Structure of heavy neutron-deficient nuclei near the proton drip line

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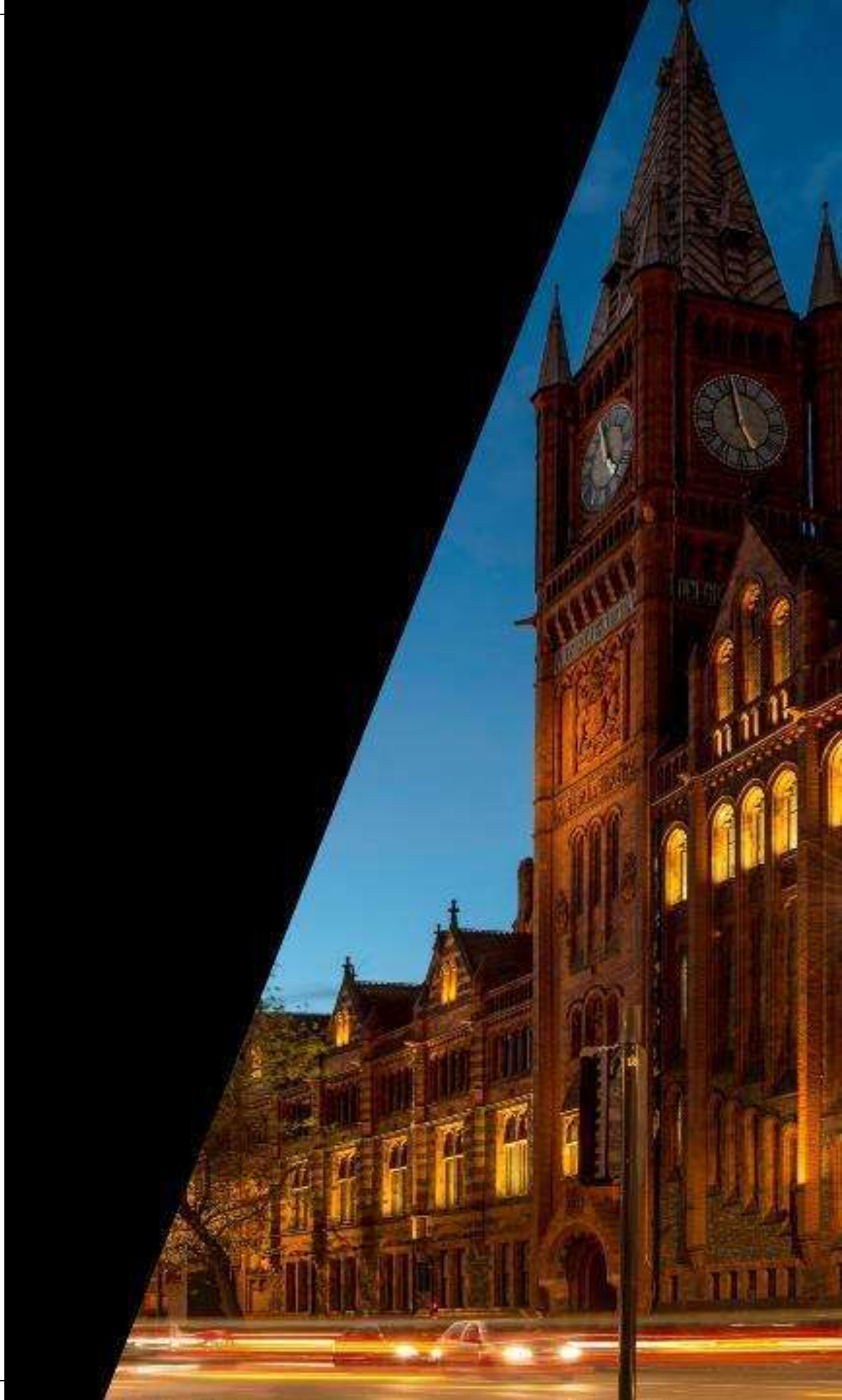
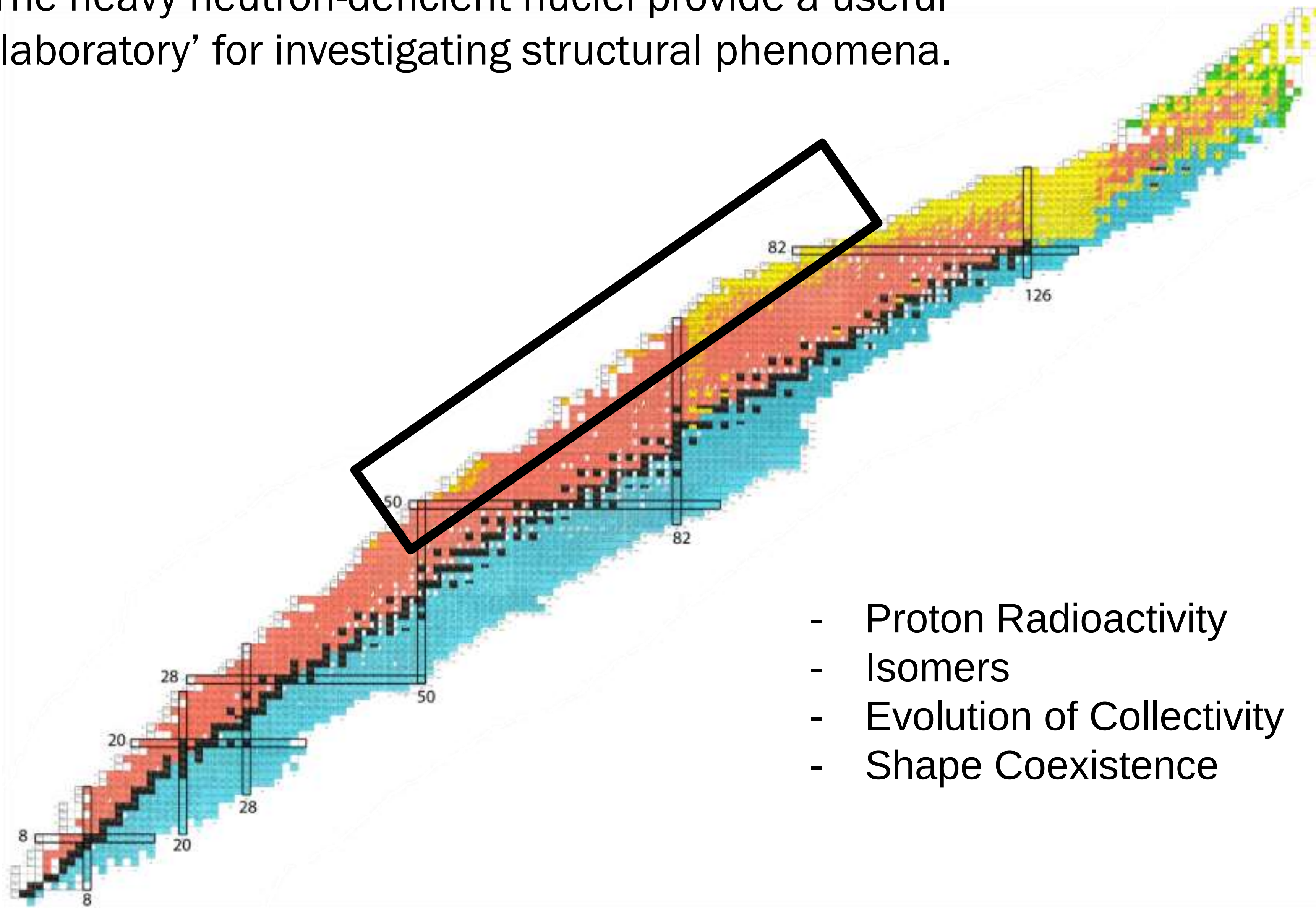
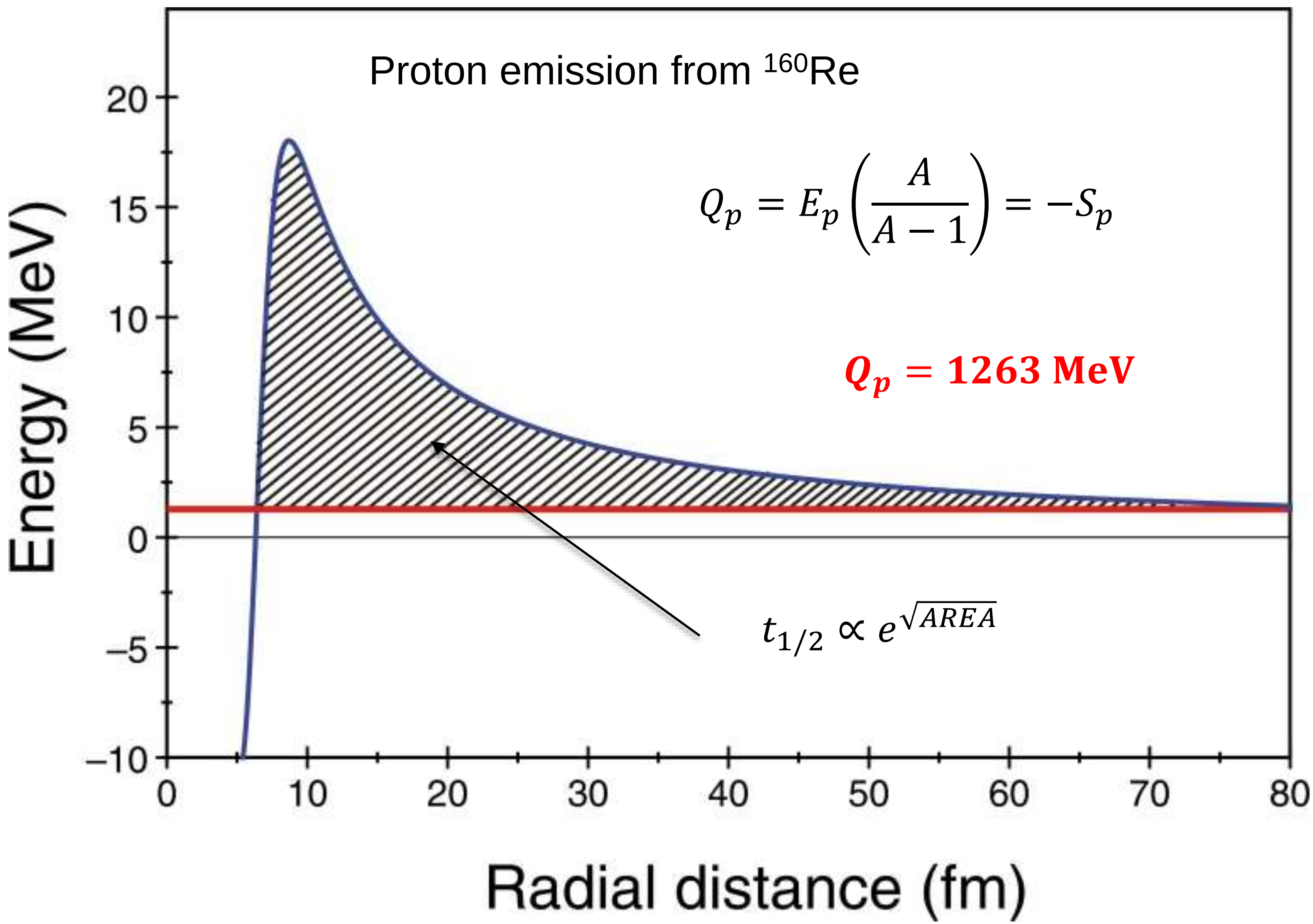


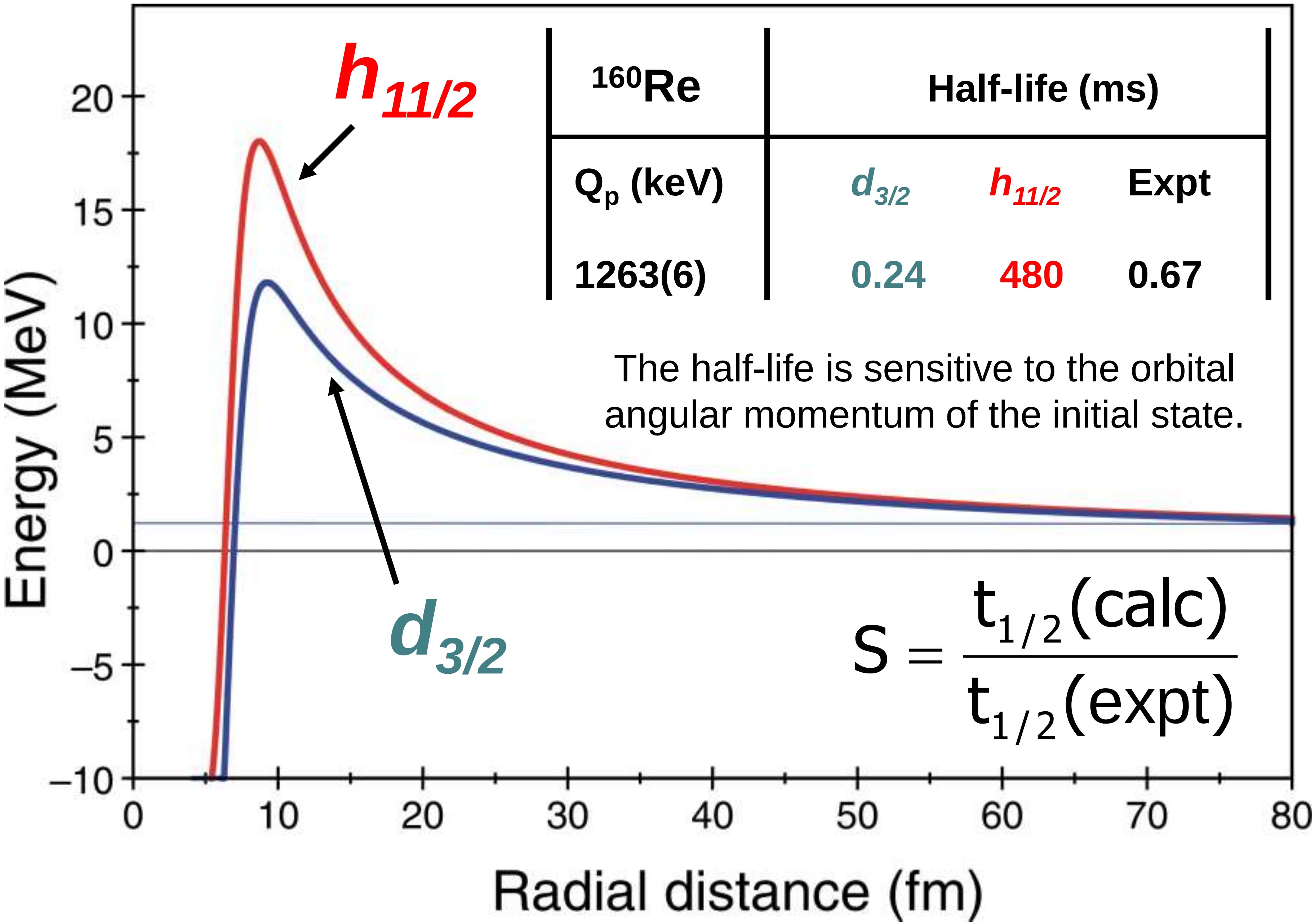
The heavy neutron-deficient nuclei provide a useful ‘laboratory’ for investigating structural phenomena.



