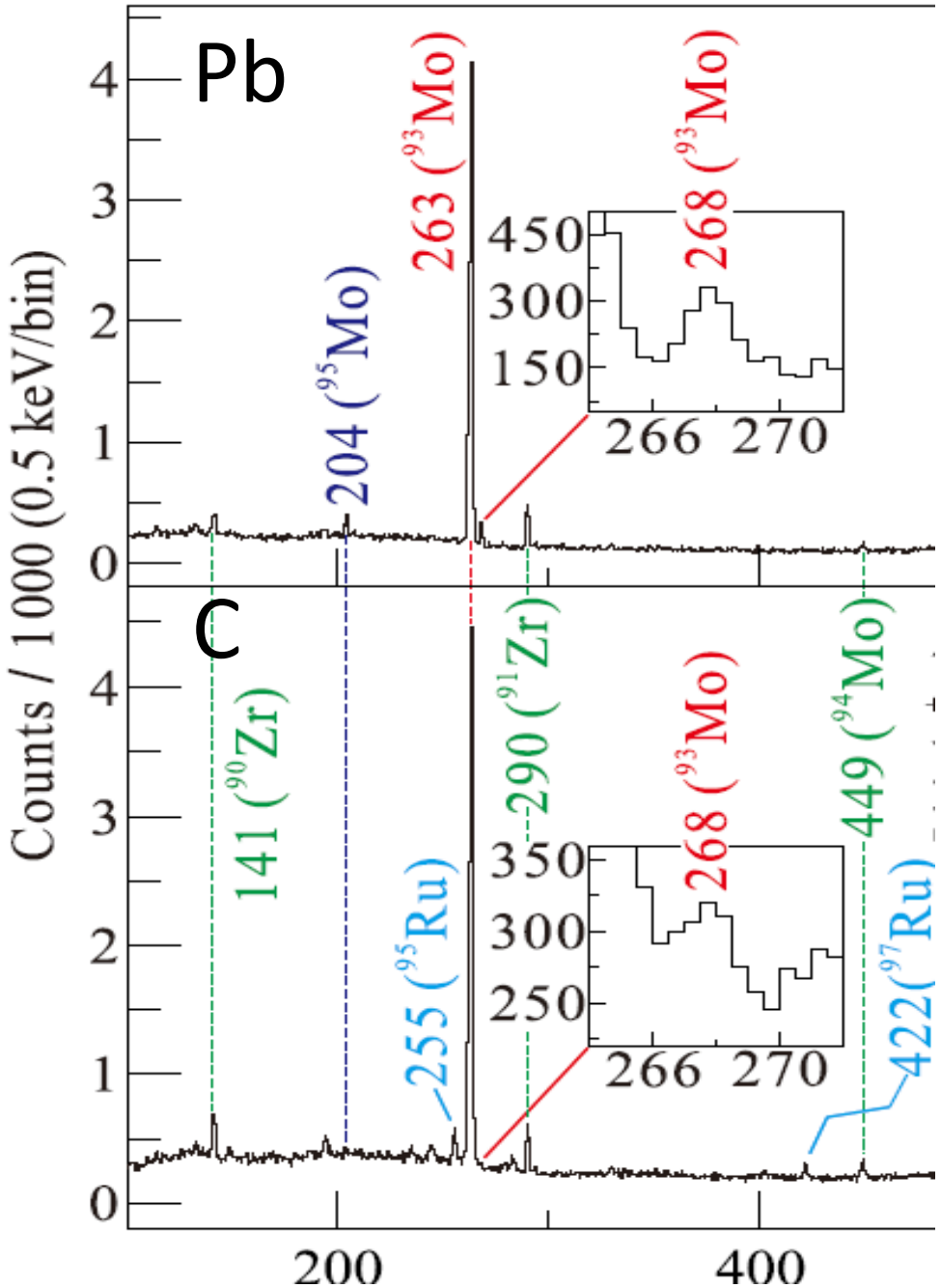
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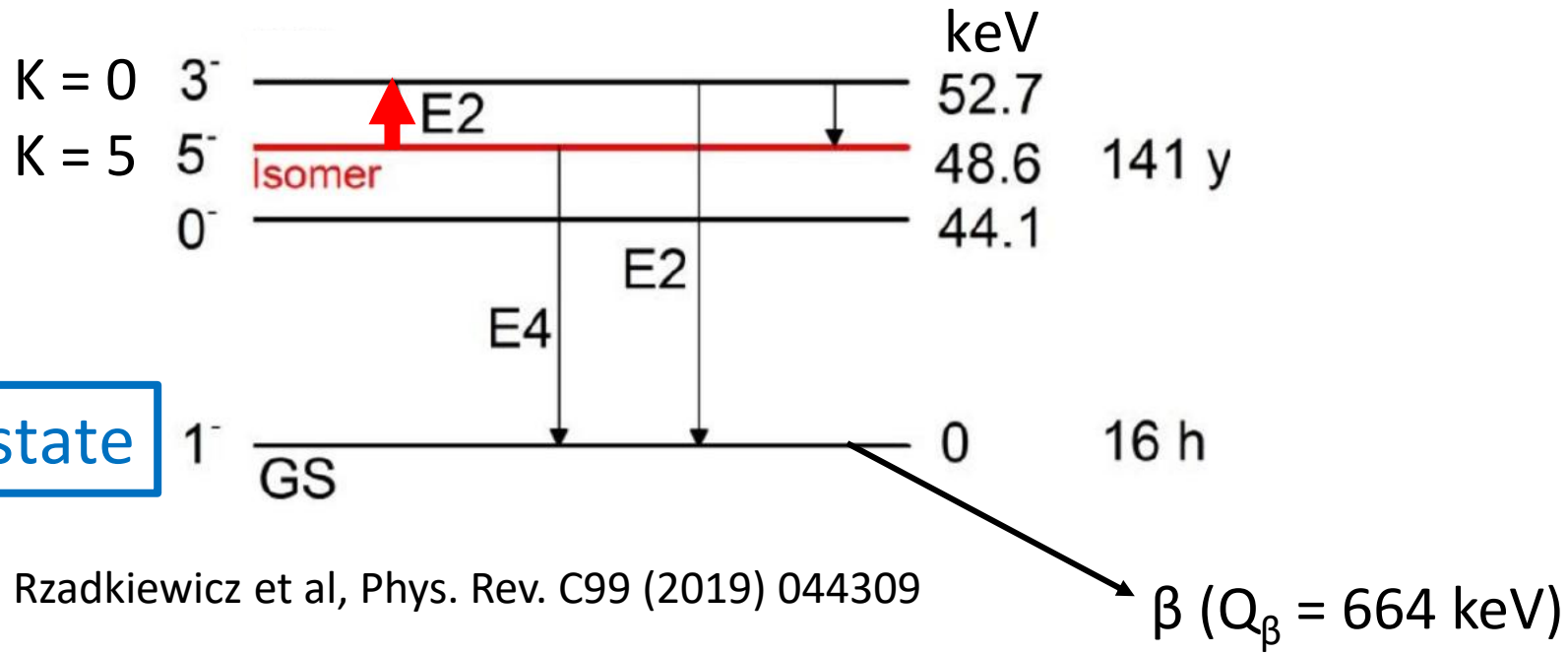
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al., Nature 554 (2018) 216



^{242}Am 141 y isomer: possible 4 keV E2 excitation



NB: short-lived ground state

Rzadkiewicz et al, Phys. Rev. C99 (2019) 044309

Advantages of ^{242m}Am for induced isomer de-excitation:

isomer can be produced from ^{141}Am(n,γ) reaction

“pure” isomeric nuclide – just wait a few days (gs $T_{1/2}$ = 16 h)

long isomeric half-life (141 y)

NEEC rate ≈100 times more than for ^{93m}Mo
[Palffy et al., Phys. Rev. Lett. 99 (2007) 172502]

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BUT how strong is the ^{242}Am E2 transition? 1 Wu?

See Zadernovsky and Carroll, Hyp. Int. 143 (2002) 153):

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"[^{242m}Am] may have a significantly decreased trigger transition probability due to the 3-fold excess orientation change (i.e., due to the effect of the K quantum number). This may produce a reduction of the transition rate and, thus, of the triggering cross sections by a factor of as much as 10^3–10^4."

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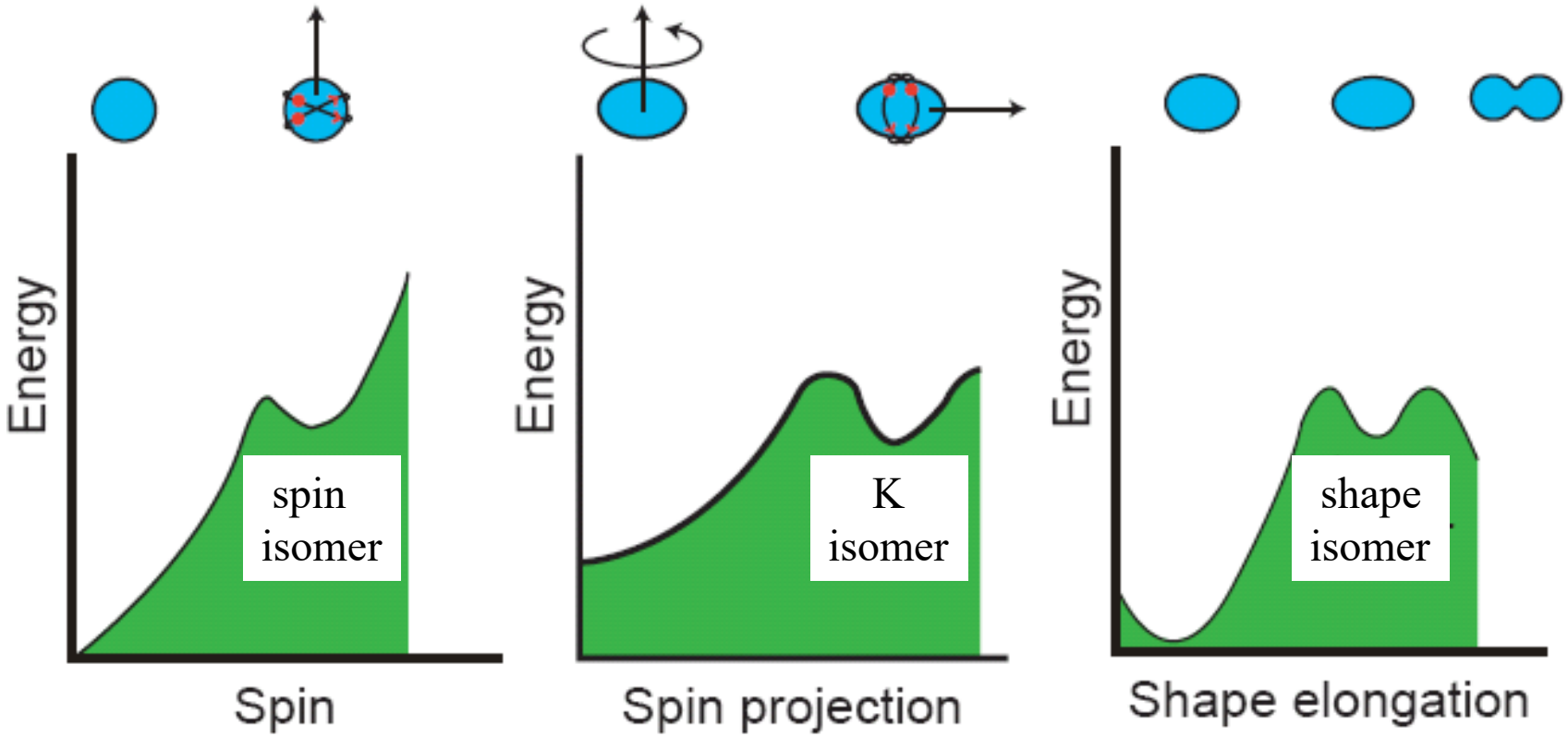
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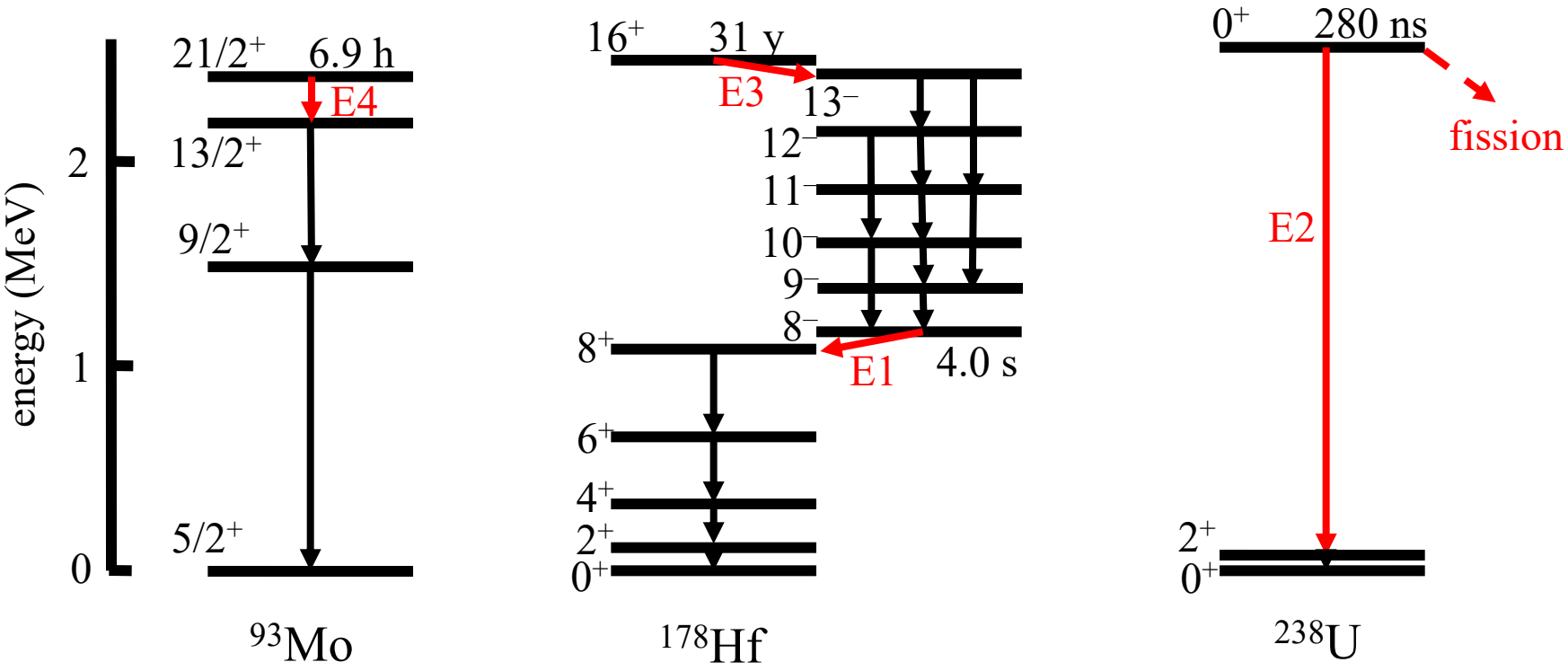
Isomer types

