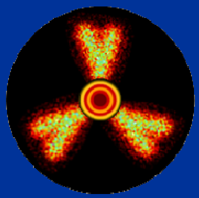


Emisja dwóch protonów jako granica spektroskopii jądrowej

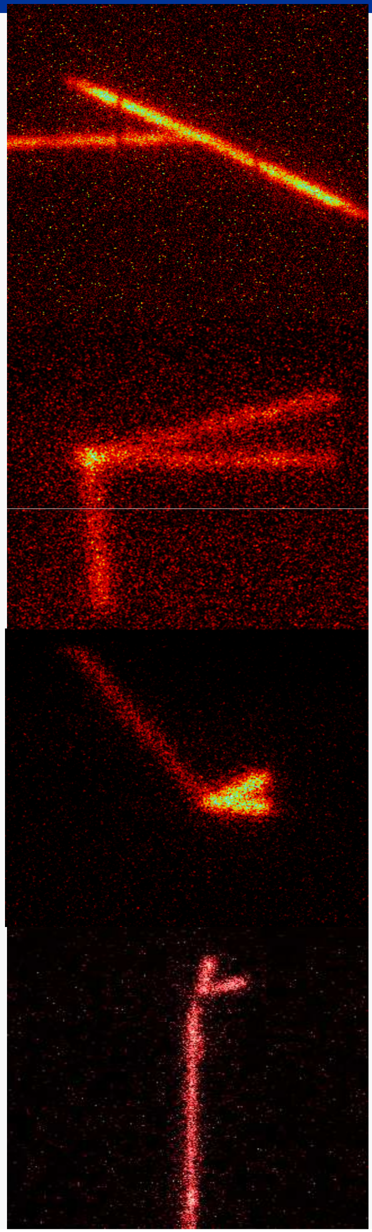
obraz całościowy

Marek Pfützner

Zakład Fizyki Jądrowej
Uniwersytet Warszawski

Seminarium „Fizyka Jądra Atomowego”, 15 maja 2014

Plan



- Mapa nuklidów i granice spektroskopii
- Emisja dwóch protonów (2p) – stan obecny
- Uproszczone modele emisji 2p
- Emisja równoczesna a sekwencyjna
- Globalne przewidywania
  - → między cynkiem a telurem
  - → między telurem a ołowiem

PRL **110,** 222501 (2013) PHYSICAL REVIEW LETTERS week ending 31 MAY 2013

Landscape of Two-Proton Radioactivity

E. Olsen,[1,2] M. Pfützner,[3,4] N. Birge,[1,2] M. Brown,[1,5] W. Nazarewicz,[1,2,3] and A. Perhac[1,2]
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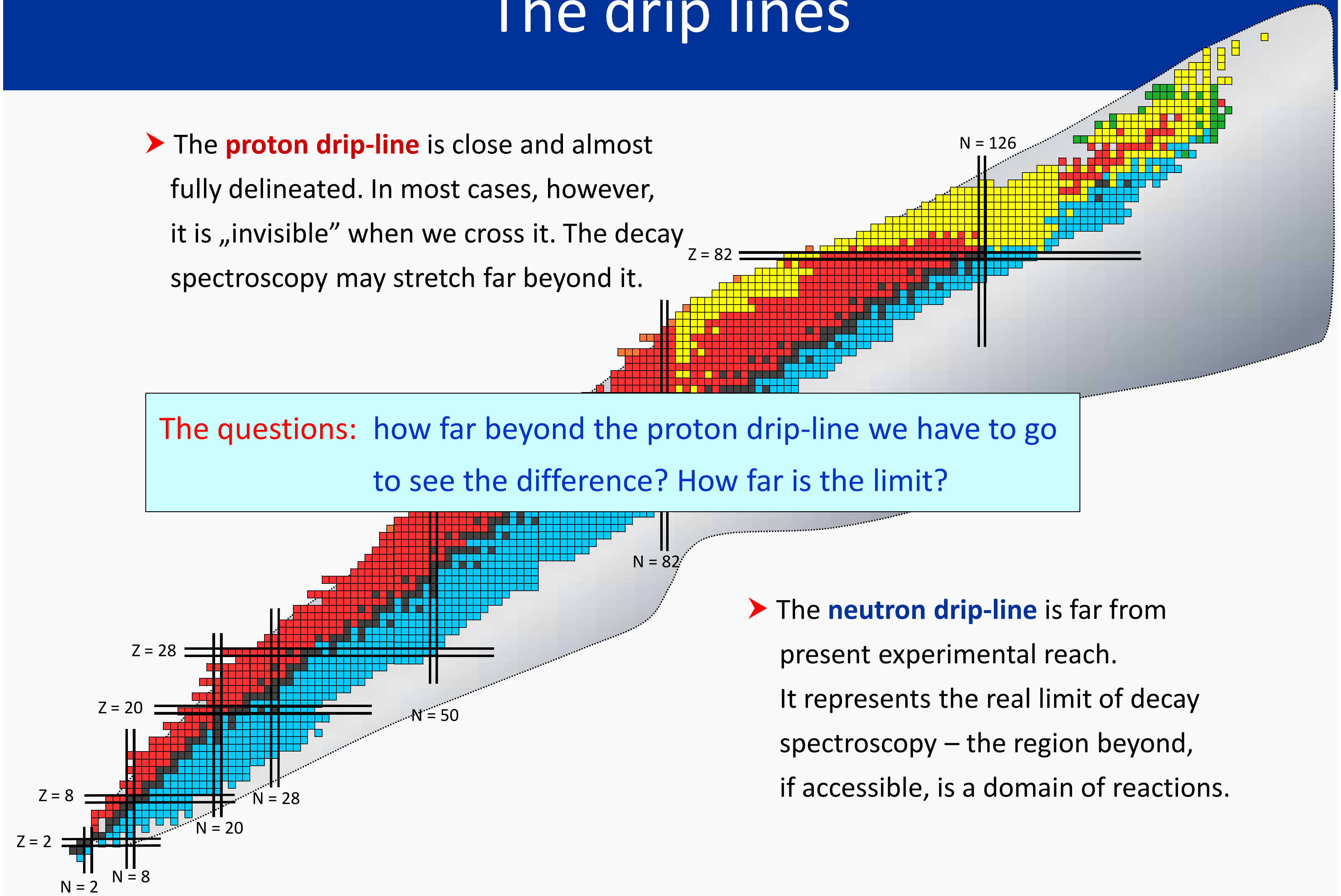
PRL **111,** 139903 (2013) PHYSICAL REVIEW LETTERS week ending 27 SEPTEMBER 2013

Erratum: Landscape of Two-Proton Radioactivity [Phys. Rev. Lett. 110, 222501 (2013)]

E. Olsen, M. Pfützner, N. Birge, M. Brown, W. Nazarewicz, and A. Perhac
(Received 12 September 2013; published 25 September 2013)

The drip lines

- The **proton drip-line** is close and almost fully delineated. In most cases, however, it is „invisible" when we cross it. The decay spectroscopy may stretch far beyond it.



The questions: how far beyond the proton drip-line we have to go to see the difference? How far is the limit?

- The **neutron drip-line** is far from present experimental reach. It represents the real limit of decay spectroscopy – the region beyond, if accessible, is a domain of reactions.

Beyond the proton drip-line

Competition between two decay modes

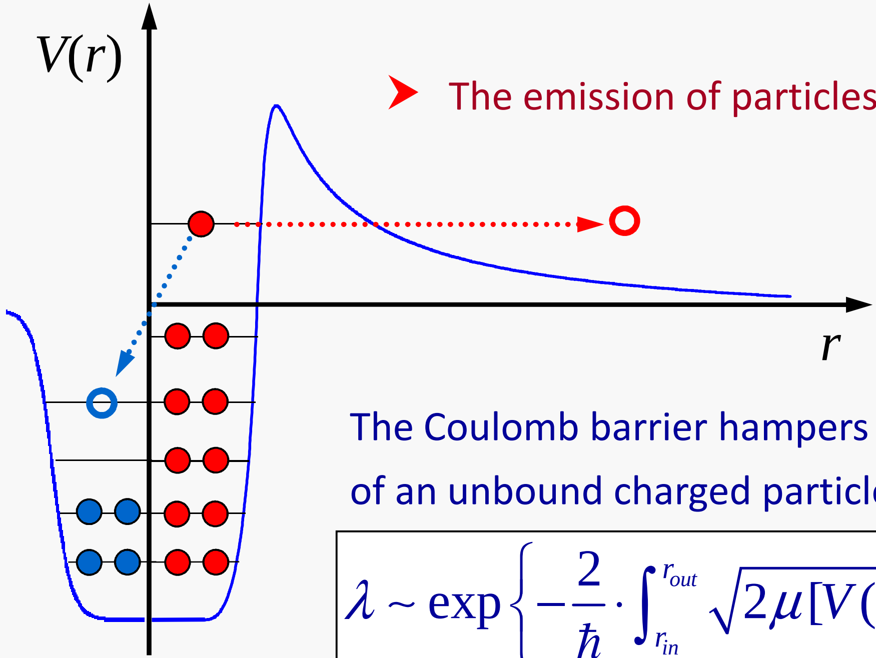
- The β^+ decay

Probability of transition:

$$\lambda \sim Q^5$$

Decay energy may be large, but the weak interaction is really weak

$$T_{1/2} > 1\ \text{ms}$$



- The emission of particles

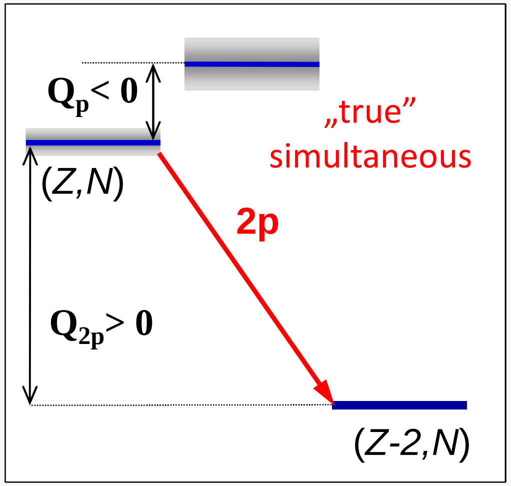
The Coulomb barrier hampers emission of an unbound charged particle (α, p, 2p,…)

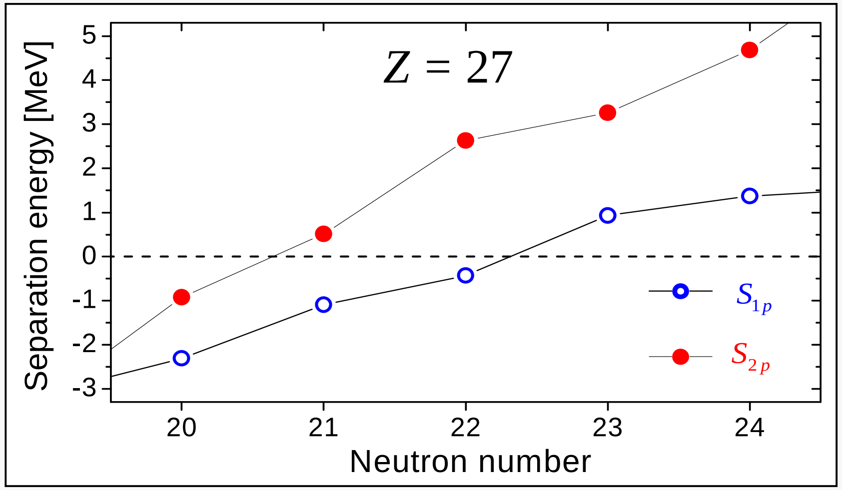
$$\lambda \sim \exp\left\{-\frac{2}{\hbar}\cdot\int_{r_{in}}^{r_{out}}\sqrt{2\mu[V(r)-Q]}\cdot dr\right\}$$

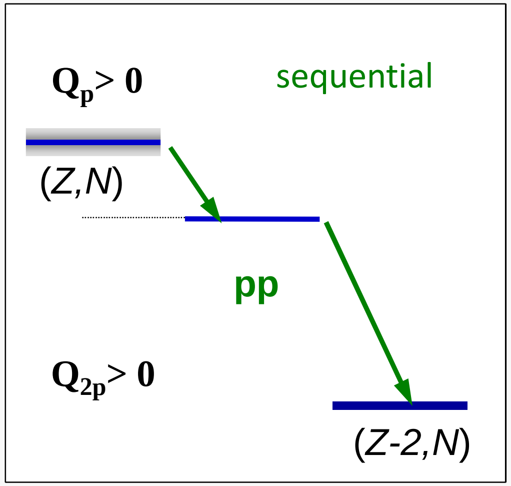
→ To find where the drip-line actually is and to predict which decay will happen, we need: *a*) atomic masses, *b*) decay models

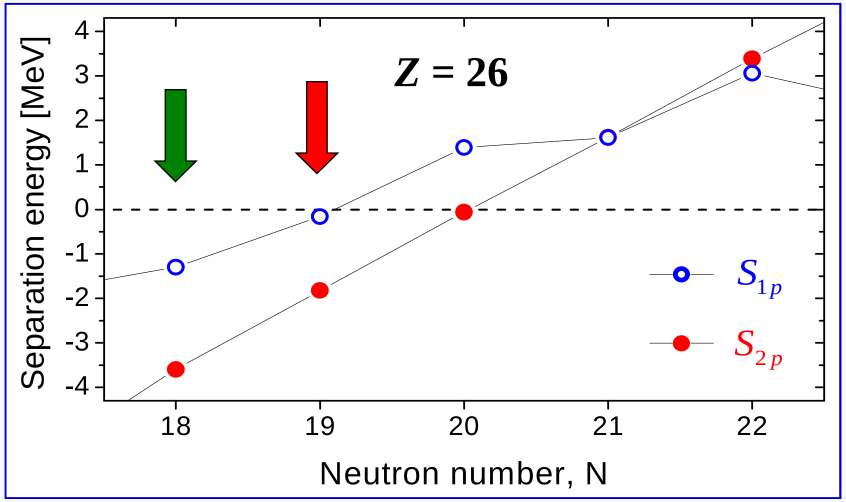
The answer for even Z

- The limit of „existence” for even-Z elements is determined by two-proton emission









