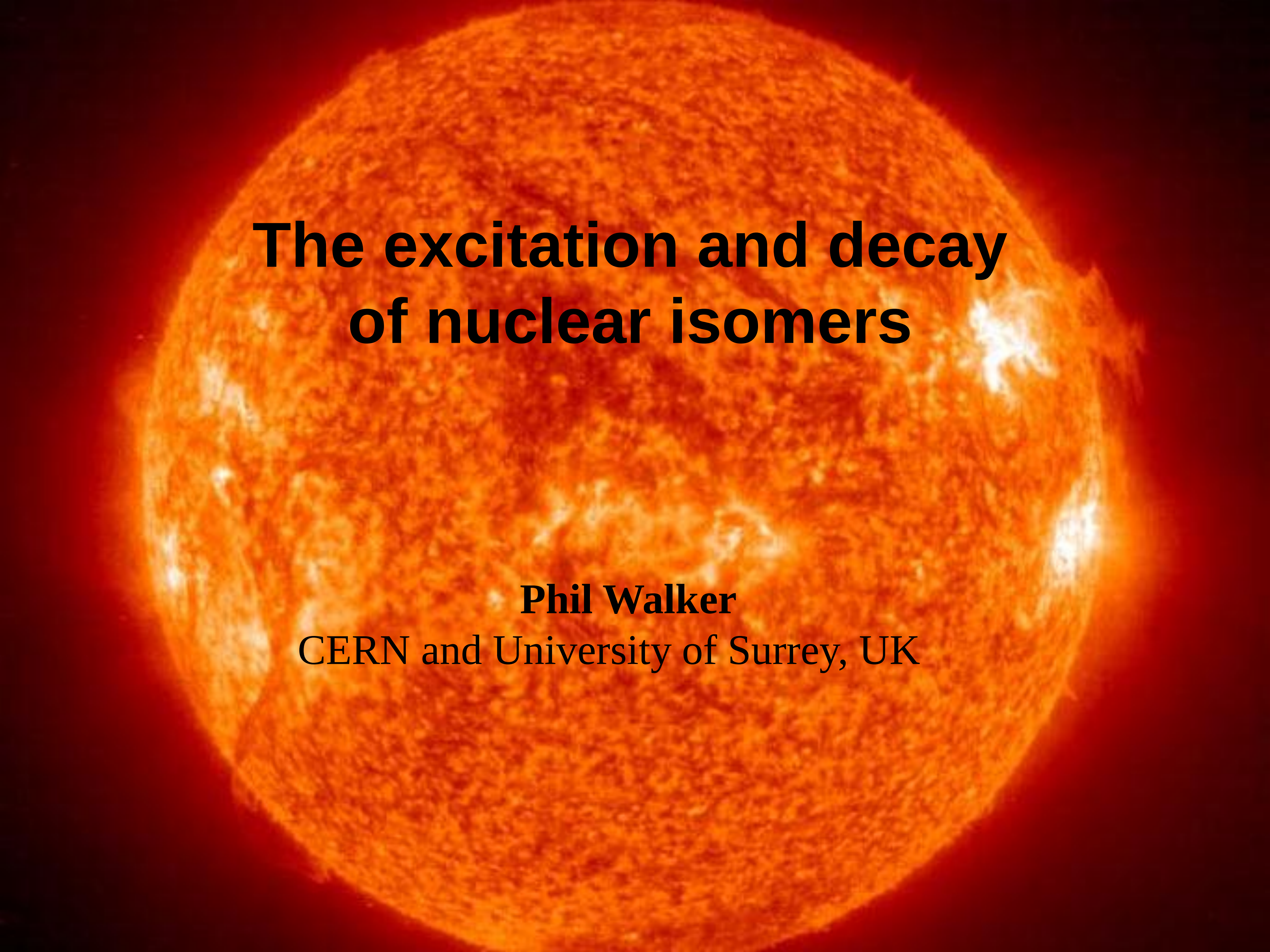

The excitation and decay of nuclear isomers

Phil Walker
CERN and University of Surrey, UK

The excitation and decay of nuclear isomers

<u>1. Isomer perspectives</u>

Phil Walker
CERN and University of Surrey, UK

- historical notes
- aspects of stability
- imaging with isomers
- isomer manipulation
- isomer detection

***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."

***explanation**:*
von Weizsäcker, Naturwissenshaften 24 (1936) 813

Frederick Soddy

isomeric state τ_m

α β γ

ground state τ_g

α β

importance of spin

Carl von Weizsäcker

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

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isomeric state

α

β

γ

τ_m

gr

importance of

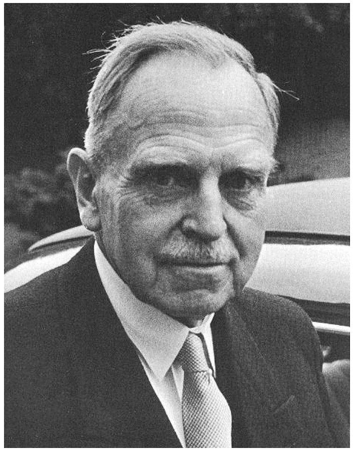
Carl von Weizsäcker

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

possibility of external manipulation of isomers through the electromagnetic interaction

Historical background: isomers

1917: Soddy predicts existence of isomers
1921: Hahn observes uranium-X isomers
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



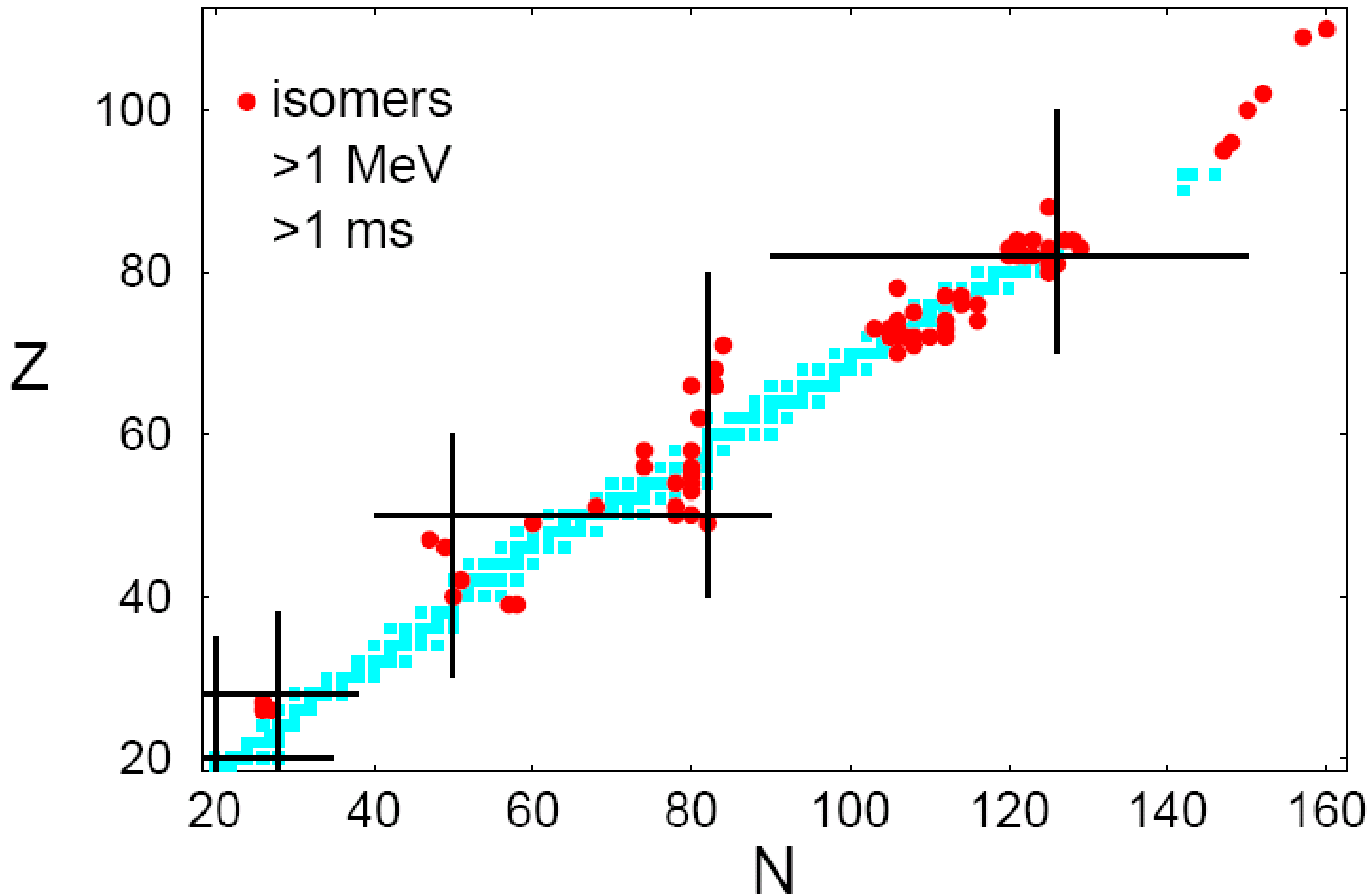
Otto Hahn:
discoverer of isomers (1921)
discoverer of fission (1938)

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

***Meitner** and Frisch,*
Nature, Feb 1939

Lise Meitner
"mother of nuclear structure"

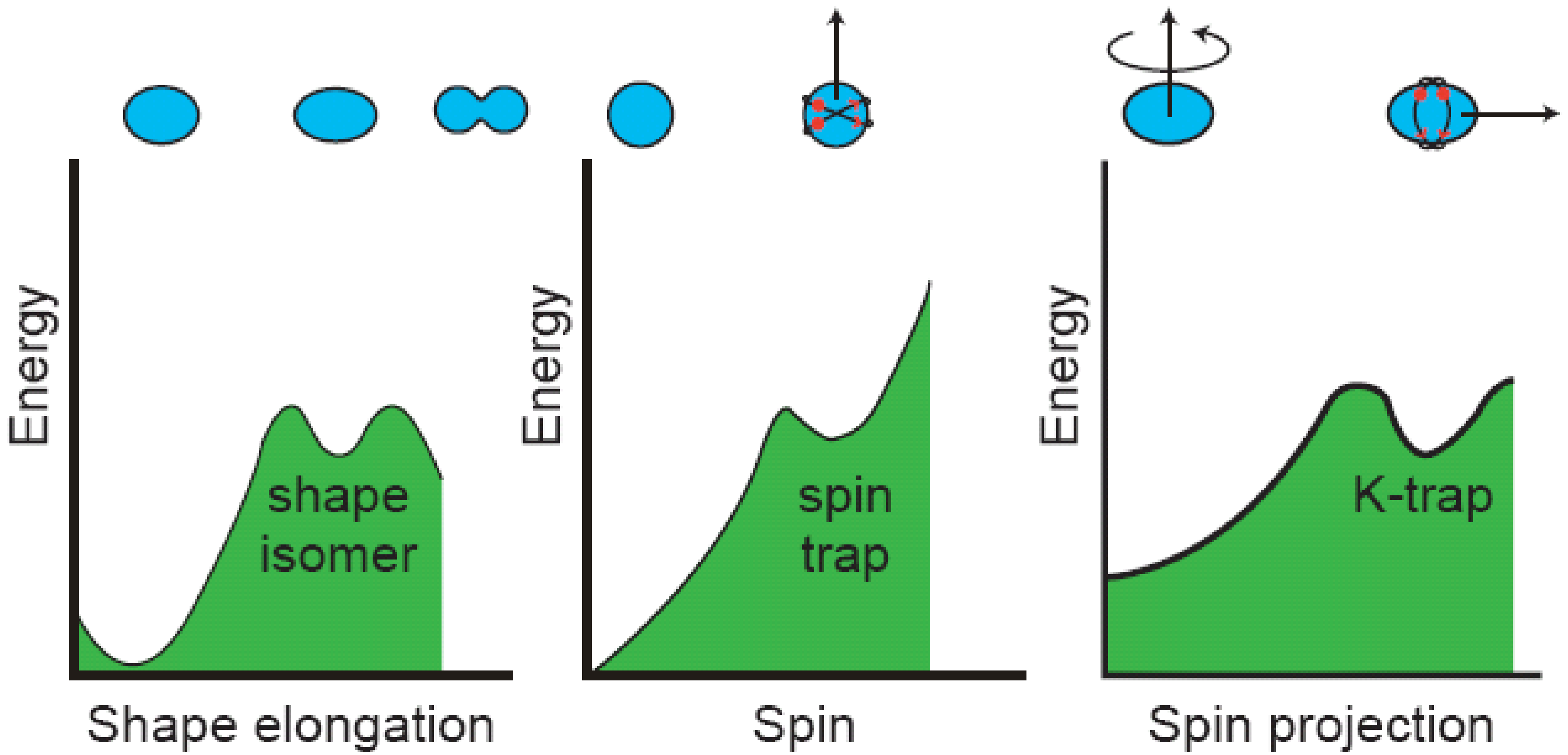
nuclear chart with >1 MeV isomers



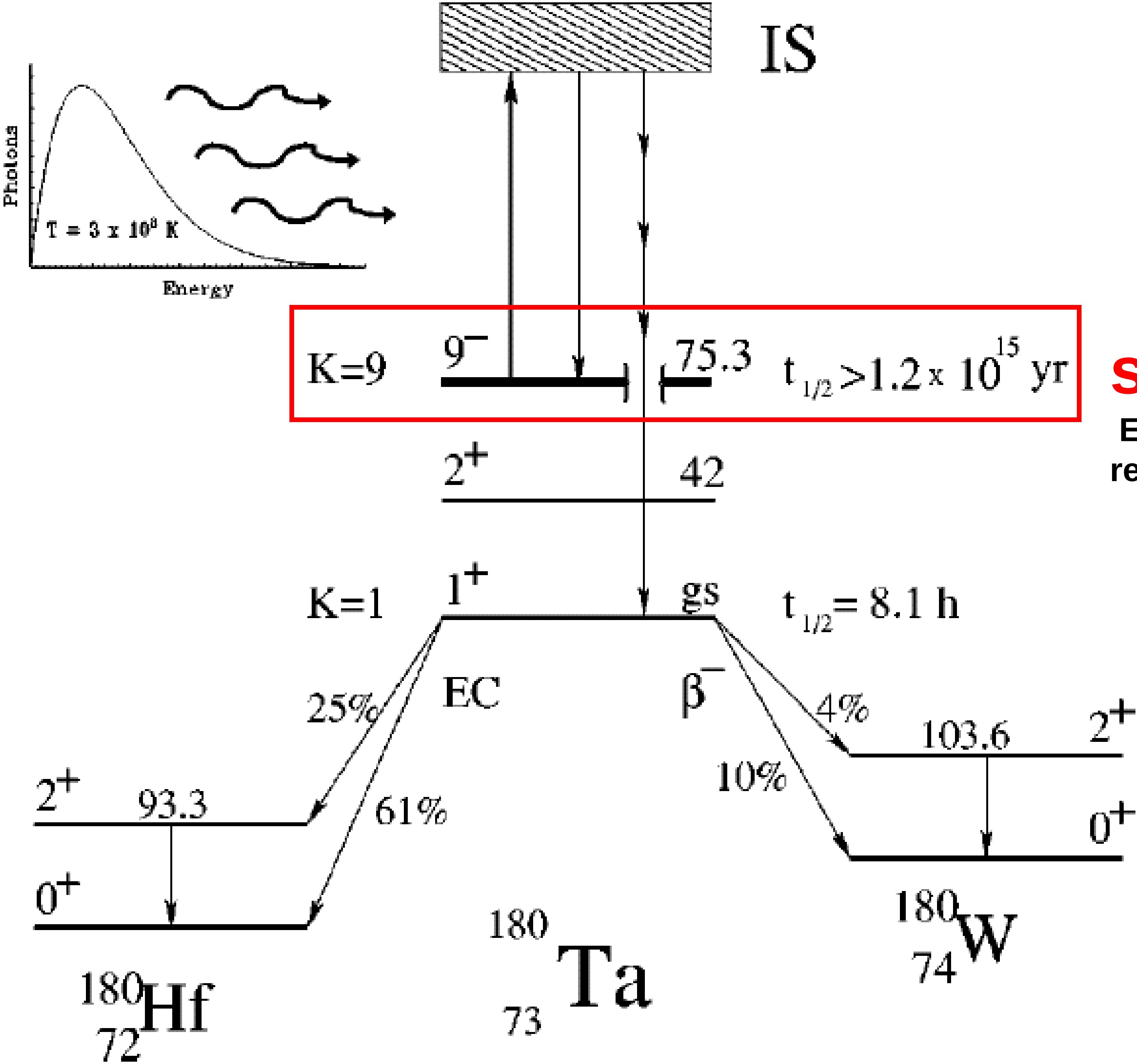
adapted from Walker and Dracoulis, Nature 399 (1999) 35