von Weizsäcker 1937 Alaga et al. 1955 Polikanov et al. 1962



Walker & Dracoulis, Nature 399 (1999) 35

Isomer types



spin isomer K isomers shape isomer

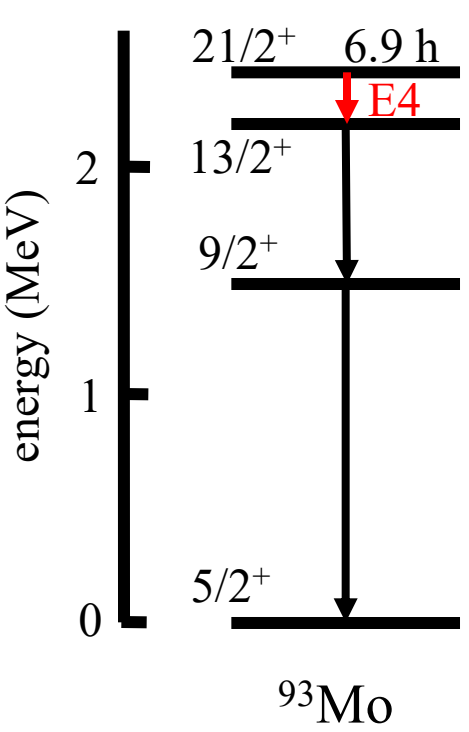
Walker & Podolyák, chapter in Handbook of Nuclear Physics (Springer Nature 2023)

Isomer types

Weisskopf hindrance factor: $F_W = T^{\gamma}_{1/2}/T^{W}_{1/2}$

Blatt and Weisskopf 1952

$F_W(E4) = 1$

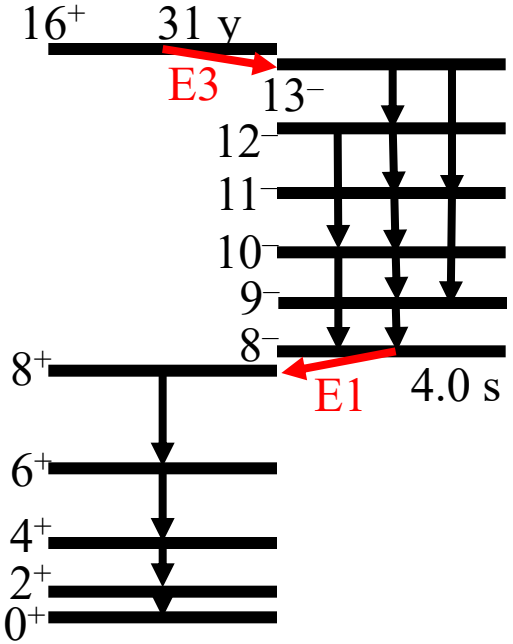


^{93}Mo

spin isomer

$F_W(E3) = 1x10^9$

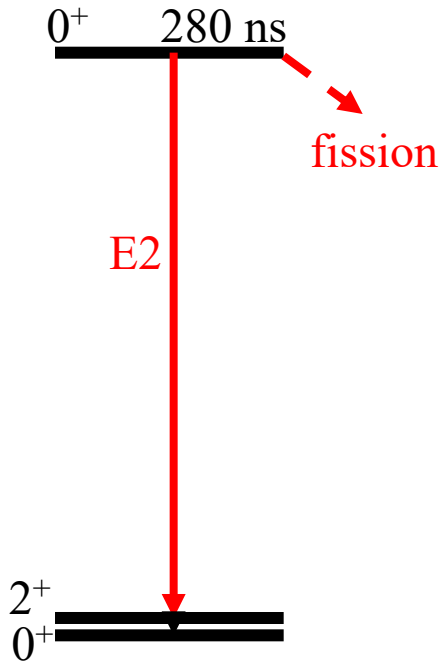
$F_W(E1) = 2x10^{13}$



^{178}Hf

K isomers

$F_W(E2) = 7x10^6$



^{238}U

shape isomer

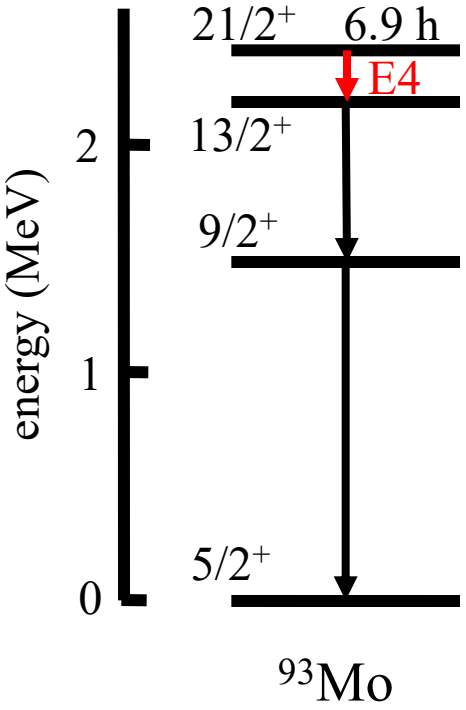
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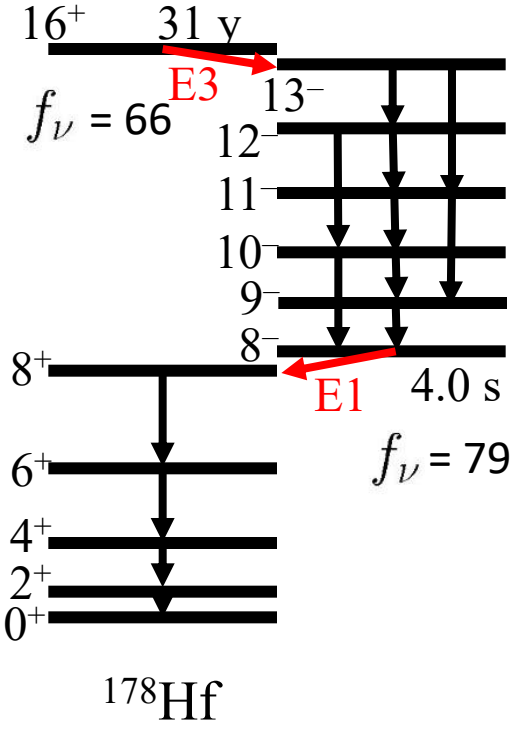
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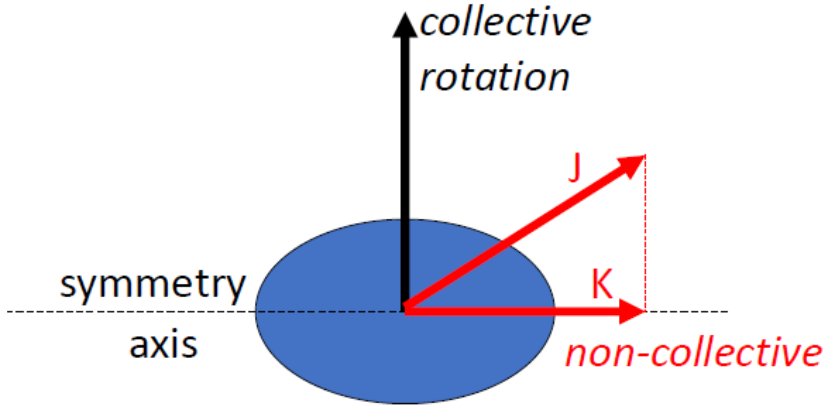
K isomers

degree of forbiddenness

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

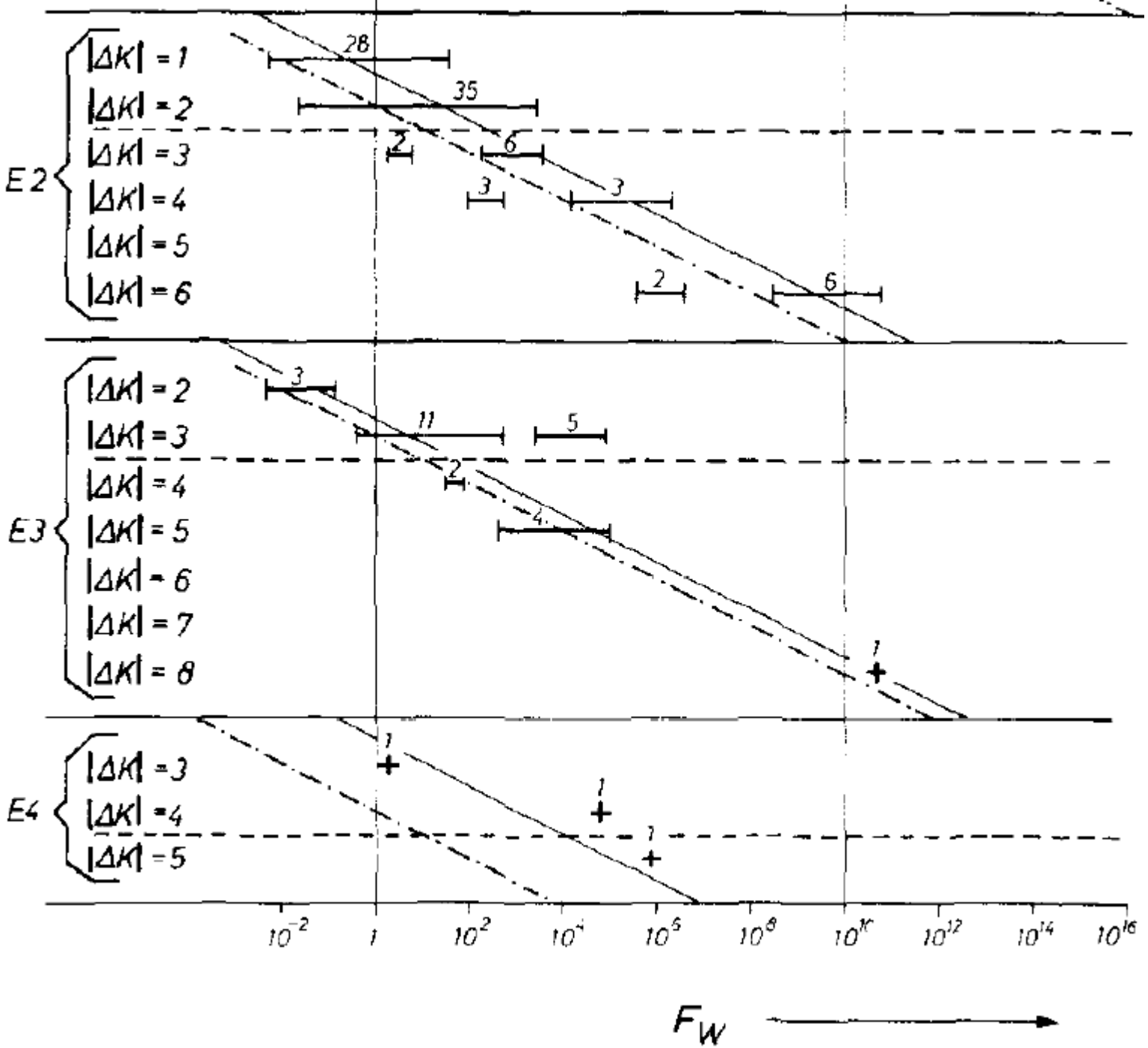
reduced hindrance

$$f_\nu = (F_W)^{1/\nu}$$



Walker & Podolyák, chapter in Handbook of Nuclear Physics (Springer Nature 2023)