V.I. Goldanskii, Nucl. Phys. 19 (60) 482

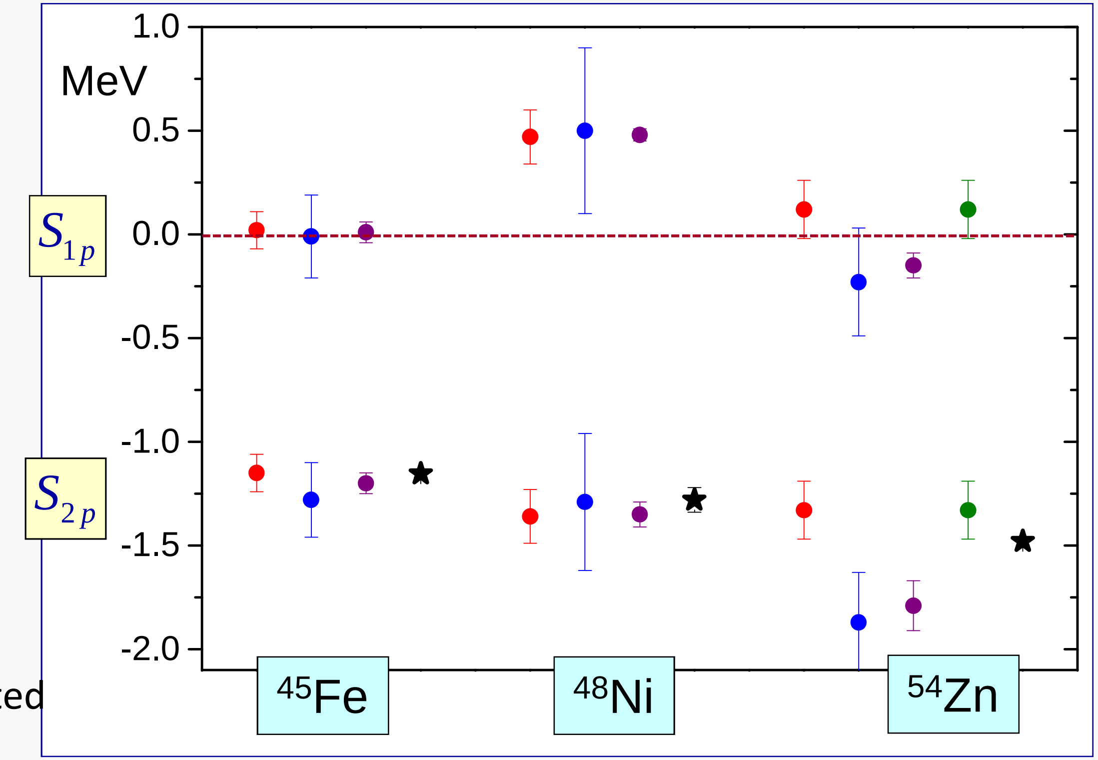
First 2p candidates

- Light and medium masses can be precisely predicted by a trick based on the IMME:

$$BE(T_z = -T) = BE(T_z = T) - 2bT$$

- Binding energy of the neutron-deficient nuclide is calculated from the **measured mass** of its neutron-rich analogue and from the calculated coefficient *b* (shell-model, systematics…)

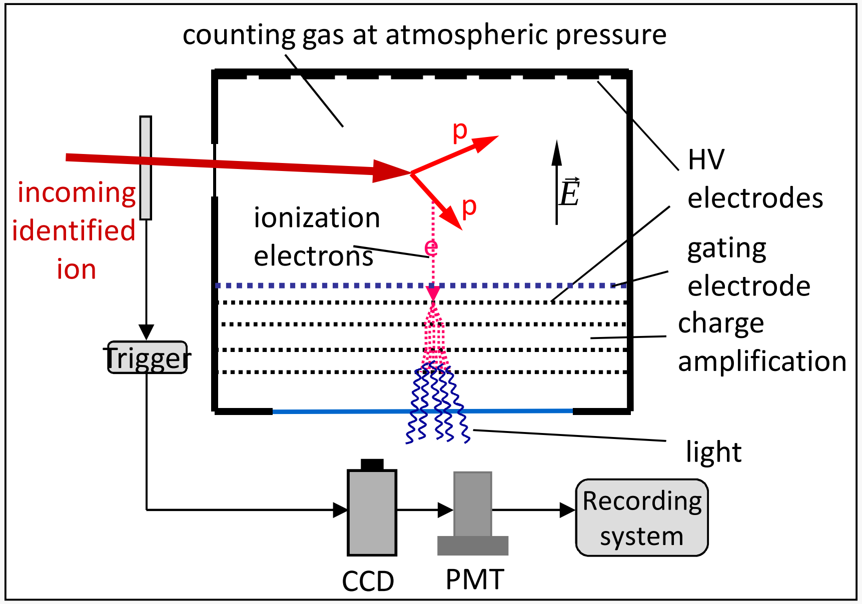
Predicted 1p and 2p separation energies

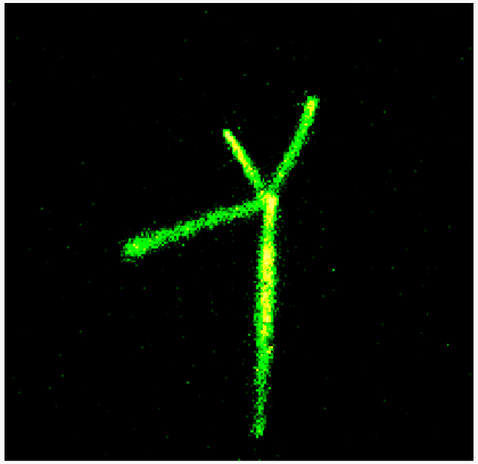


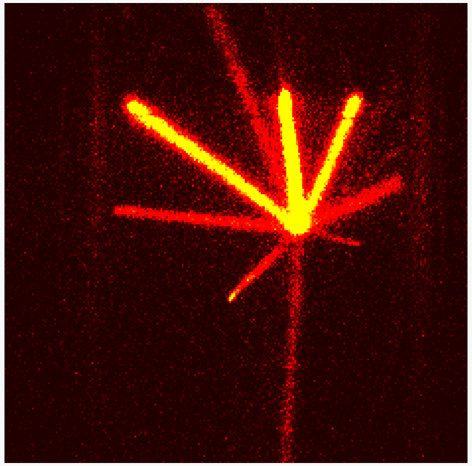
- Brown, PRC 43 (91) R1513
- Ormand, PRC 55 (97) 2407
- Cole, PRC 54 (96) 1240
- Brown *et al.*, PRC 65 (02) 045802

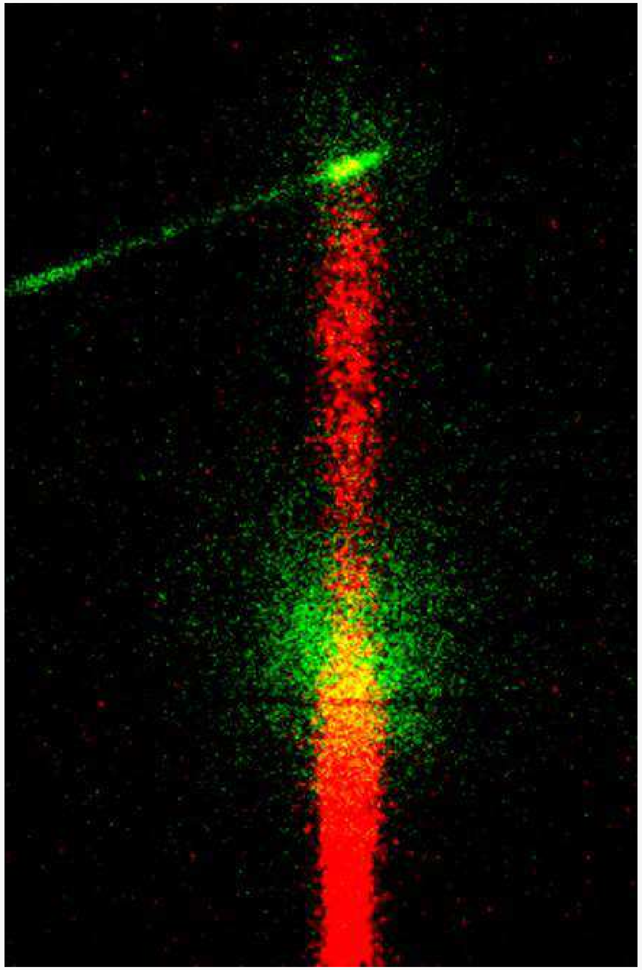
★ exp

TPC with optical readout





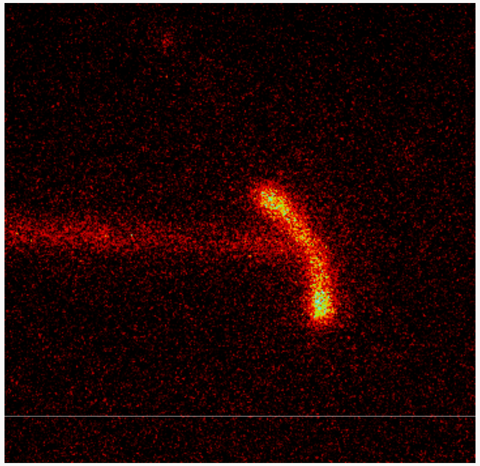




→ Decay event ^{6}He → α + *d* seen on the background of about 10^4 beta rays

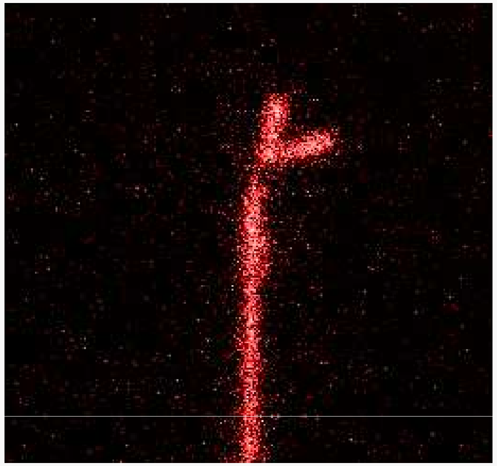
Three cases around Z=28

^{45}Fe



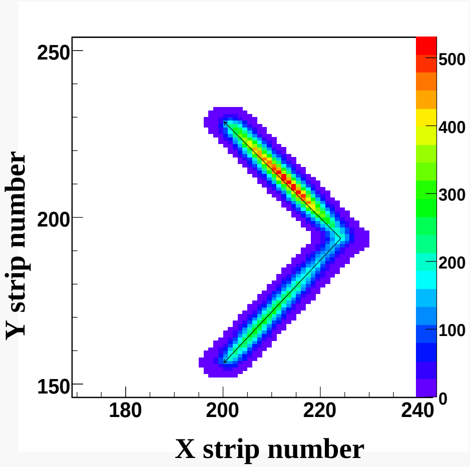
K. Miernik et al., PRL 99 (07) 192501

^{48}Ni

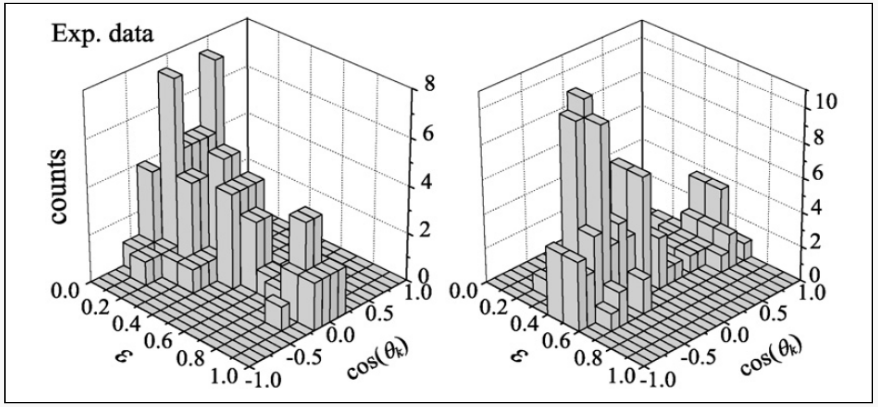


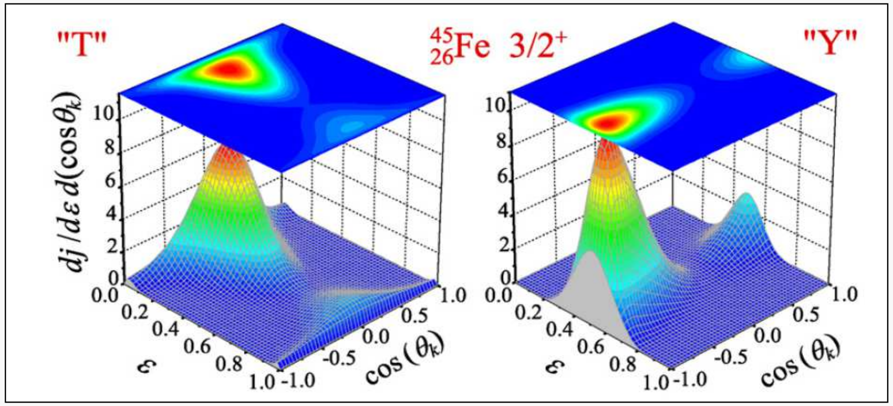
Pomorski et al., PRC 83 (2011) 061303(R)