Nuclear isomers: energy traps

excited state half-lives ranging from nanoseconds to years



Walker and Dracoulis, Nature 399 (1999) 35



spin trap

E7 and M8 decays remain unobserved

[Belic et al., Phys. Rev. C65 (2002) 035801]

aspects of nuclear stability

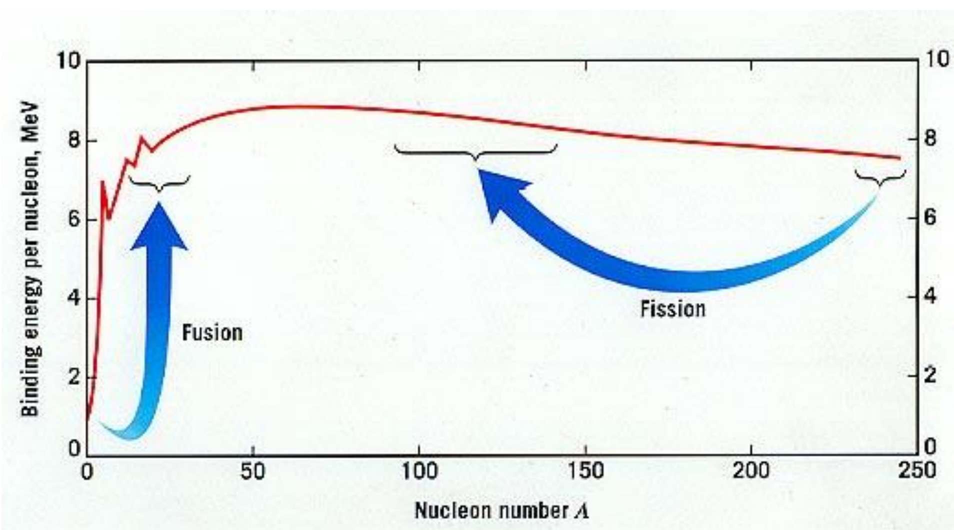
Bi207 31.55 y 9/2- EC	Bi208 3.68E+5 y (5)+ * EC	Bi209 9/2- 100
Pb206 0+ 24.1	Pb207 1/2- * 22.1	Pb208 0+ 52.4
Tl205 1/2+ 70.476	Tl206 4.199 m 0- * β-	Tl207 4.77 m 1/2+ * β-

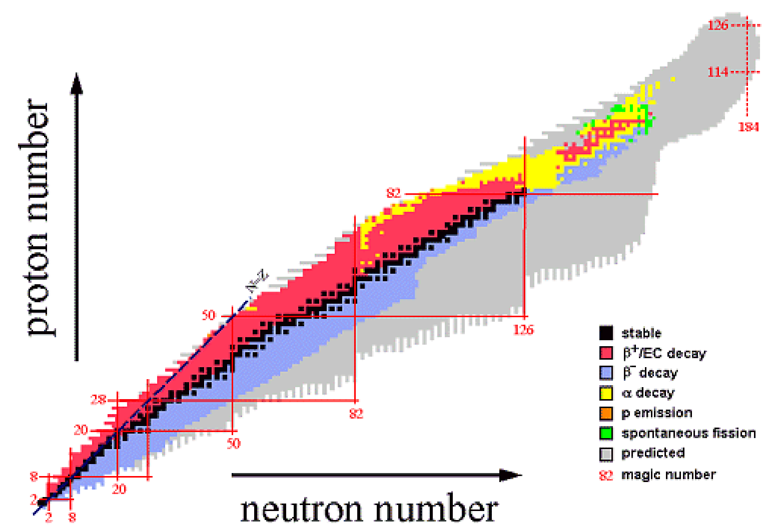
^{209}Bi 2x10^{19} y

α stability
β stability
γ stability
particle stability
fission stability

W180 0+ * 0.13	W181 121.2 d 9/2+ EC	W182 0+ 26.3
Ta179 1.82 y 7/2+ * EC	Ta180 8.152 h 1+ EC,β- 0.012 *	Ta181 7/2+ 99.988
Hf178 0+ * 27.297	Hf179 9/2+ * 13.629	Hf180 0+ * 35.100

^{180m}Ta >10^{16} y





[^{209}Bi α decay: Nature 422 (2003) 876]

aspects of nuclear stability

At the limits of nuclear binding,
isomers may be more stable than 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

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At the limits of nuclear bindin

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more details in 3rd lecture

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isomer examples

^{99m}Tc	**143 keV**	**6 hours**
^{178m2}Hf	**2.45 MeV**	**31 years**
^{180m}Ta	**75 keV**	**$>10^{16}$ years**
^{229m}Th	**8 eV**	**hours?**

isomer examples

^{99m}Tc	143 keV	6 hours
$^{178m2}Hf$	2.45 MeV	31 years
^{180m}Ta	75 keV	$>10^{16}$ years
^{229m}Th	8 eV	hours?

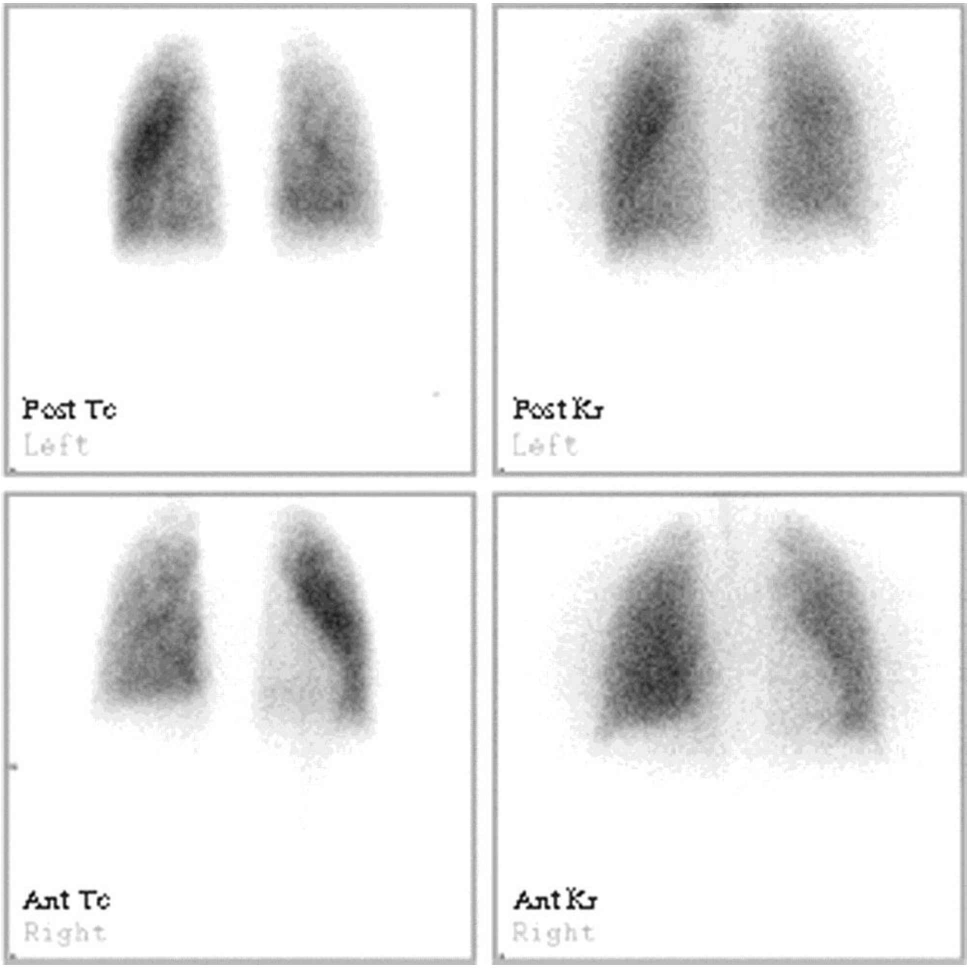
energies range over
6 orders of magnitude

half-lives range over
33 orders of magnitude

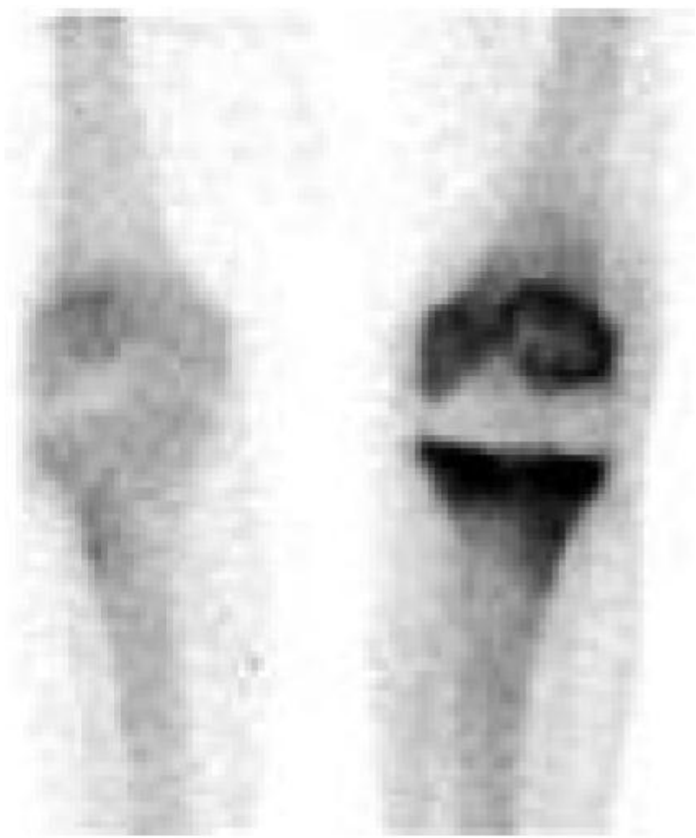
isomer images

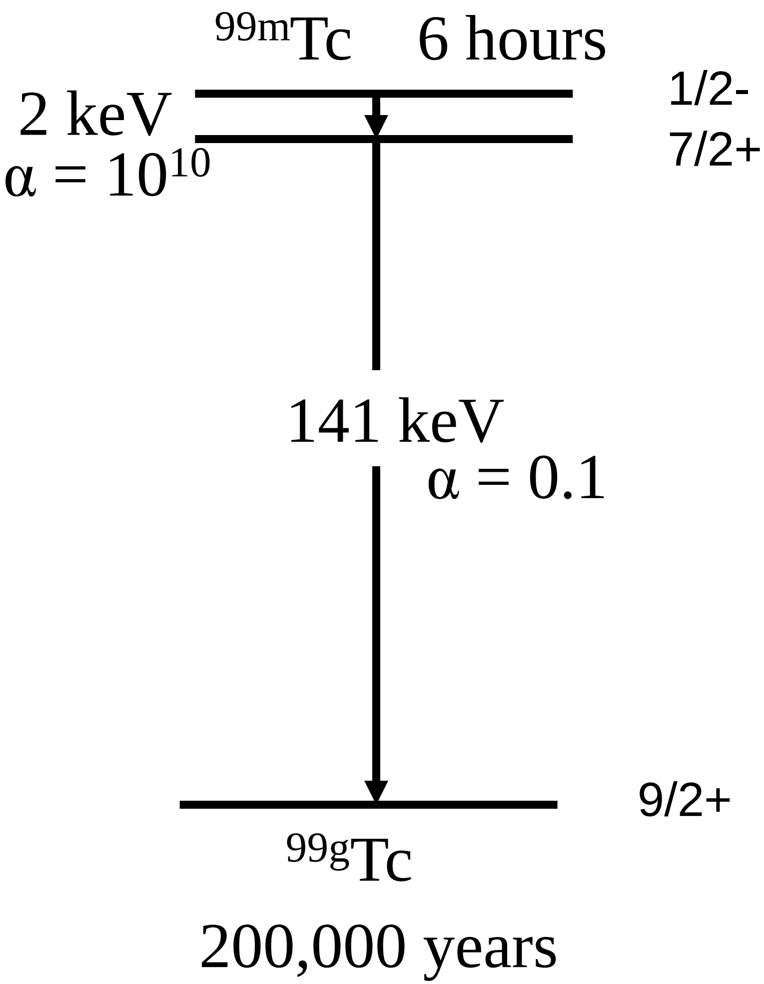
^{81m}Kr, 13 s, 190 keV

^{99m}Tc, 6 h, 141 keV



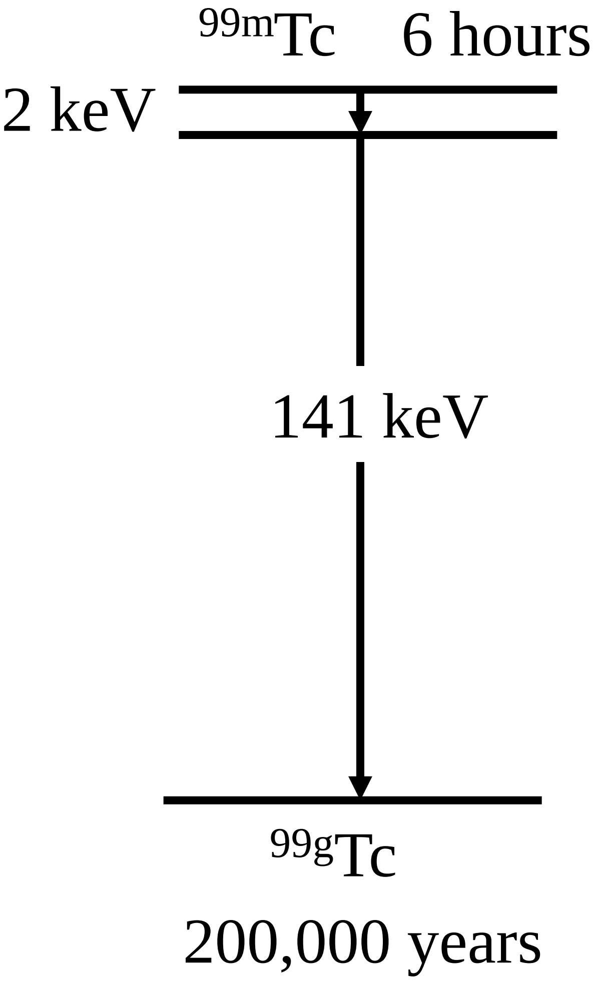
^{99m}Tc: an isomer in the clinic





^{99m}Tc: a nuclear battery??

Bikit et al. used 15 MeV bremsstrahlung to de-excite the isomer [J. Phys G19 (1993) 1359].