- Proton Radioactivity
- Isomers
- Evolution of Collectivity
- Shape Coexistence

Proton Radioactivity





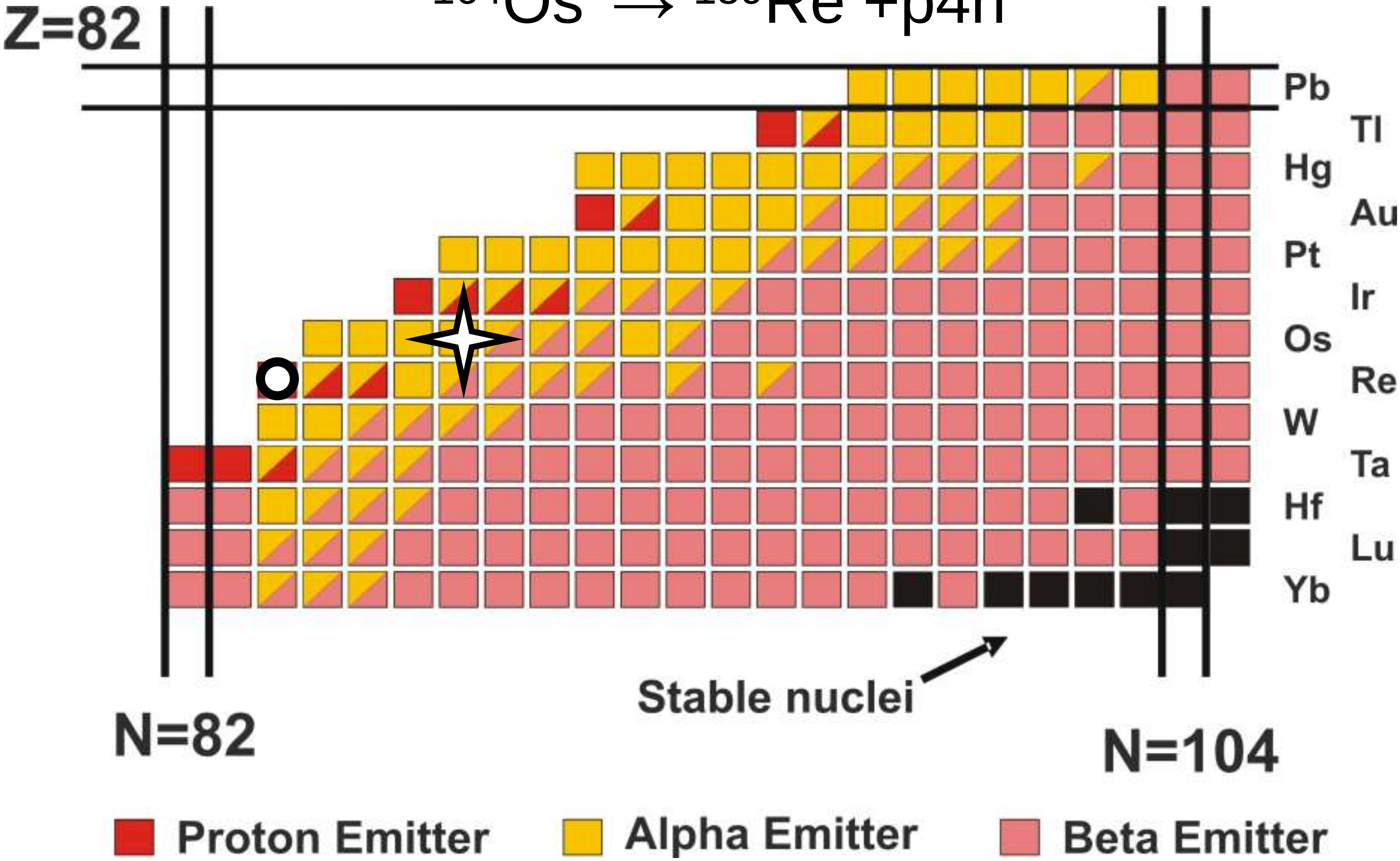
^{160}Re	Half-life (ms)		
Q_p (keV)	$d_{3/2}$	$h_{11/2}$	Expt
1263(6)	0.24	480	0.67

The half-life is sensitive to the orbital angular momentum of the initial state.

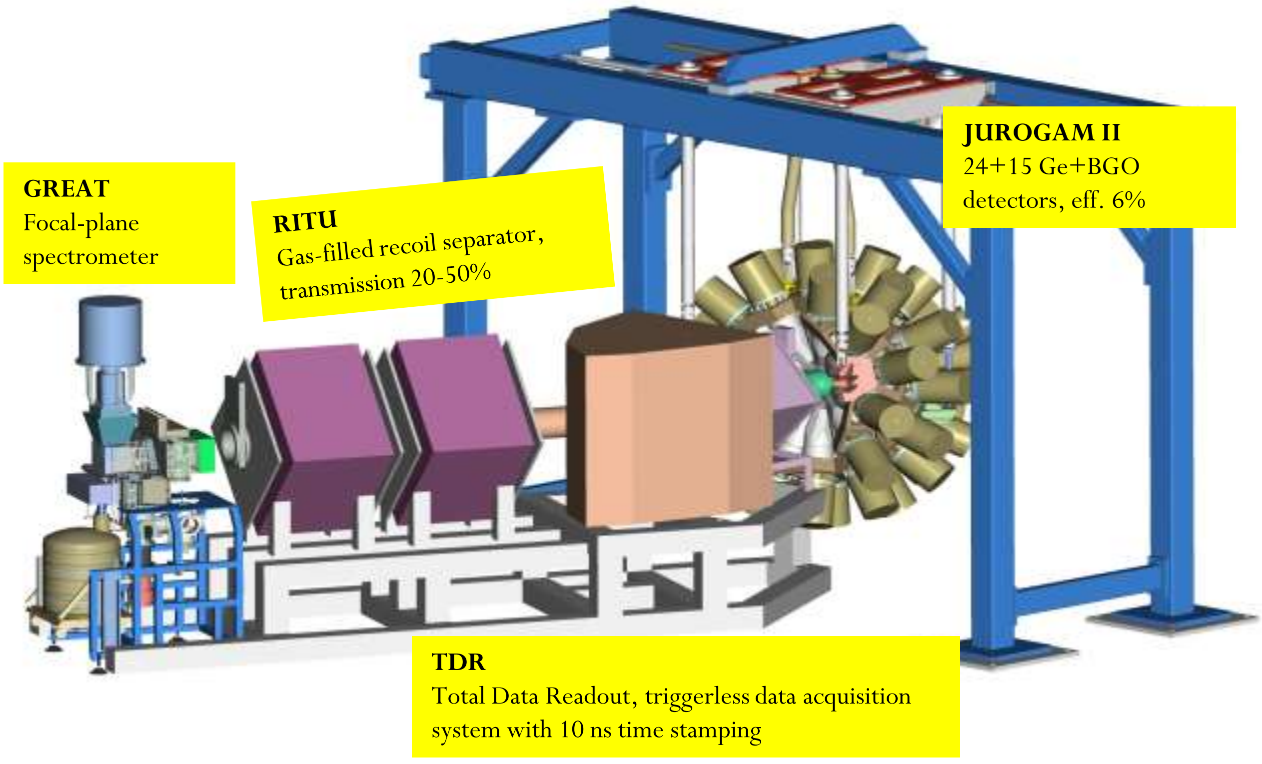
$$S = \frac{t_{1/2}(\text{calc})}{t_{1/2}(\text{expt})}$$

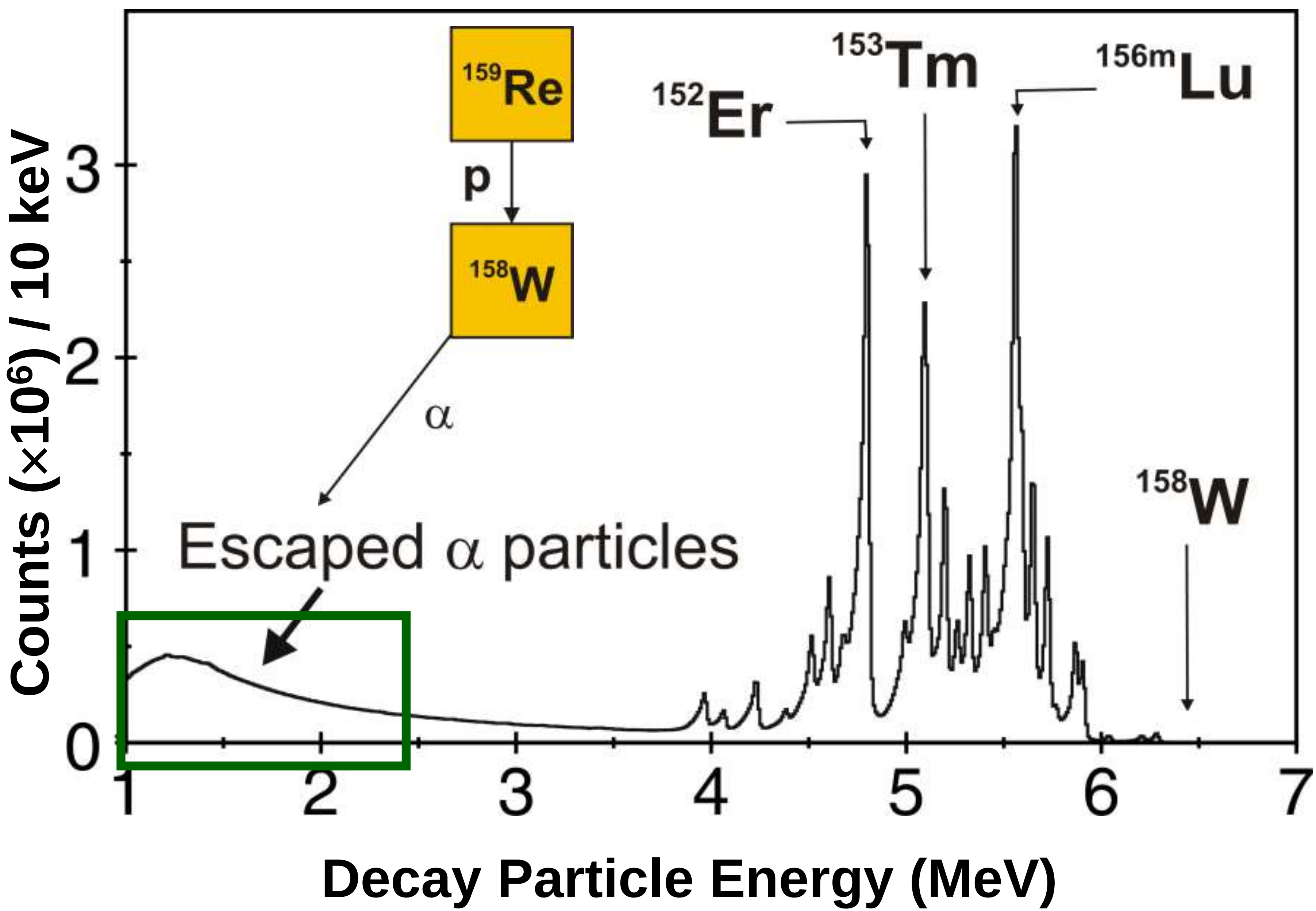
$^{58}Ni + ^{106}Cd \rightarrow ^{164}Os^*$