^{54}Zn



Ascher et al., PRL 107 (2011) 102502

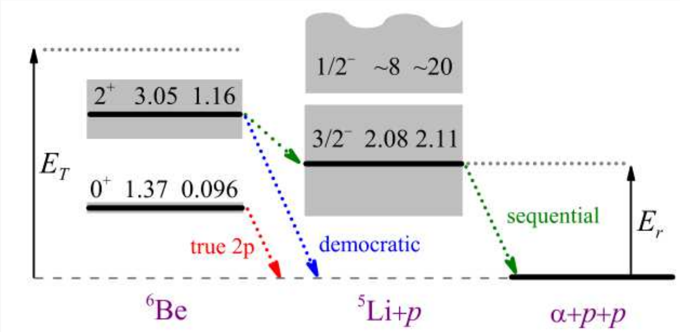


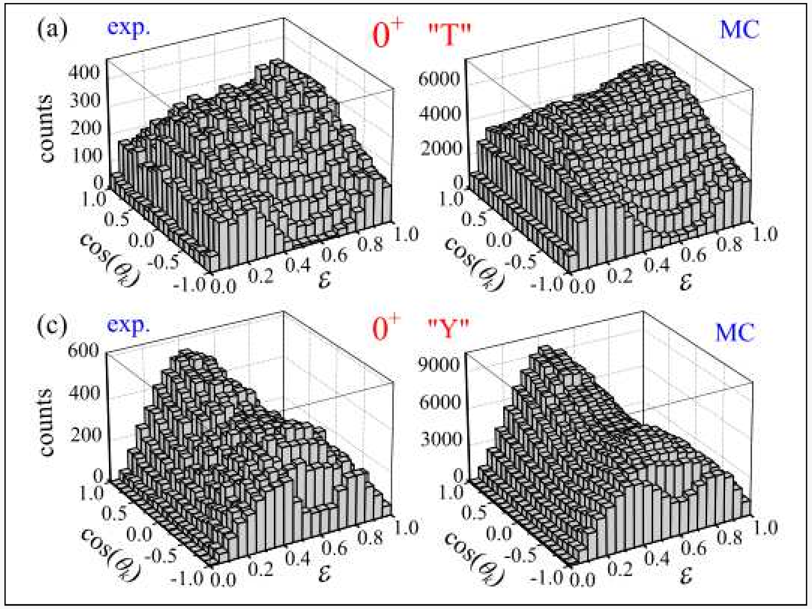


Grigorenko *et al.*, PLB 677 (2009) 30

^{6}Be and ^{19}Mg

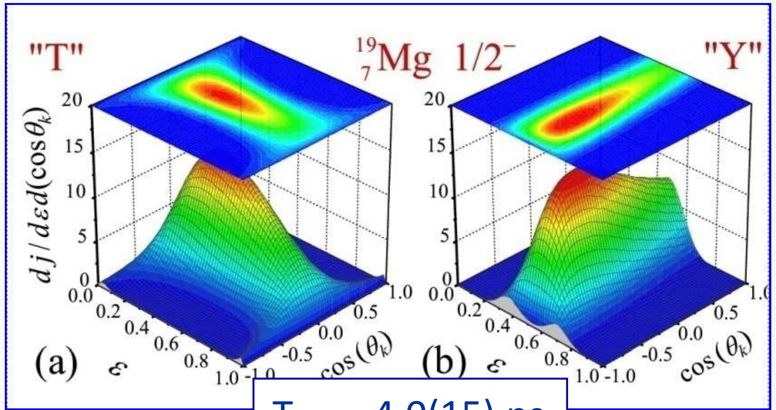
^{7}Be + Be → ^{6}Be @ NSCL



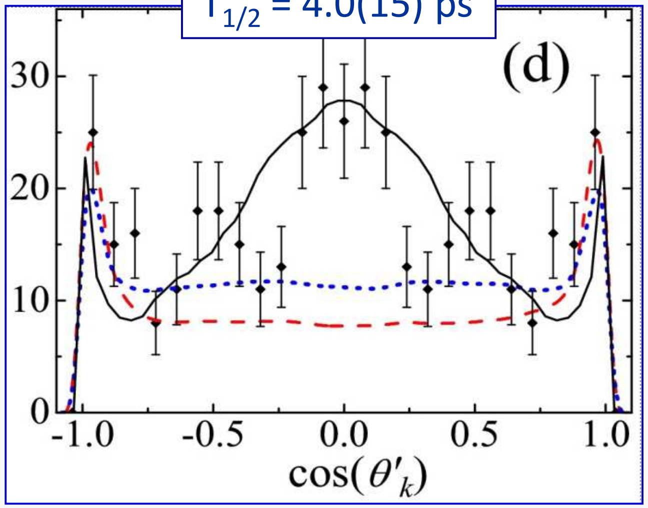


Egorova *et al.*, PRL 109 (2012) 202502

^{20}Mg + Be → ^{19}Mg @ GSI



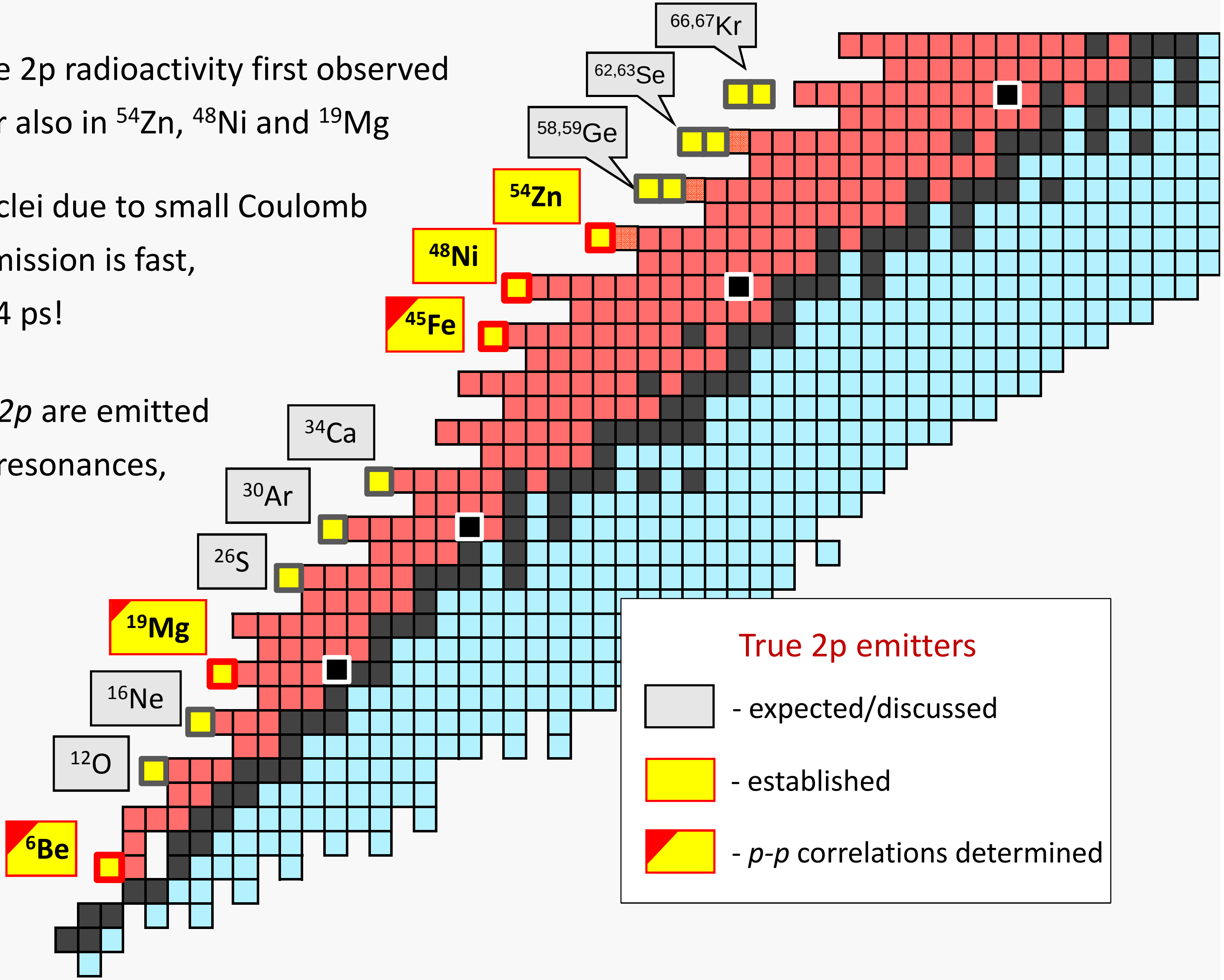
$T_{1/2}$ = 4.0(15) ps



Mukha et al., PRL 99 (2007) 182501
Mukha et al., EPJA 42 (2009) 421

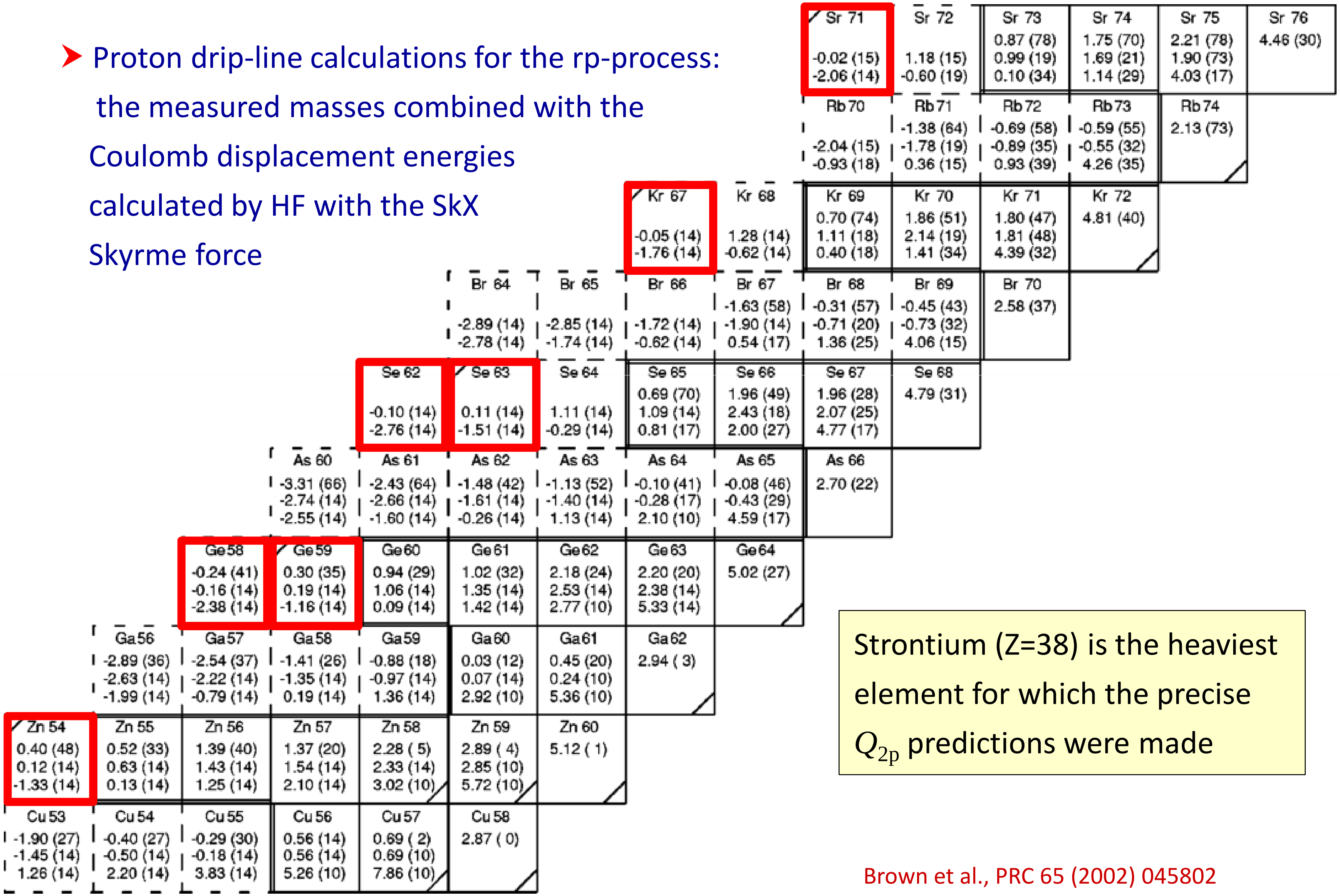
The current status of *2p* emission

- Ground-state 2p radioactivity first observed in ^{45}Fe. Later also in ^{54}Zn, ^{48}Ni and ^{19}Mg
- In lighter nuclei due to small Coulomb barrier *2p* emission is fast, $T_{1/2}(^{19}\mathrm{Mg}) = 4$ ps!
- Below ^{19}Mg *2p* are emitted from broad resonances, like ^{6}Be



Heavier 2p candidates

- Proton drip-line calculations for the rp-process: the measured masses combined with the Coulomb displacement energies calculated by HF with the SkX Skyrme force