Löbner (1968)
systematics:
$f_\nu \approx 100$

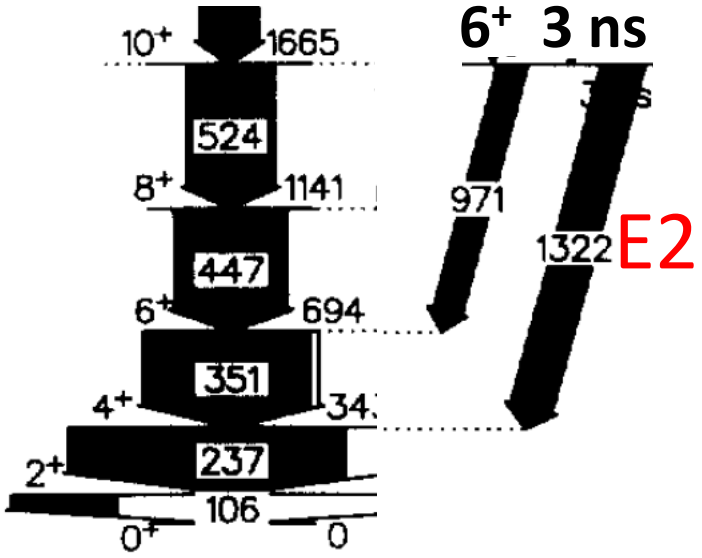


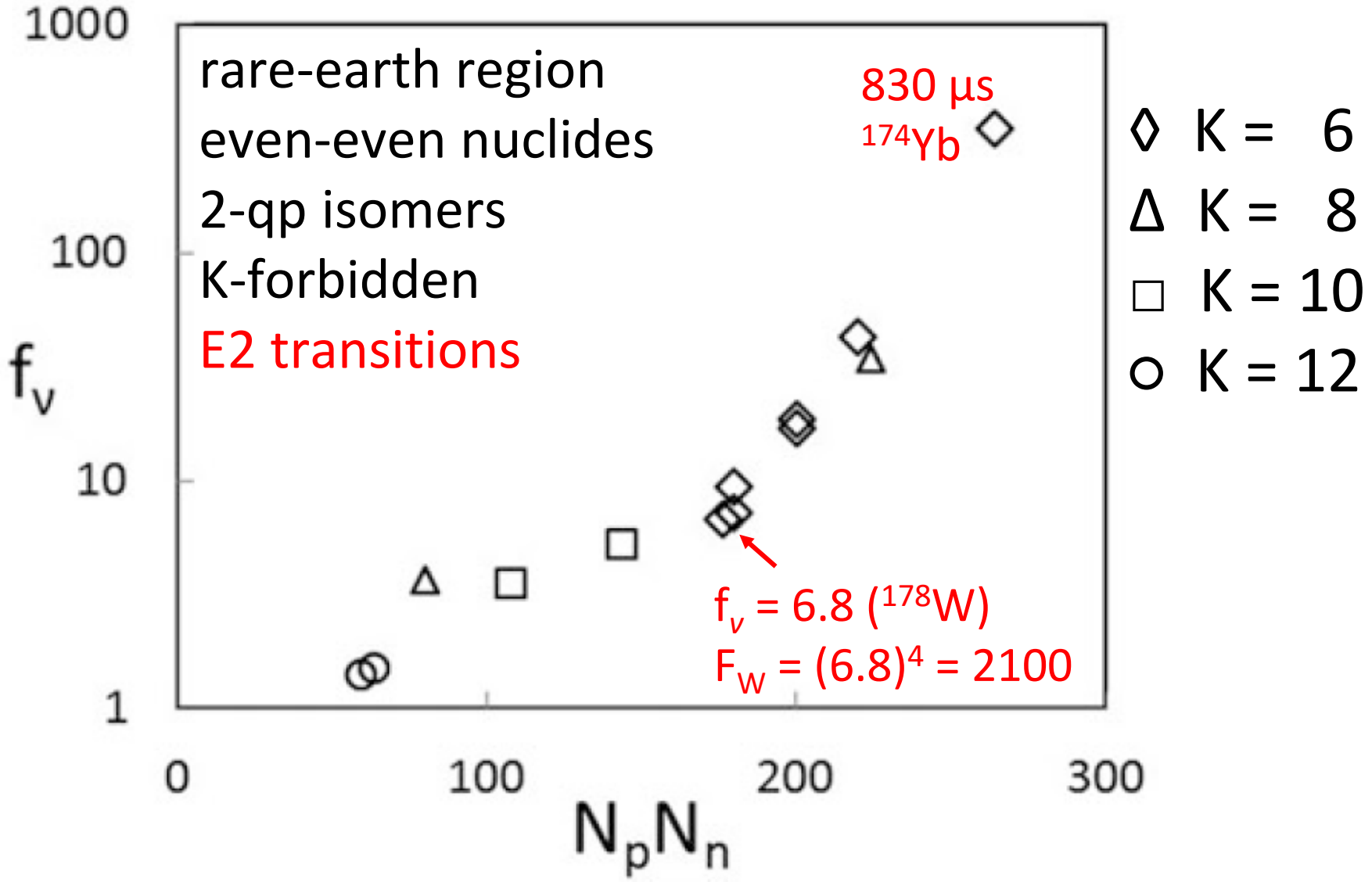
Löbner Phys. Lett. B 26 (1968) 369

$N_p = 82 - 74 = 8$
$N_n = 126 - 104 = 22$
$N_p N_n = 176$

^{178}W partial

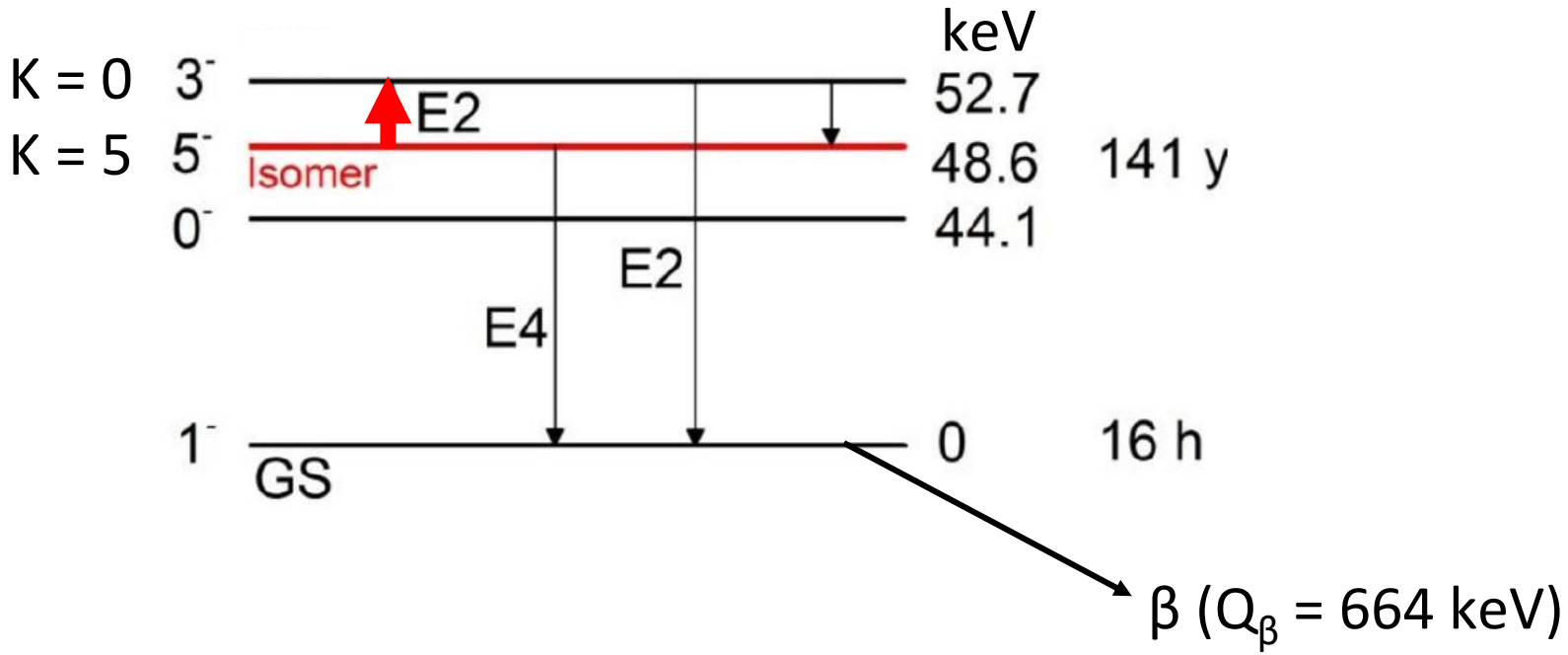
Purry et al., Nucl. Phys. A 632 (1998) 229





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^{242}Am 141 y isomer: possible 4 keV E2 excitation