$^{164}Os^* \rightarrow ^{159}Re + p4n$



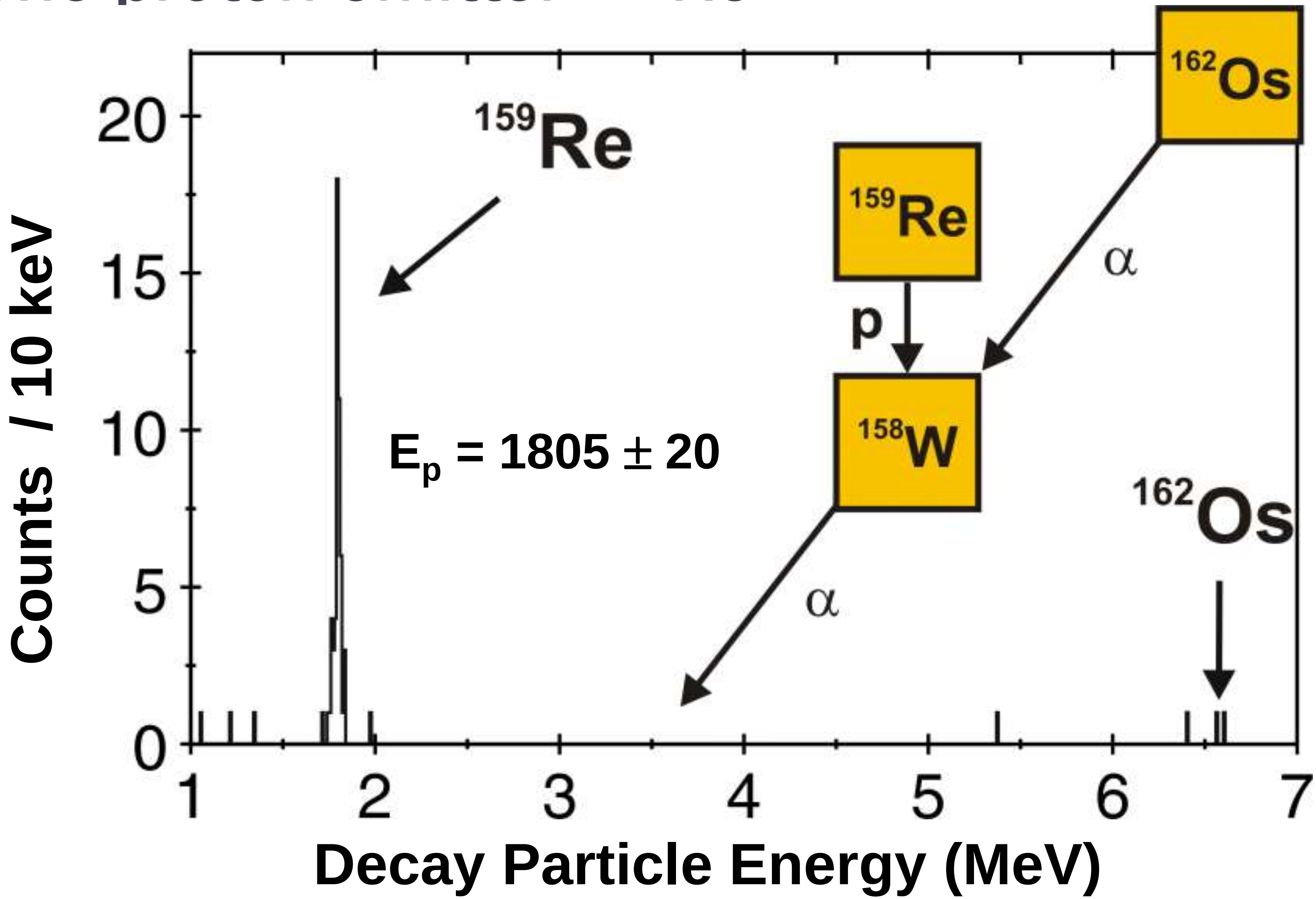
Tagging instrumentation at JYFL





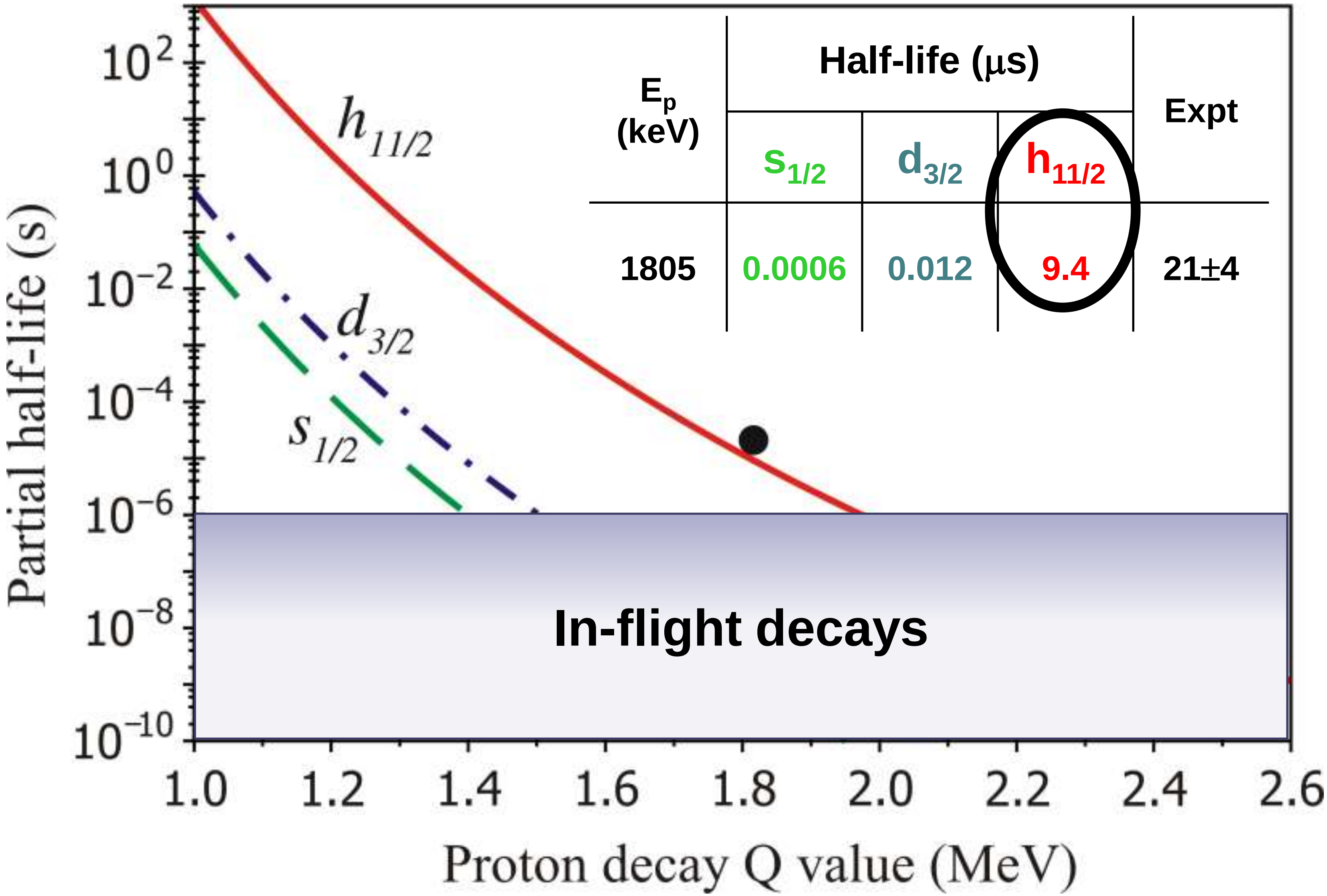
159Re
p
158W
α
152Er
153Tm
156mLu
158W
Escaped α particles
Counts (×10^6) / 10 keV
0
1
2
3
1
2
3
4
5
6
7
Decay Particle Energy (MeV)

The proton emitter ^{159}Re

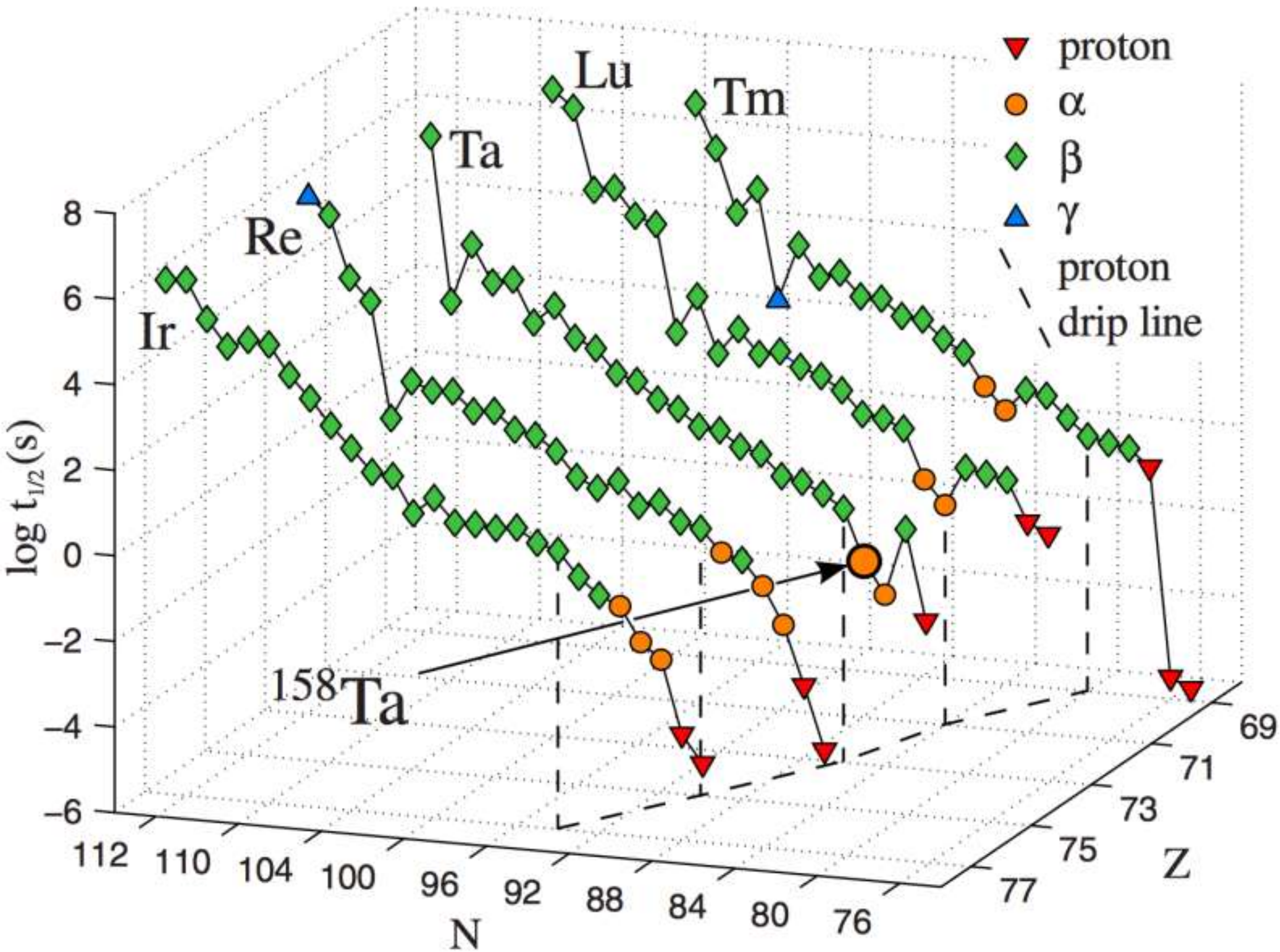


D. T. Joss et al, Phys. Lett. B 641, (2006) 34.

Determining the angular momentum of the initial state

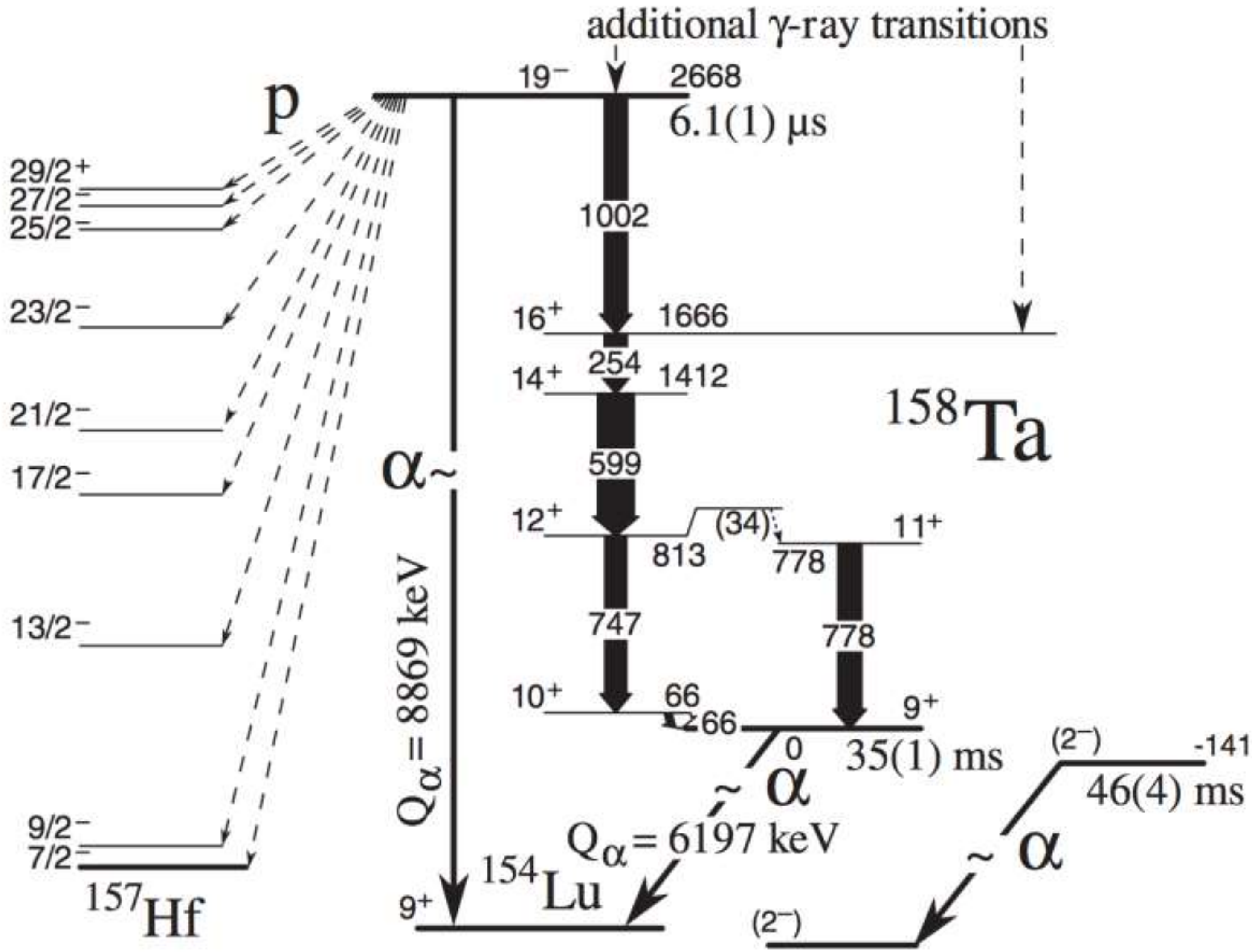


E_p (keV)	Half-life (μs)			Expt
	$s_{1/2}$	$d_{3/2}$	$h_{11/2}$	
1805	0.0006	0.012	9.4	21±4

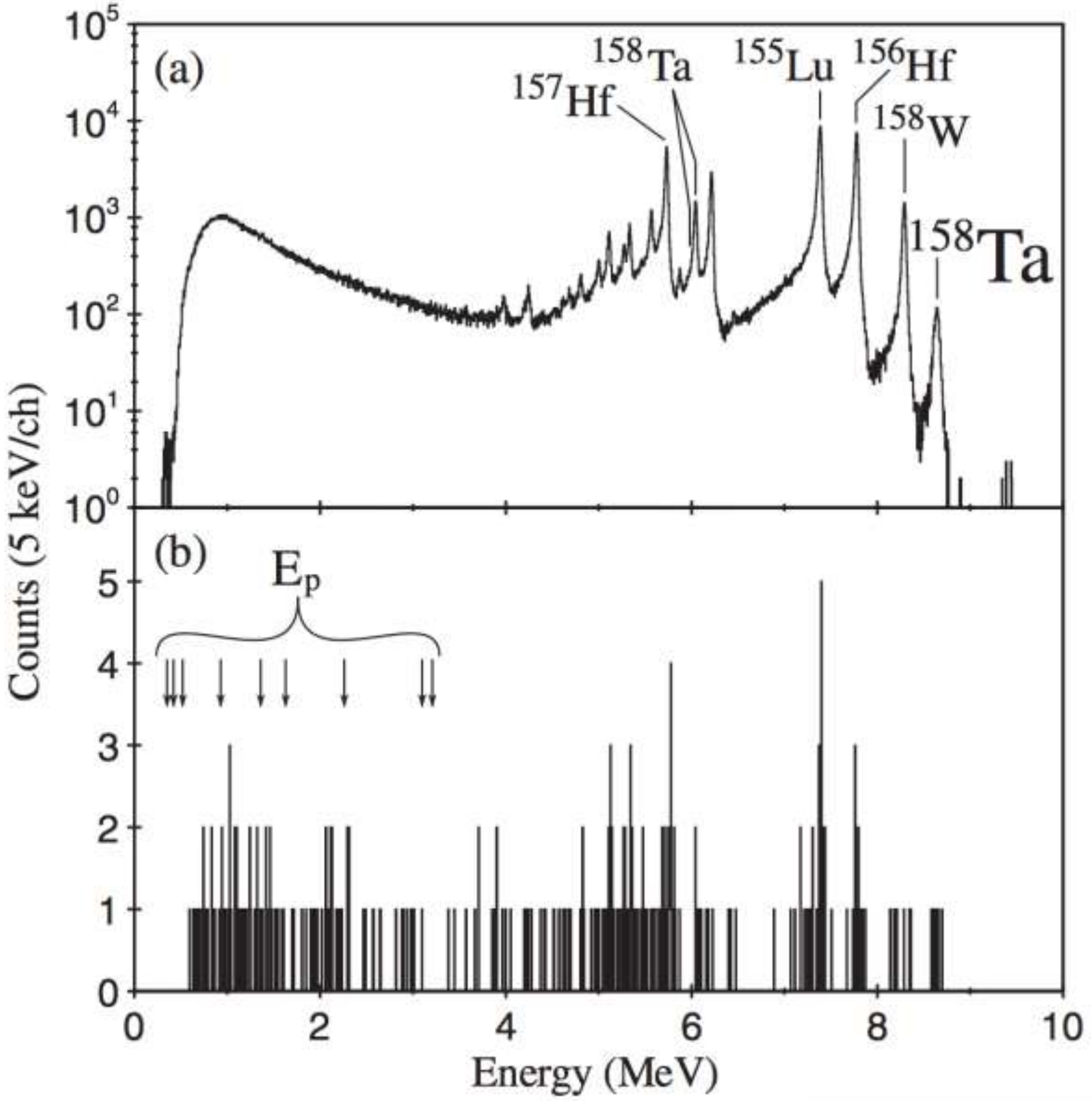


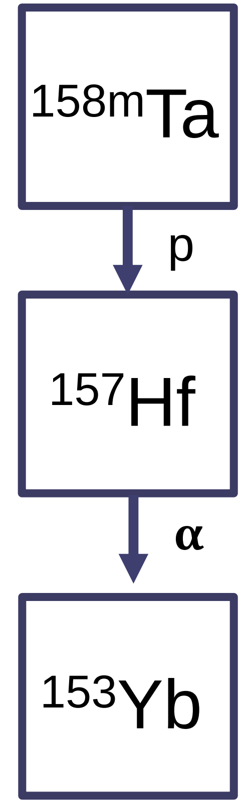
proton
α
β
γ
proton drip line
Lu
Tm
Ta
Re
Ir
^{158}Ta
log $t_{1/2}$(s)
8
6
4
2
0
−2
−4
−6
112
110
104
100
96
92
88
84
80
76
N
69
71
73
75
77
Z

Proton emission from isomeric states?