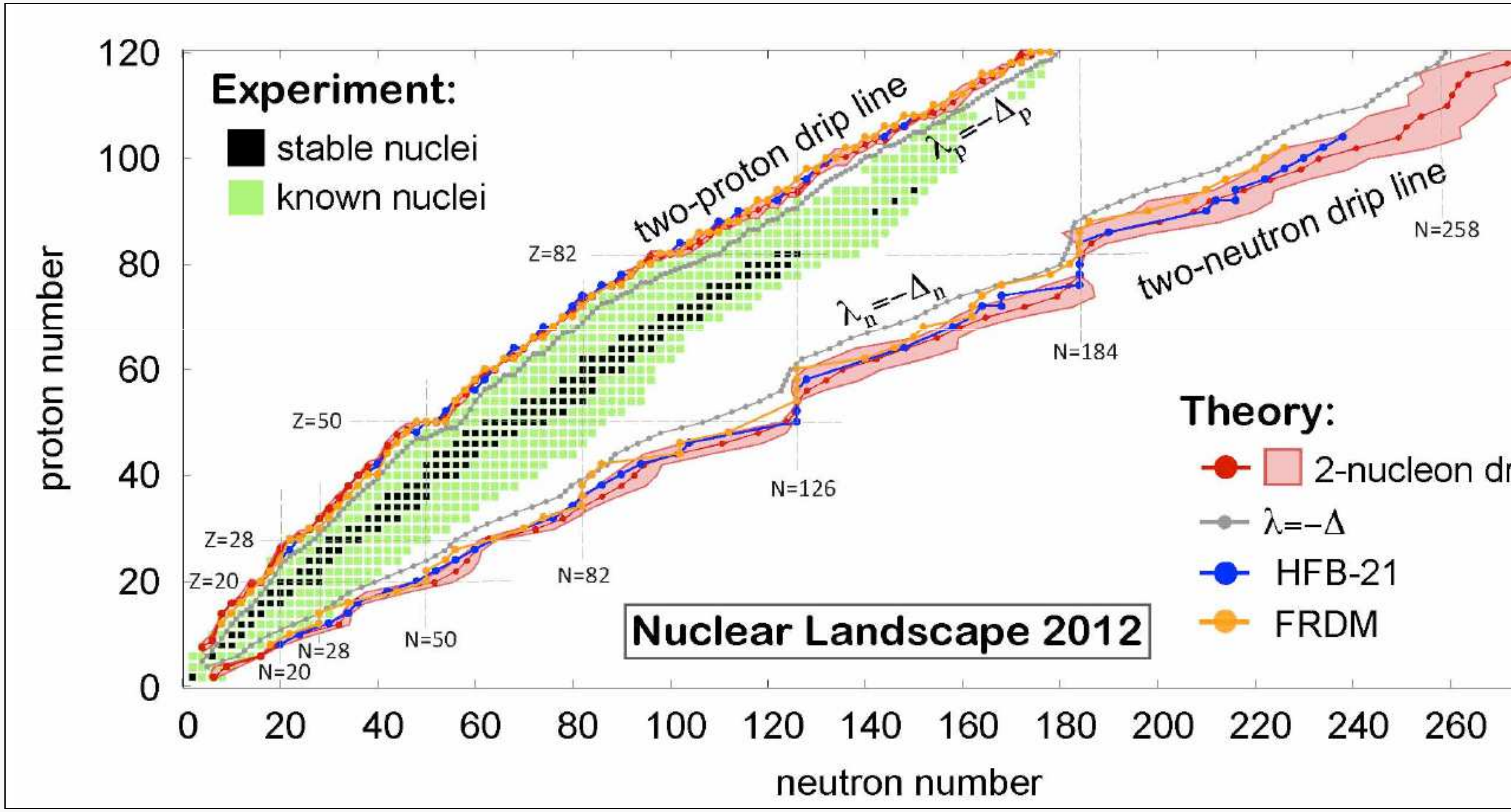


Strontium (Z=38) is the heaviest element for which the precise Q_{2p} predictions were made

Brown et al., PRC 65 (2002) 045802

Nuclear landscape

➤ Global mass predictions using density functional theory with **6 different Skyrme interactions**



SkM
SkP
SLy4
SV-min
UNEDF0
UNEDF1

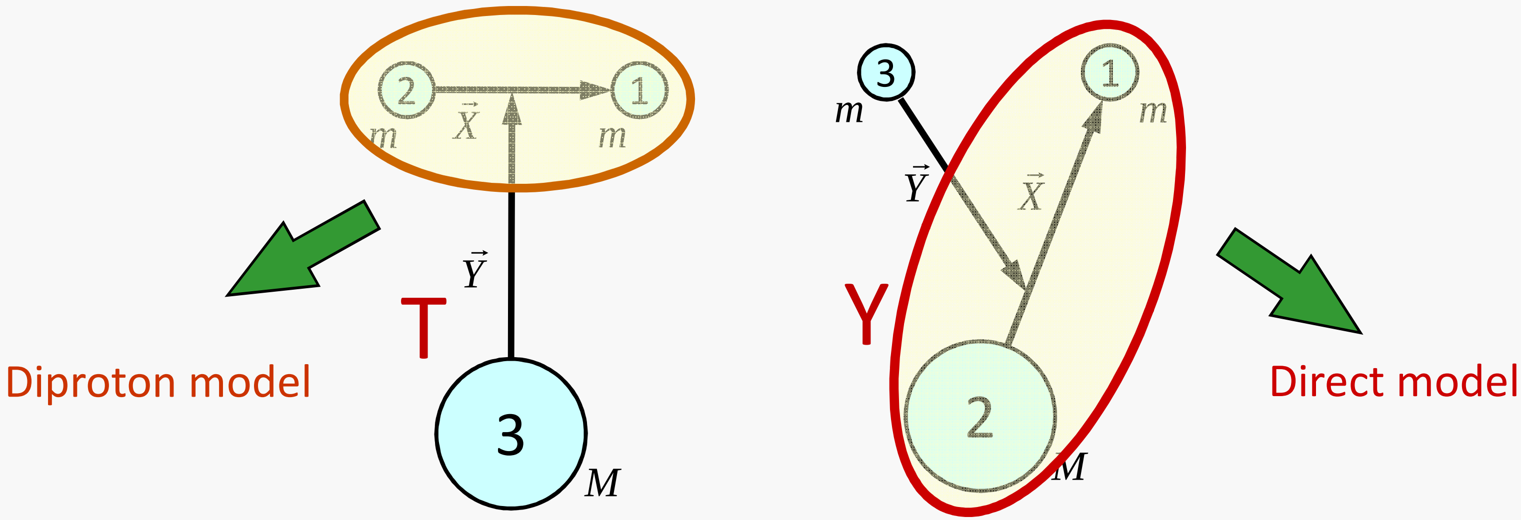
→ There are 6900 ± 500 nuclei bound with Z ≤ 120

Erler et al., Nature 486 (2012) 509

Simplified models

- By simplifying interactions describing the $core+p+p$ system, the three-body decay can be reduced to the combination of two-body processes. With the simplified Hamiltonian, the problem can be solved exactly.

→ Two types of approximations are considered:



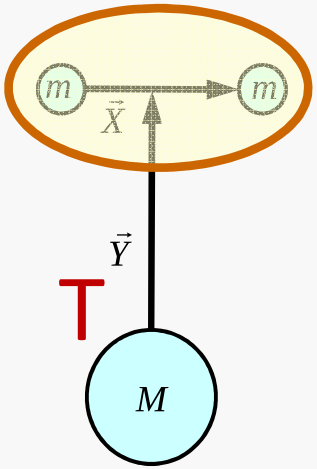
- The simplified models are very useful to estimate decay rates and to verify numerical procedures used in the full three-body model.

Diproton model

- Jacobi T system → **diproton model**

The WKB approximation

$$\Gamma_{2p,dipr} = \theta_{dipr}^2 \mathcal{N} \frac{\hbar^2}{4\mu} \exp\left[-2\int_{r_2}^{r_3} k(r)\,dr\right] \qquad T_{1/2} = \frac{\ln 2\,\hbar}{\Gamma}$$



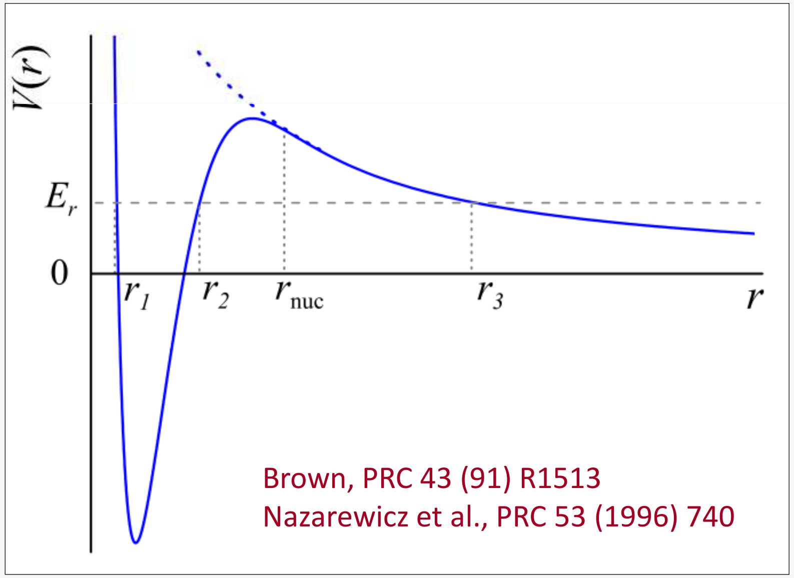
$$\mathcal{N}\int_{r_1}^{r_2} \frac{dr}{2k(r)} = 1$$

$$k(r) = \sqrt{2\mu\left|E_T - 2V_p(r)\right|}\Big/\hbar$$

$$\theta_{\rm dipr}^2 = \frac{(2n)!}{2^{2n}(n!)^2}\left[\frac{A}{A-2}\right]^{2n} \mathcal{O}^2$$

$$n \approx (3Z)^{1/3} - 1$$

$$\mathcal{O}^2 = \left|\langle \psi_f | \psi_{2p} | \psi_i \rangle\right|^2$$

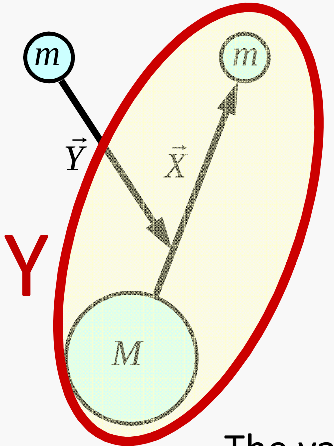


The value of cluster overlap determined from the known half-lives of 2p emitters: ^{19}Mg, ^{45}Fe, ^{48}Ni, and ^{54}Zn → $\mathcal{O}^2 = 0.015$

Direct model

- Jacobi Y system → **direct model**

$$\Gamma_{2p,dir} = \frac{Q_{2p}}{2\pi}\left(Q_{2p}-2E_p\right)^2 \int_0^1 d\varepsilon \frac{\Gamma_x\left(\varepsilon Q_{2p}\right)}{\left(\varepsilon Q_{2p}-E_p\right)^2+\Gamma_x\left(\varepsilon Q_{2p}\right)^2/4} \times \frac{\Gamma_y\left(\left(1-\varepsilon\right)Q_{2p}\right)}{\left(\left(1-\varepsilon\right)Q_{2p}-E_p\right)^2+\Gamma_y\left(\left(1-\varepsilon\right)Q_{2p}\right)^2/4}$$

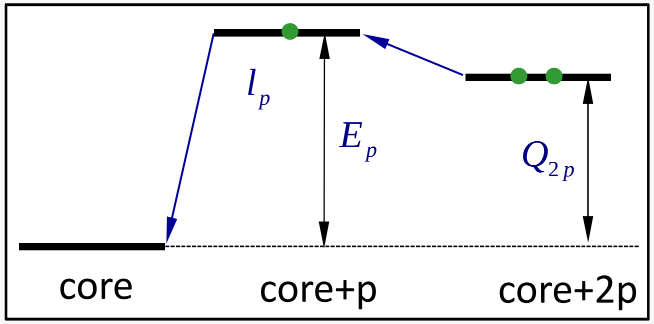


Γ_i is the width of the two-body subsystem: $\Gamma_i\left(E\right) = 2\gamma_i^2 P_{l_p}\left(E,R,Z_i\right)$

penetrability: $P_{l_p}\left(E,R,Z_i\right) = \frac{kR}{F_{l_p}^2\left(\eta,kR\right)+G_{l_p}^2\left(\eta,kR\right)}$

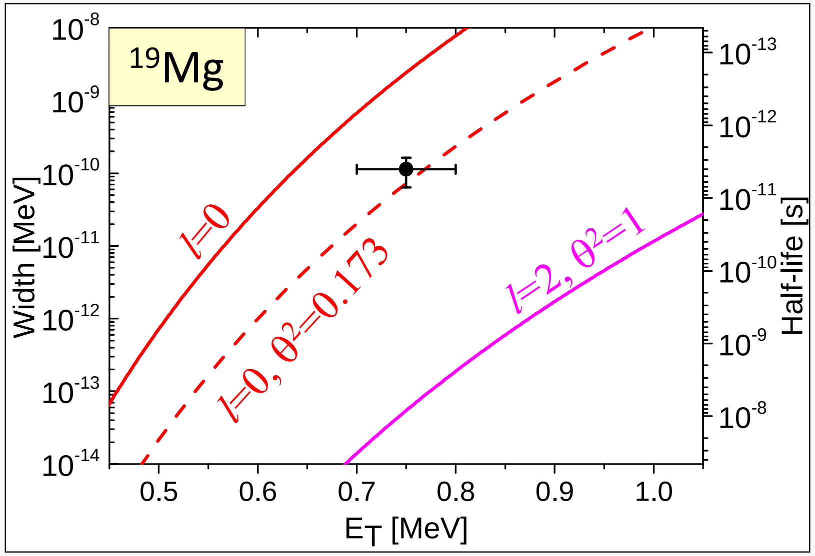
reduced width: $\gamma_i^2 = \frac{\hbar^2}{2\mu_i R^2}\theta_i^2$