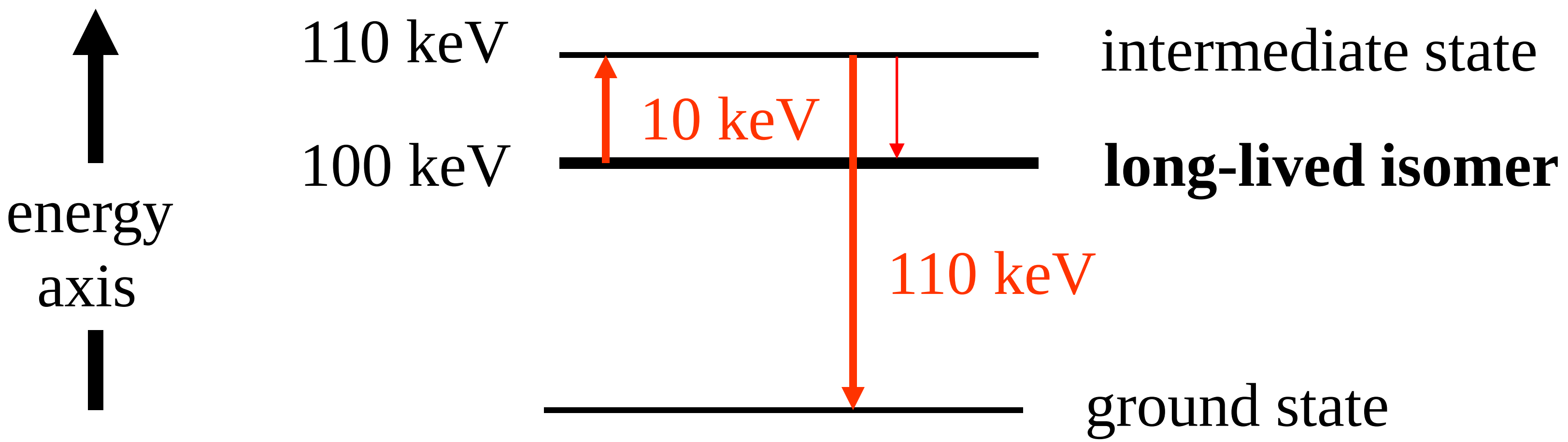


possibilities for isomer manipulation:

isomers as nuclear "batteries"?

i.e. 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

^{180}Ta is nature's only naturally occurring isomer, but

^{180}Ta forms only 0.01% of natural tantalum. (^{181}Ta is 99.99%.)

isomer 9^- *75 keV*

$>10^{16}$ yr

$K^\pi = 9^-$

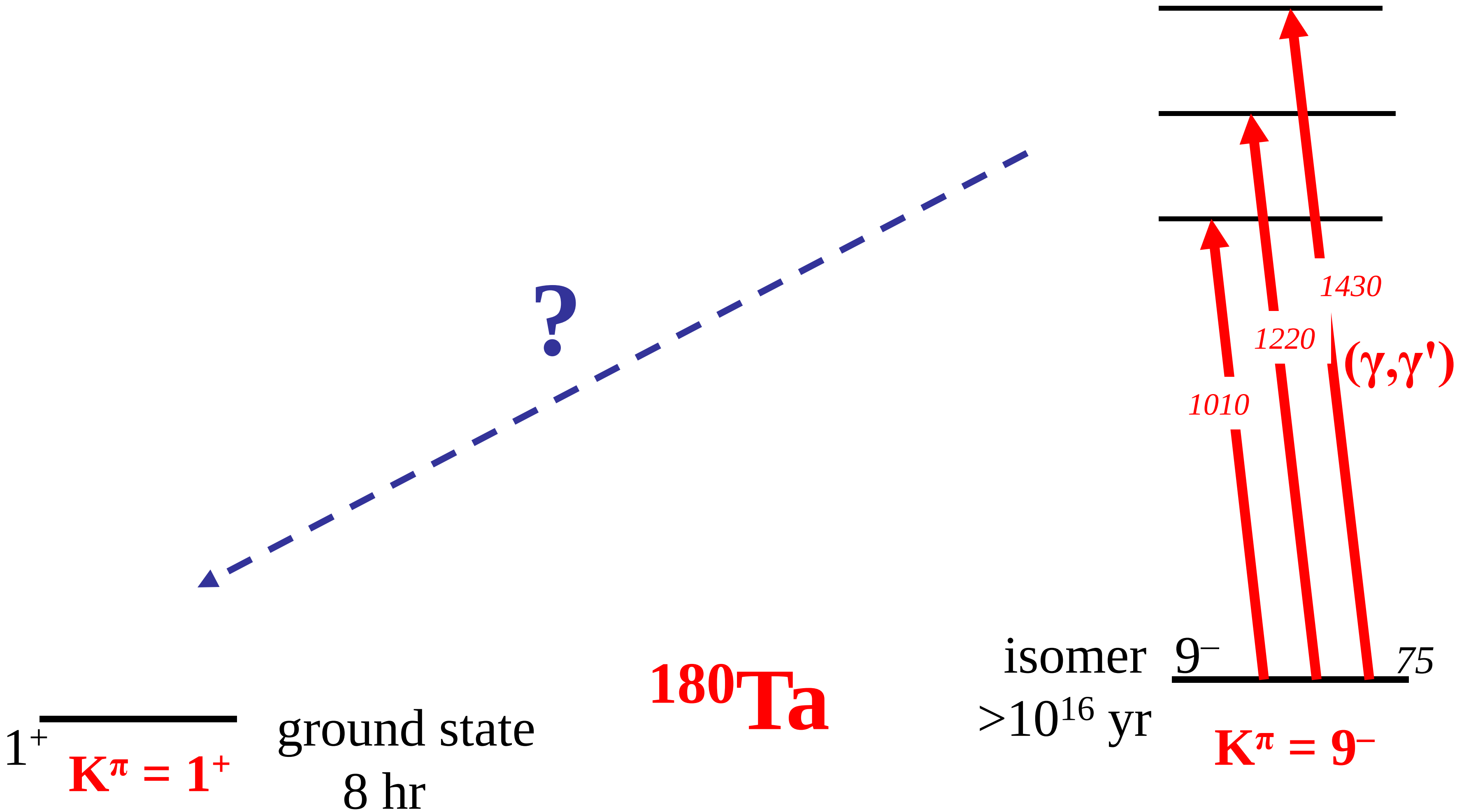
^{180}Ta

1^+ $K^\pi = 1^+$

ground state

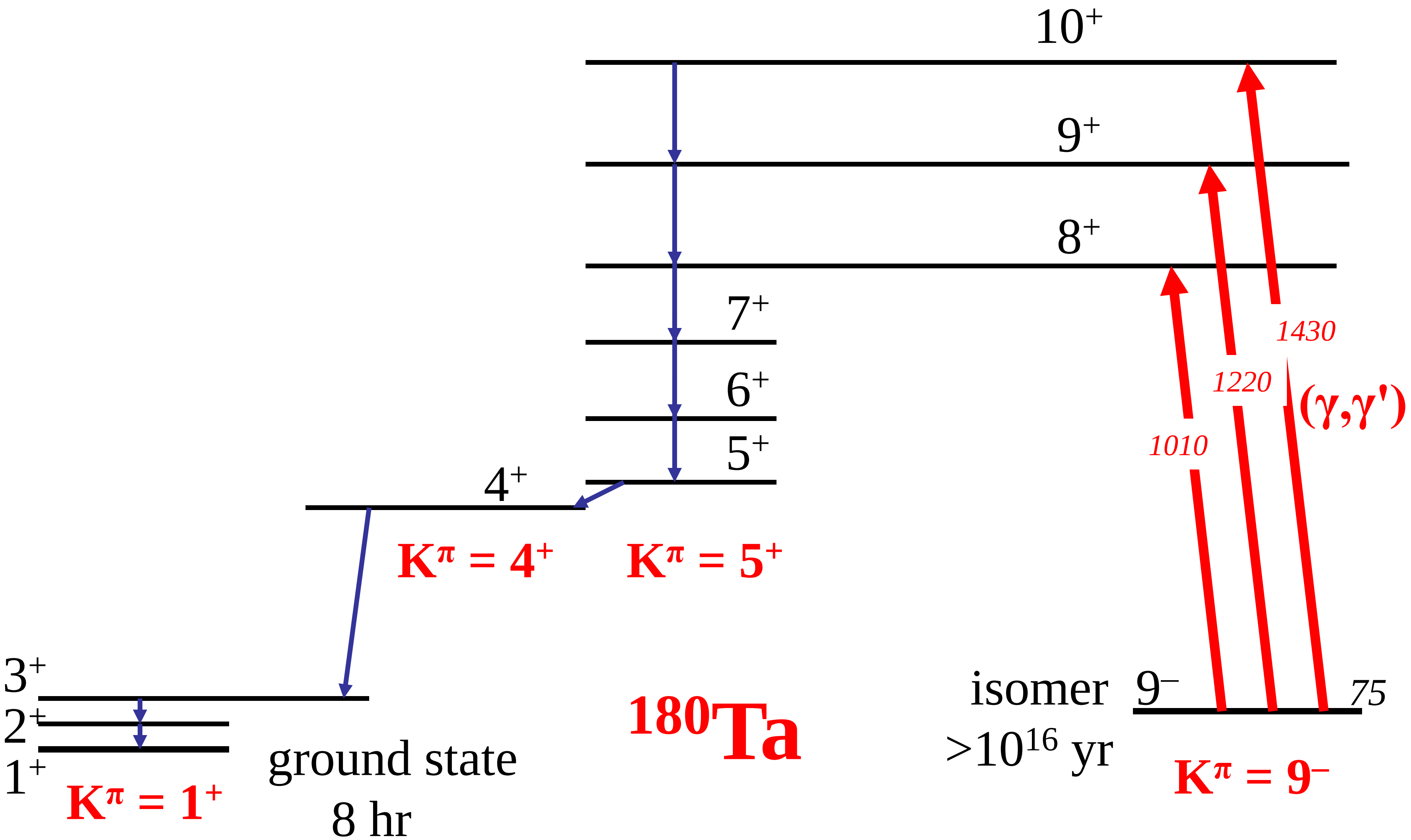
8 hr

^{180}Ta photoexcitation and decay



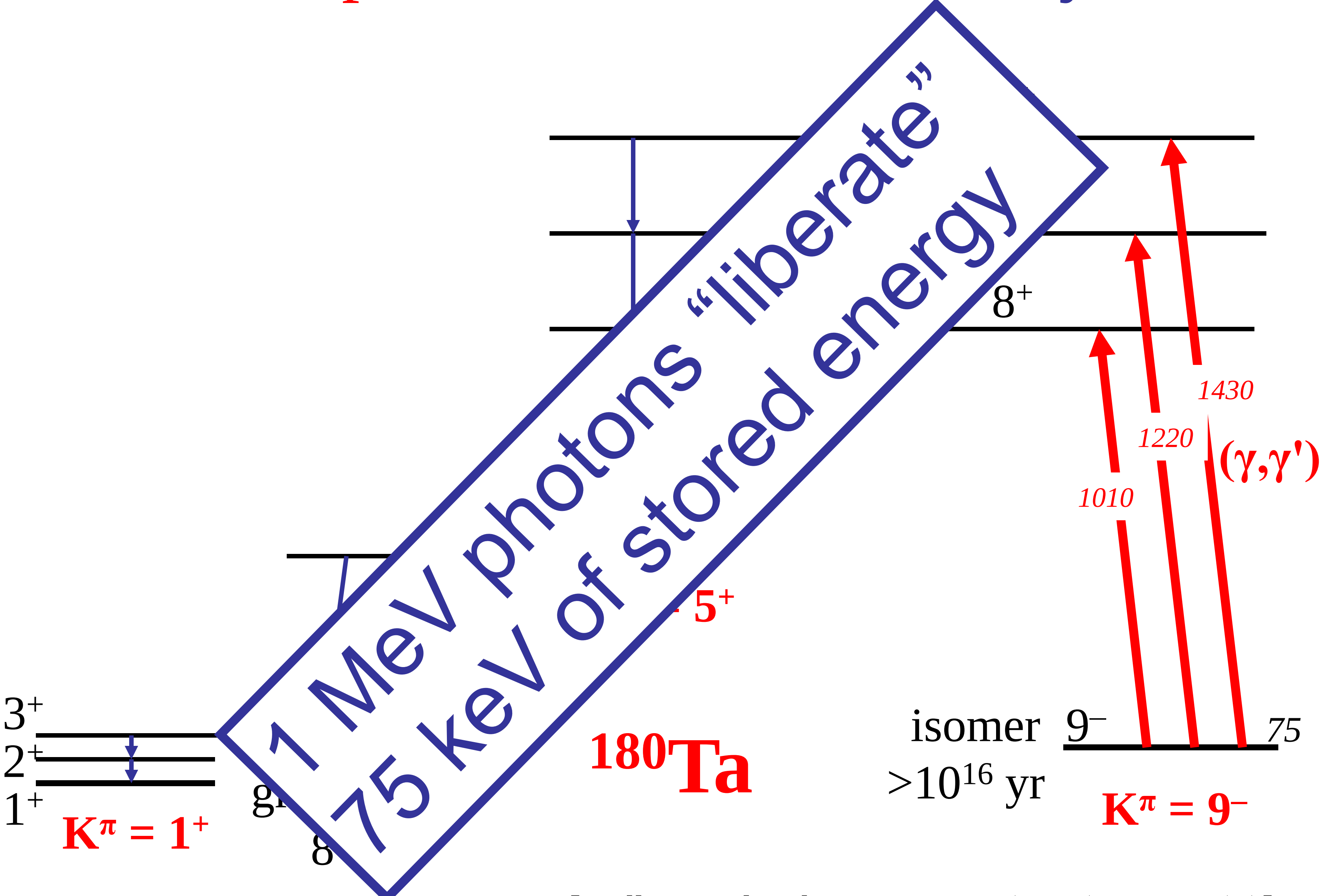
[Belic et al., Phys. Rev. Lett. 83 (1999) 5242]

^{180}Ta photoexcitation and decay



[Walker et al., Phys. Rev. C64 (2001) 061302(R)]