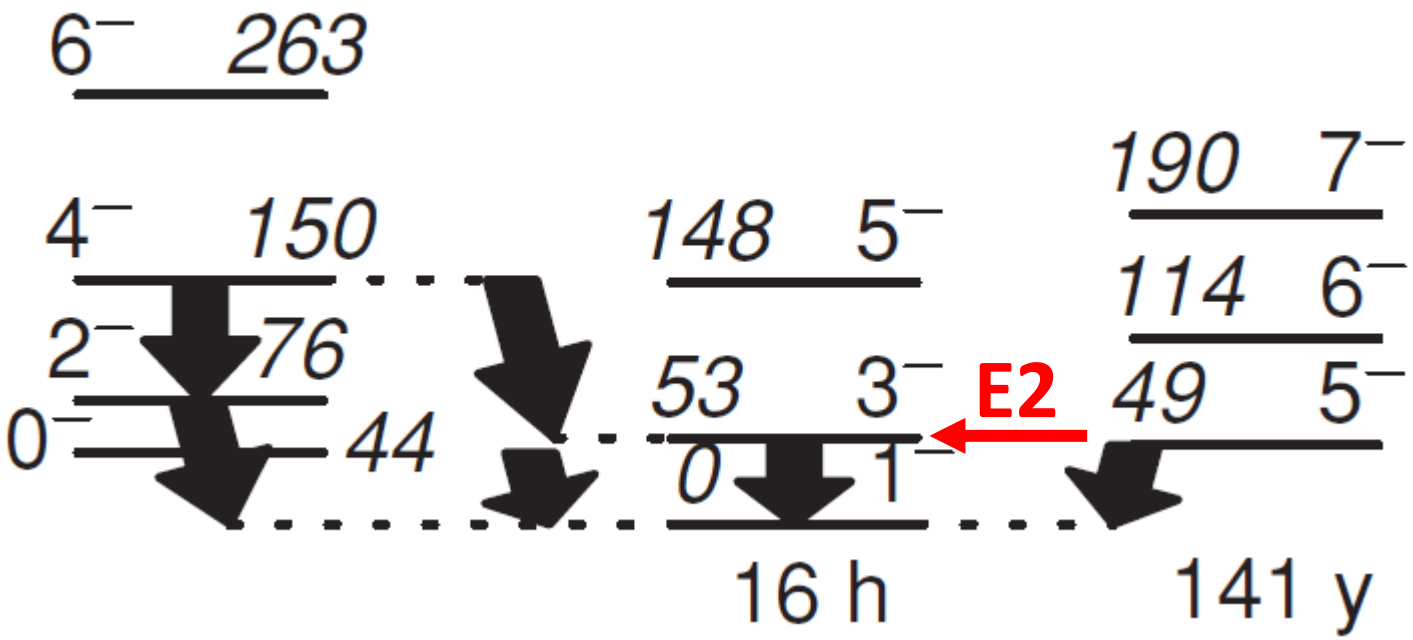


4 keV E2 has ΔK = 5

=> E2 is 3-fold K-forbidden

Rzadkiewicz et al, Phys. Rev. C99 (2019) 044309

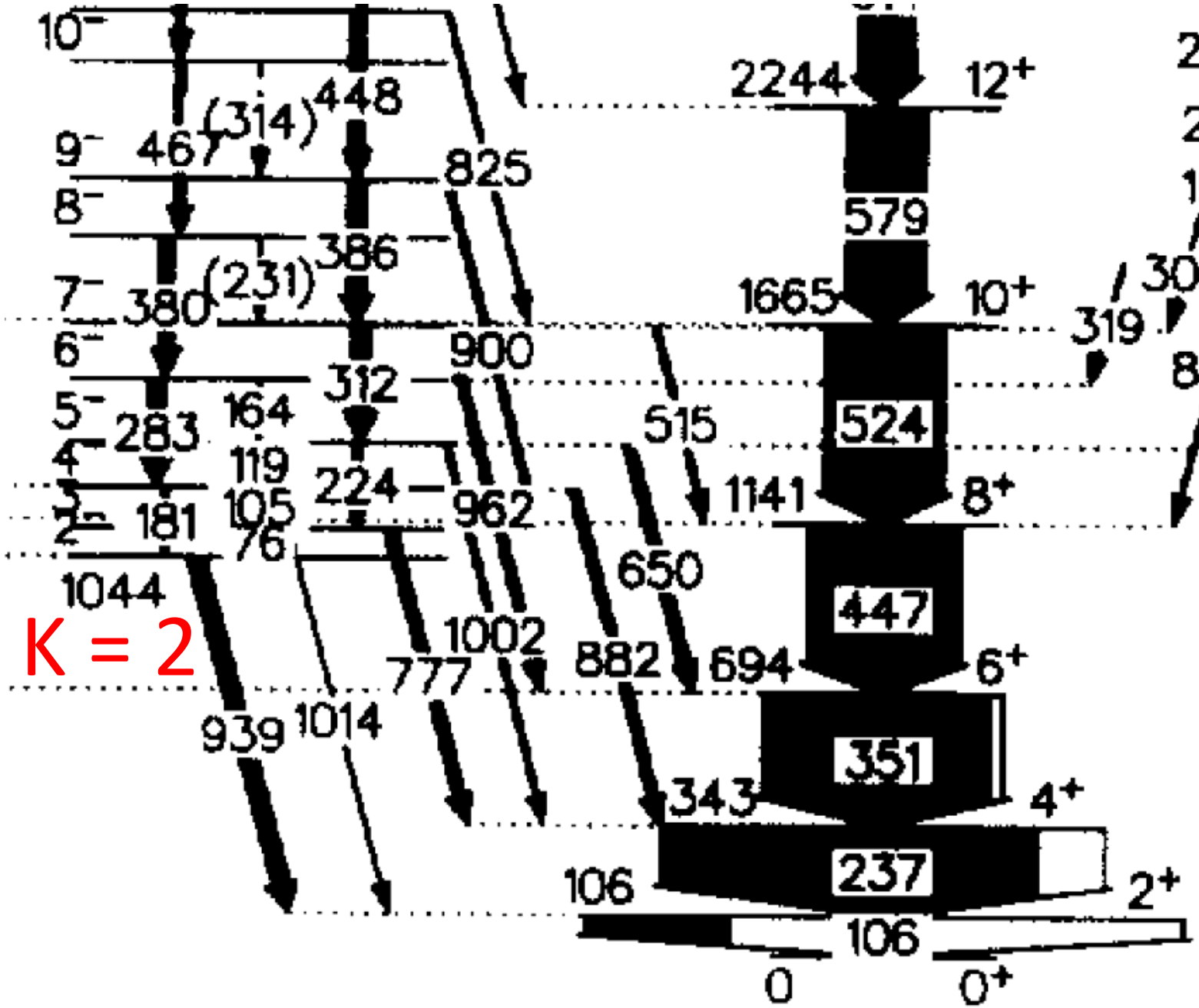
K = 0 K = 5 $^{242}_{95}Am_{147}$

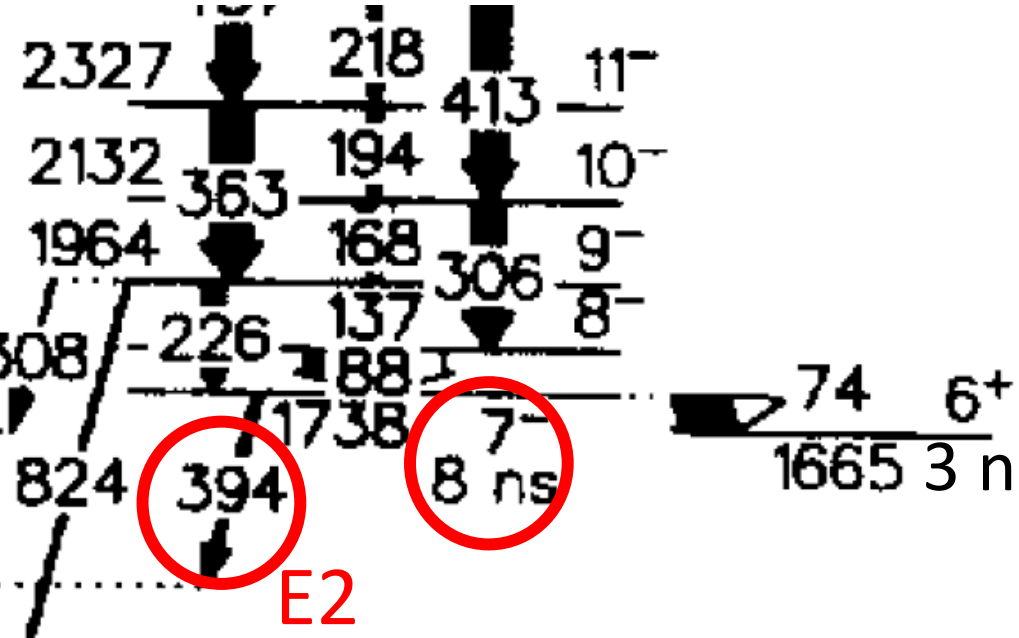


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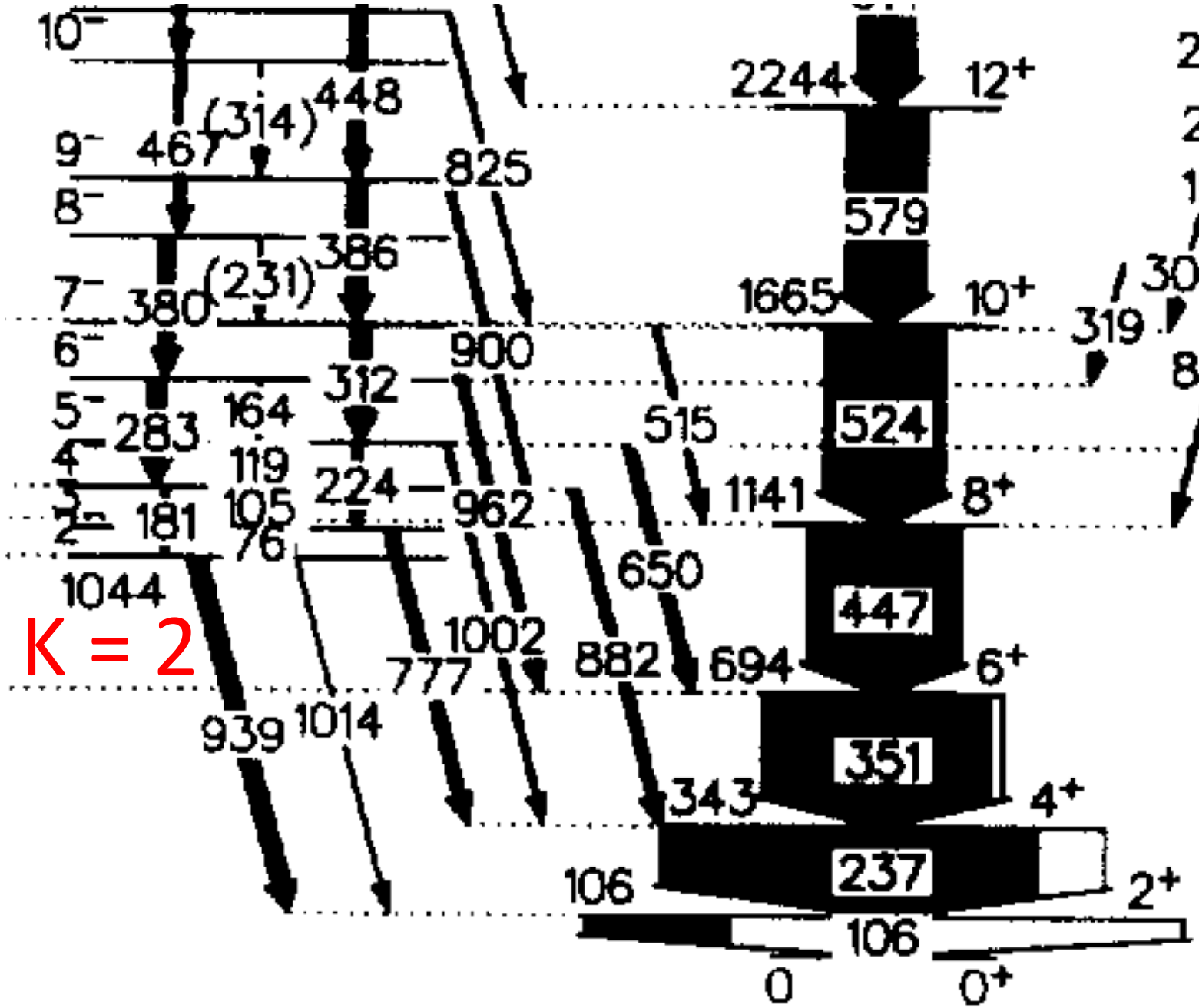
Hayes et al. Phys. Rev. C 82 (2010) 044319

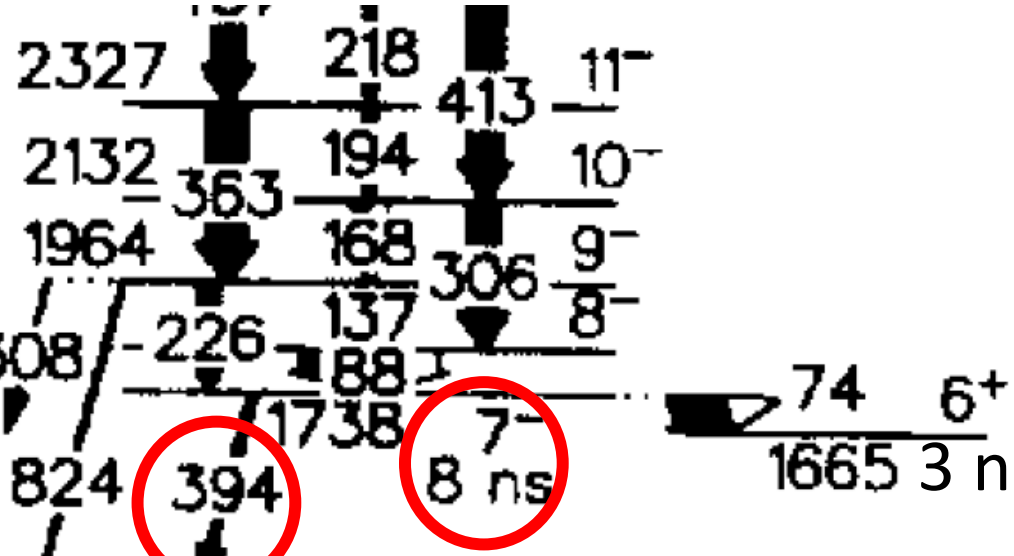




^{178}W partial scheme

Purry et al., Nucl. Phys. A 632 (1998) 229





E2

$f_\nu(E2) = 6.2$

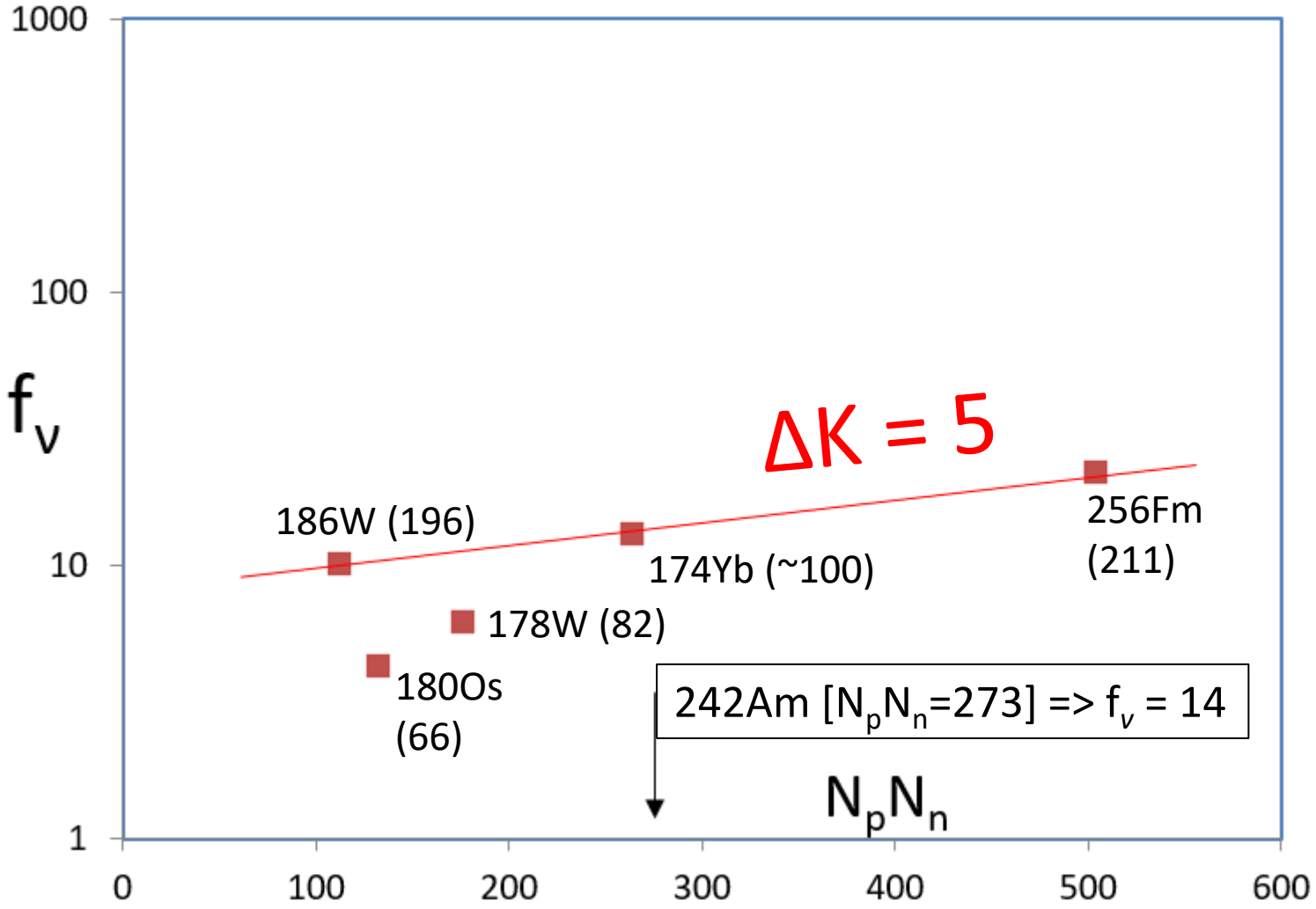
K = 2

K = 7

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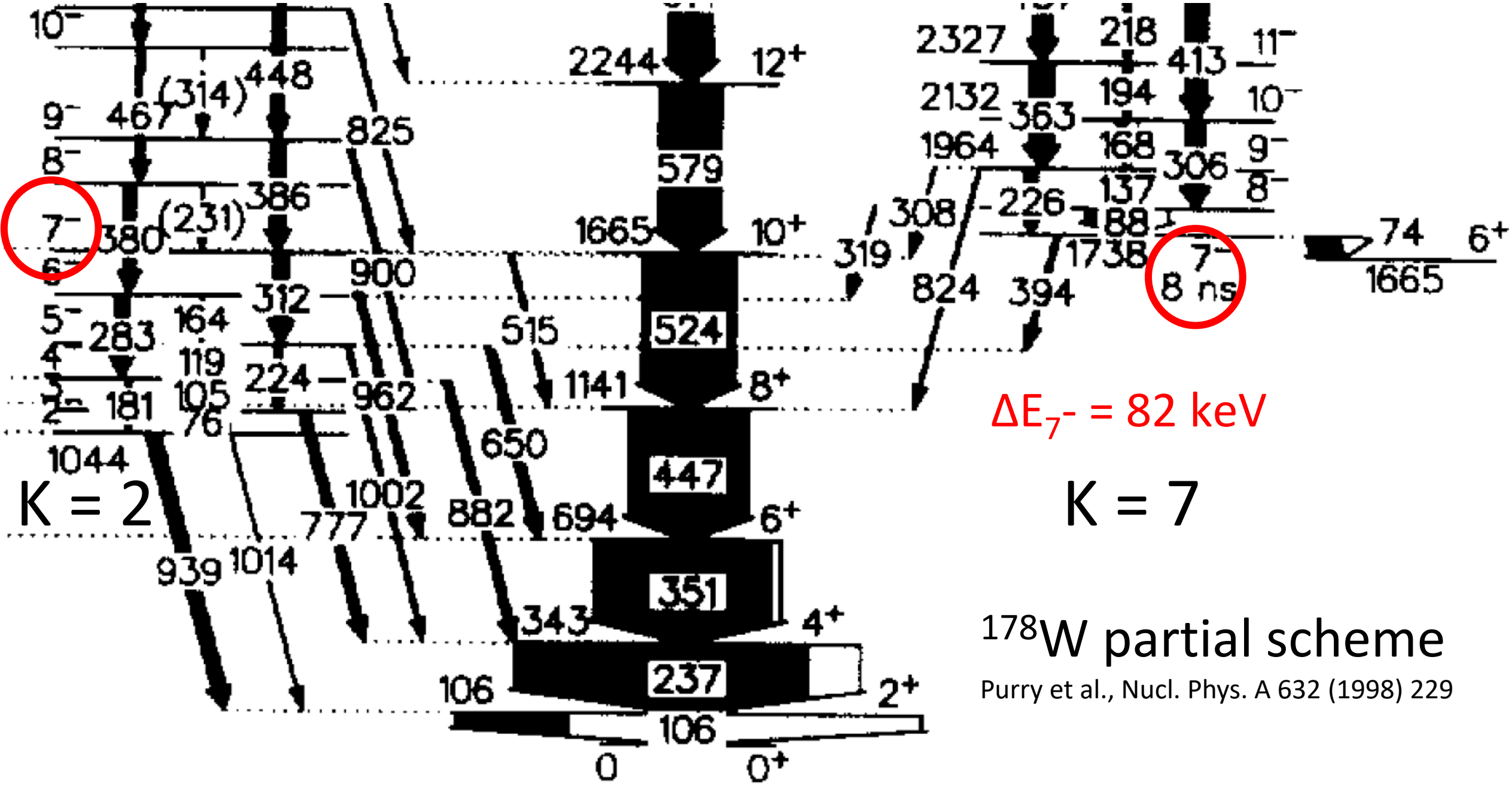
Purry et al., Nucl. Phys. A 632 (1998) 229