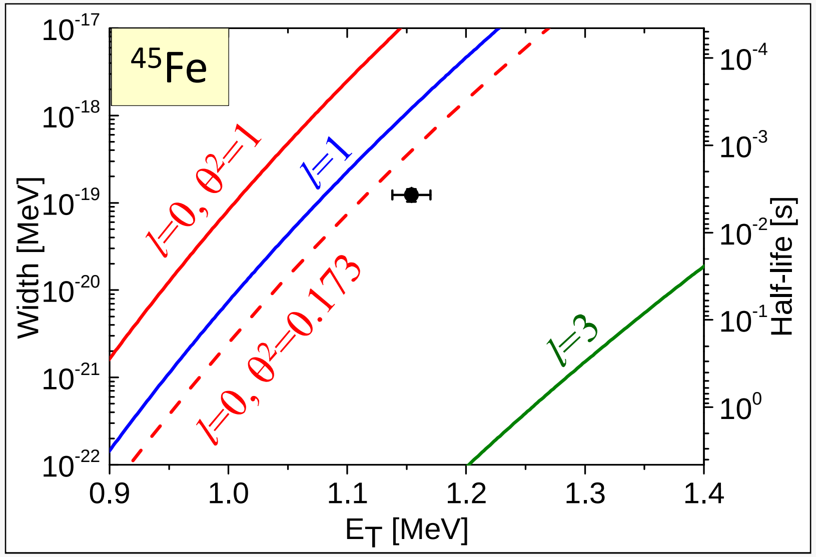
The value of spectroscopic factor determined from the experimental half-lives of known 2p emitters: ^{19}Mg, ^{45}Fe, ^{48}Ni, and ^{54}Zn, assuming $l_p = 0$ ➡ $\theta_x^2 = \theta_y^2 = 0.173$

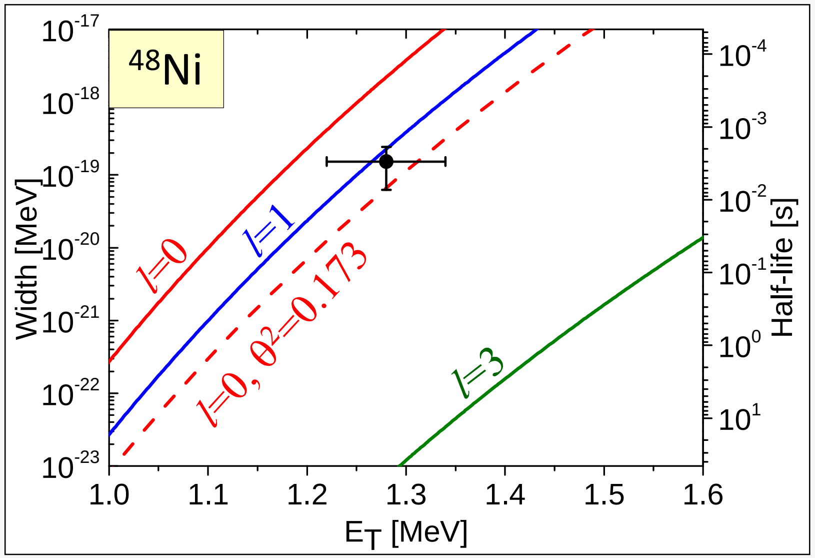


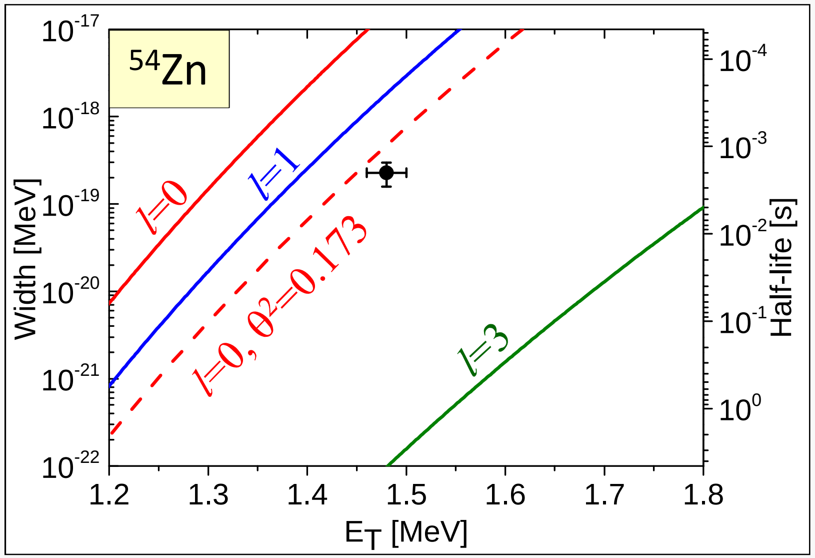
Grigorenko and Zhukov, PRC 76 (07) 014009
M.P. et al, RMP (2012) 567

Direct model for known 2p emitters









2p-emission half-lives

Direct model

$$\Gamma_{2p,dir} \cong \frac{8Q_{2p}}{\pi\left(Q_{2p}-2E_p\right)^2}\int_0^1 d\varepsilon\,\Gamma_x\left(\varepsilon Q_{2p}\right)\Gamma_y\left(\left(1-\varepsilon\right)Q_{2p}\right)$$

Diproton model

$$\Gamma_{2p,dipr} = \theta_{dipr}^2\mathcal{N}\frac{\hbar^2}{4\mu}\exp\left[-2\int_{r_{in}}^{r_{out}} k\left(r\right)dr\right]$$

- The comparison of predicted half-lives with experiment

$$T_{1/2} = \frac{\ln 2\hbar}{\Gamma}$$

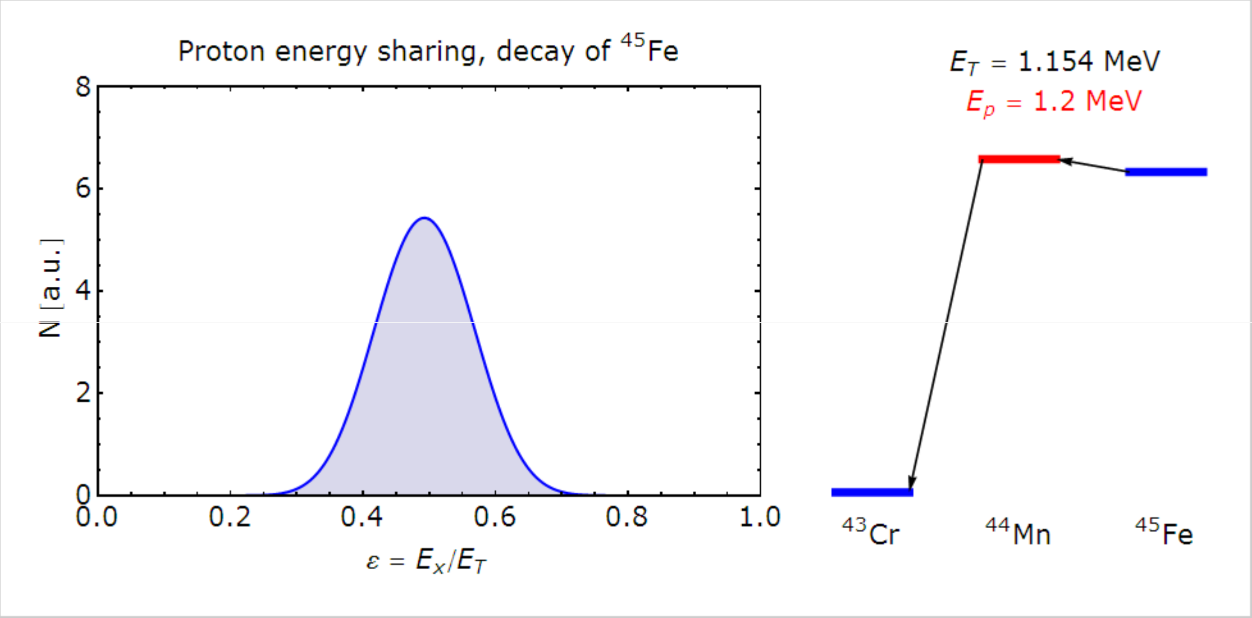
$l_p = 0$

Nucleus	Experiment	Direct	Diproton
^{19}Mg [7]	4.0(15) ps	6.2 ps	12.3 ps
^{45}Fe [10]	3.7(4) ms	1.1 ms	8.7 ms
^{48}Ni [8]	$3.0^{+2.2}_{-1.2}$ ms	6.8 ms	5.3 ms
^{54}Zn [9]	$1.98^{+0.73}_{-0.41}$ ms	1.0 ms	0.8 ms

Olsen et al., PRL 110 (2013) 222501

Simultaneous vs. sequential

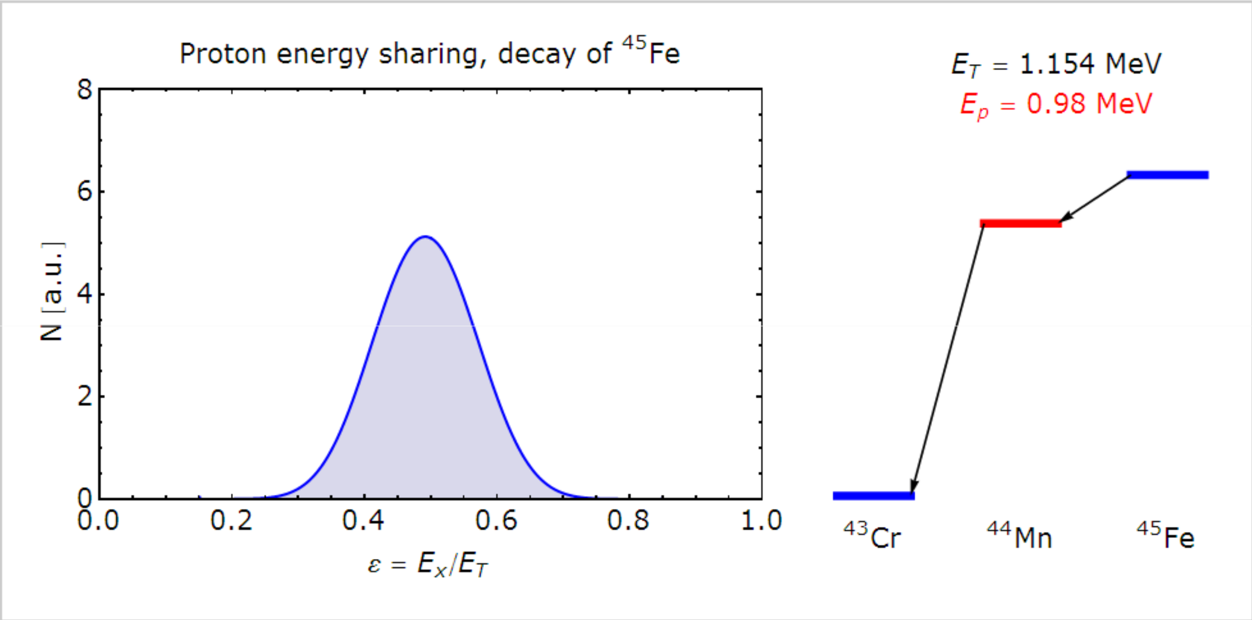
- In the direct model we can investigate how the proton's energy spectrum depends on the position of the intermediate state



$Q_{2p} = 1.15\ \text{MeV},\ \ Q_{1p} = -0.05\ \text{MeV}$ ➡ True 2p decay (simultaneous)

Simultaneous vs. sequential

- In the direct model we can investigate how the proton's energy spectrum depends on the position of the intermediate state

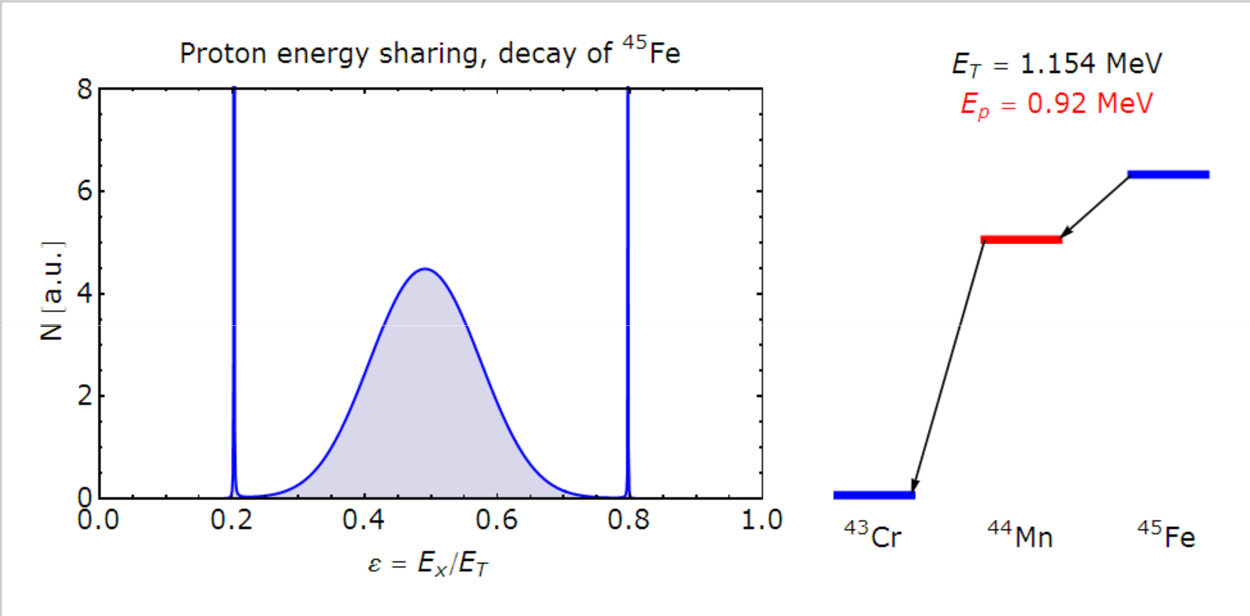


$$Q_{2p} = 1.15 \text{ MeV}, \ Q_{1p} = 0.17 \text{ MeV}$$

➡ Still simultaneous 2p!