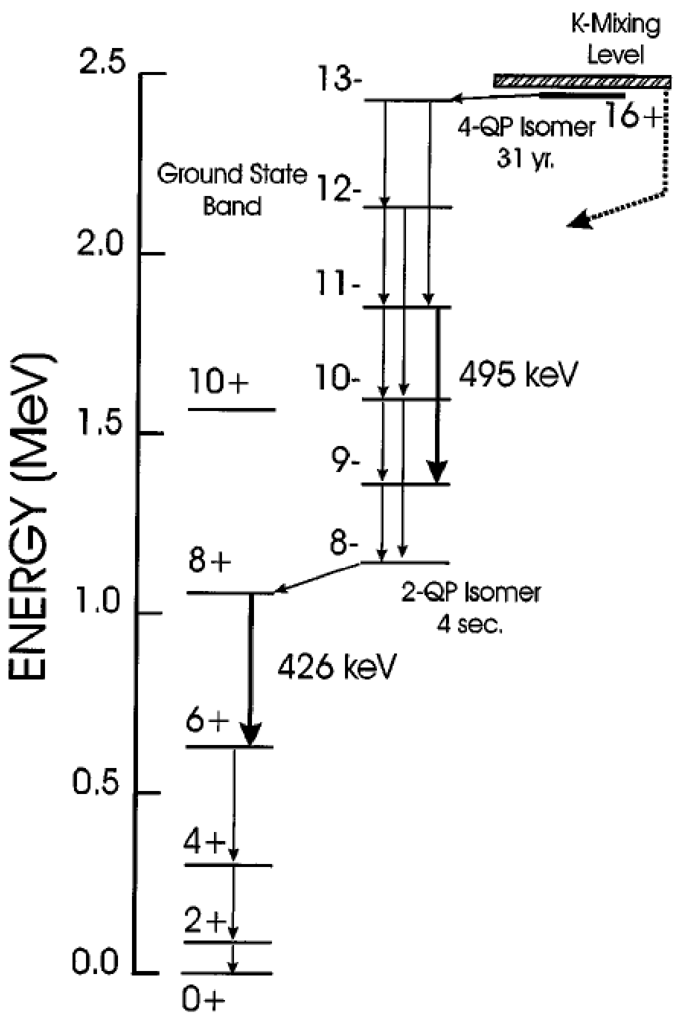
^{180}Ta photoexcitation and decay

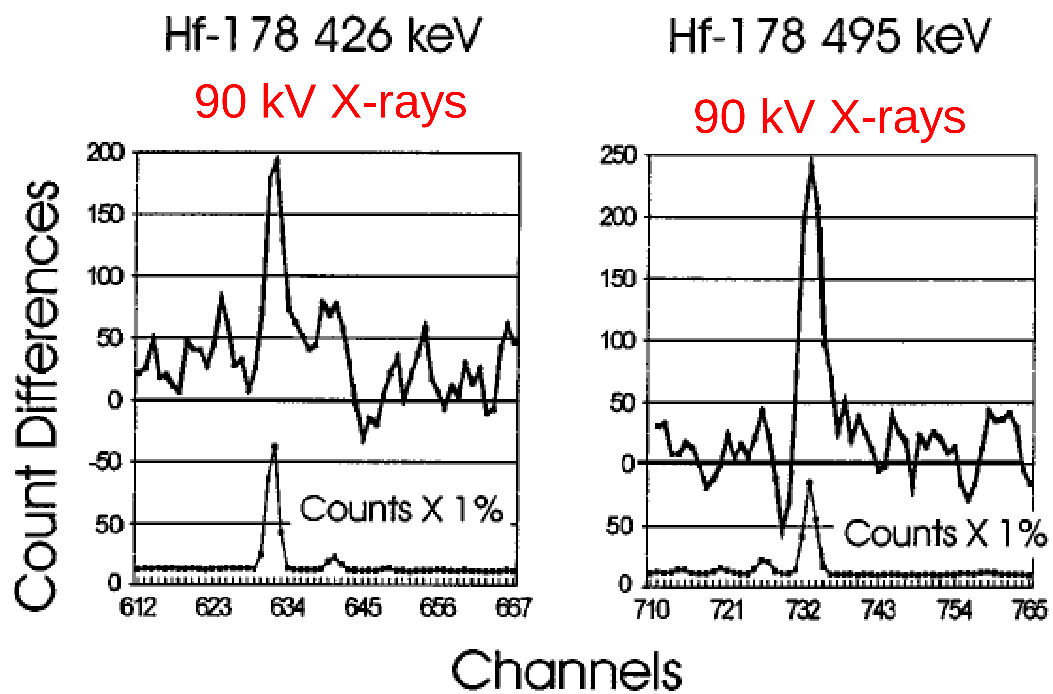


[Walker et al., Phys. Rev. C64 (2001) 061302(R)]

Accelerated Emission of Gamma Rays from the 31-yr Isomer of ^{178}Hf Induced by X-Ray Irradiation

^{178m2}Hf Collins et al. 1999





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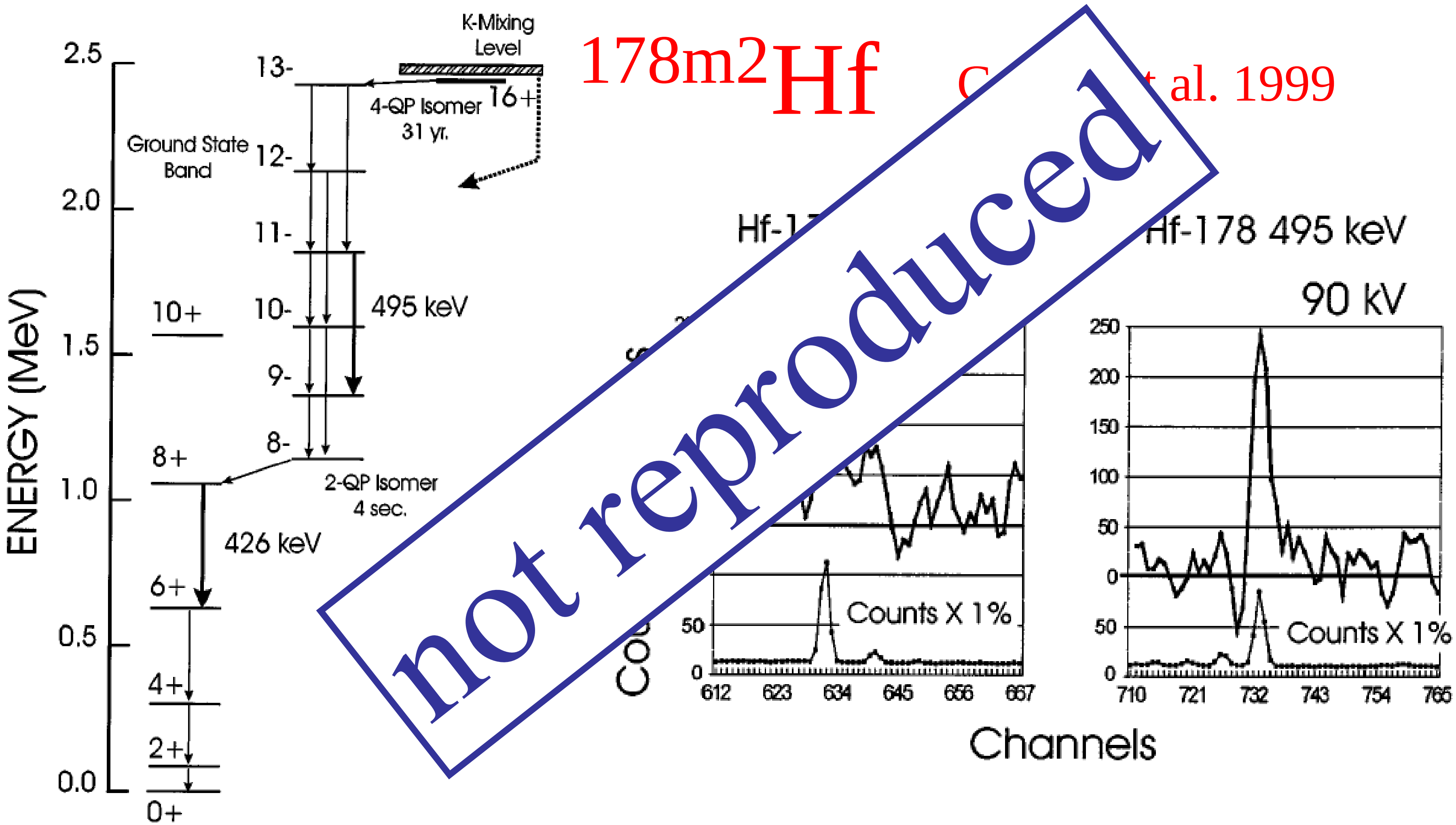

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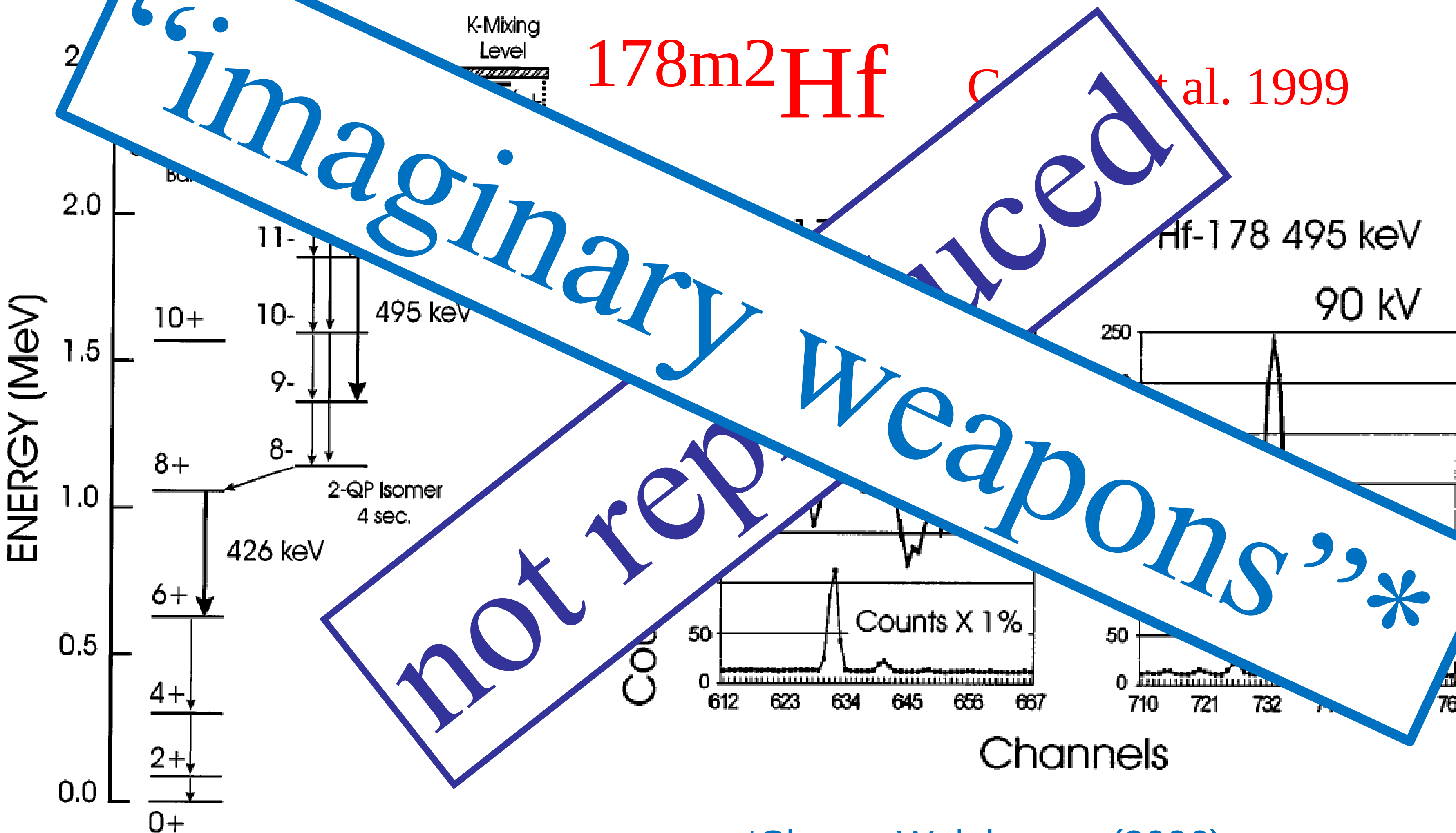


^{178m2}Hf

C... et al. 1999

"imaginary weapons"*

not reproduced

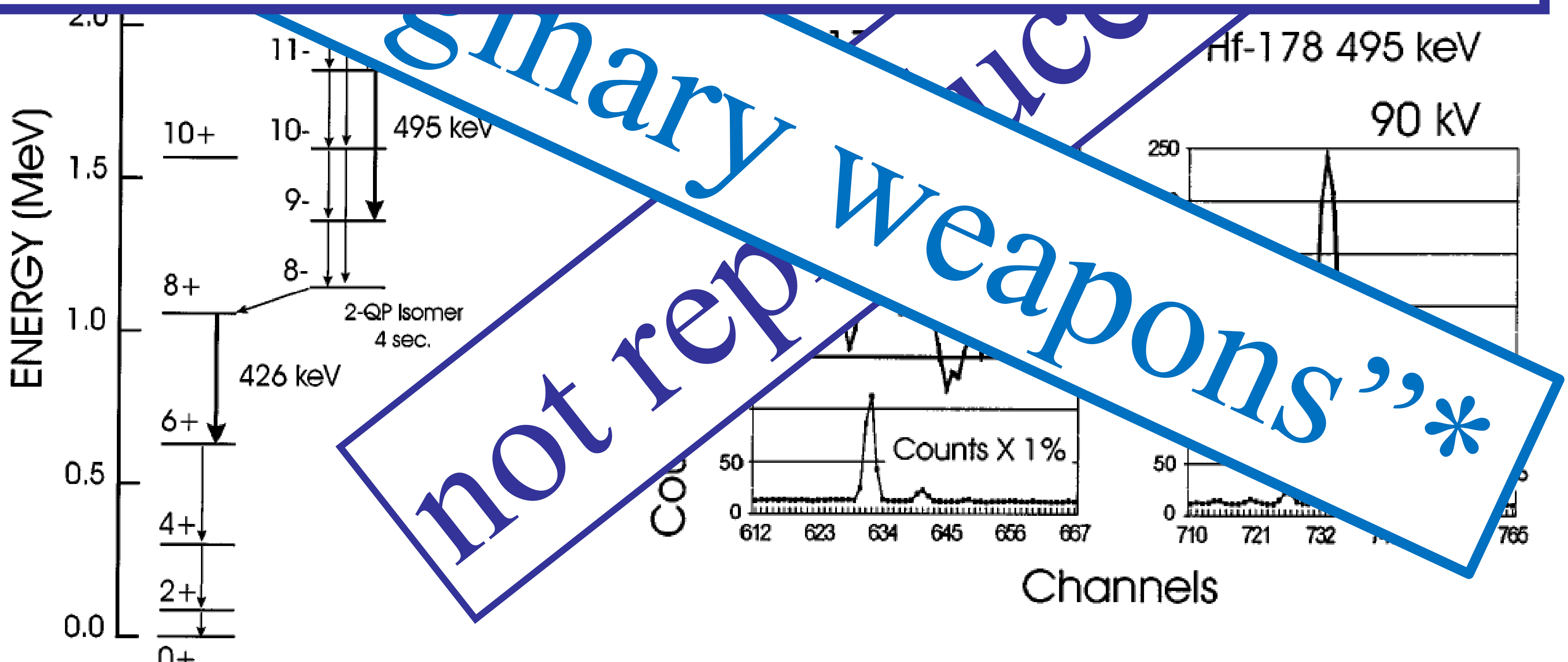
*Sharon Weinberger (2006)