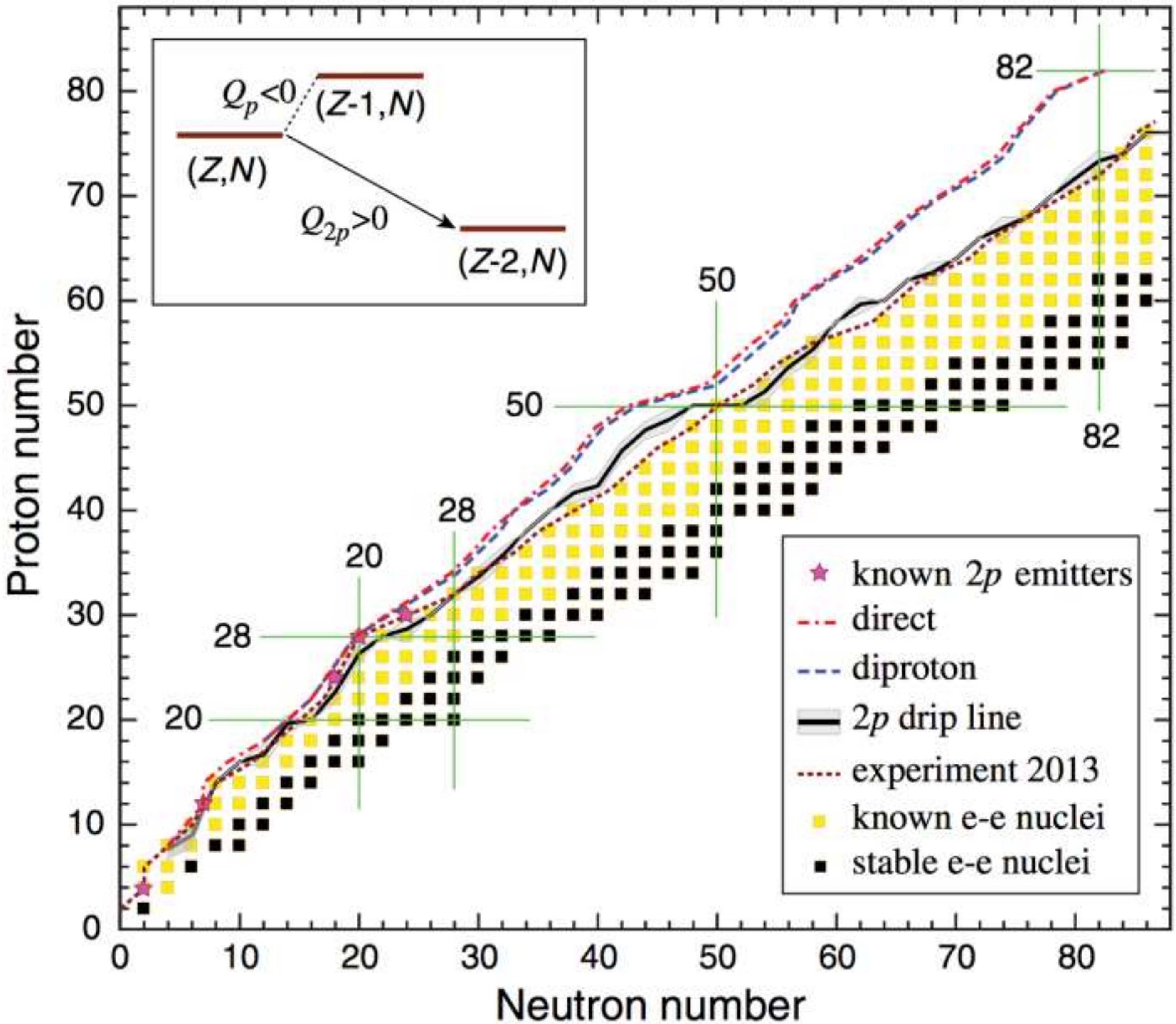


R. J. Carroll et al, Phys. Rev. Lett. 112, (2014) 092501.



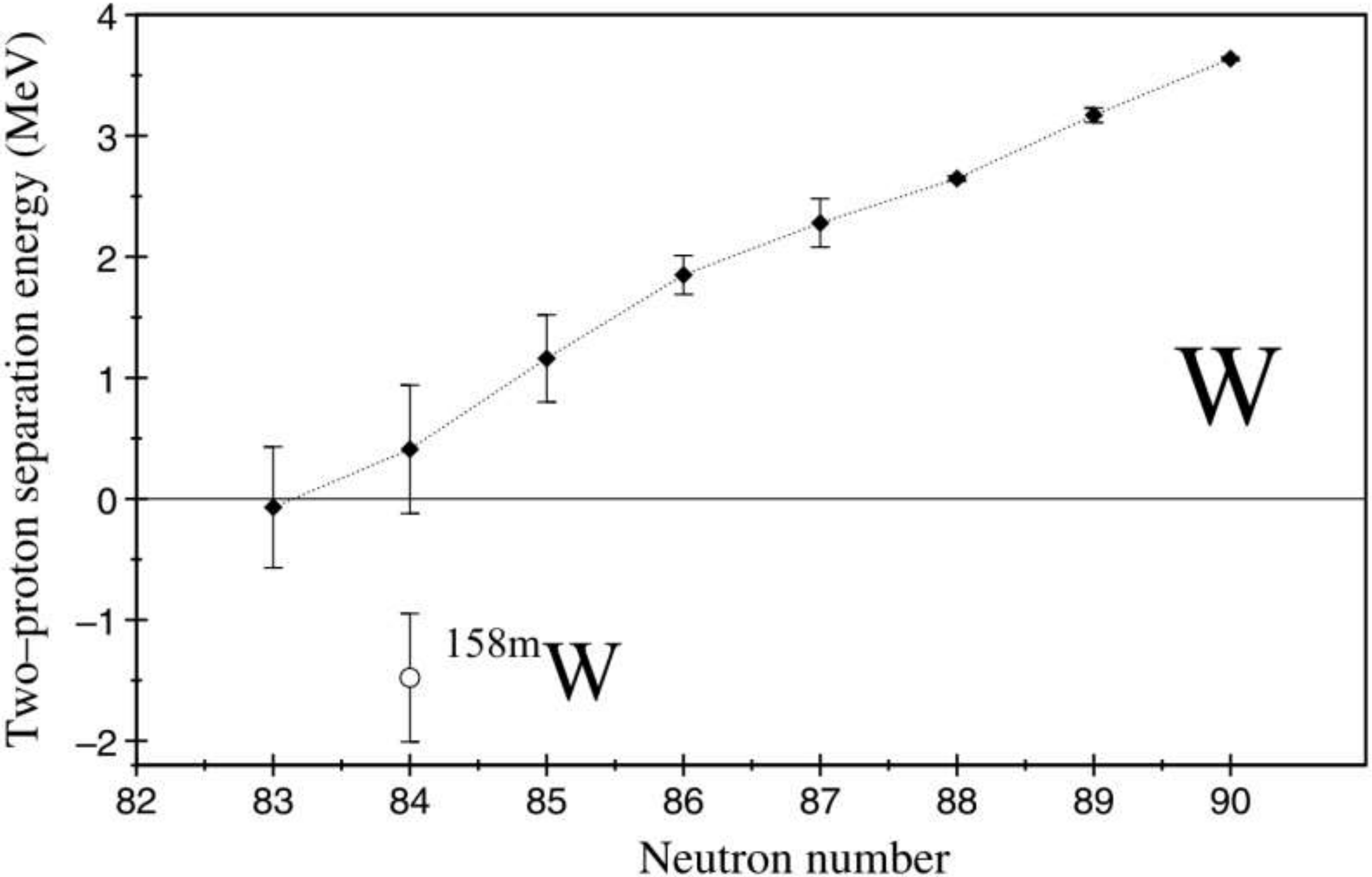


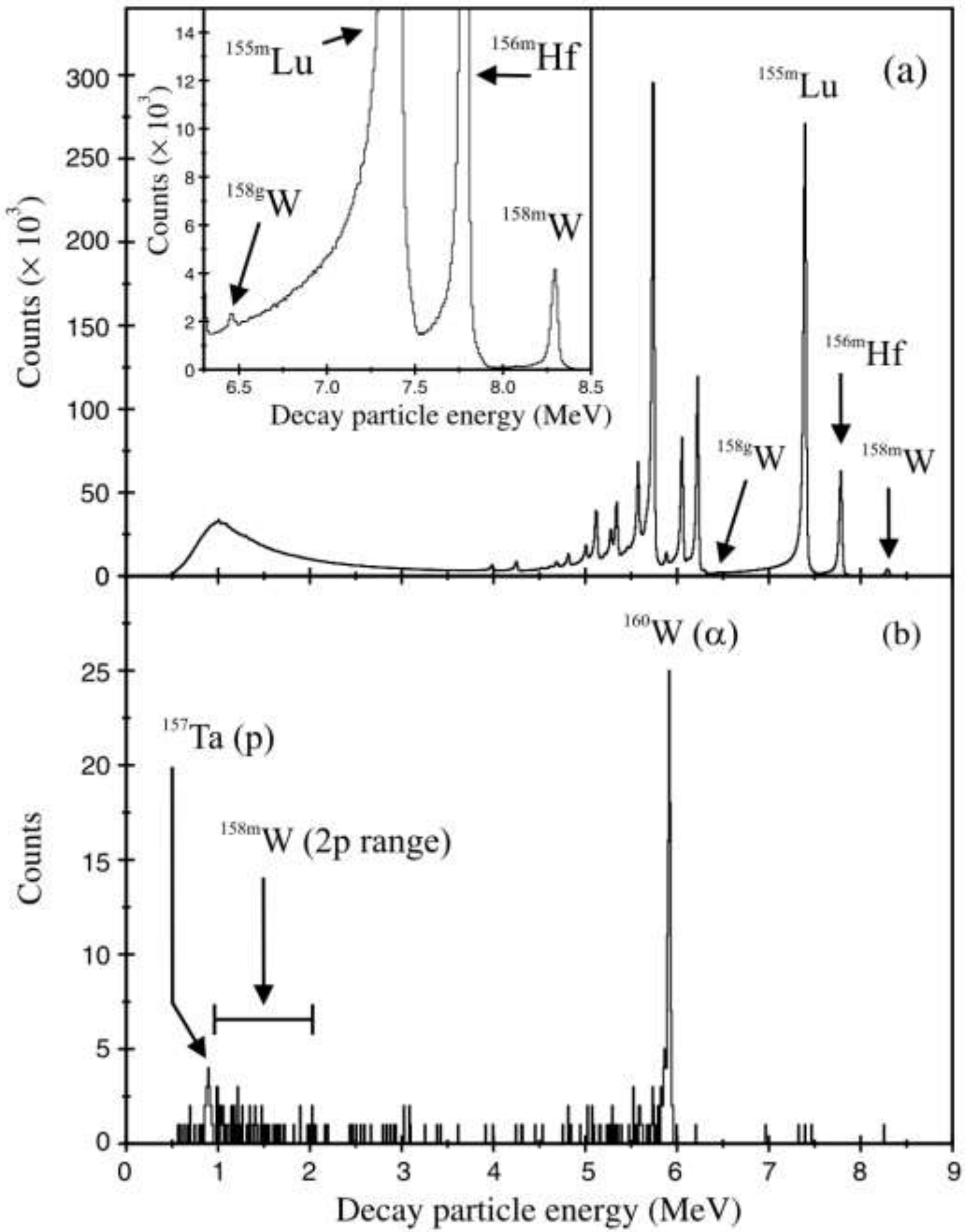
R. J. Carroll et al, Phys. Rev. Lett. 112, (2014) 092501.



E. Olsen et al, Phys. Rev. Lett. 110, (2013) 222501.

Two-proton radioactivity in heavy nuclei?





Absence of decay mode reflects balance of Q values to angular momentum.

Very difficult to predict decay half-lives for 2p emission.