Simultaneous vs. sequential

- In the direct model we can investigate how the proton's energy spectrum depends on the position of the intermediate state

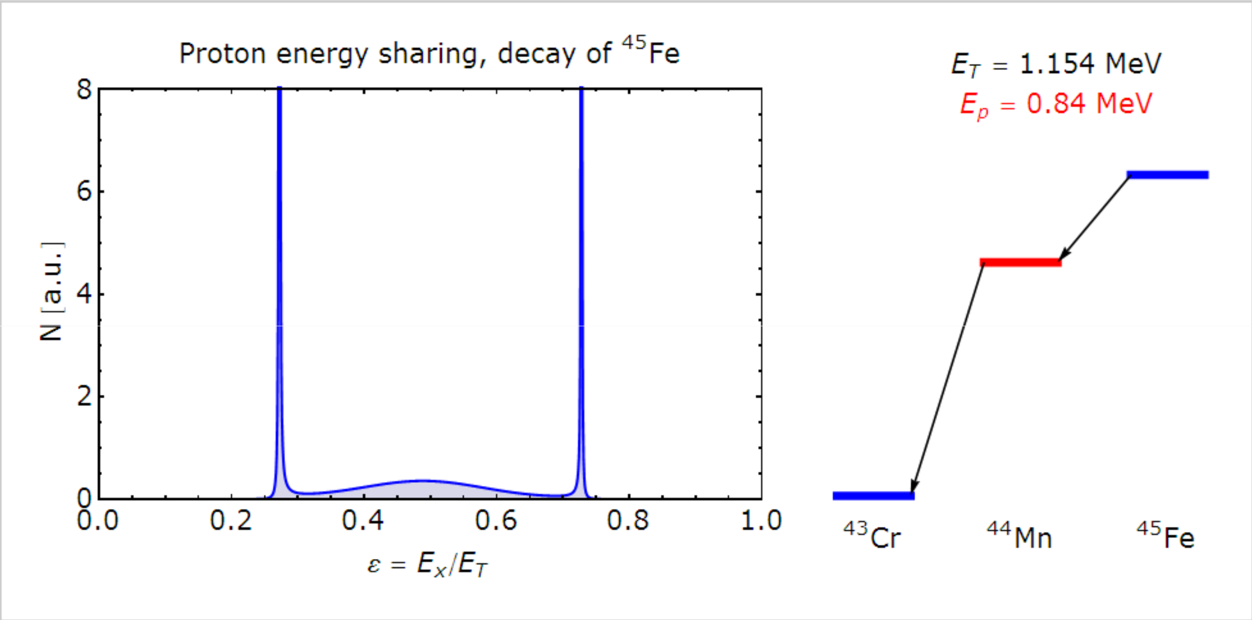


$$Q_{2p} = 1.15 \text{ MeV}, \; Q_{1p} = 0.23 \text{ MeV}$$

➡ Sequential emission shows up!
Simultaneous component still visible.

Simultaneous vs. sequential

- In the direct model we can investigate how the proton's energy spectrum depends on the position of the intermediate state



$Q_{2p} = 1.15$ MeV, $Q_{1p} = 0.31$ MeV → Sequential 2p emission dominates

→ Rough criterion: for $Q_p < 0.2\, Q_{2p}$ true, simultaneous 2p decay

for $Q_p > 0.2\, Q_{2p}$ sequential 2p emission

Predictions

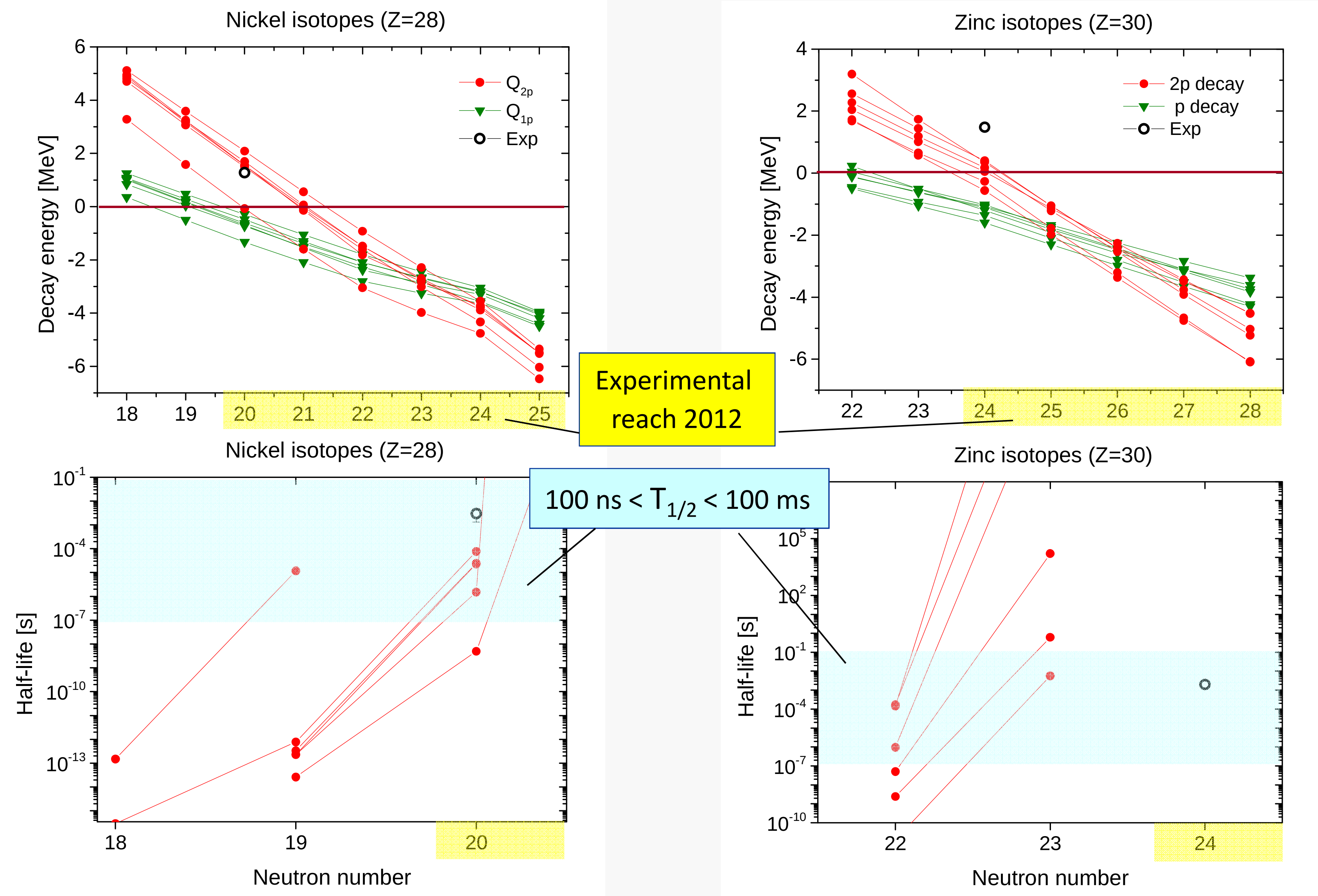
- Nuclear binding energies: deformed DFT with six effective Skyrme interaction plus density-dependent zero-range pairing term (Erler et al., Nature 486 (2012) 509)

- The half-lives for 2p emission: estimated with the direct and diproton models. The α decay half-lives calculated using global, fenomenological formula by Koura, J. Nucl. Science and Tech. 49 (2012) 816

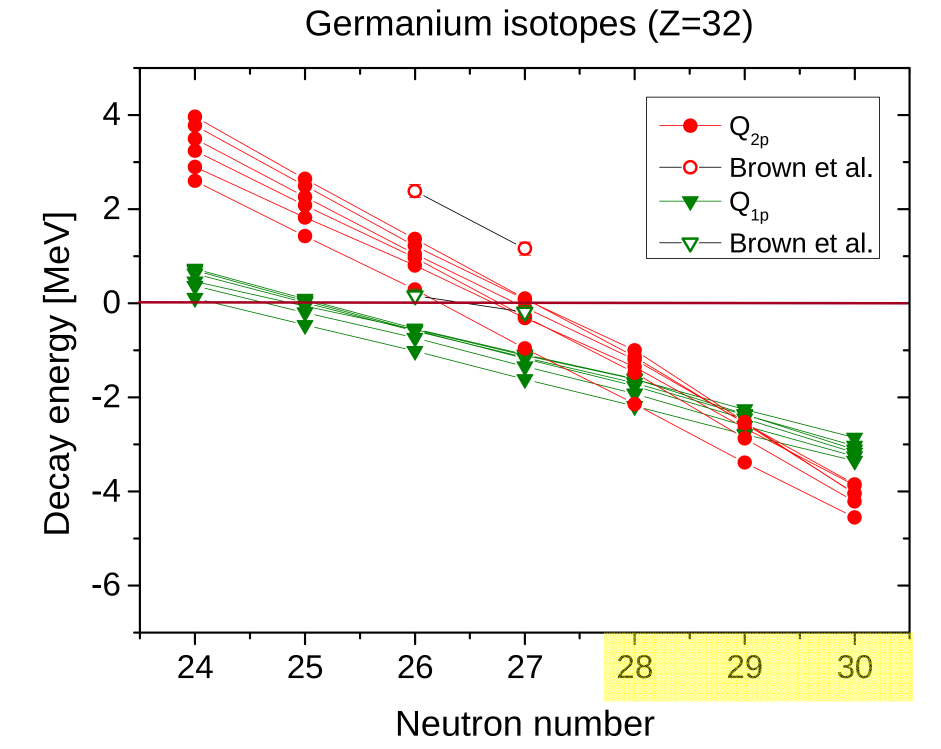
- The adopted decay-time criterion (arbitrary):
  we consider a nucleus to be a **2p decay candidate** predicted by a given mass (and decay) model when 100 ns < $T_{1/2}$ < 100 ms.
  Longer half-life will loose competition with β decay.
  Shorter will be difficult to detect using in-flight separation and implantation technique.

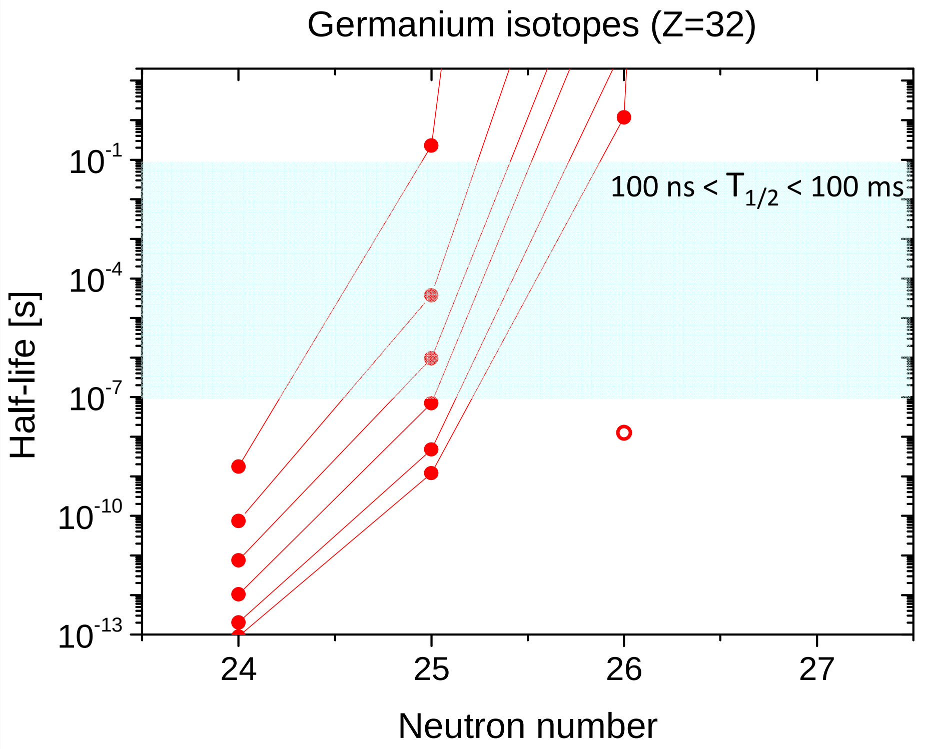
- Counting:
  a candidate has the model multiplicity $m(Z,N) = k$
  when it is predicted by k mass models.