E2 transitions



$K^\pi = 7^-$ isomers

^{174}Yb	256 ns
^{178}W	8 ns
^{186}W	18 µs
^{180}Os	25 ns
^{256}Fm	70 ns



ΔE_{7^-} = 82 keV

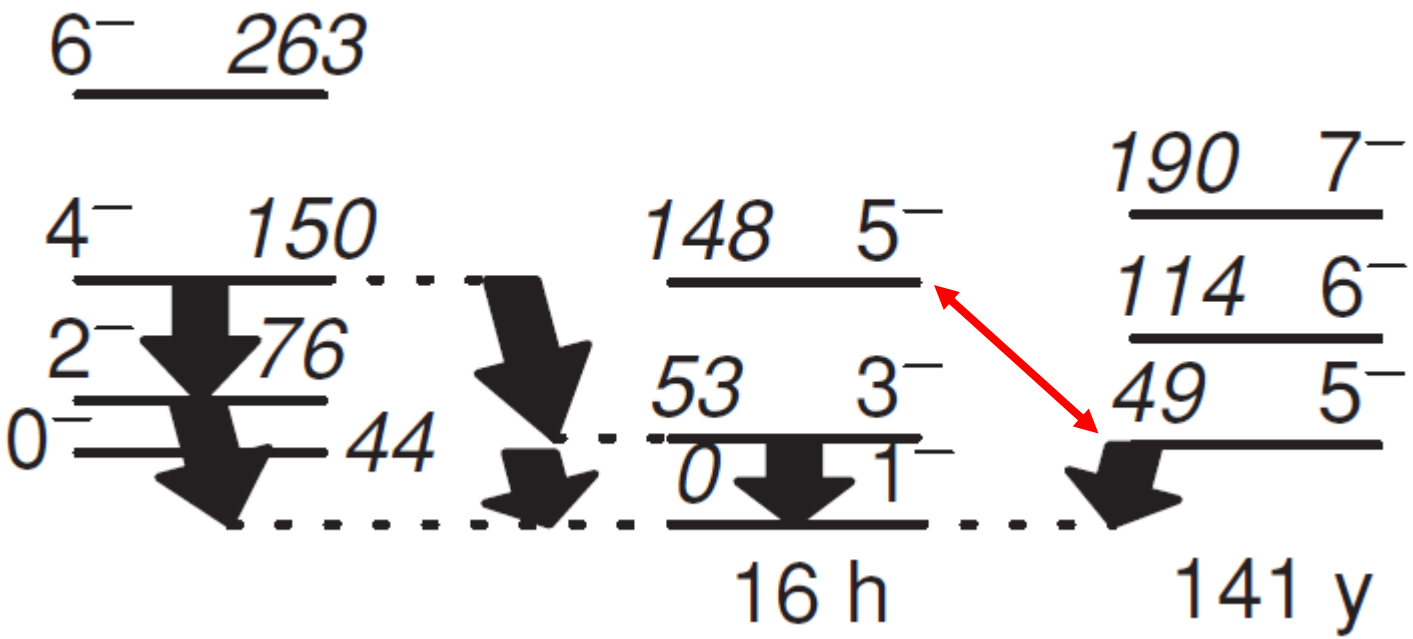
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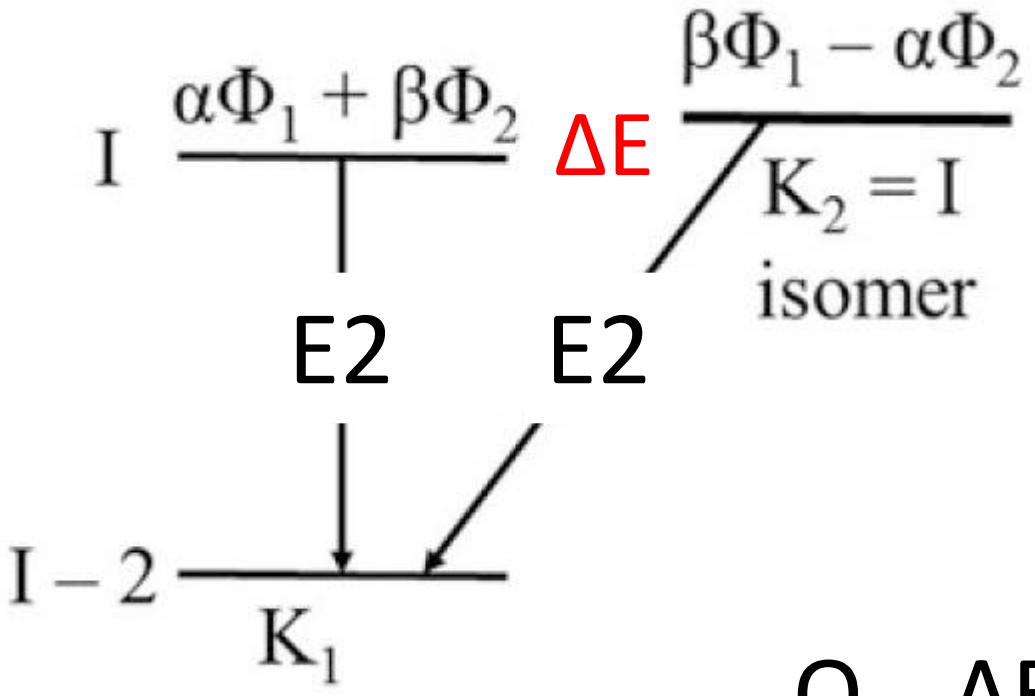
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$\Delta E_{5^-} = 99$ keV

Hayes et al. Phys. Rev. C 82 (2010) 044319

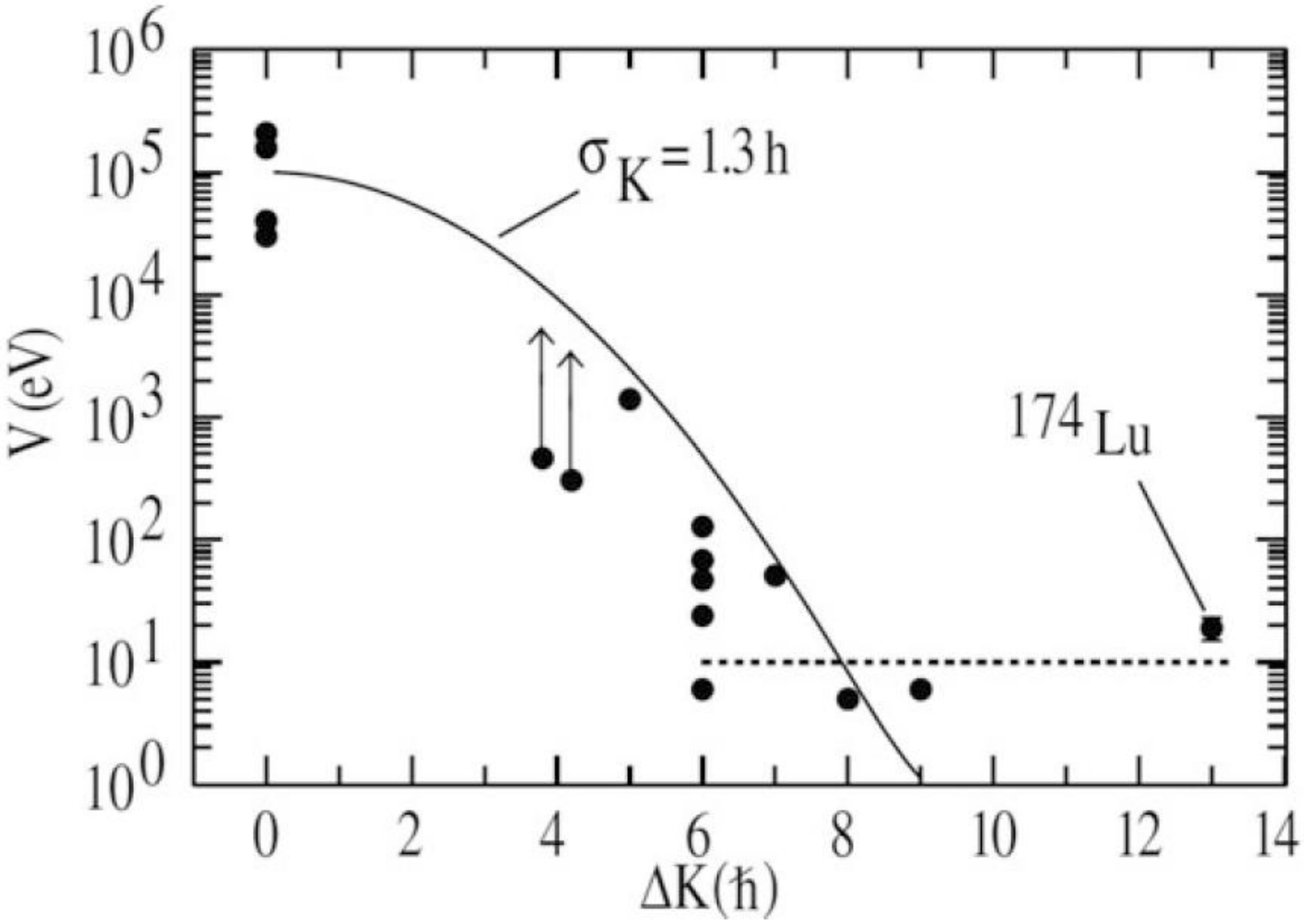
Two-state mixing



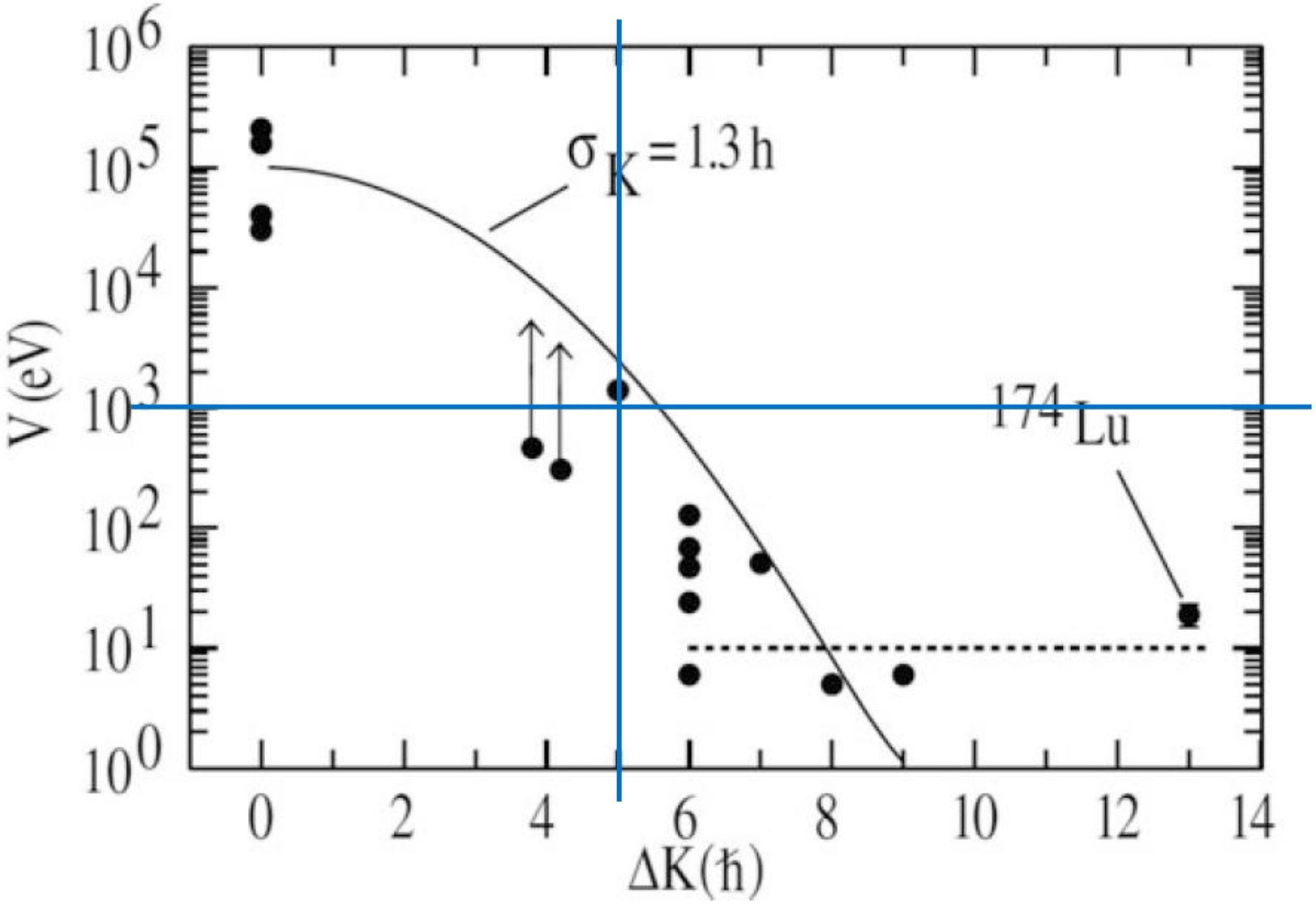
Q_0, ΔE, $T^{\gamma}_{1/2}$ => |V|

β ≈ |V|/ΔE (small β)

See: Dracoulis et al., Phys. Rev. Lett. 97 (2006) 122501;
Walker and Stevenson, Phys. Rev. C 103 (2021) 064305