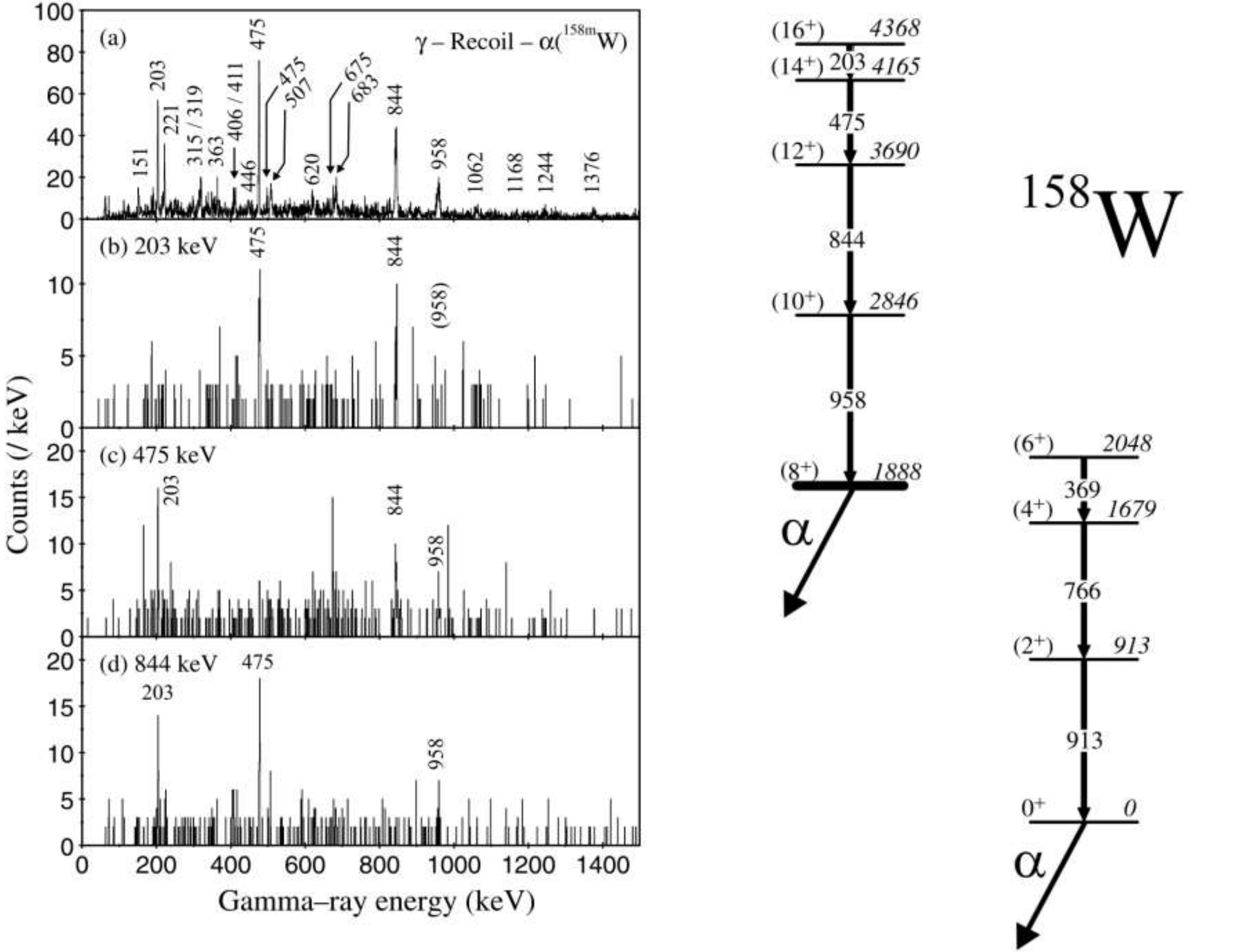
L.V. Grigerenko *et al*.
Phys. Rev. C95 (2017) 021601(R).

Possibilities for proton-unbound isomers all along the drip line.

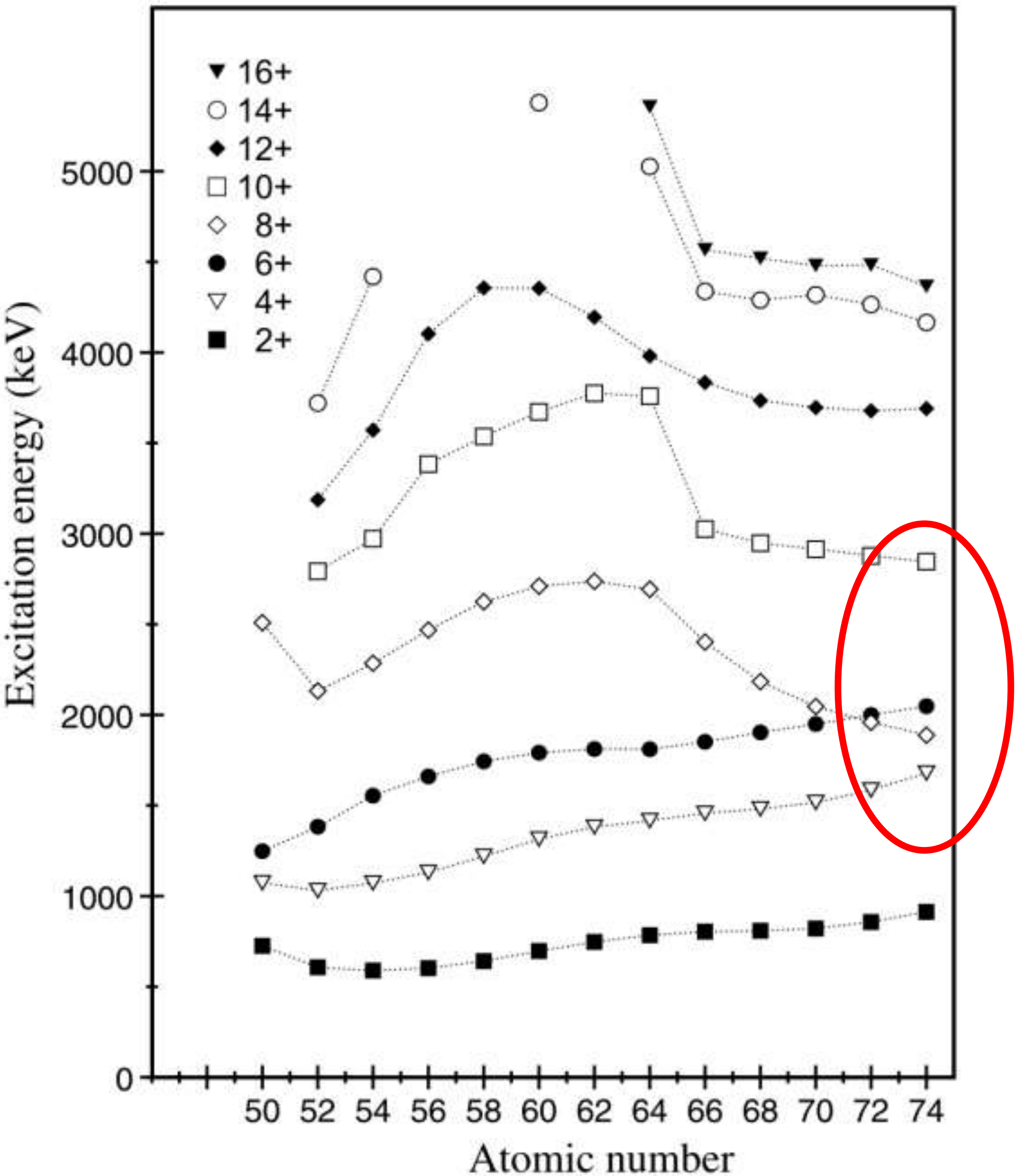
Challenge for synthesis.

Proton evaporation channels from fusion-evaporation reactions with radioactive beams?

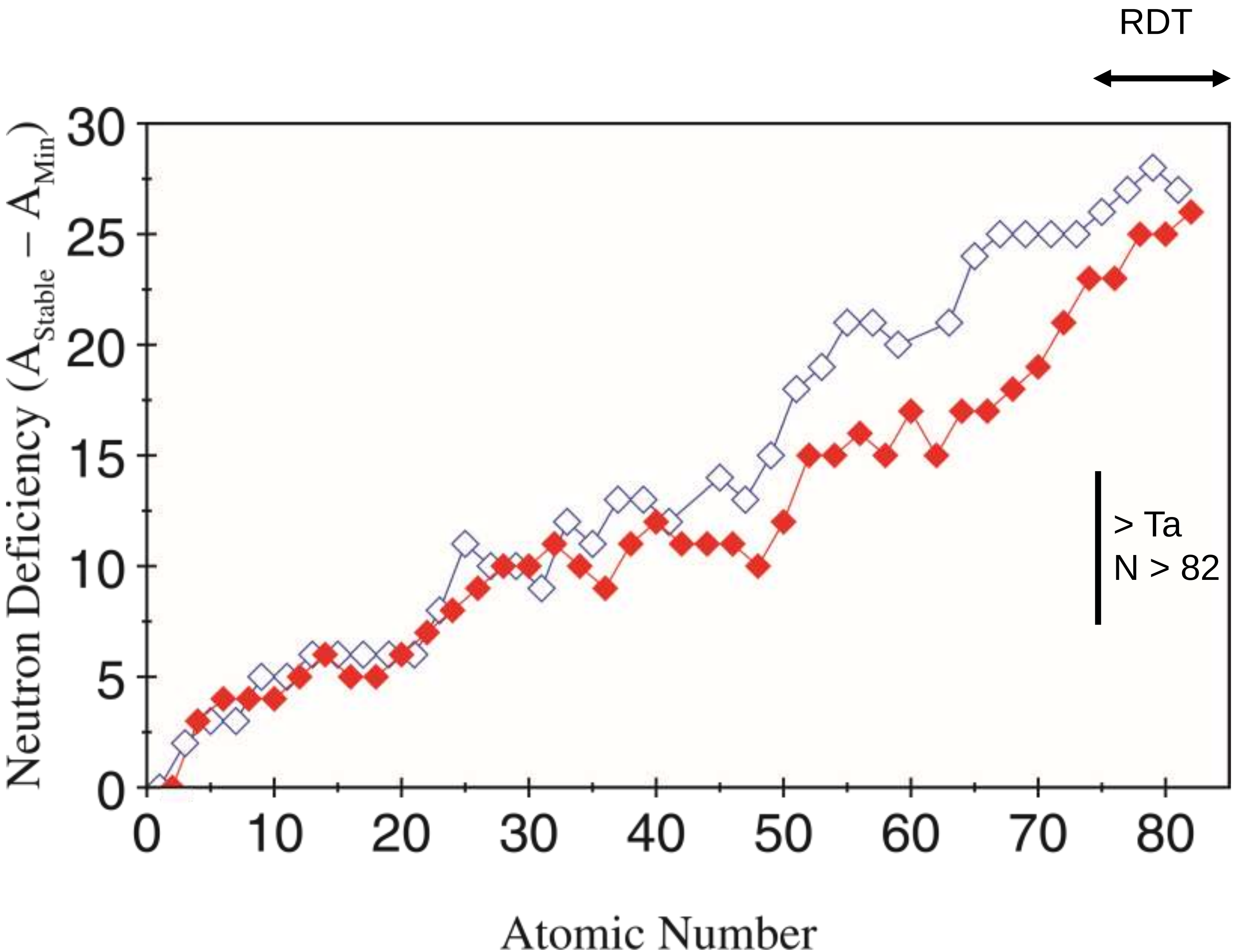
D. T. Joss et al, Phys. Lett. B 772, (2017) 703.



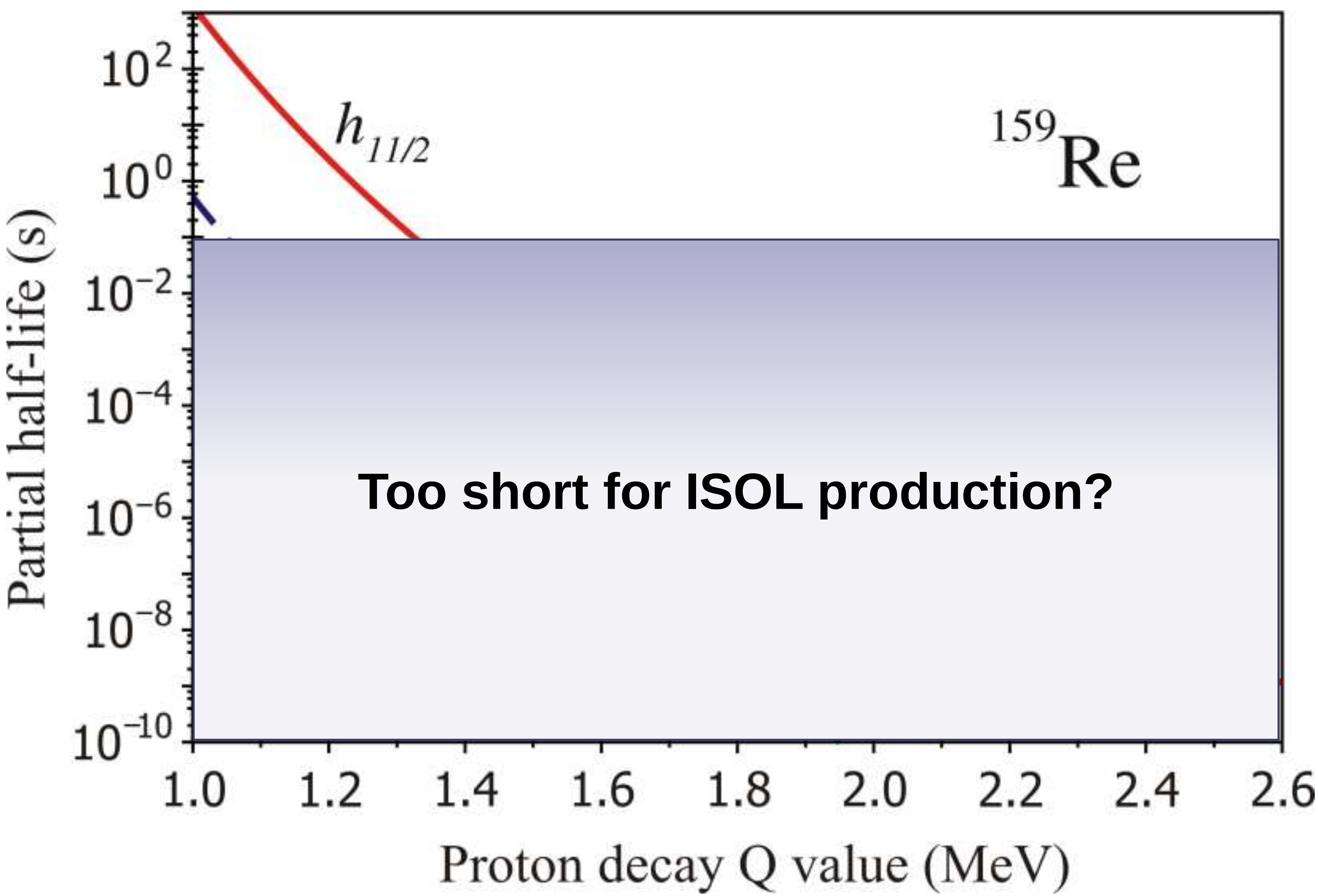
(a) γ – Recoil – α(158mW)
151
203
221
315 / 319
363
406 / 411
446
475
475
507
620
675
683
844
958
1062
1168
1244
1376
(b) 203 keV
475
844
(958)
(c) 475 keV
203
844
958
(d) 844 keV
475
203
958
Counts (/ keV)
Gamma–ray energy (keV)
158W
(16+) 4368
203
(14+) 4165
475
(12+) 3690
844
(10+) 2846
958
(8+) 1888
α
(6+) 2048
369
(4+) 1679
766
(2+) 913
913
0+ 0
α