Accelerated Emission of Gamma Rays from the 31-yr Isomer of ^{178}Hf Induced

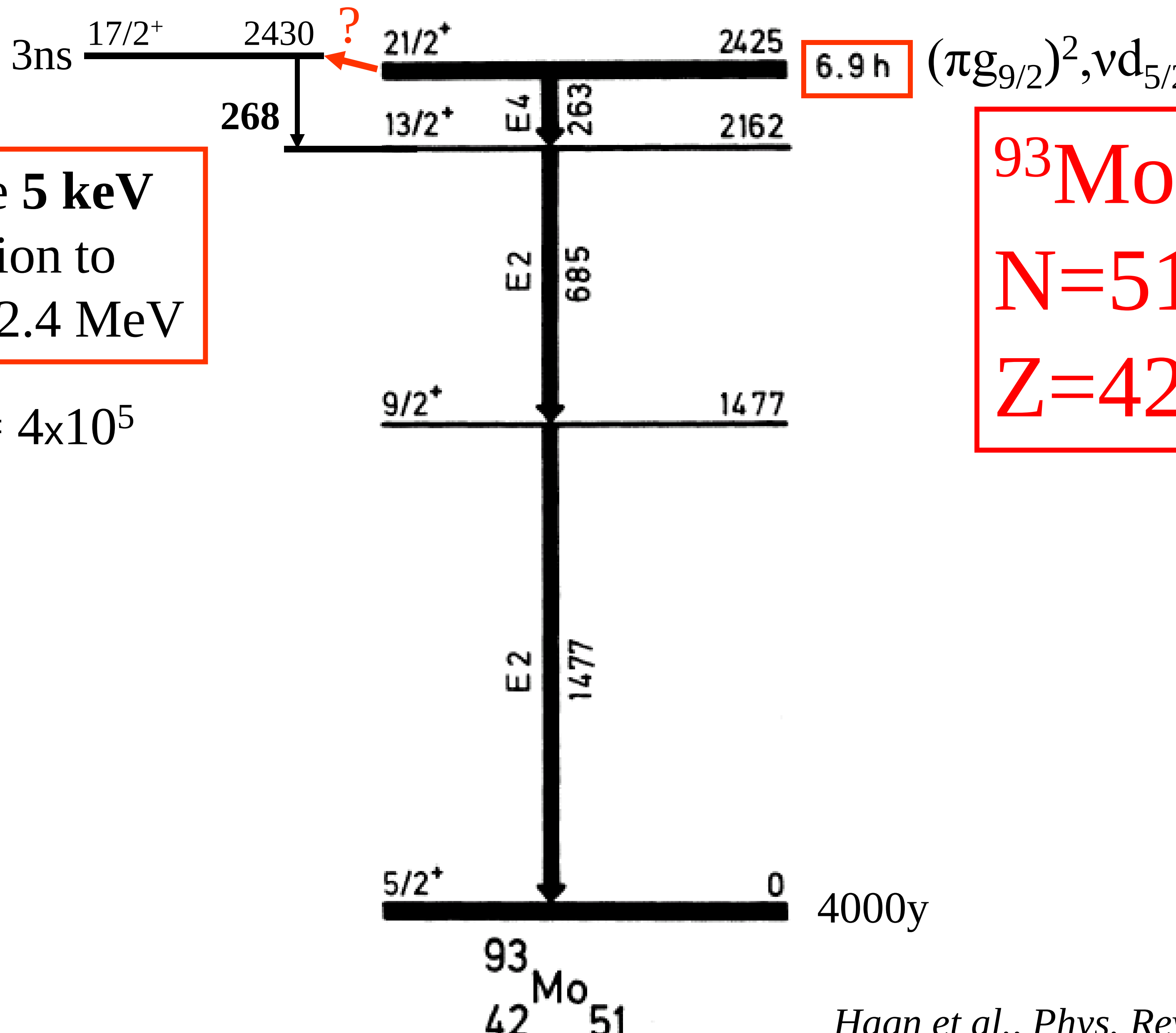
Search for low-energy induced depletion of $^{178}\text{Hf}^{m2}$ at the SPring-8 synchrotron

J.J. Carroll [a,*], S.A. Karamian [b], R. Propri [a], D. Gohlke [a], N. Caldwell [a], P. Ugorowski [a,1], T. Drummond [a], J. Lazich [a], H. Roberts [c], M. Helba [c], Z. Zhong [d], M.-T. Tang [e], J.-J. Lee [e], K. Liang [e]

Physics Letters B679 (2009) 203



*Sharon Weinberger (2006)



possible **5 keV** transition to release 2.4 MeV

$\alpha = 4\text{x}10^5$

^{93}Mo

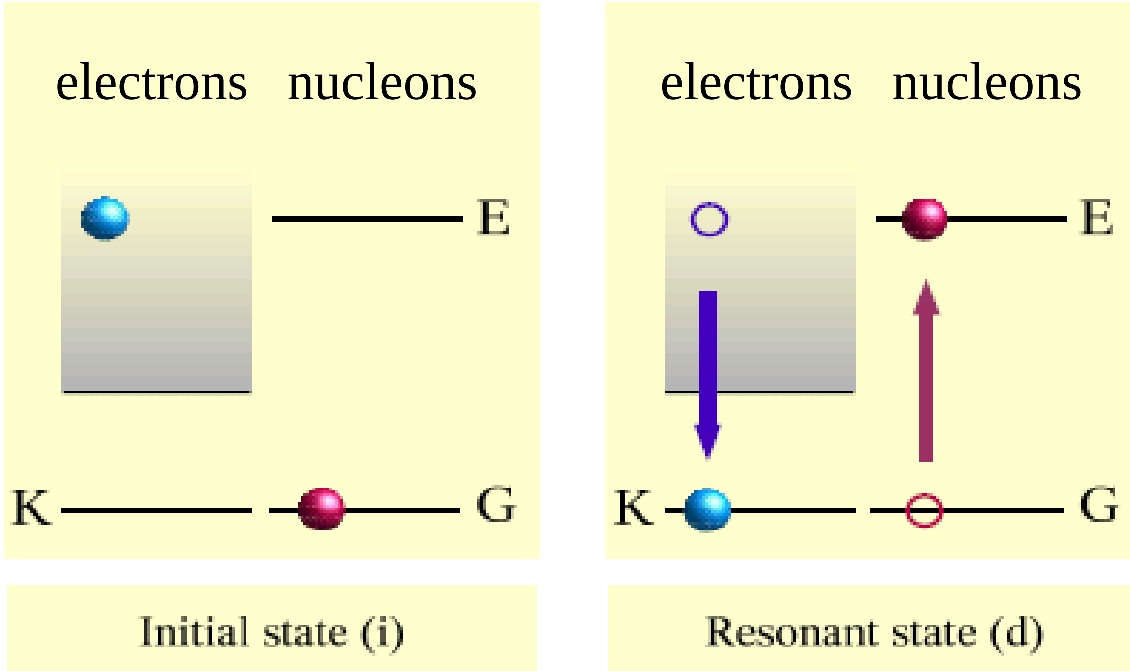
N=51

Z=42

Hagn et al., Phys. Rev. C23 (1981) 2252

Nuclear Excitation by Electron Capture

an as-yet unobserved process



inverse of electron conversion

[A. Palffy et al., Phys. Rev. Lett. 99 (2007) 172502]

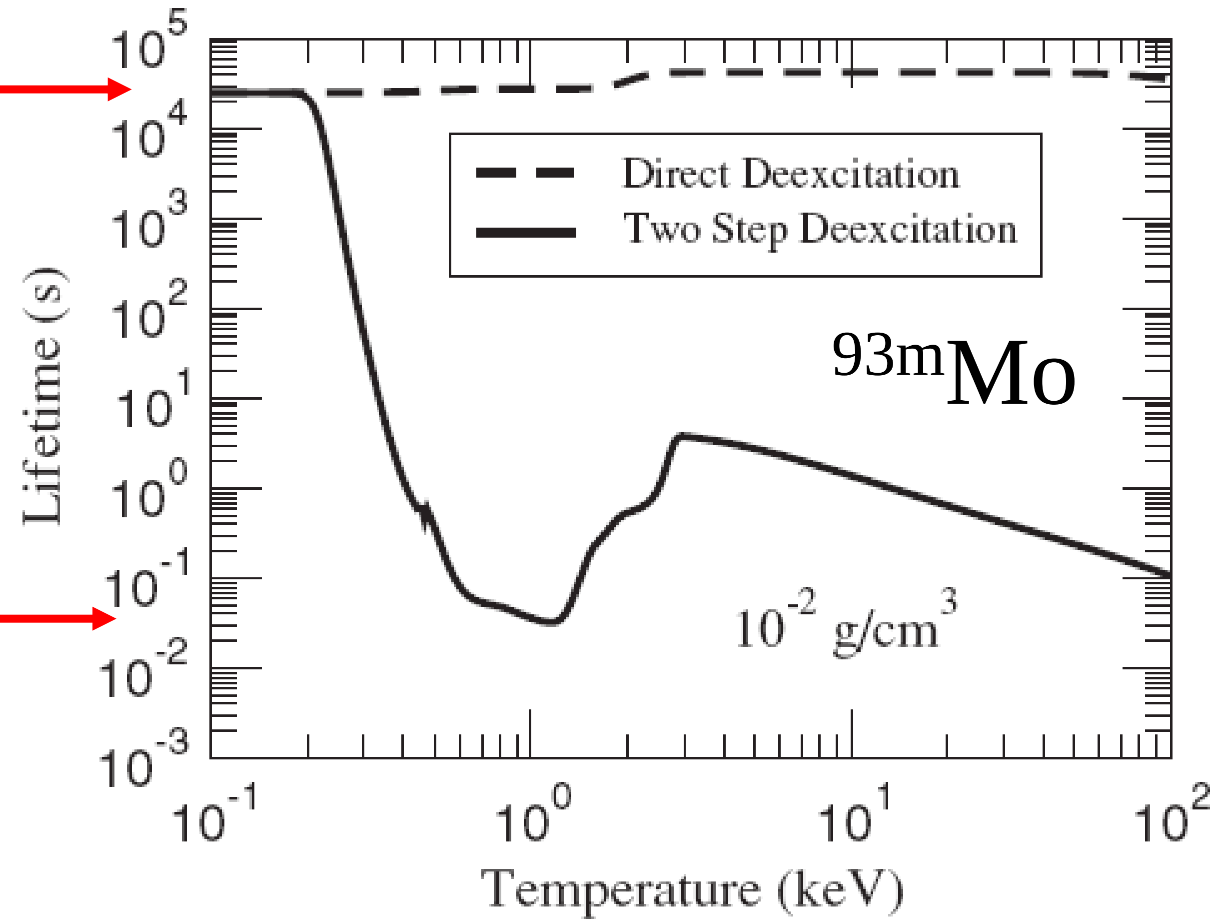
Prediction of accelerated isomer decay in a plasma

based on nuclear excitation by electron capture (NEEC)

[Gosselin et al., Phys. Rev. C70 (2004) 064603; C76 (2007) 044611]

7 h

30 ms



NB: widespread astrophysics implications

isomer techniques (γ-ray decays)

1. Pulsed beam (>5 ns)
2. Recoil shadow (>5 ns)
3. Recoil separator (>500 ns)
4. Mass separator (>500 ms)

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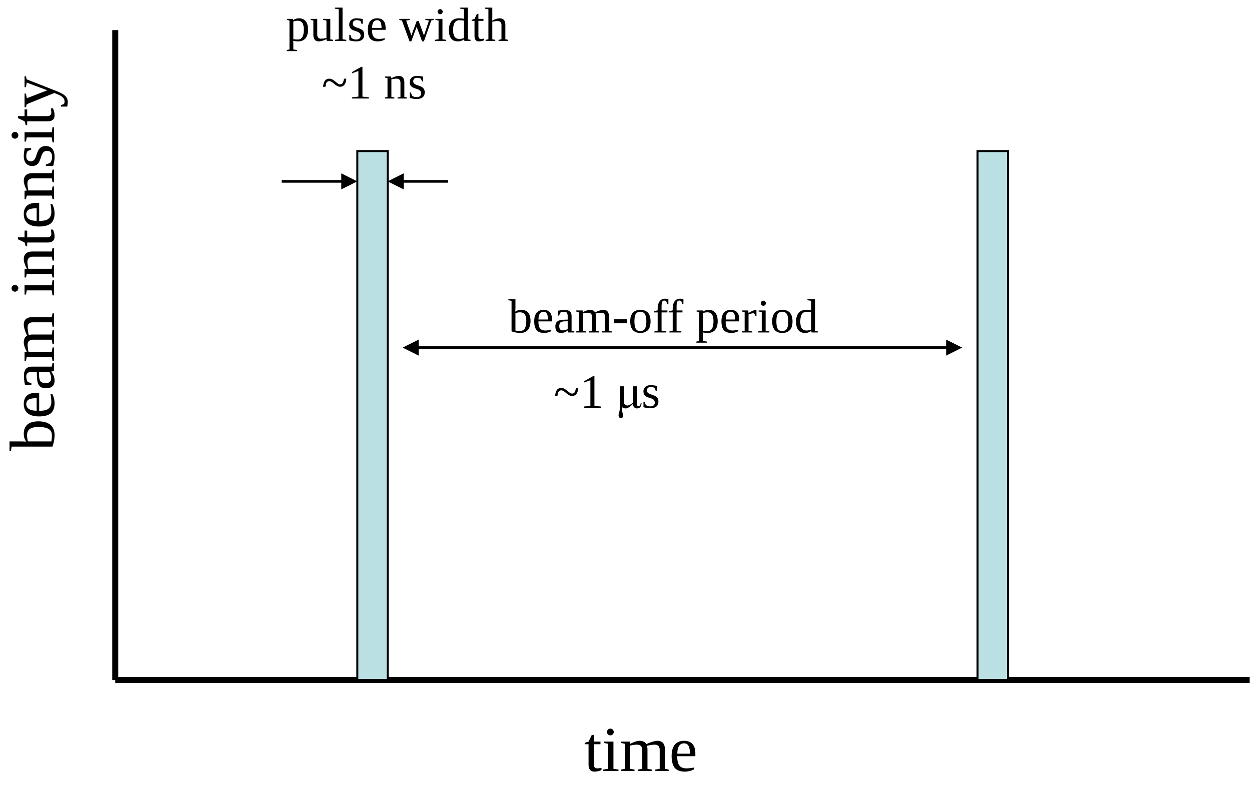
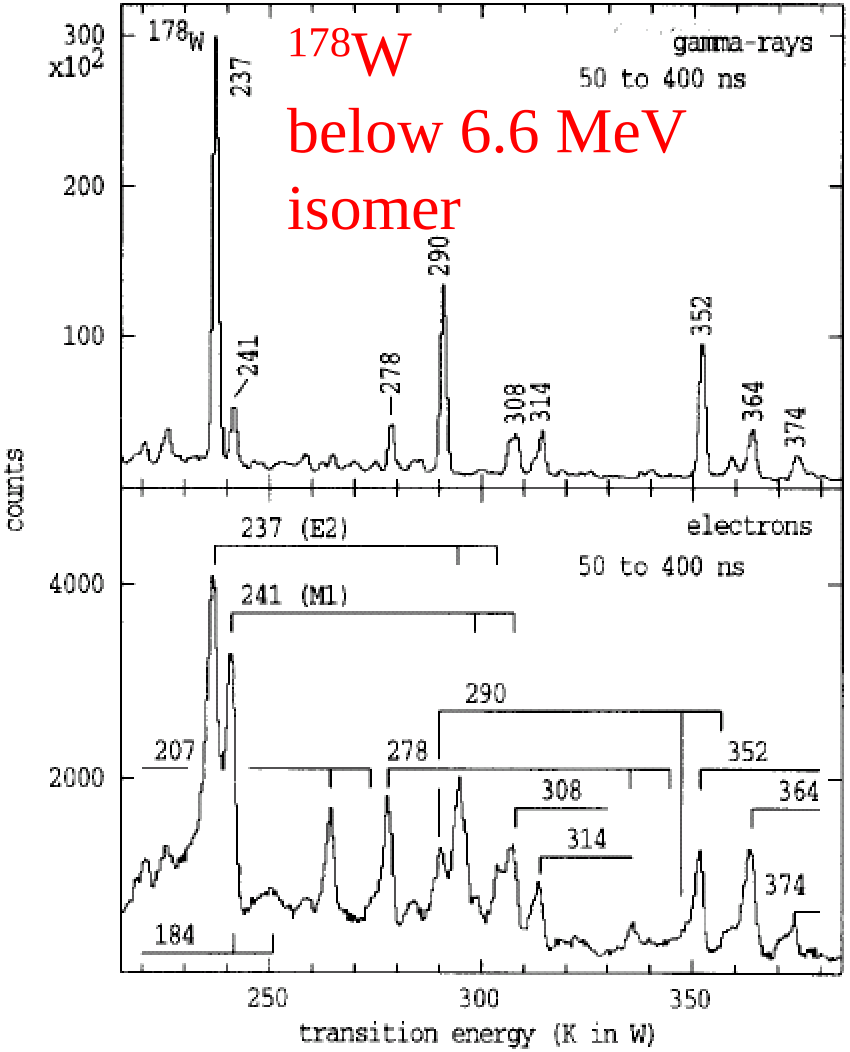