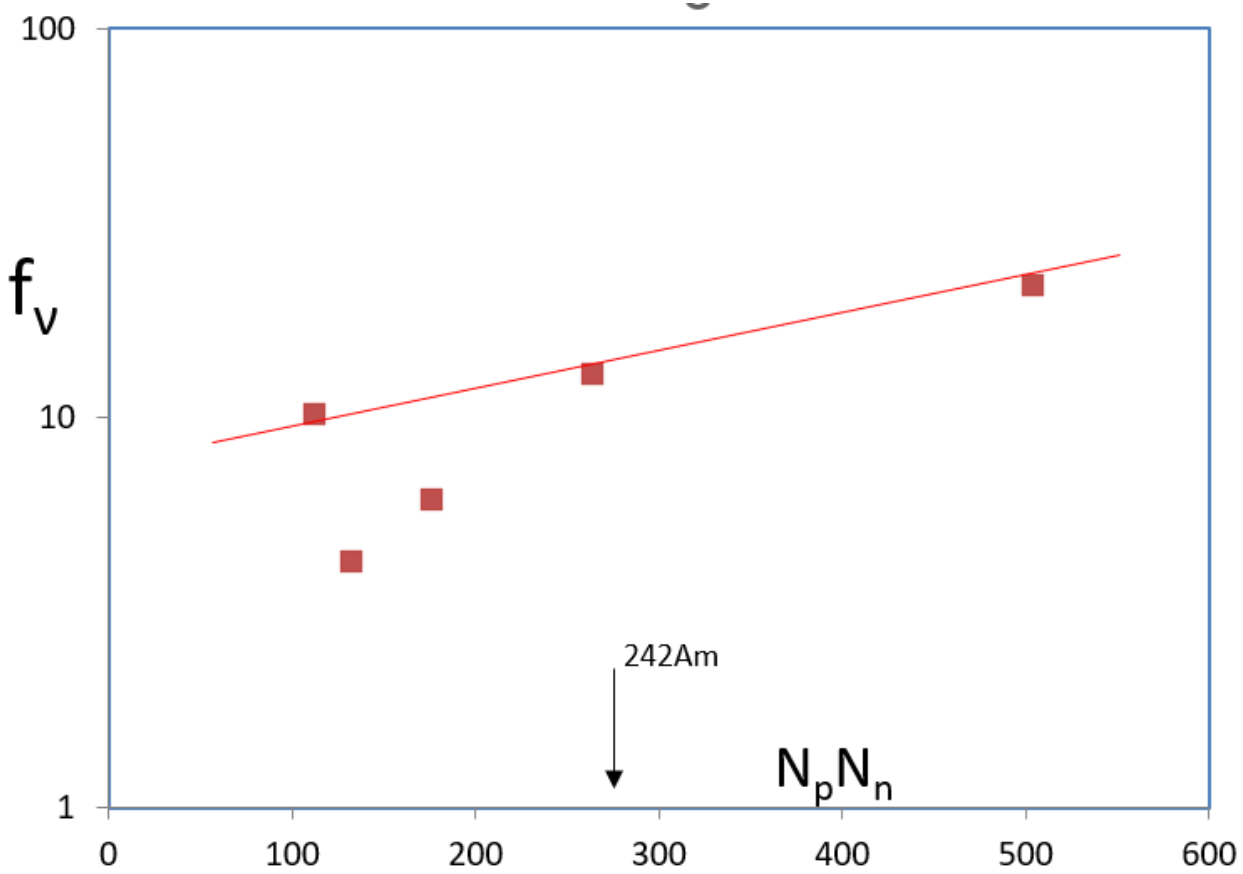


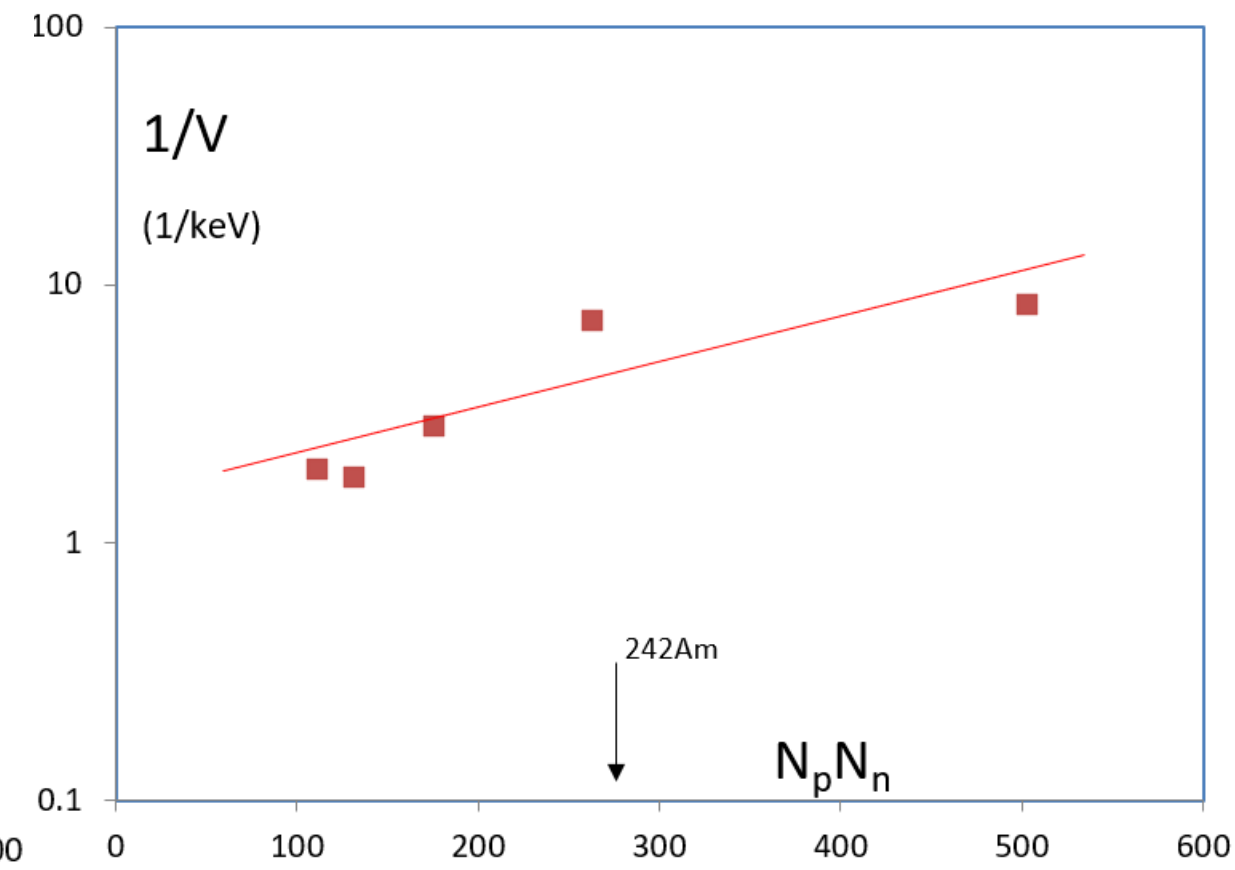
Dracoulis et al., Phys. Rev. Lett. 97 (2006) 122501



Dracoulis et al., Phys. Rev. Lett. 97 (2006) 122501

ΔK = 5, E2 transitions





^{242}Am: $F_W = (14)^3 = 3000$, i.e. 3×10^{-4} Wu and V = 0.2 keV => 8×10^{-4} Wu

BUT how strong is the ^{242}Am E2 transition? 1 Wu?

See Zadernovsky and Carroll, Hyp. Int. 143 (2002) 153):

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See Zadernovsky and Carroll, Hyp. Int. 143 (2002) 153):

"It should be noted that for the overwhelming majority of isomers the reduced transition probabilities of trigger transitions are unknown."

"[^{242m}Am] may have a significantly decreased trigger transition probability due to the 3-fold excess orientation change (i.e., due to the effect of the K quantum number). **This may produce a reduction of the transition rate and, thus, of the triggering cross sections by a factor of as much as 10^3–10^4."**

N.B. Analysis from Löbner [Phys. Lett. B 26 (1968) 369] => ≈10^6

Empirical systematics:

$B(E2; 4\ keV; {}^{242}Am) \approx 10^{-3}$ Wu

$F_W \approx 10^3$

$f_\nu \approx 10$

Advantages of ^{242m}Am for induced isomer de-excitation:

isomer can be produced from ^{141}Am(n,γ) reaction

“pure” isomeric nuclide – just wait a few days (gs $T_{1/2}$ = 16 h)

long isomeric half-life (141 y)

NEEC rate ≈100 times more than for ^{93m}Mo
[Palffy et al., Phys. Rev. Lett. 99 (2007) 172502]
“Where the experimental reduced transition probabilities were not available, single-particle (Weisskopf) estimations have been used.”

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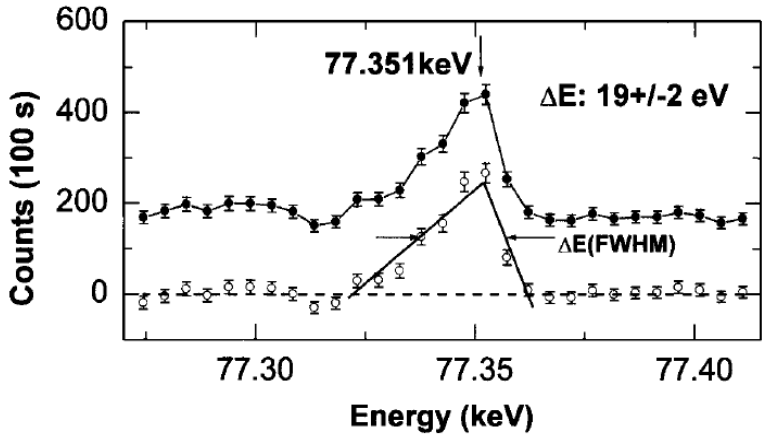
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Examples of successful isomer pumping

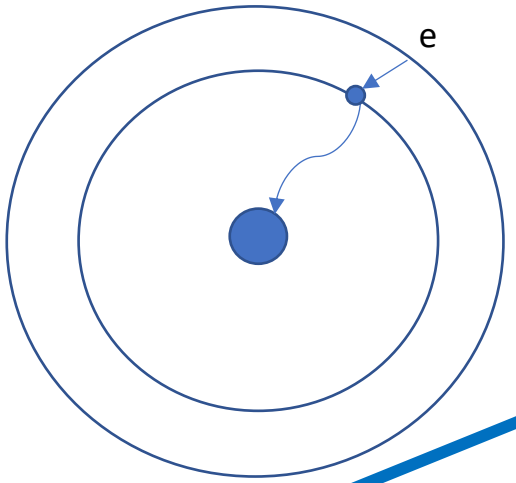
– all are from stable or long-lived target ground sates

^{229}Th: 8000 y,
^{45}Sc, ^{57}Fe, ^{83}Kr, ^{197}Au: stable

Nuclear excitation by electron transition (NEET) in ^{197}Au

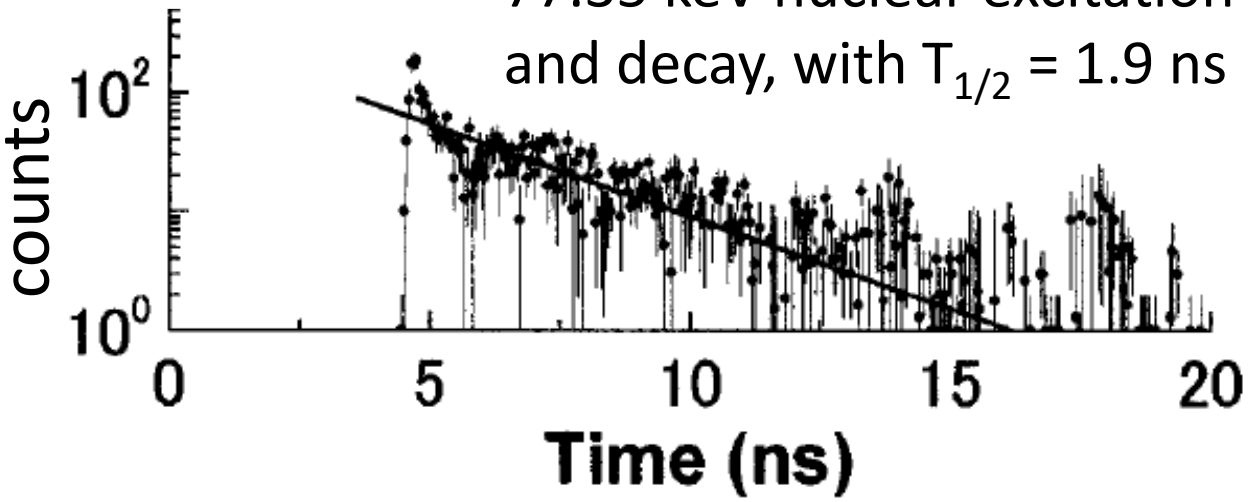


@SPring-8 synchrotron
(81 keV to eject K-shell electrons)



now well established

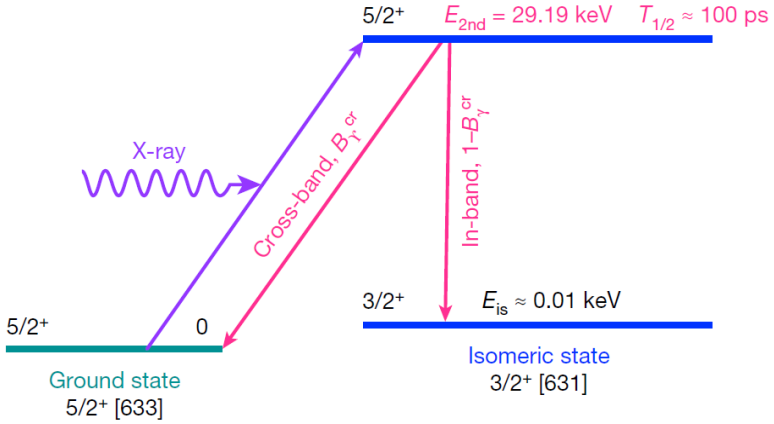
77.35 keV nuclear excitation and decay, with $T_{1/2}$ = 1.9 ns