Nickel and zinc in the direct model



Germanium

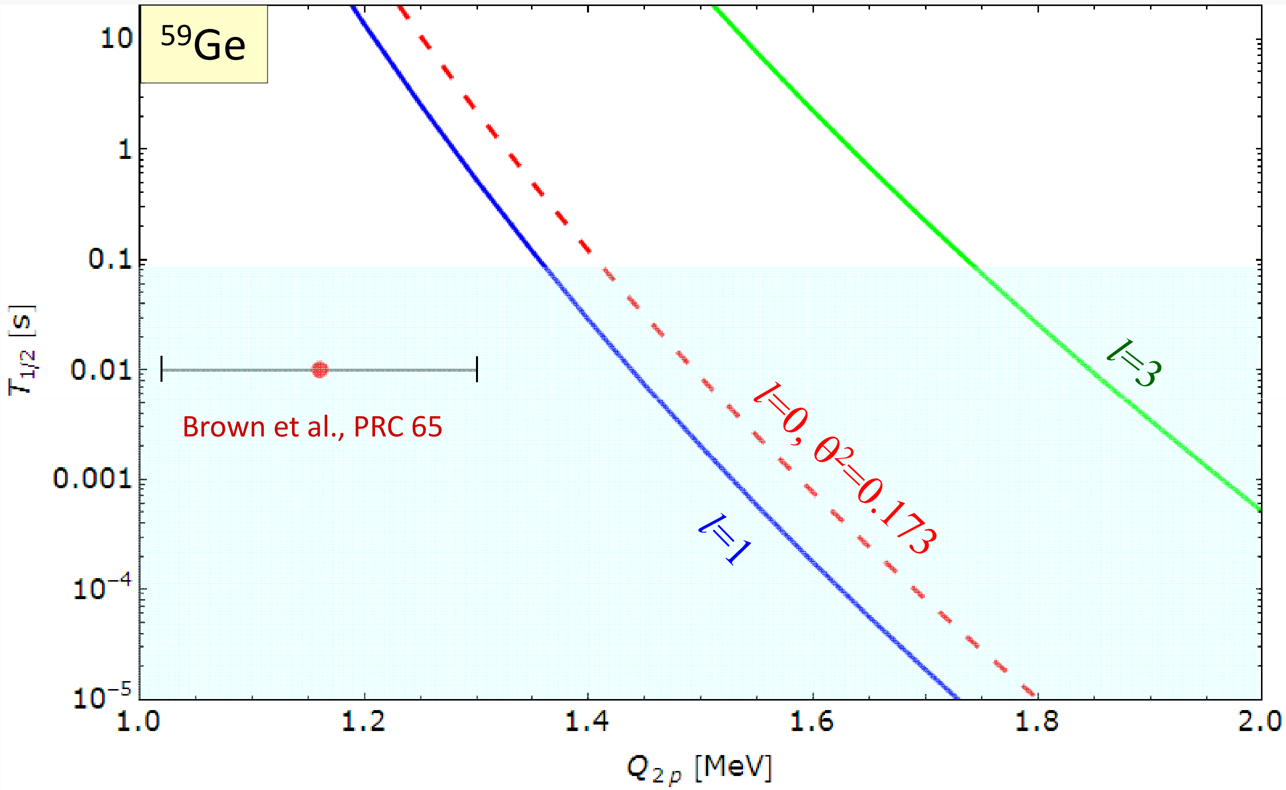




- We predict ^{57}Ge to be 2p radioactive ($m=2$)
- Taking decay energies from Brown, the 2p half-life of ^{58}Ge comes shorter than 100 ns and that of ^{59}Ge longer than 100 ms

Brown et al., PRC 65 (2002) 045802

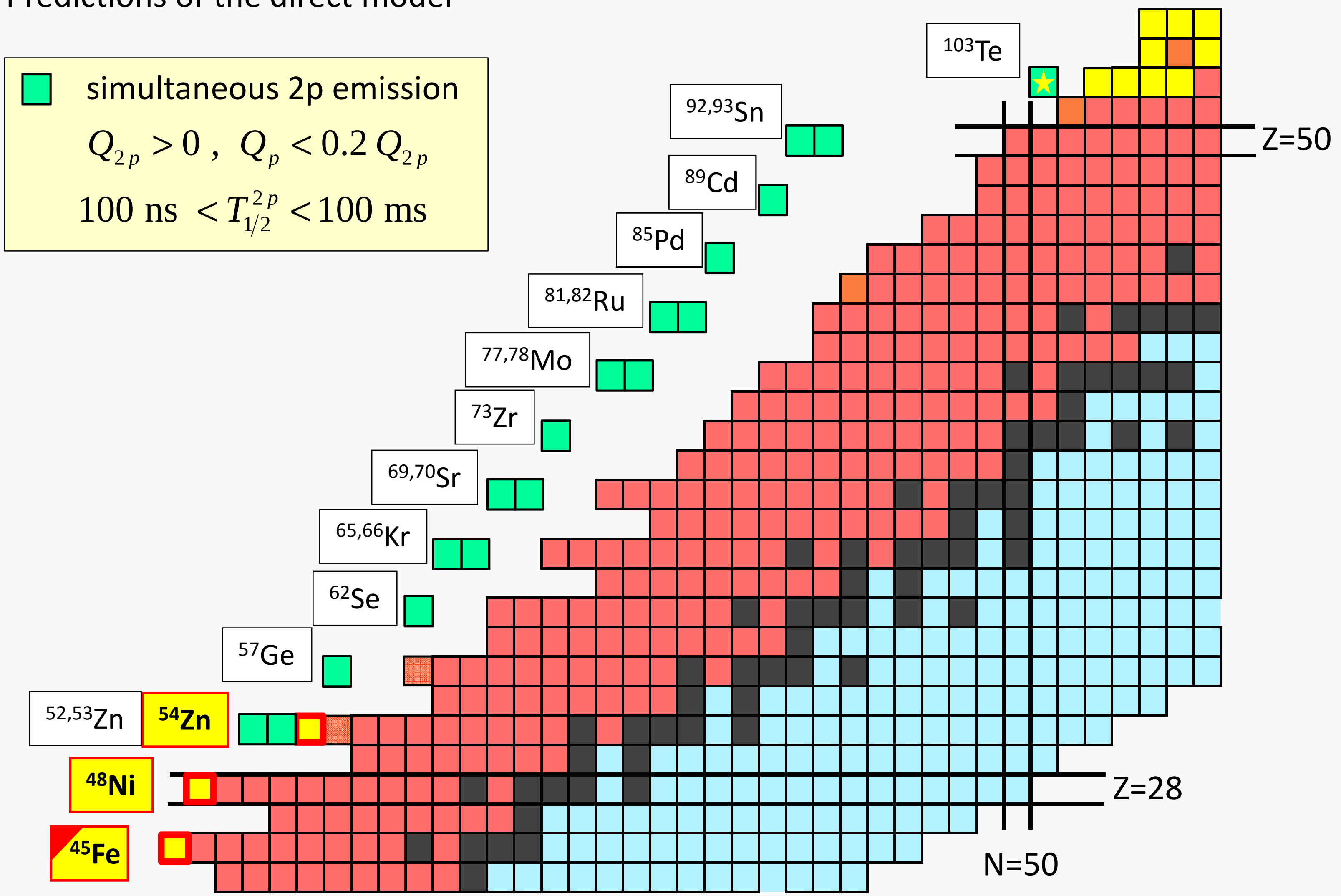
^{59}Ge – do we have a chance?



- Observation of 2p decay of ^{59}Ge in rather unlikely, unless Brown et al. are wrong by 2σ …

Heavy 2p landscape

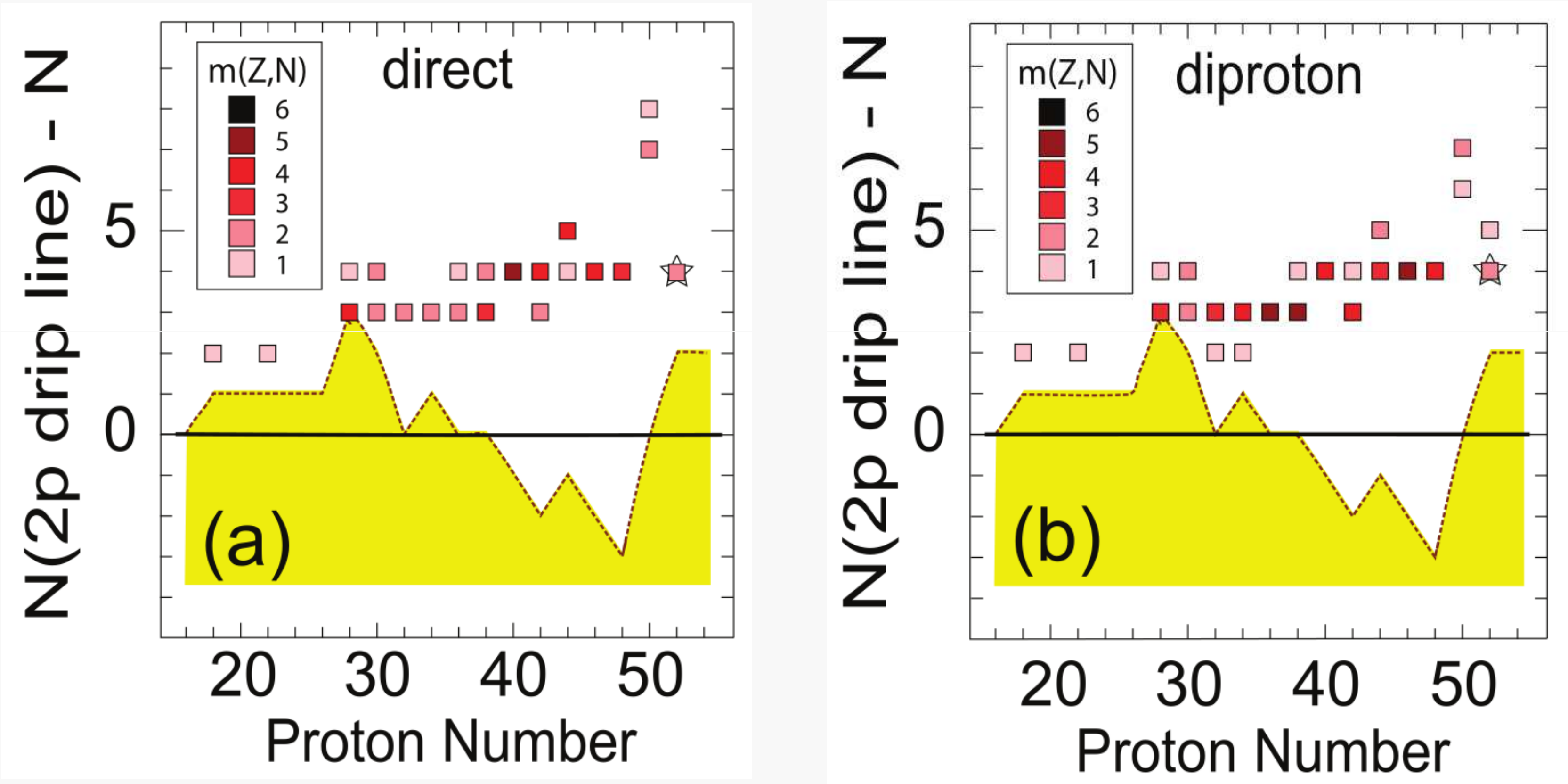
- Predictions of the direct model



True 2p landscape

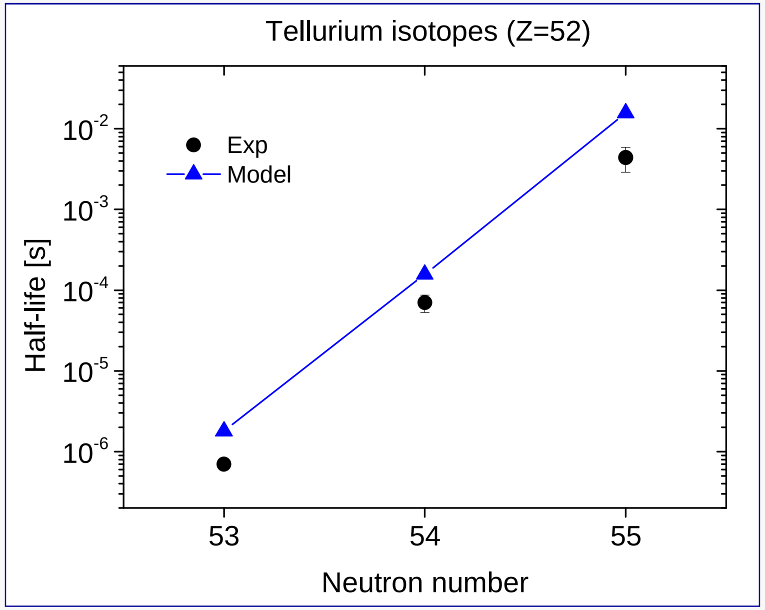
- Predicted candidates relative to the 2p dripline

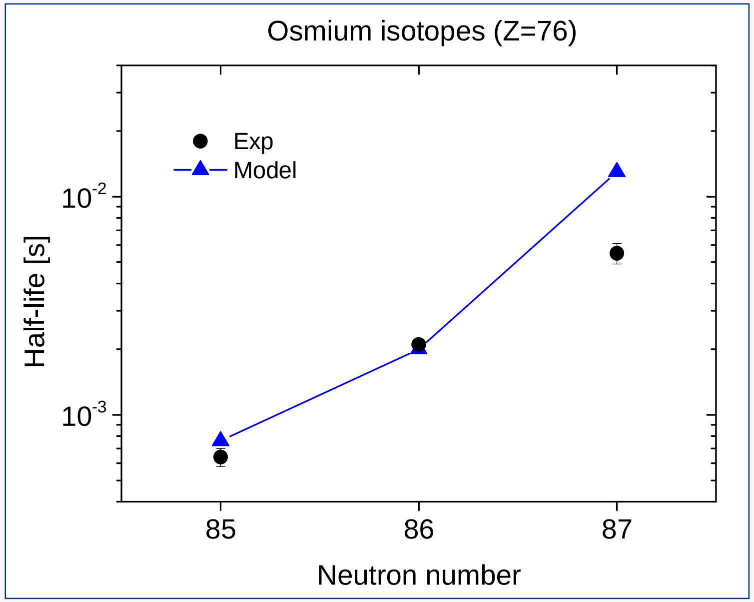
$100\ \text{ns} < T_{2p} < 100\ \text{ms}$