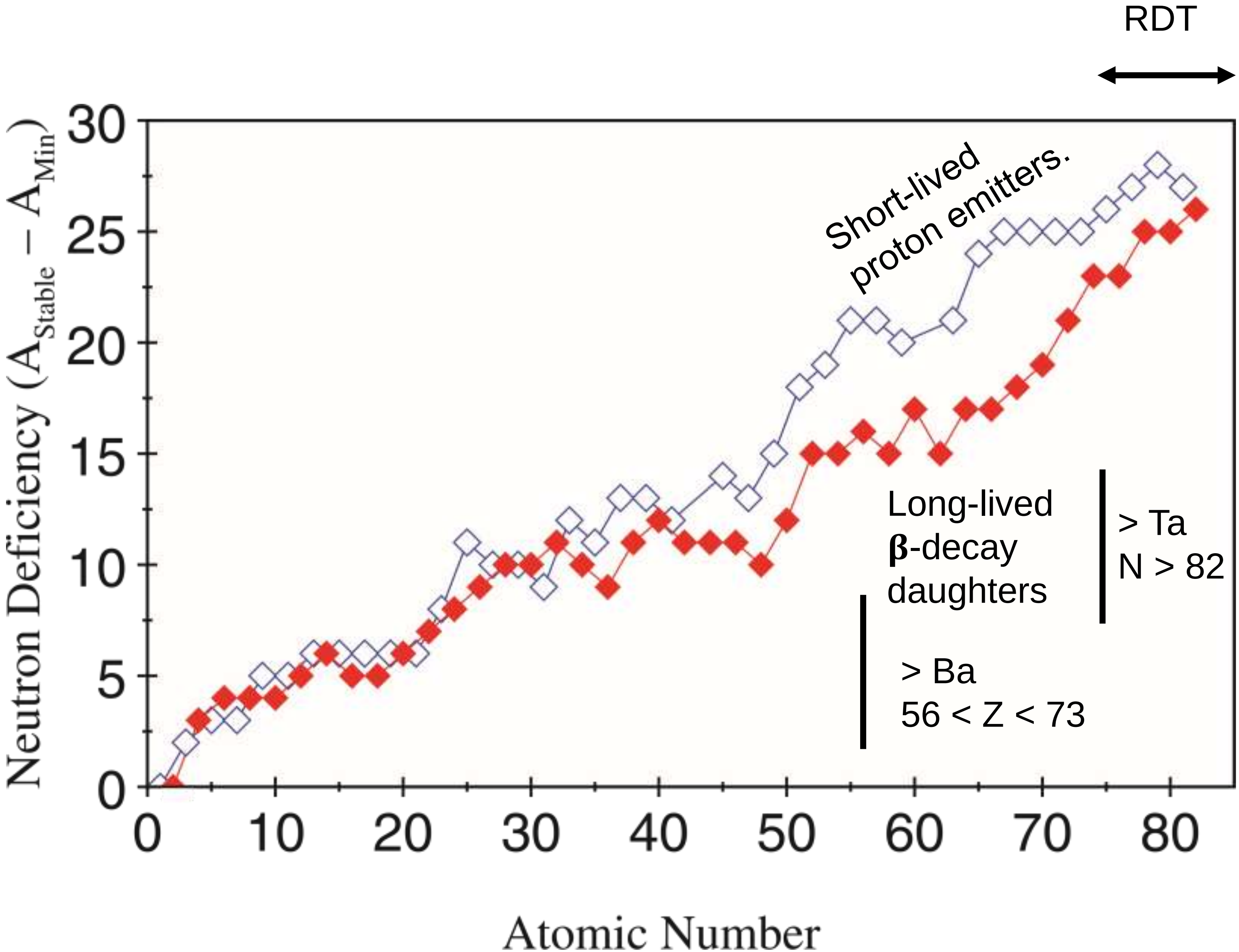
16+
14+
12+
10+
8+
6+
4+
2+
Excitation energy (keV)
5000
4000
3000
2000
1000
0
50
52
54
56
58
60
62
64
66
68
70
72
74
Atomic number



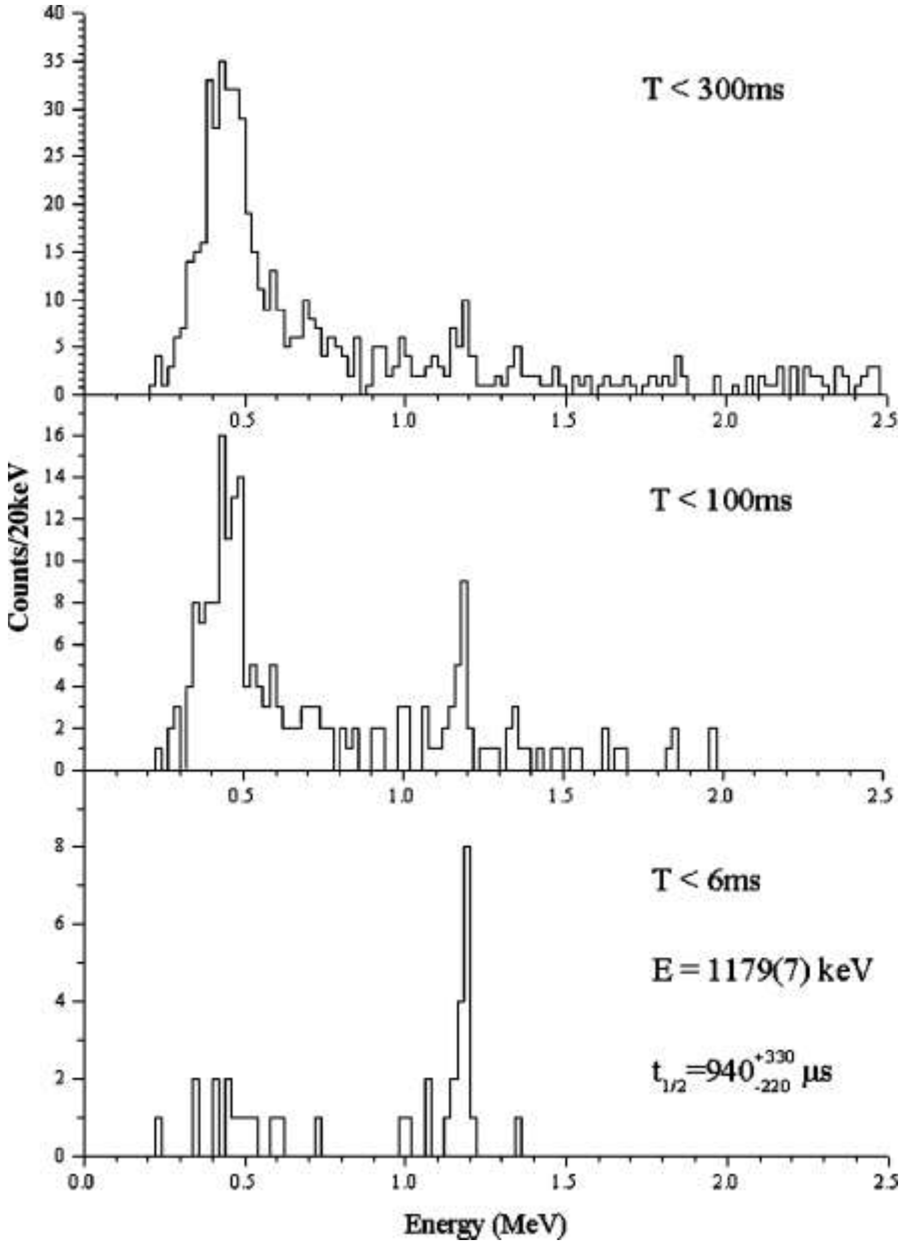
RDT
Neutron Deficiency ($A_{Stable} - A_{Min}$)
30
25
20
15
10
5
0
0
10
20
30
40
50
60
70
80
> Ta
N > 82
Atomic Number



10^{2}
10^{0}
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
Partial half-life (s)
$h_{11/2}$
^{159}Re
Too short for ISOL production?
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
Proton decay Q value (MeV)


RDT
Short-lived proton emitters.
Long-lived β-decay daughters
> Ta
N > 82
> Ba
56 < Z < 73
Neutron Deficiency ($A_{Stable} - A_{Min}$)
Atomic Number
0
5
10
15
20
25
30
40
50
60
70
80