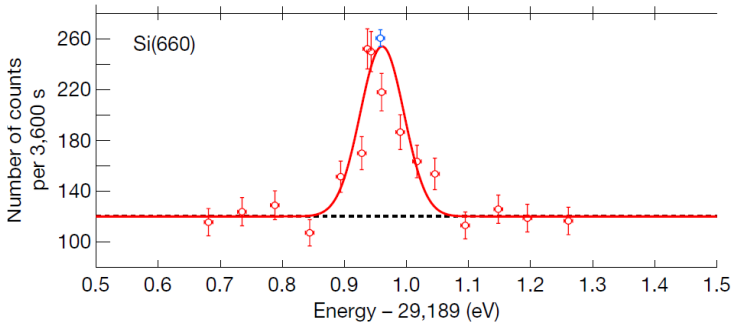


Kishimoto et al. Phys. Rev. Lett. 85 (2000) 1831

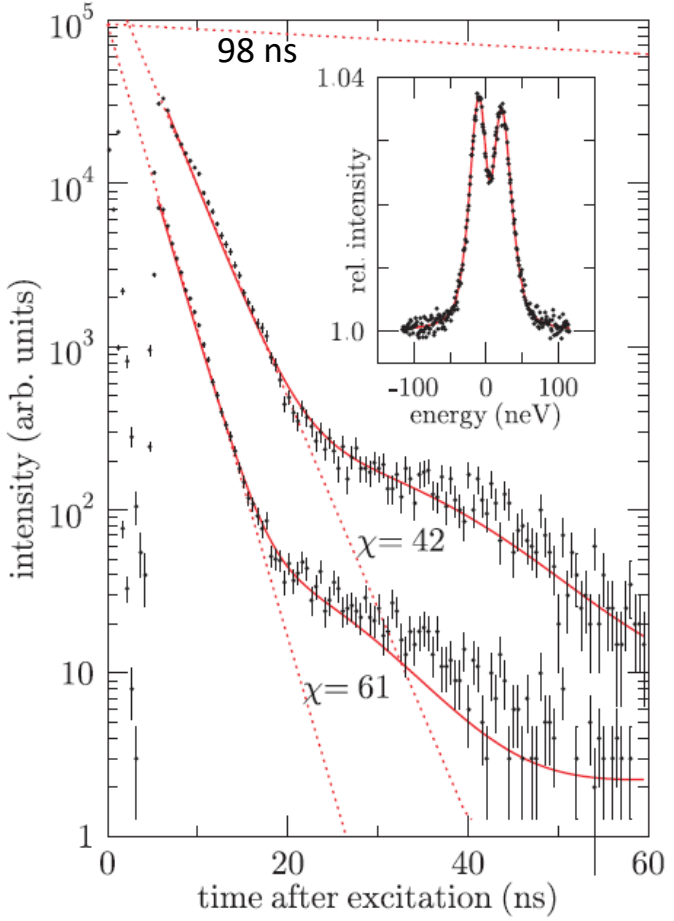
Isomer pumping with synchrotron radiation

^{229}Th (29 keV): X-ray pumping of the ^{229}Th nuclear clock isomer,
Masuda et al, @SPring-8
Nature 573 (2019) 238

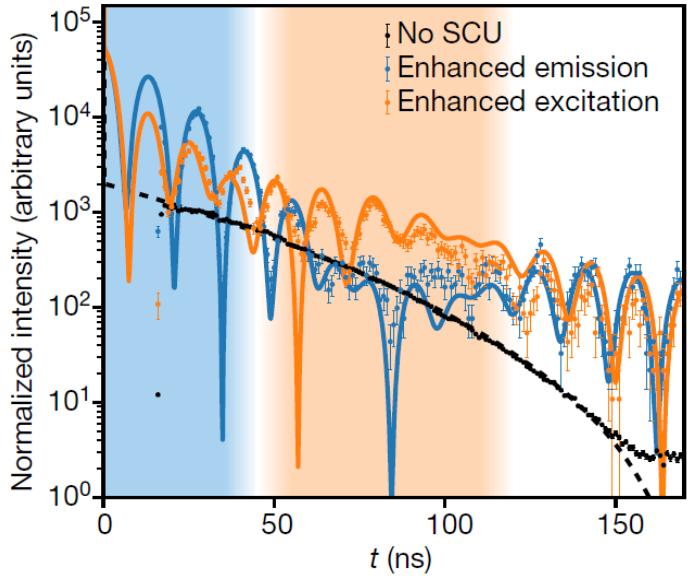




^{57}Fe (14 keV): Collective Lamb Shift in Single-Photon Superradiance,
Röhlsberger et al, @DESY
Science 328 (2010) 1248



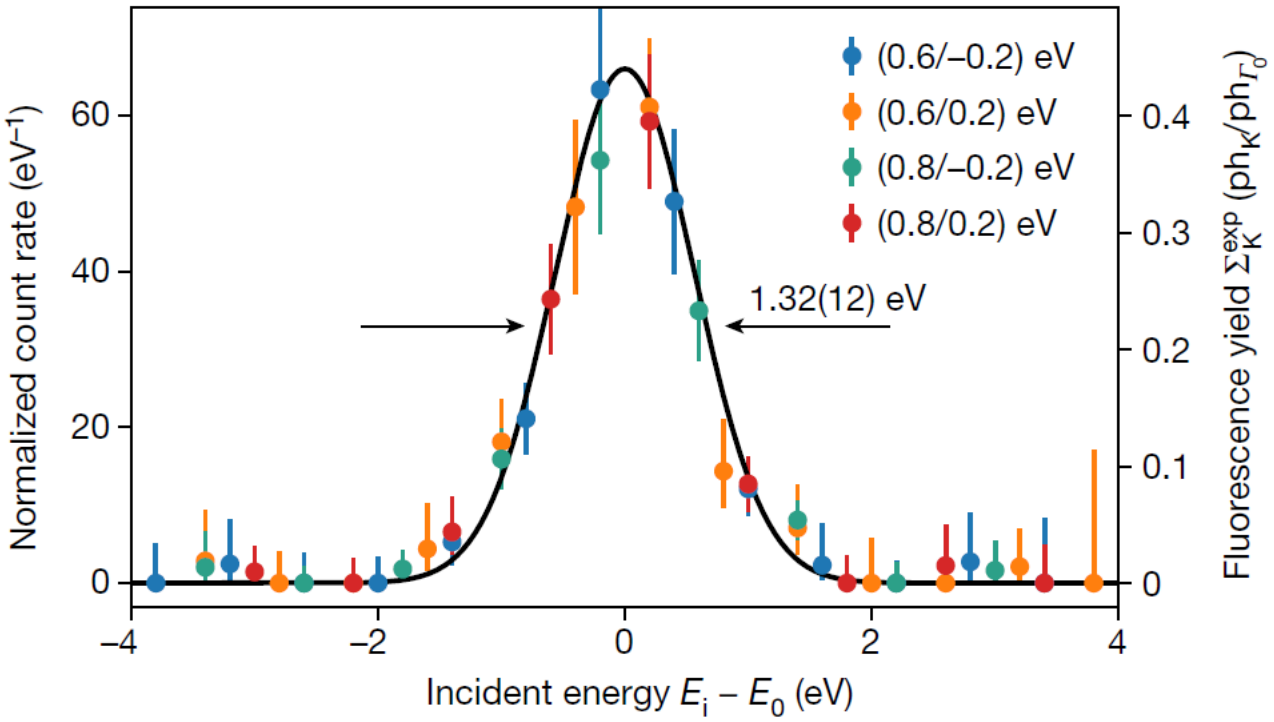
^{57}Fe (14 keV): Coherent X-ray –optical control of nuclear excitons,
Heeg et al, @ESRF
Nature 590 (2021) 401



double pulses generated with a "split-and-control unit" (SCU)
--> *coherent enhanced emission*

XFEL pumping of the 12.4 keV ^{45}Sc isomer

Shvyd'ko et al. Nature 622 (2023) 471, @European X-ray Free-Electron Laser

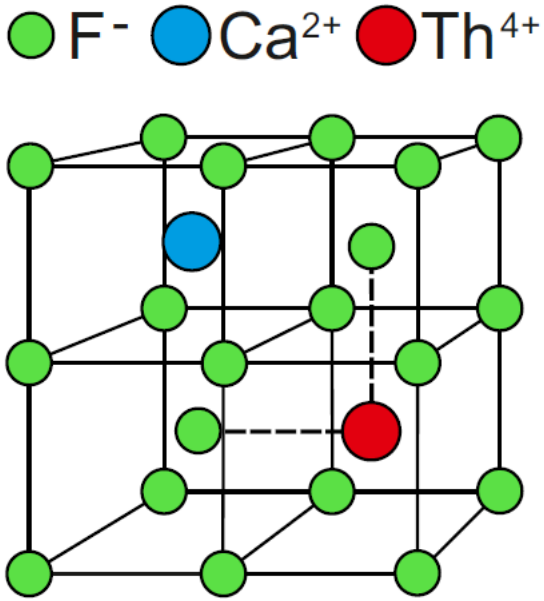


$\Rightarrow$ E = 12.3896(2) keV candidate nuclear-atomic clock isomer

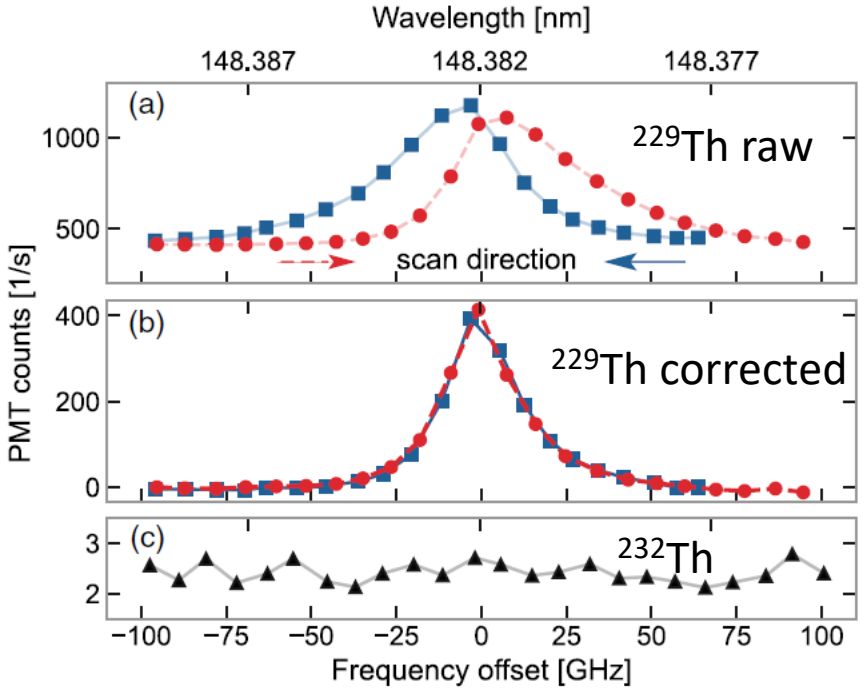
isomer half-life = 25 ms

Laser pumping of the 8.4 eV ^{229}Th isomer

Tiedau et al., Phys. Rev. Lett. 132 (2024) 182501 – @custom-built VUV laser, Braunschweig, Germany



decay rate reduction factor ≈ 10^8



Half-life of ^{229m}Th:

7(1) µs as neutral atom (Seiferle et al. PRL118(2017)042501)

630(15) s as 4+ ion in CaF_2 (Tiedau et al. PRL132(2024)182501)