C.S. Purry et al. / Nuclear Physics A 632 (1998) 229–274



1. **Pulsed beam** (>5 ns)
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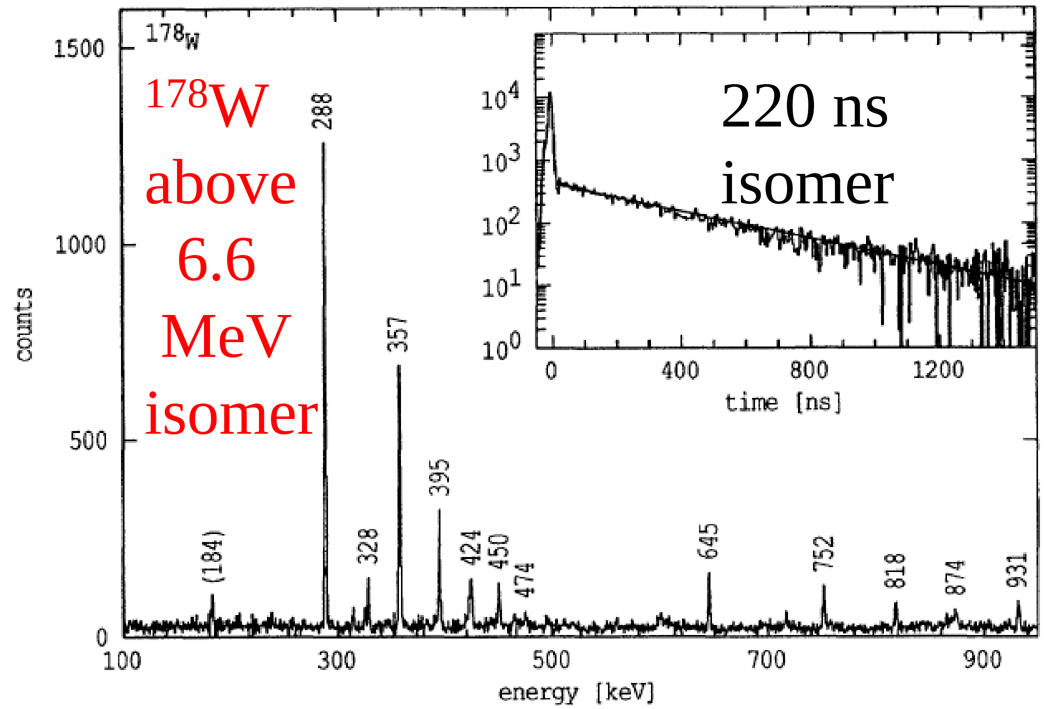


events recorded during beam-off periods

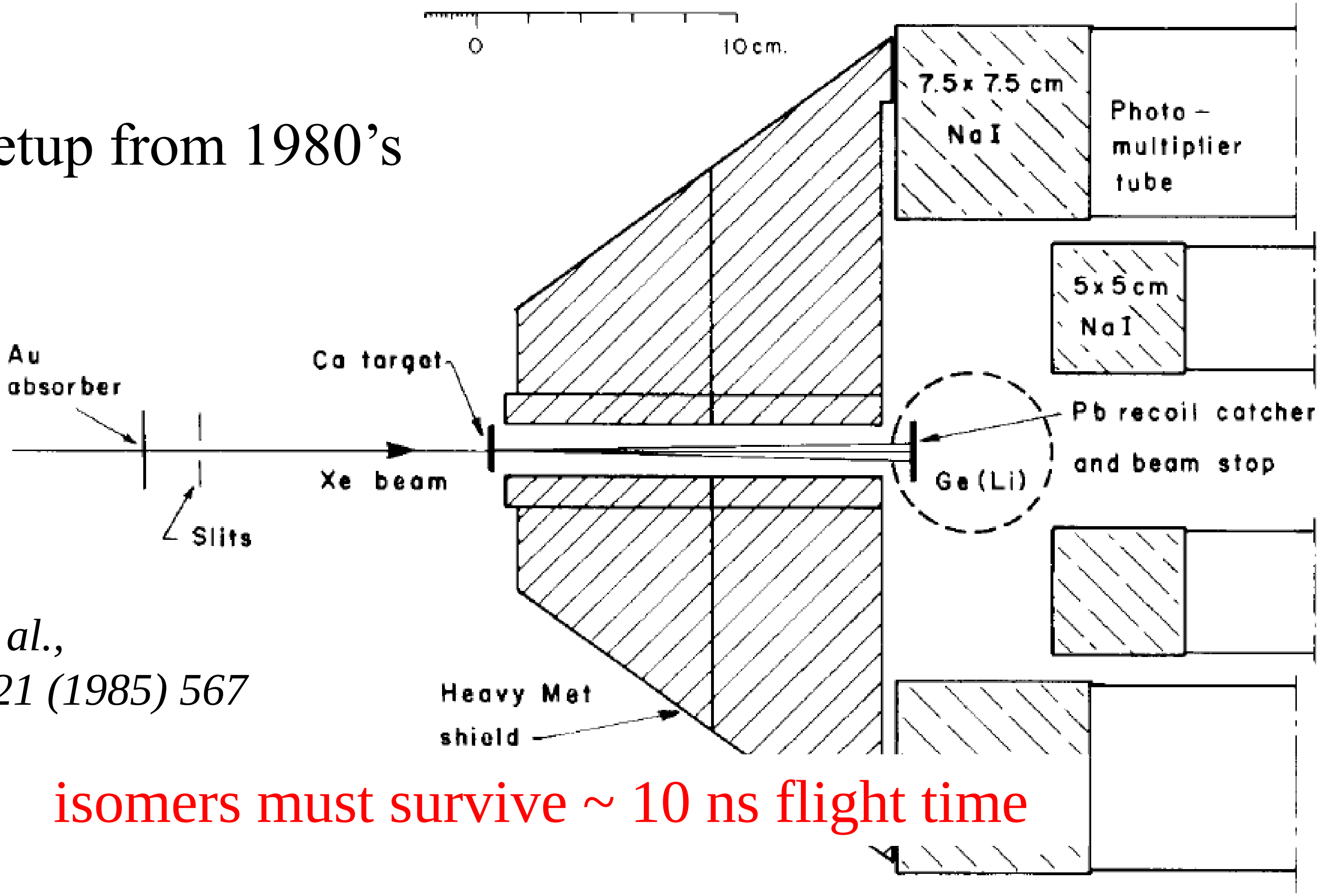
Canberra data

time-correlated events recorded during beam-on periods

isomer techniques
(γ-ray decays)

1. Pulsed beam (>5 ns)
2. **Recoil shadow** (>5 ns)
3. Recoil separator (>500 ns)
4. Mass separator (>500 ms)

GSI setup from 1980's



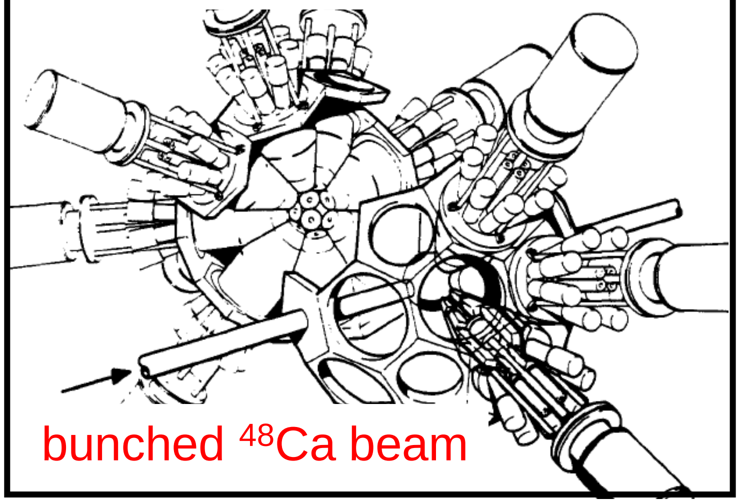
Pedersen et al.,
Z. Phys. A321 (1985) 567

isomers must survive ~ 10 ns flight time

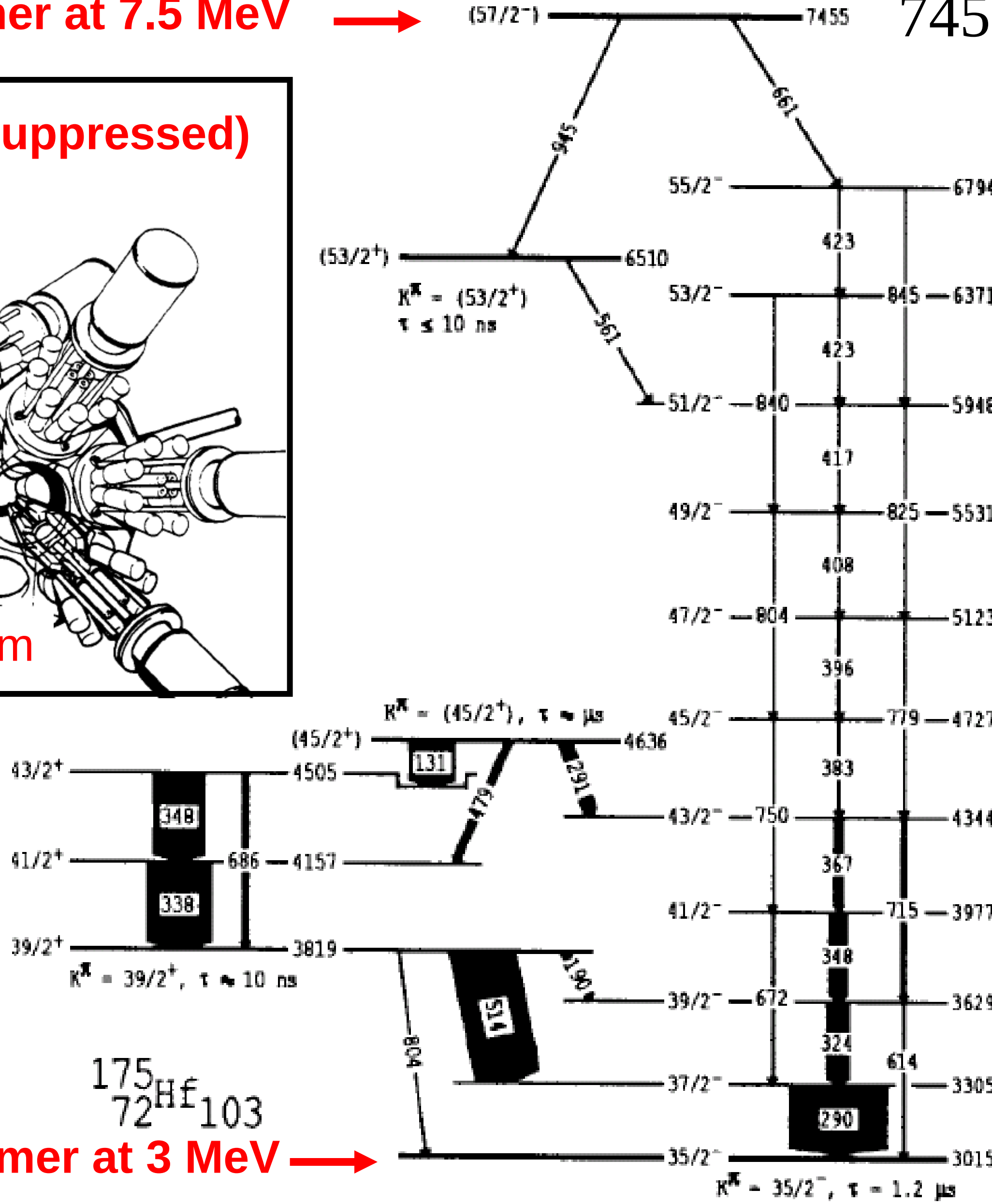
^{175}Hf **isomer at 7.5 MeV** → τ > 10 ns

7455 keV

ESSA 30 **(30 Ge suppressed)**
recoil shadow



bunched ^{48}Ca beam



Daresbury data

3015 keV

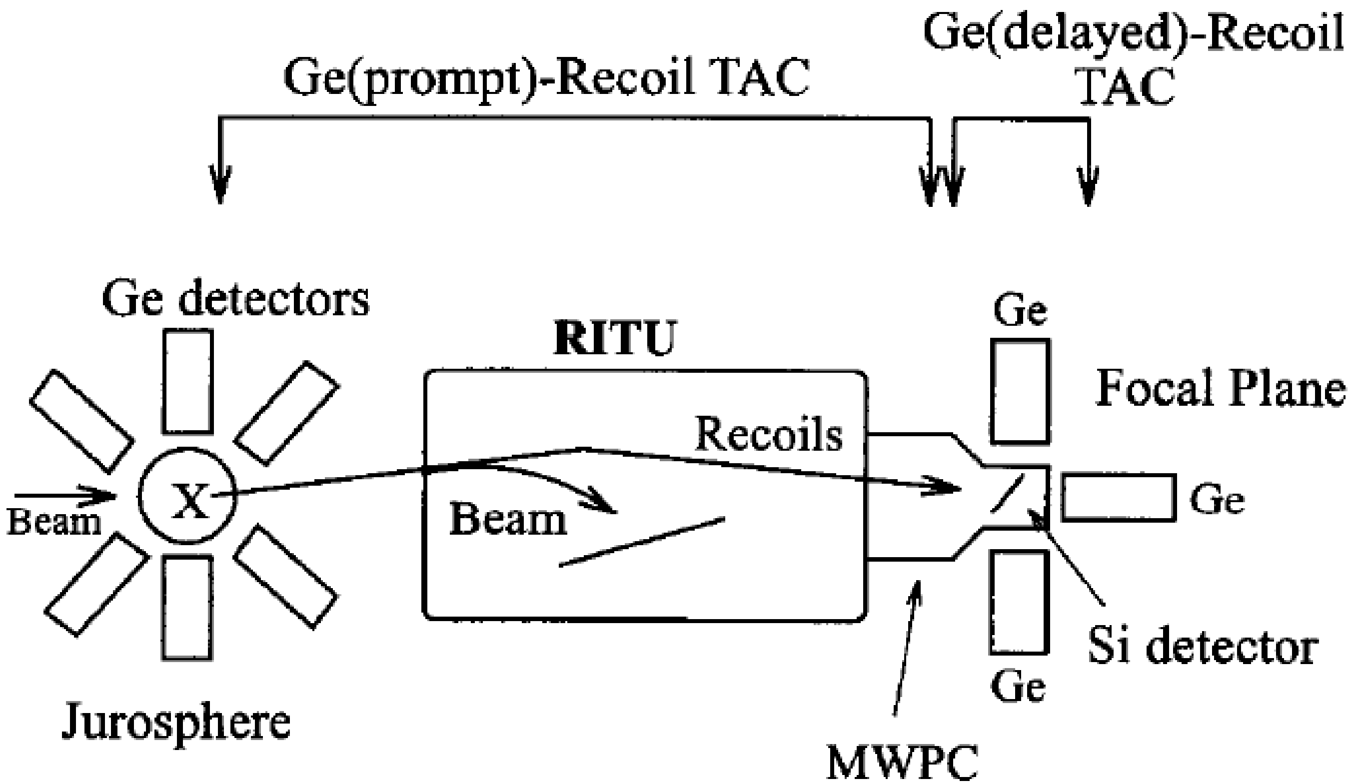
isomer at 3 MeV →

Gjørup et al.
Z. Phys. A337 (1990) 353
^{130}Te(^{48}Ca,3n)

isomer techniques
(γ-ray decays)