Implantation – proton correlations



$^{50}Cr + ^{92}Mo \rightarrow ^{135}Tb + p6n$

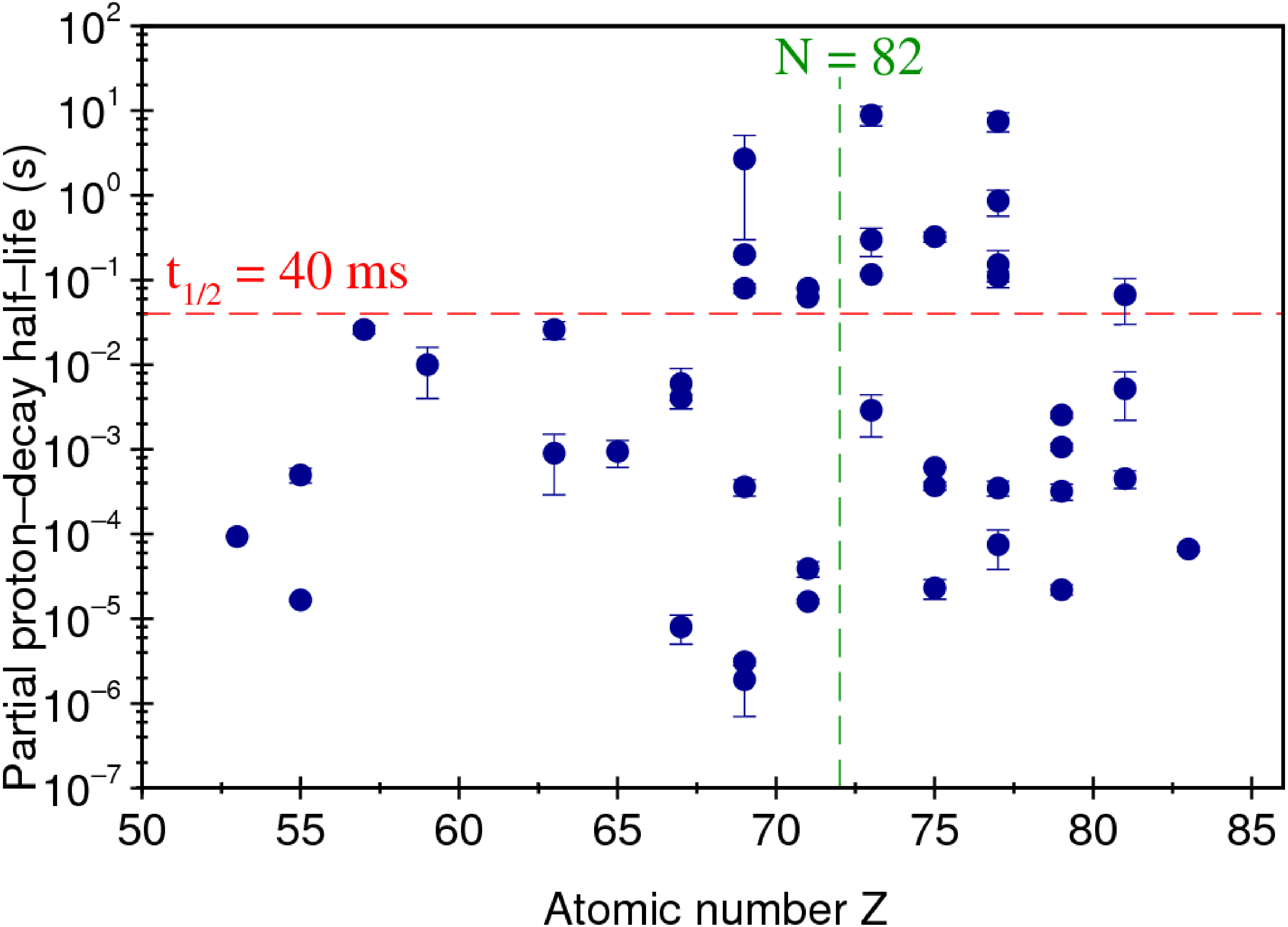
Argonne FMA

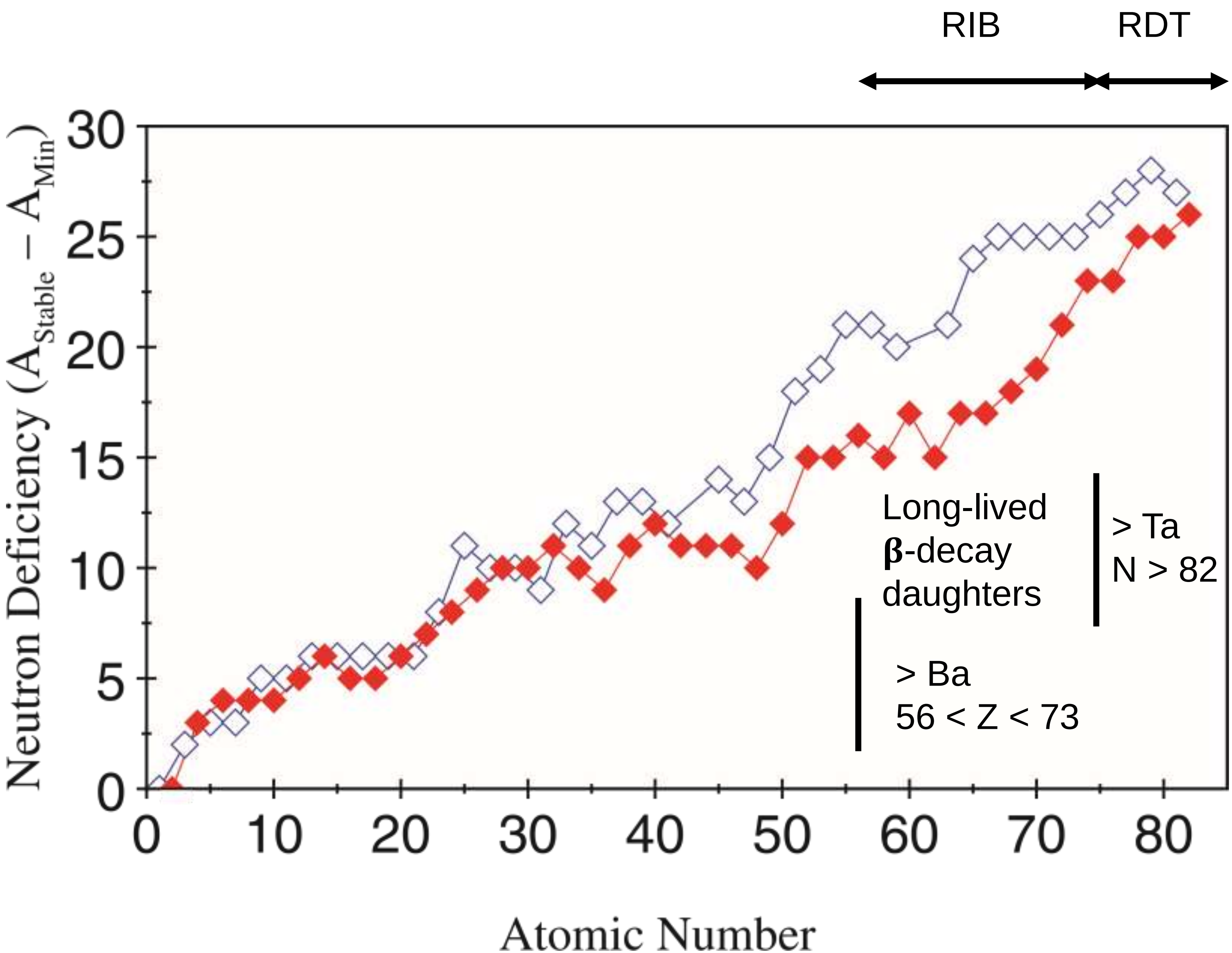
A = 135 only

60 μm thick DSSD

P.J. Woods et al., PRC69 (2004) 051302

Proton-decay half-lives



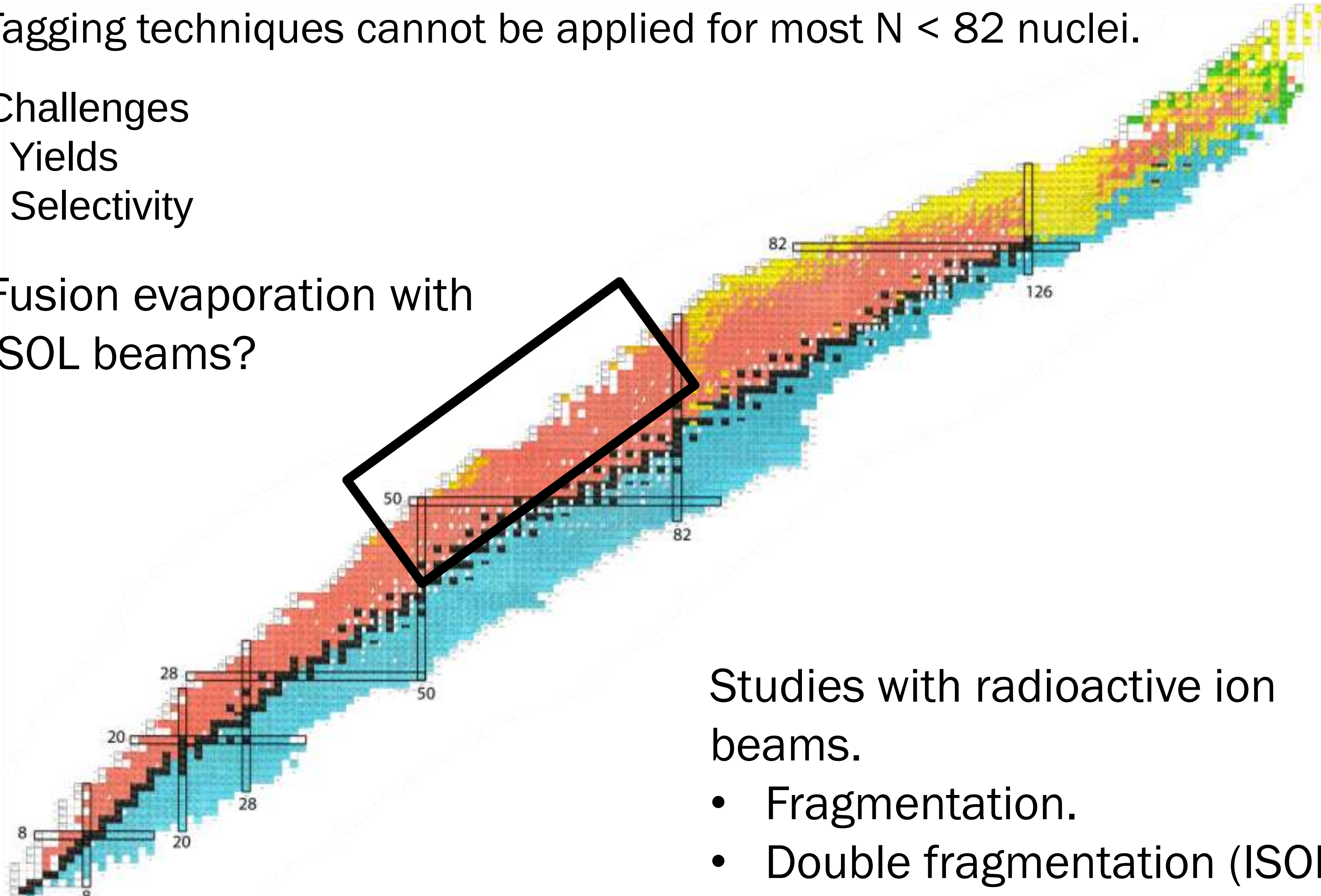


RIB
RDT
Neutron Deficiency ($A_{Stable} - A_{Min}$)
Atomic Number
Long-lived
β-decay
daughters
> Ta
N > 82
> Ba
56 < Z < 73

Tagging techniques cannot be applied for most N < 82 nuclei.

Challenges
- Yields
- Selectivity

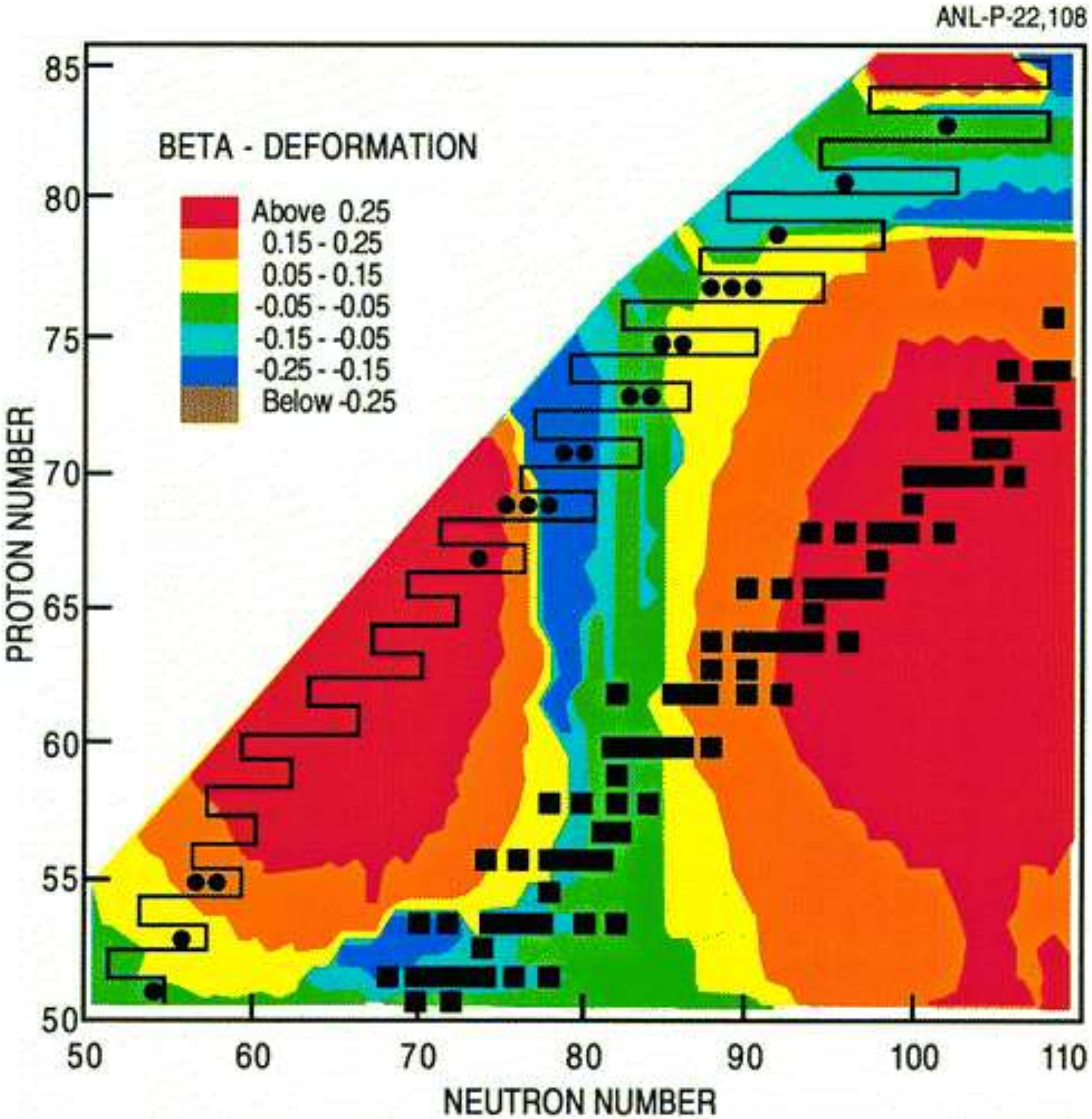
Fusion evaporation with ISOL beams?



Studies with radioactive ion beams.

- Fragmentation.
- Double fragmentation (ISOL primary beam)?
- Direct ISOL production.

Proton emission in deformed nuclei



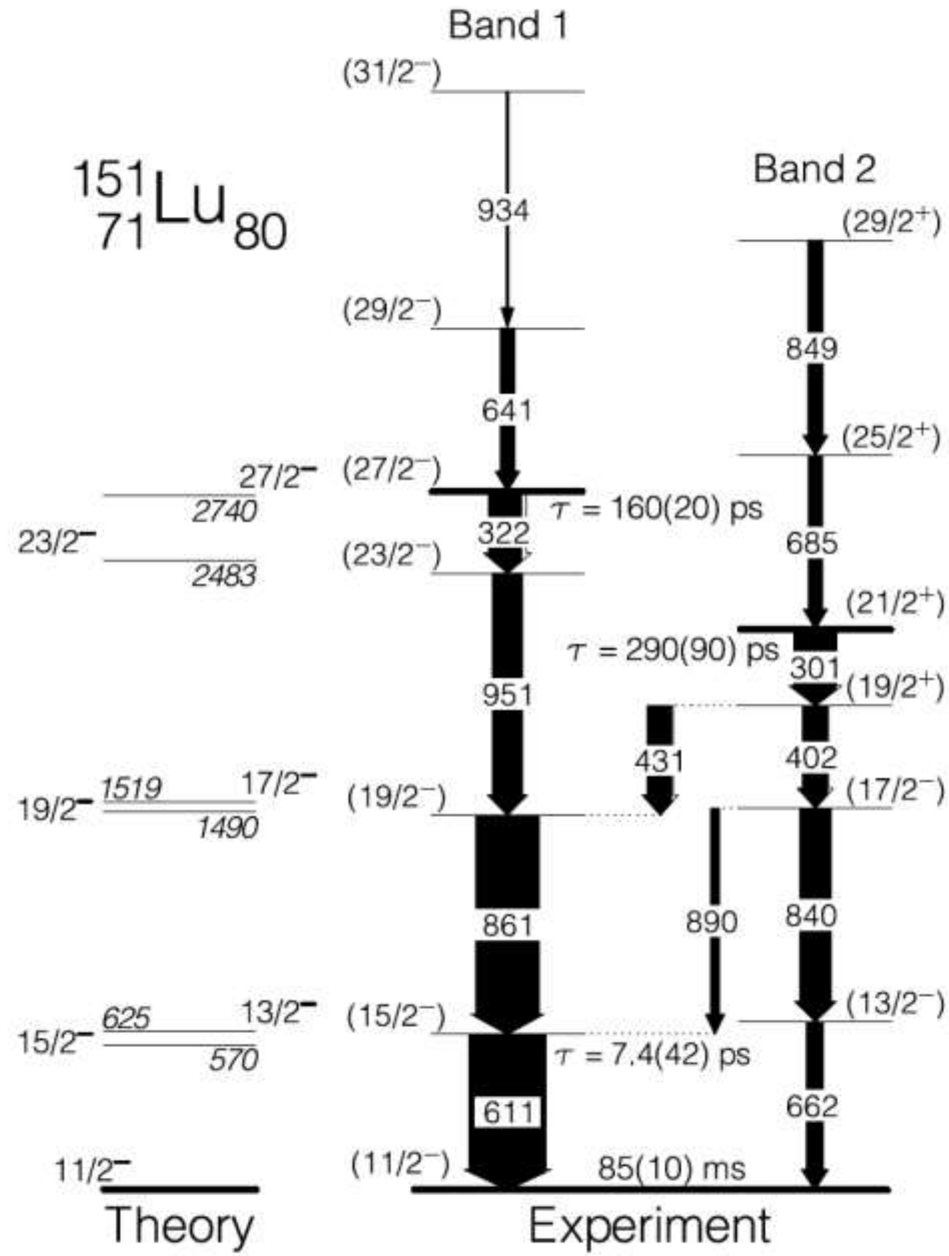
Adapted from P.J. Woods & C.N. Davids, Ann. Rev. Nucl. Part Sci 47 (1997) 541.
Proton Drip Line taken from P. Möller et al. *At. Data Nucl. Data Tables* 59 (1995) 185.

In-beam spectroscopy of deformed proton emitters

Changes in relative orbital energies?

Coupling of odd proton to core excitations?

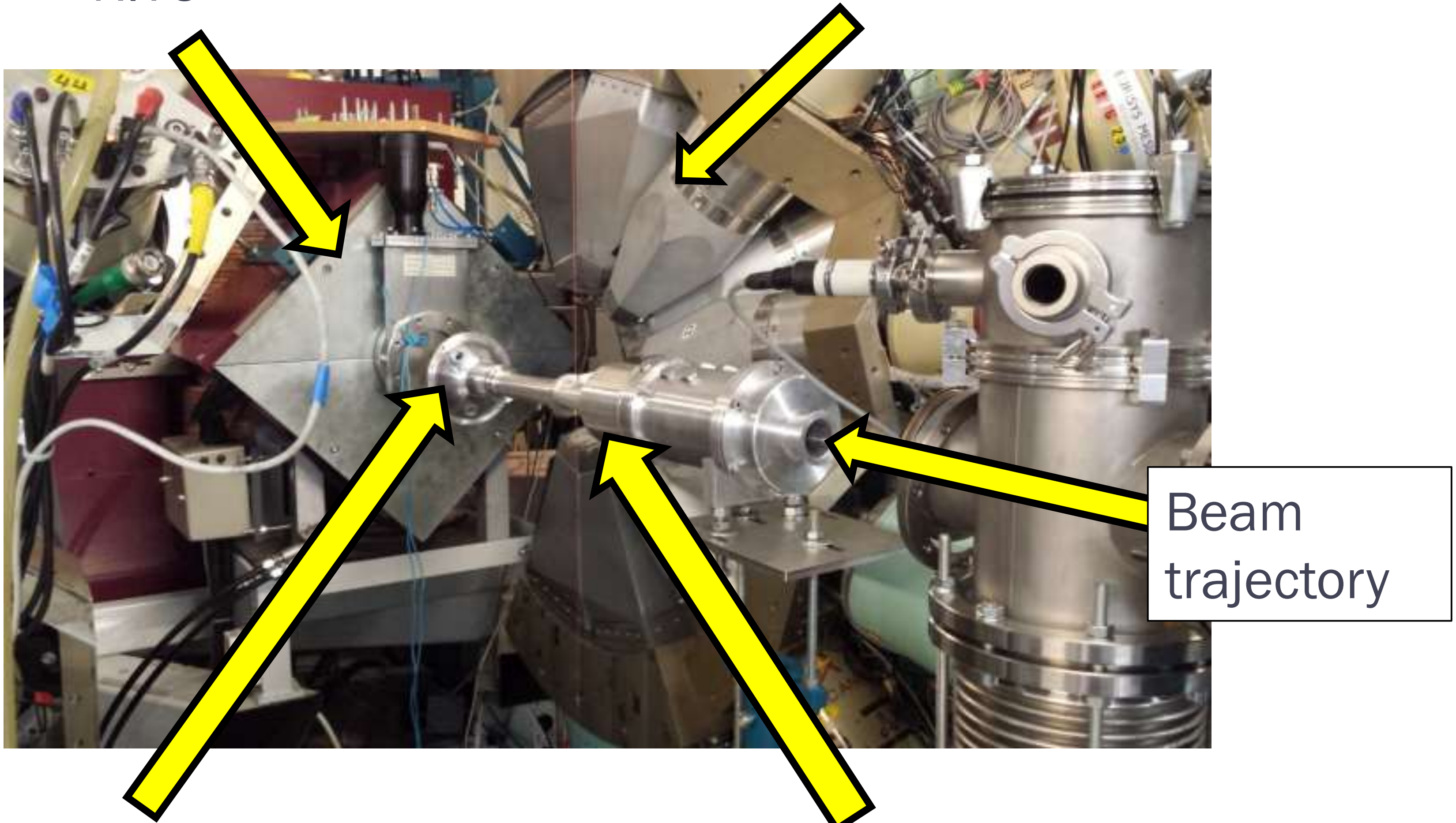
In-beam coincidences & RDDS measurements used to constrain proton emission calculations.