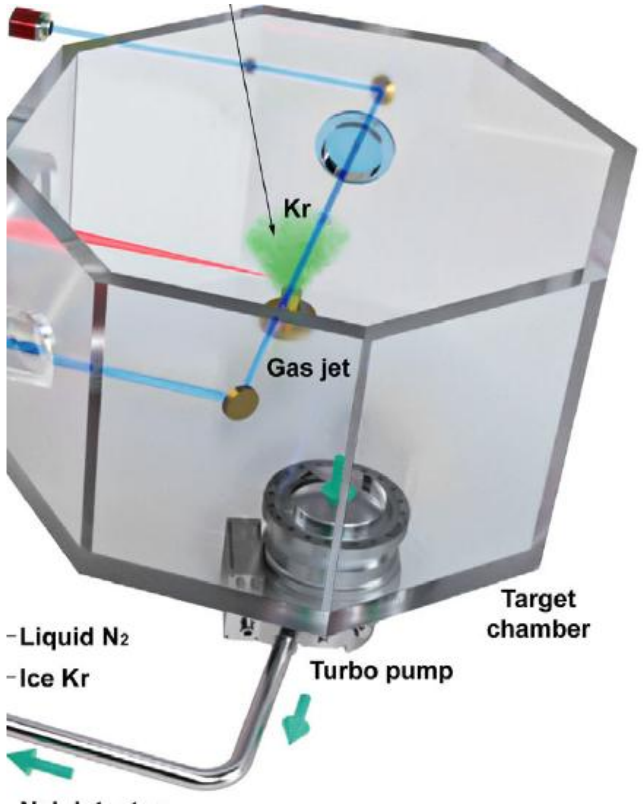
=> E = 8.35574(3) eV

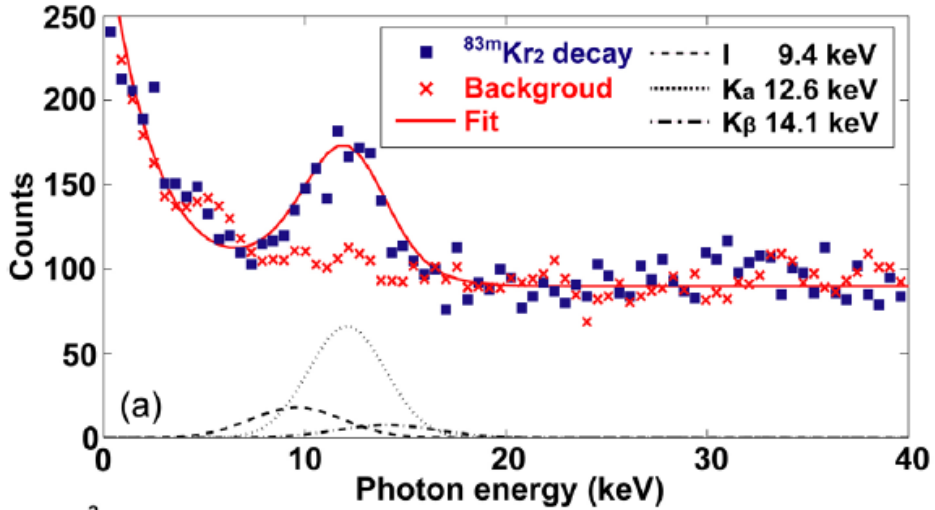
key step towards nuclear-atomic clock

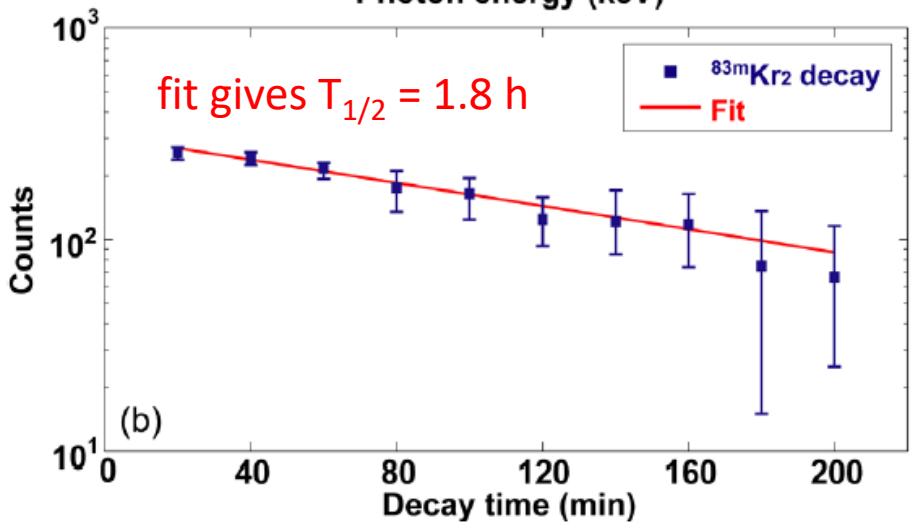
Femtosecond laser pumping of 41.6 keV isomer in ^{83}Kr

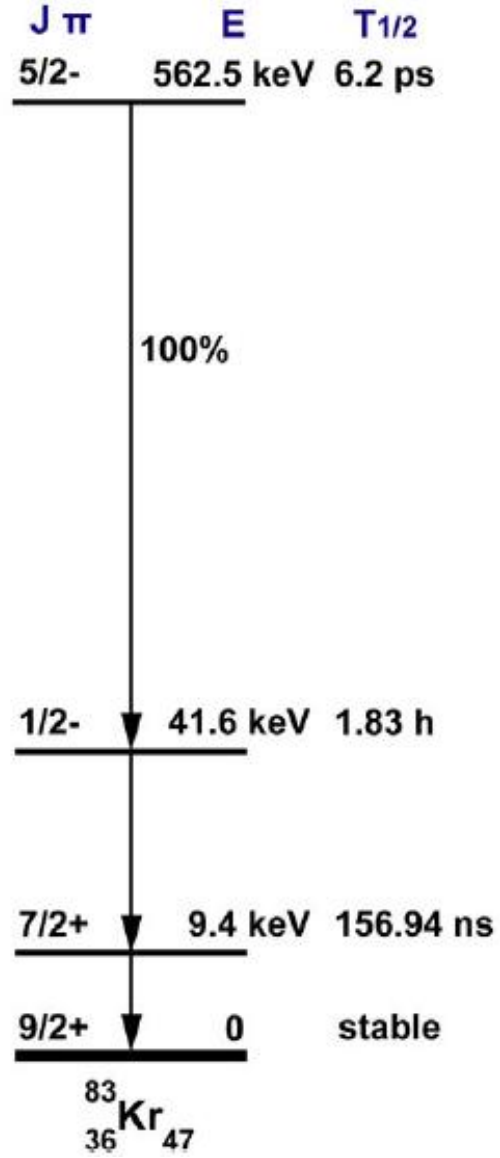
"Femtosecond pumping of nuclear isomeric states by the Coulomb collision of ions with quivering electrons", *Feng et al., Phys. Rev. Lett. 128 (2022) 052501*

@Laboratory of Laser Plasmas, Shanghai Jiao Tong University









Summary:
stimulated decay and an analysis of ^{242m}Am

- Isomers can store large amounts of energy (≈1 MeV per atom)
- Controlled energy release remains challenging
- ^{242m}Am is a promising candidate for further study
- Isomer manipulation is an emerging field of research

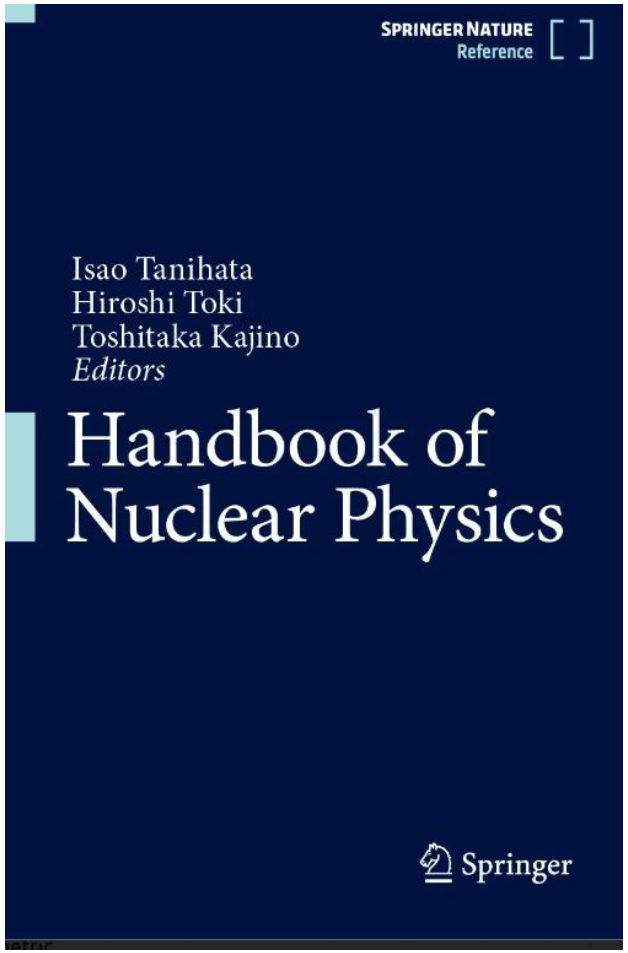
Thank you!

Thanks to Surrey colleagues *Paddy Regan, Zsolt Podolyák, Paul Stevenson*
and many others!

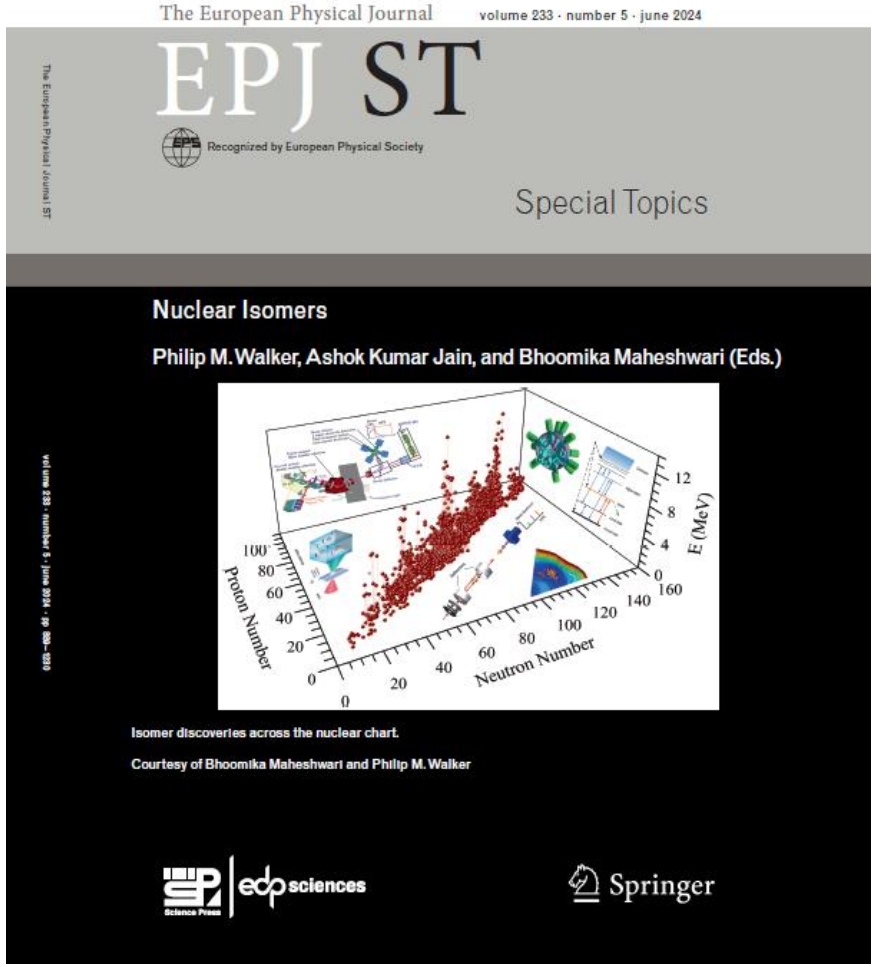
Striding Edge, English Lake District

Further reading:

P.M. Walker & Zs. Podolyák , "*Nuclear isomers*", *Chapter 12 in* "Handbook of Nuclear Physics" Springer Nature (2023)



Eur. Phys. J. *Special Topics 233(5)*: Special issue on "Nuclear Isomers" (2024) Eds. P.M. Walker, A.K. Jain & B. Maheshwari

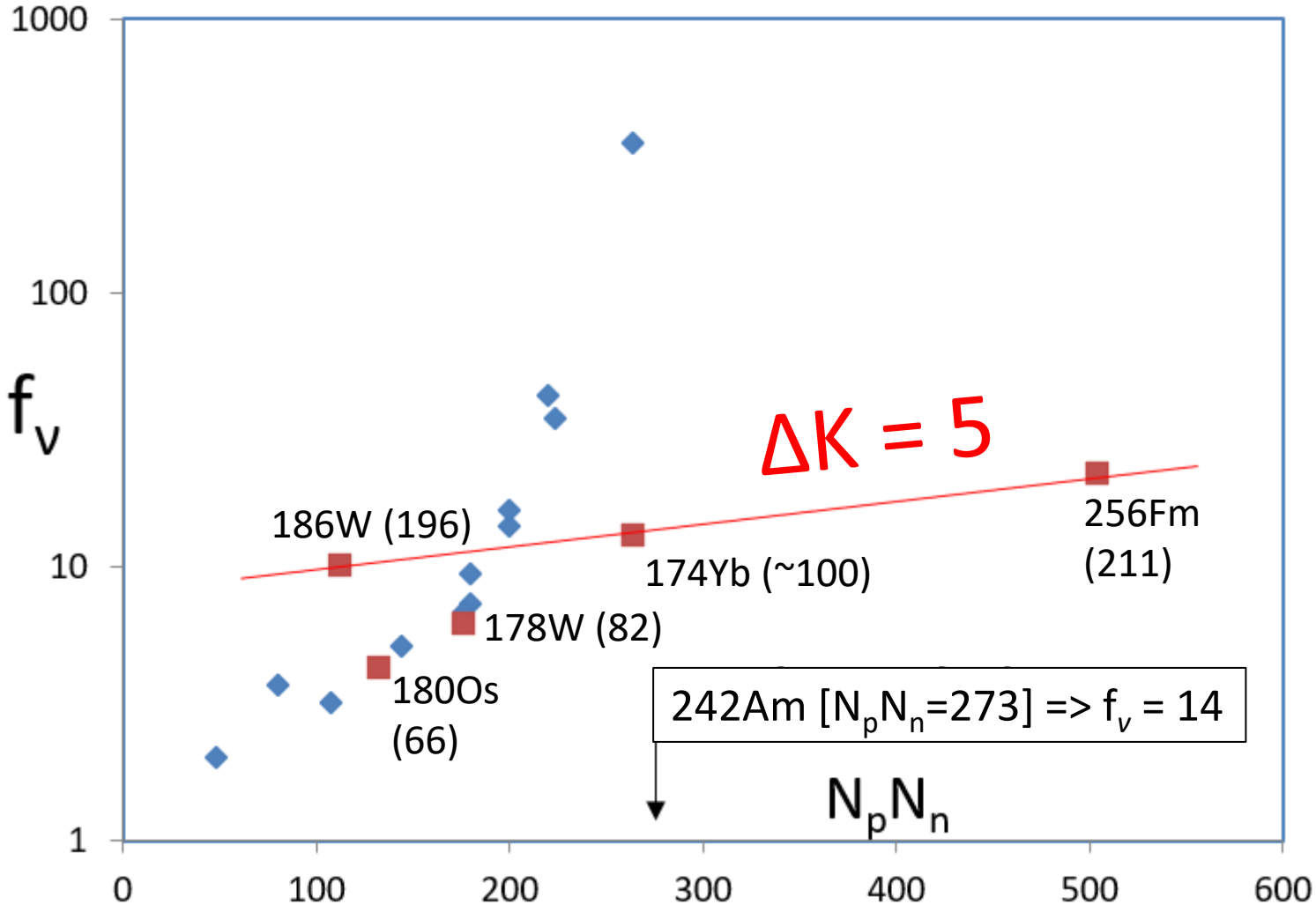


$$B(E2) = \frac{5}{16\pi} e^2 Q_o^2 | < I_1 K 20 | I_2 K > |^2$$

$$(f_\nu)^{\nu/2} = \sqrt{F_W} = \frac{\Delta E}{|V|} \frac{0.71}{Z\beta_2(1 + 0.36\beta_2)| < I_1 K 20 | I_2 K > |}$$

Walker and Stevenson, Phys. Rev. C 103 (2021) 064305

E2 transitions



$K^\pi = 7^-$ isomers

^{174}Yb	256 ns
^{178}W	8 ns
^{186}W	18 µs
^{180}Os	25 ns
^{256}Fm	70 ns