Jyväskylä example

1. Pulsed beam (>5 ns)
2. Recoil shadow (>5 ns)
3. **Recoil separator** (>500 ns)
4. Mass separator (>500 ms)



isomers must survive ~ 500 ns flight time

isomer techniques
(γ-ray decays)

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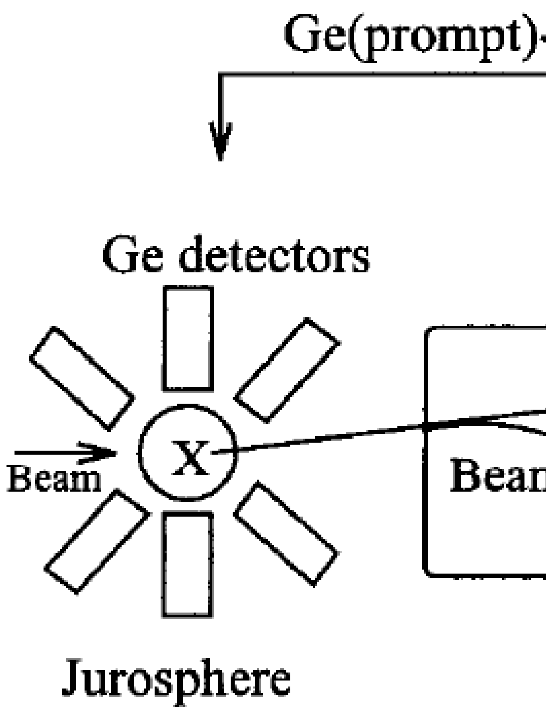
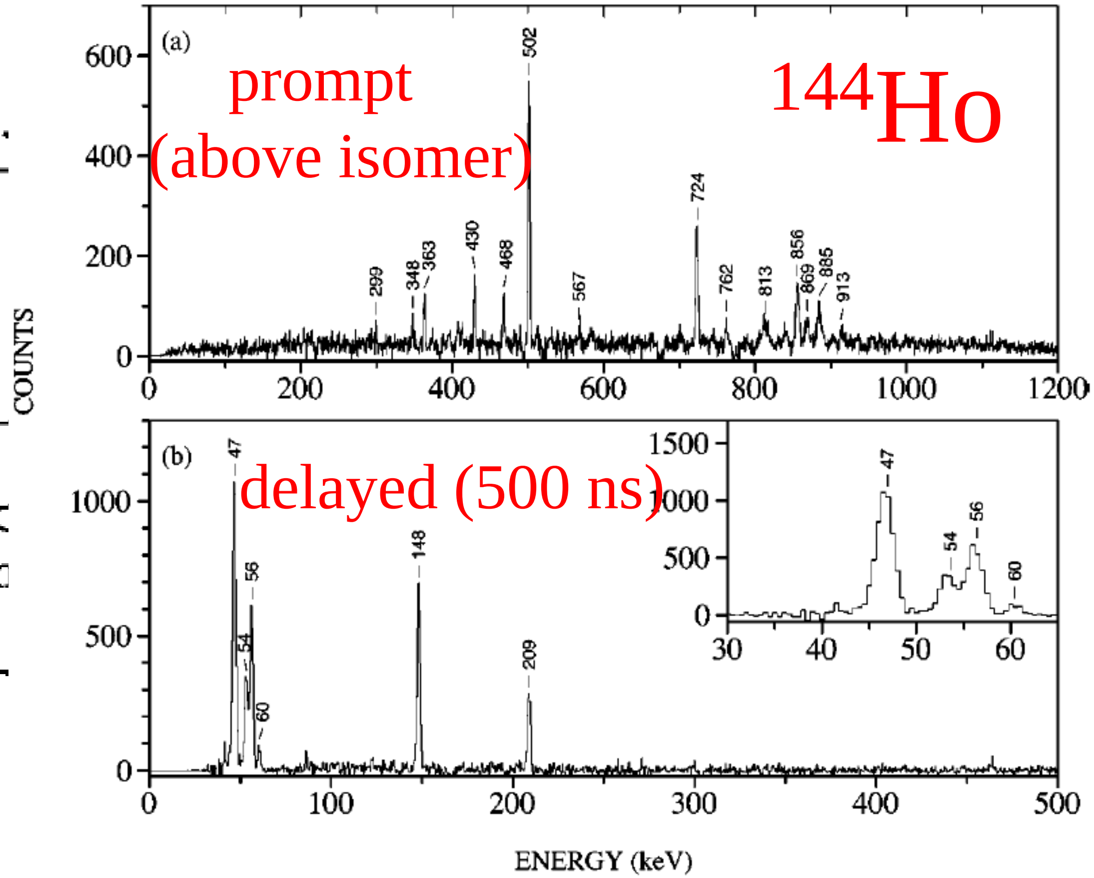
Jyväskylä example





Cullen et al. Nucl. Phys. A692 (2001) 264; Scholes et al. Phys. Rev. C63 (2001) 034321

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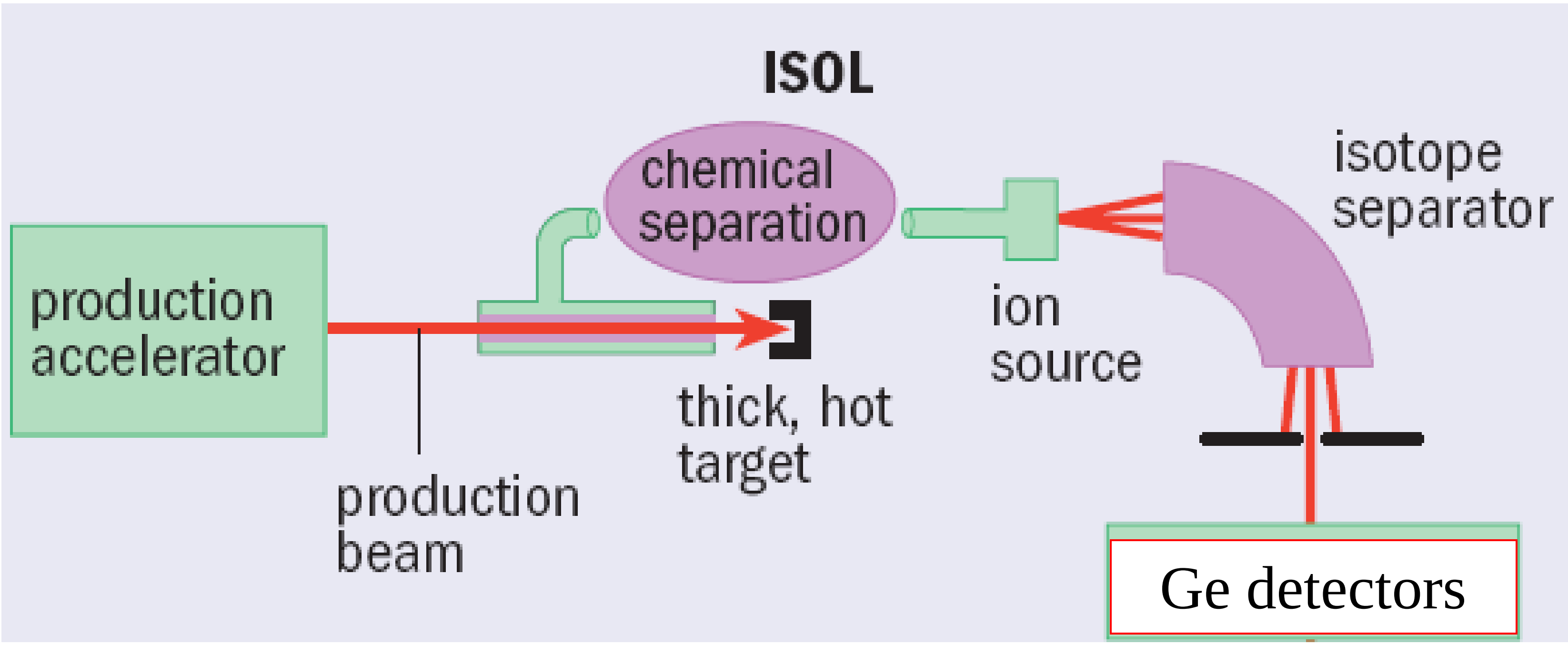
4. **Mass separator** (>500 ms)



isomers must survive ~ 500 ms (ionisation and transport)

isomer techniques (γ-ray decays)

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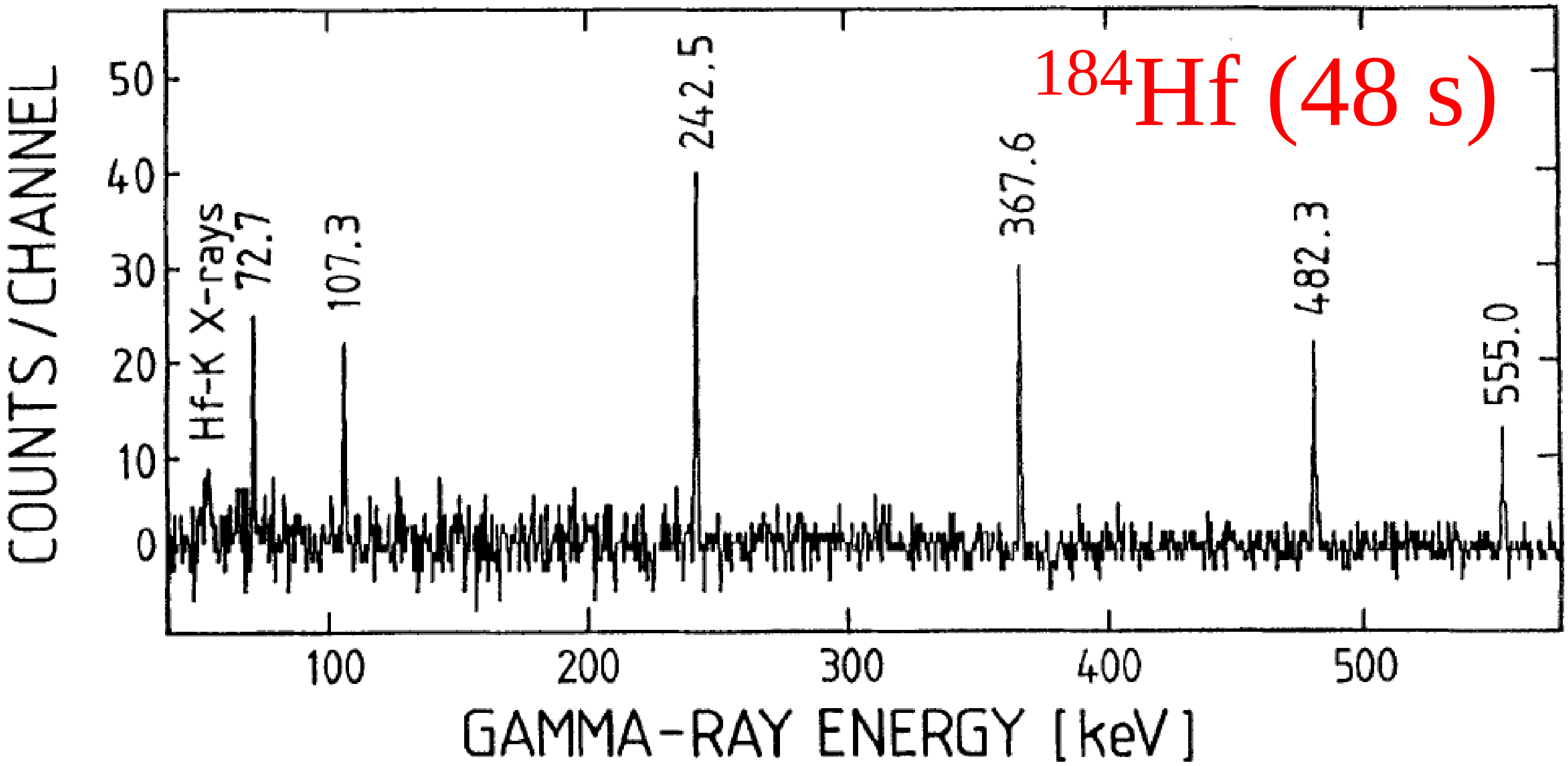
3. Recoil separator (>500 ns)
4. **Mass separator** (>500 ms)