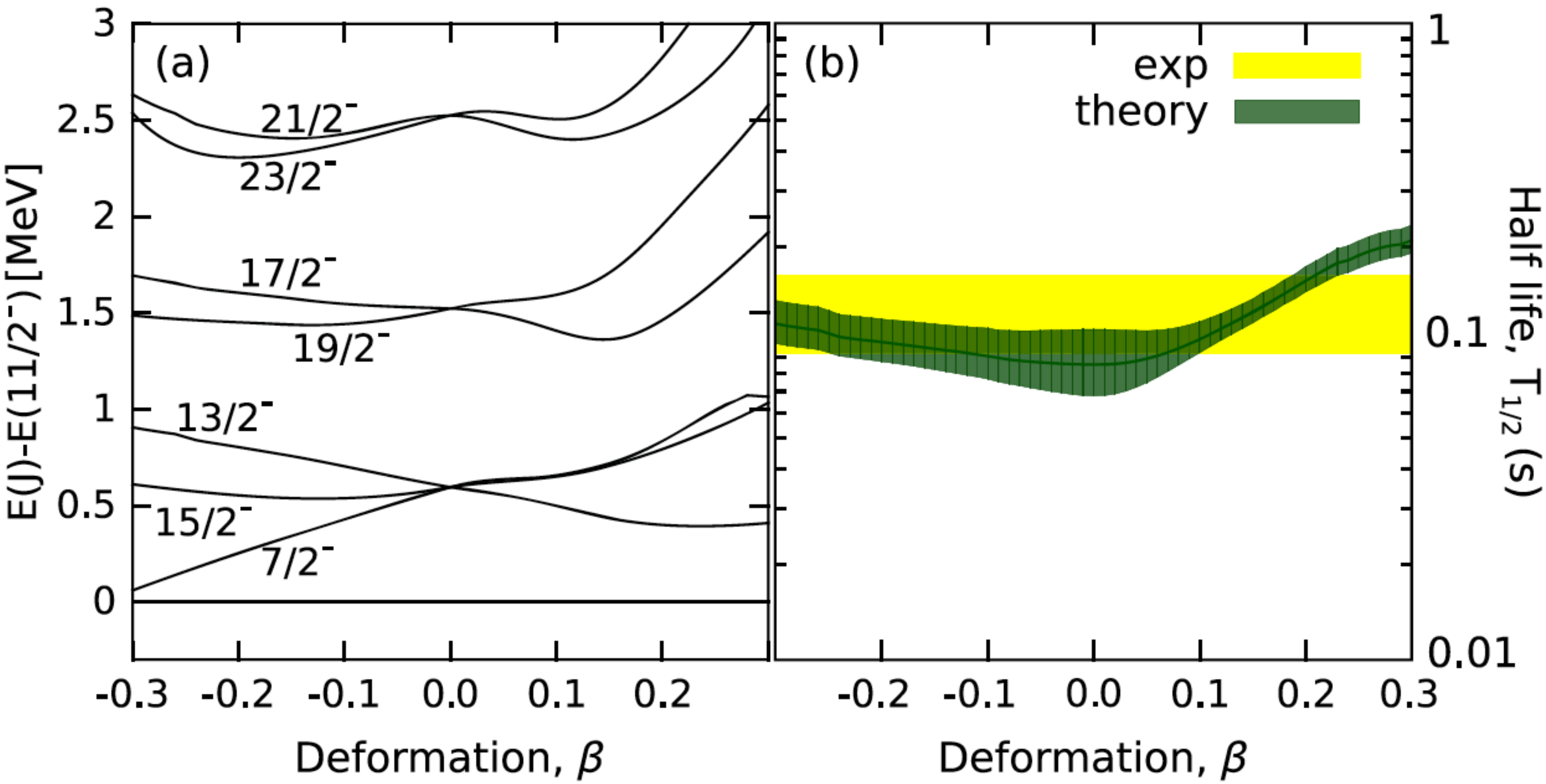
M.G. Proctor et al., Phys. Lett. B 725, 79 (2013) .

Reduced B(E2) Transition Probabilities & Lifetime Measurements

$$\frac{1}{\tau} = 1.23 \times 10^{13} E_\gamma^5 B(E2)$$



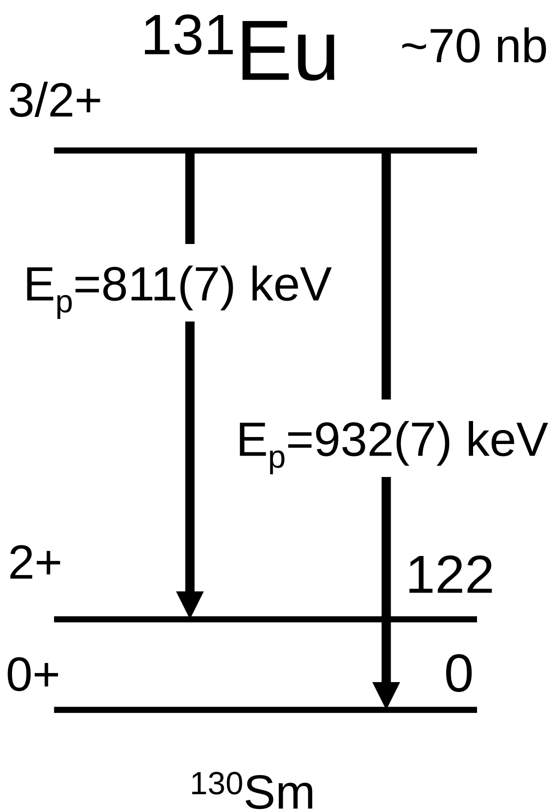
In-beam spectroscopy of deformed proton emitters

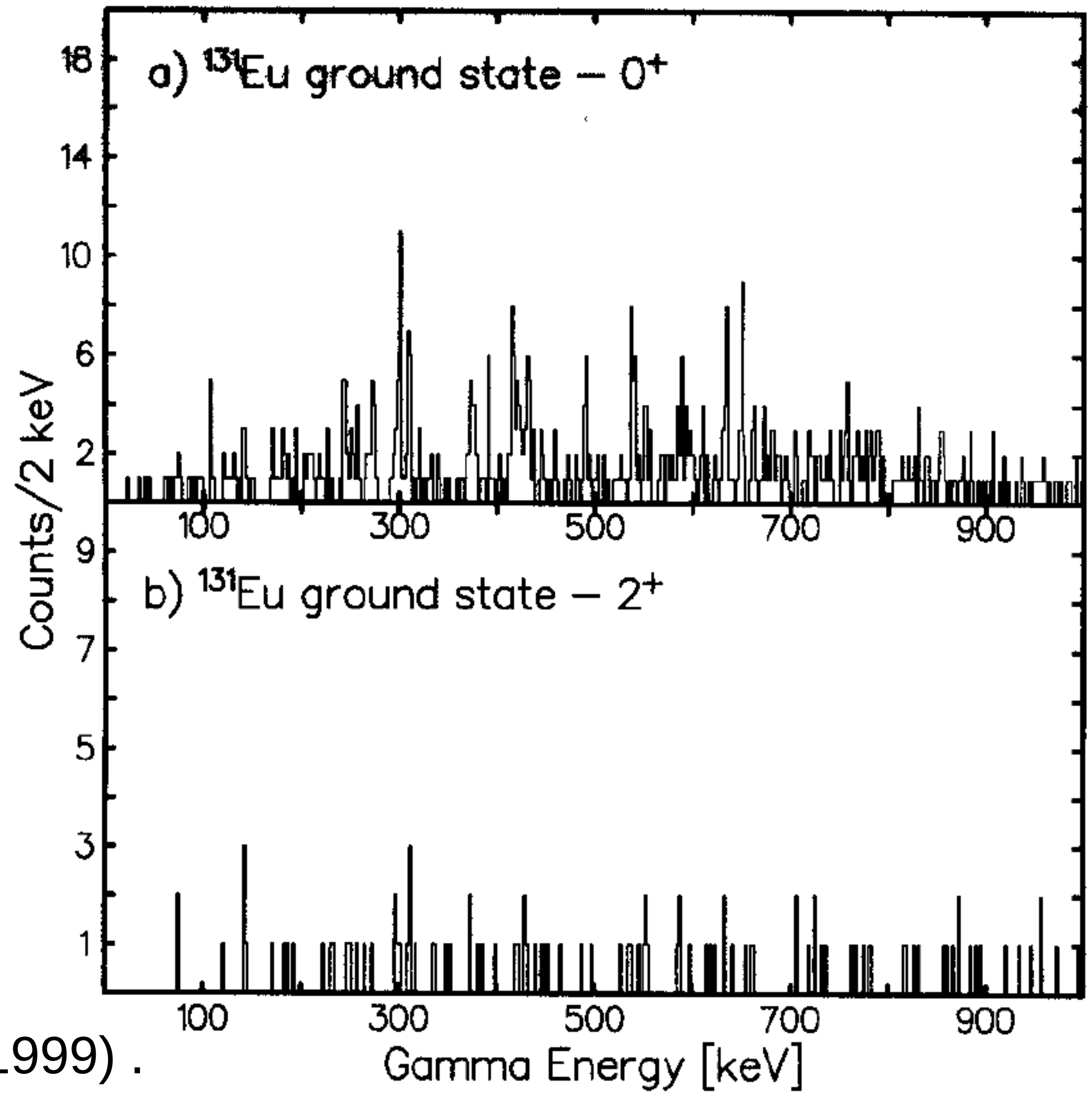


Level ordering and lifetime measurement constrains deformation of ^{151}Lu to be mildly oblate β=-0.11(2)

M.G. Proctor et al., Phys. Lett. B 725, 79 (2013) .

Proton emission from deformed nuclei.

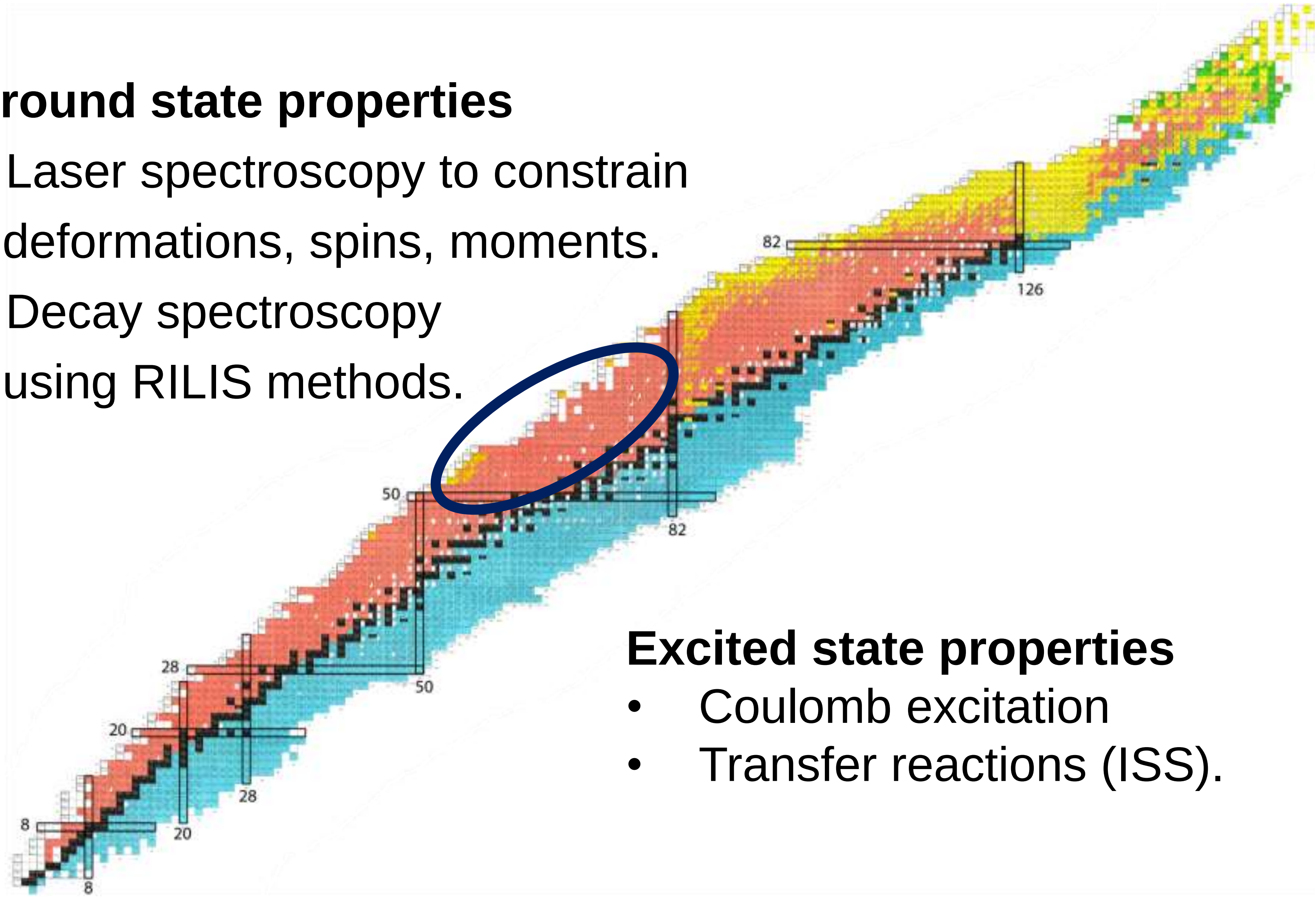




A.A. Sonzogni et al.,
Phys. Rev. Lett. 83, 1116 (1999) .

D. Seweryniak et al., Nucl. Phys. A682, 247c (2001) .

Summary: Future Prospects



Ground state properties

- Laser spectroscopy to constrain deformations, spins, moments.
- Decay spectroscopy using RILIS methods.

Excited state properties

- Coulomb excitation
- Transfer reactions (ISS).