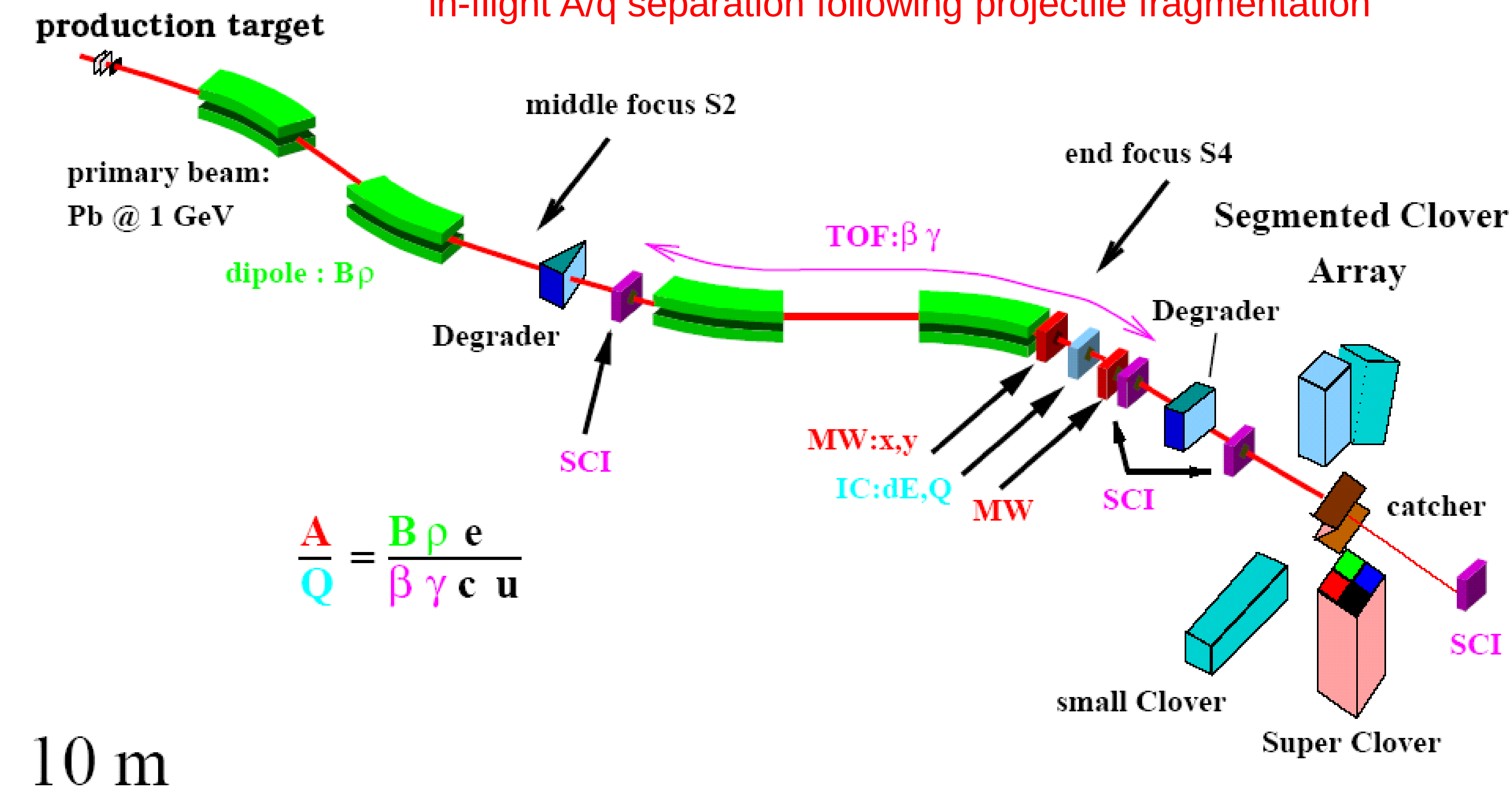
GSI example: ^{136}Xe on ^{186}W



Krumbholz et al. Z. Phys. A351 (1995) 11

Fragment Separator (FRS) at GSI

in-flight A/q separation following projectile fragmentation

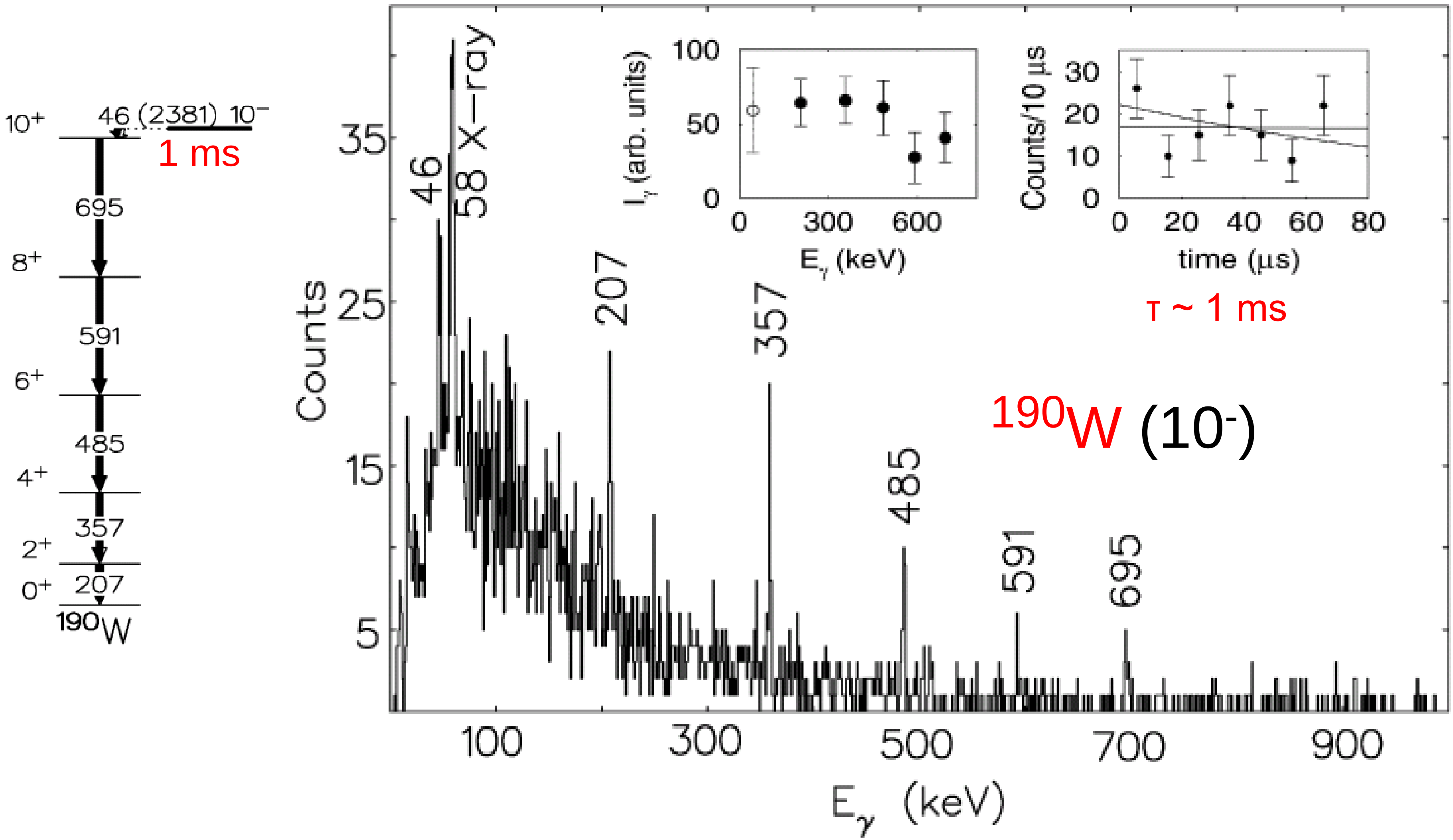


$$\frac{A}{Q} = \frac{B\rho\, e}{\beta\gamma\, c\, u}$$

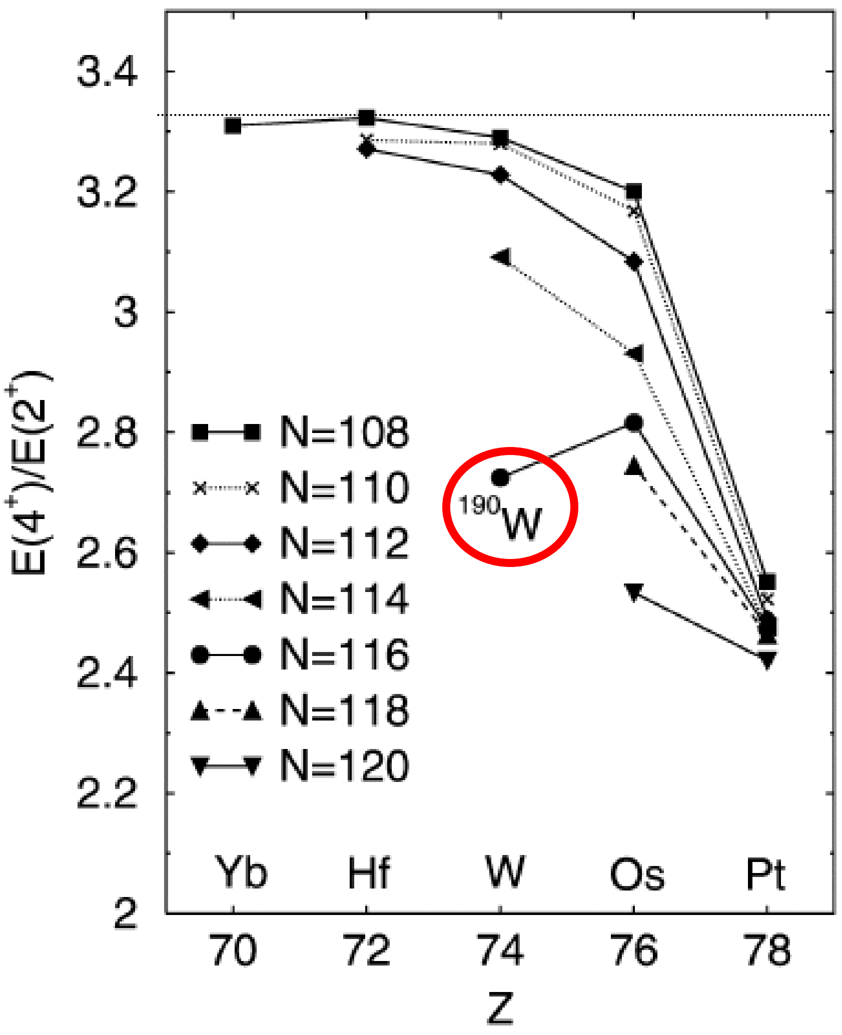
isomers must survive ~ 300 ns flight time through FRS

Zs. Podolyák et al. / Physics Letters B 491 (2000) 225–231

delayed gamma rays from ^{208}Pb fragmentation at 1 GeV per nucleon



^{190}W $E(4^+)/E(2^+)$ energy ratio

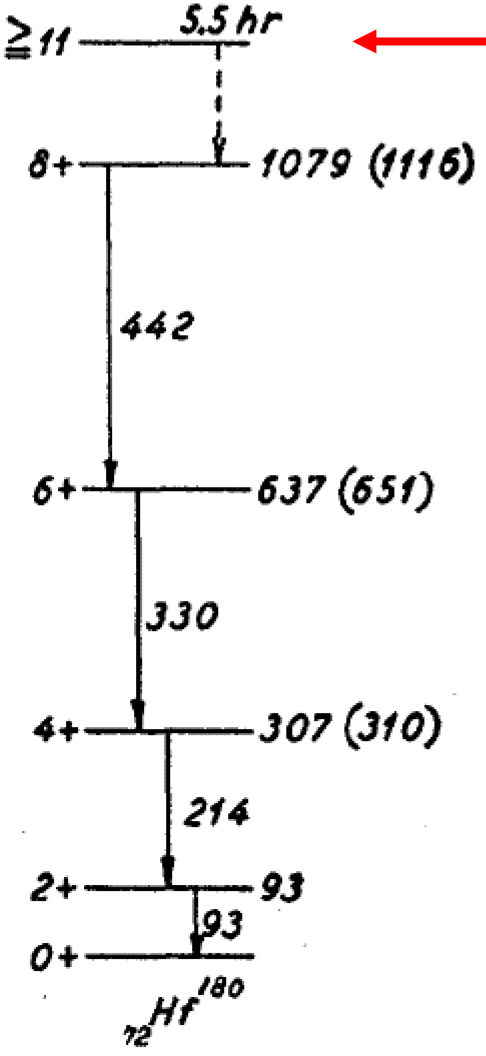


perfect rotor

prolate-oblate mixing in ^{190}W?
Stevenson et al., Phys. Rev. C72 (2005) 047303

[Podolyak et al., Phys. Lett. B491 (2000) 225]

^{180}Hf isomer decay: nuclear collective rotation



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

$E(I) = (\hbar^2/2\mathcal{J})\ I(I+1)$

$\mathcal{J} \sim 1/3\ \mathcal{J}_{rigid}$ => superfluidity

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

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

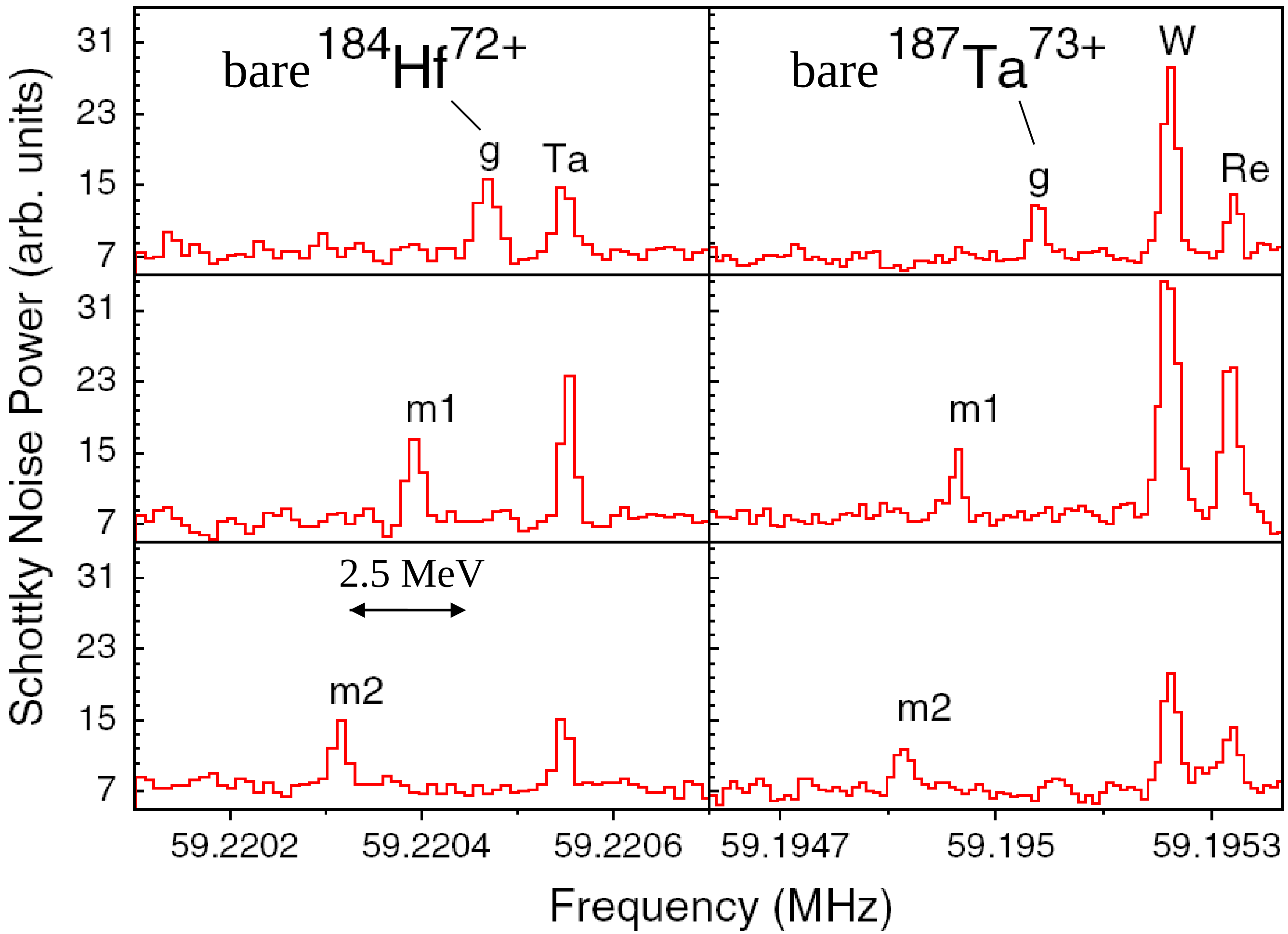
interplay between individual-particle and collective degrees of freedom

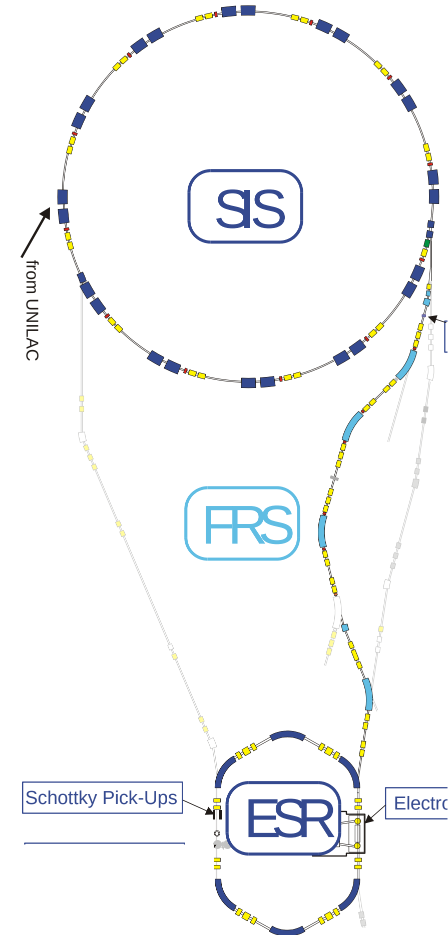
Bohr and Mottelson, Phys. Rev. 90 (1953) 717

isomers without decay in the ESR at GSI

10-second snapshots following ^{197}Au fragmentation

A = 184, q = 72+ A = 187, q = 73+





Experimental Storage Ring
(circumference = 108 m)

Reed et al., Phys. Rev. Lett. 105 (2010) 172501

summary

Isomers exist over a wide range of the nuclear chart, but the definition of an isomer in terms of its half-life is based more on technique than physics.

The open channel of electromagnetic decay from isomers suggests that isomer half-lives may be manipulated using electromagnetic probes.

Isomer half-lives enable their separation from the reaction (in space and/or time) permitting sensitive measurements to be made.

Isomer decays can give access to other interesting excited states.

Isomers are often simple states, but their “forbidden” decays are not so simple → **next lecture.**

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Are there any specific isomers that you would like to discuss tomorrow?