α -emission

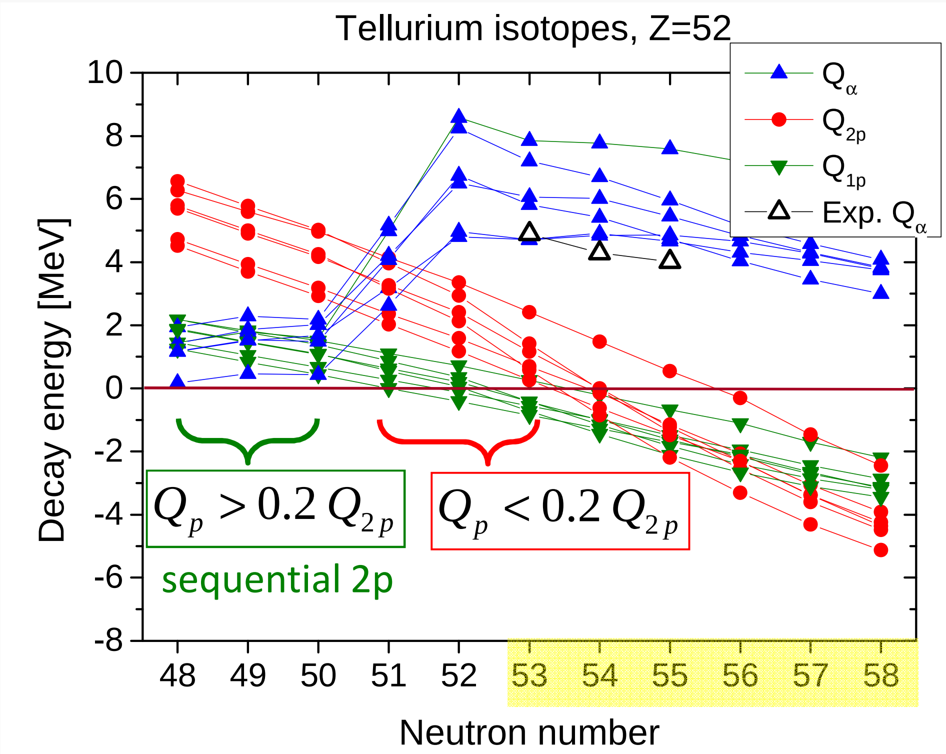
- Global, fenomenological formula for α decay half-lives: H. Koura 2012

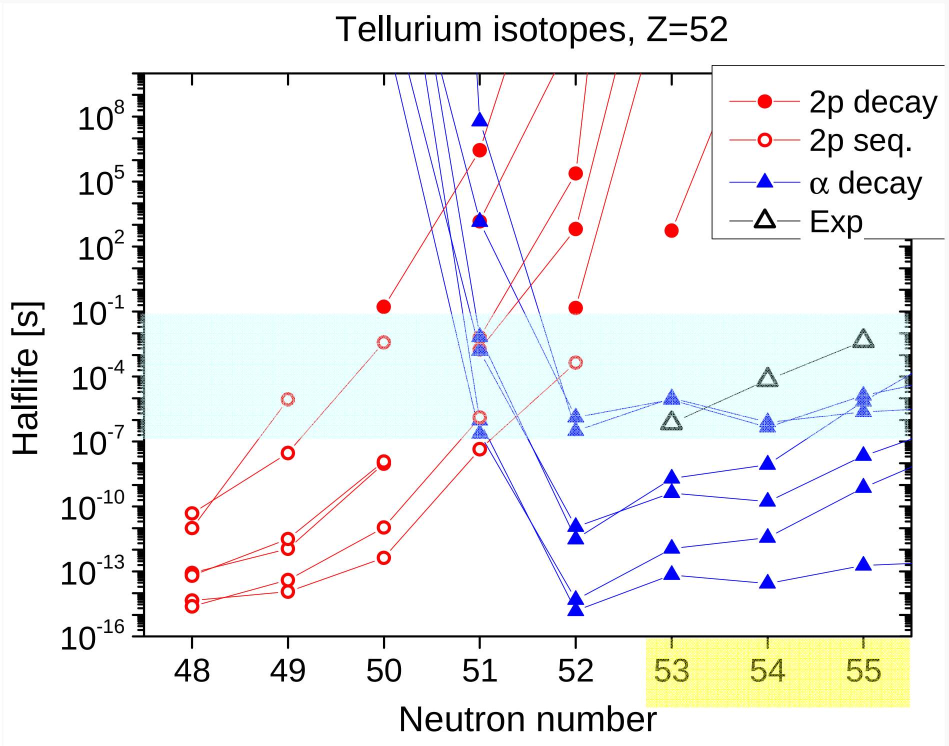




Koura, J. Nucl. Science and Tech. 49 (2012) 816

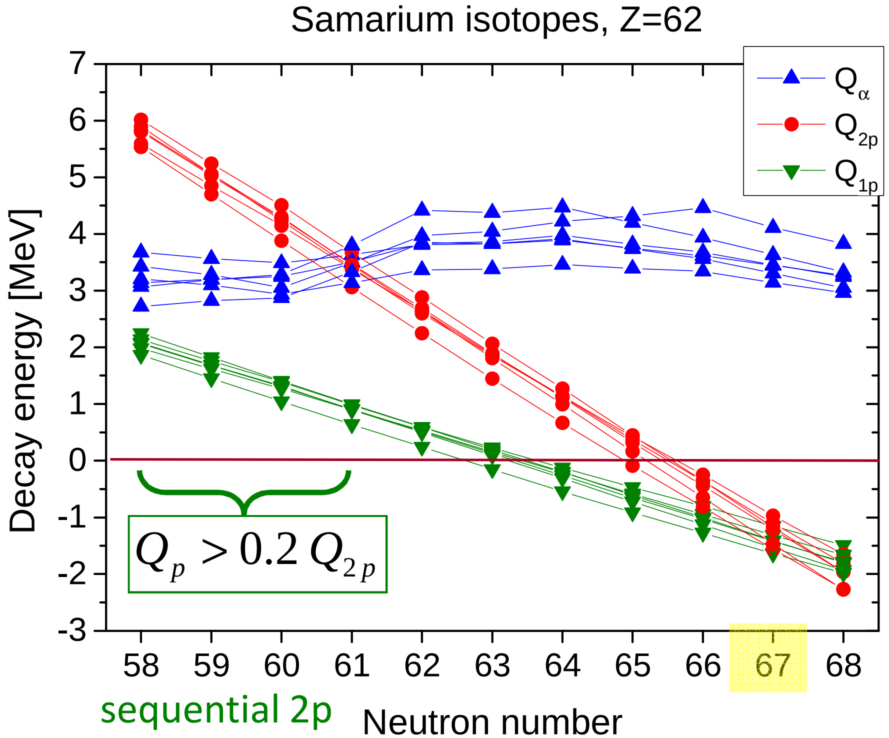
Tellurium

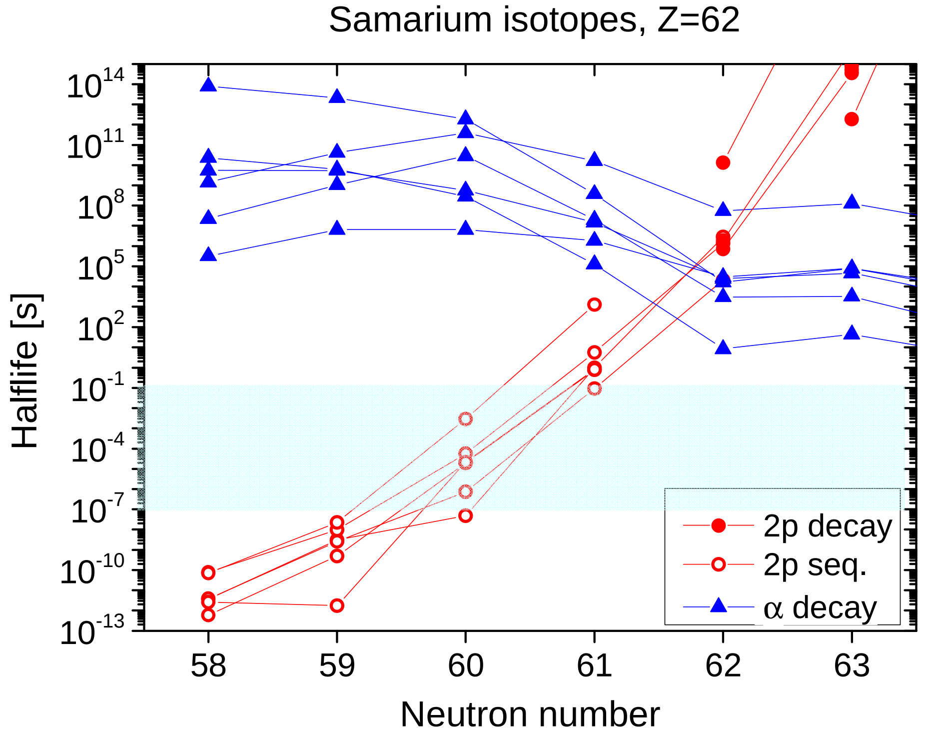




- At [103]Te a transition from the simultaneous 2p to the sequential emission occurs
- In addition, in [103]Te both decays, α and 2p may be observable!

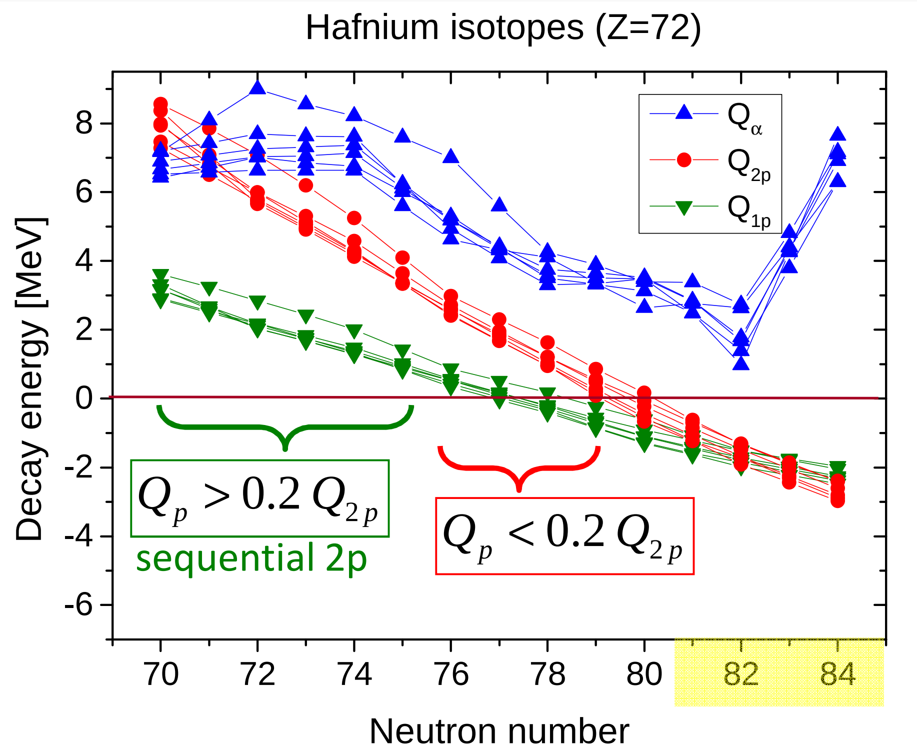
Samarium

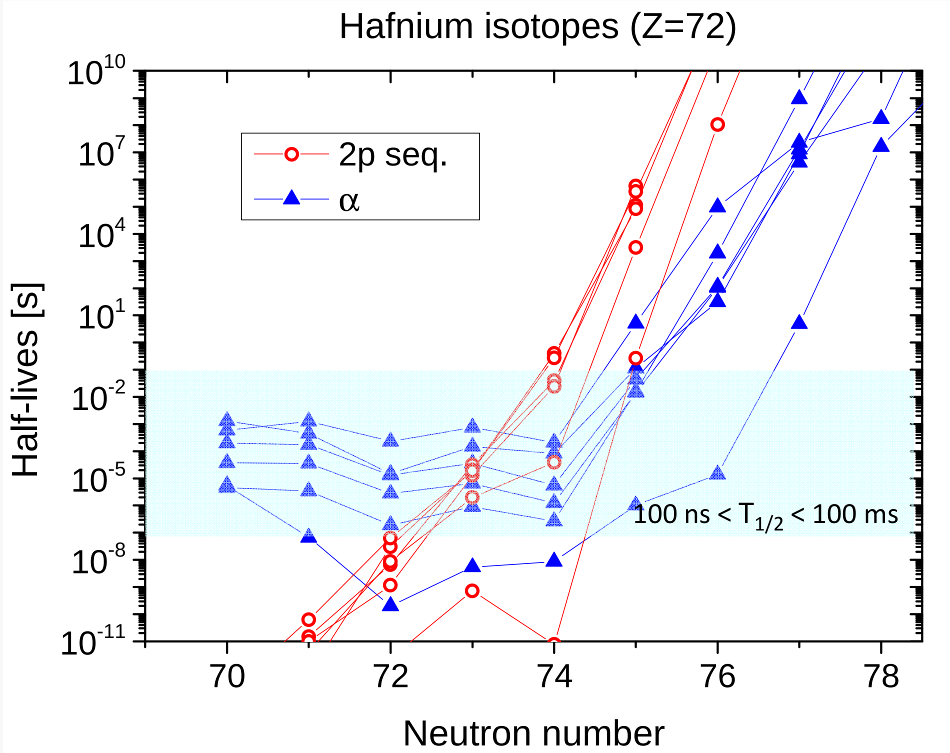




- When the energy condition for the true 2p decay is fulfilled, the predicted half-life is extremely long
- When the fast proton emission becomes possible, it proceeds as the sequential 2p decay

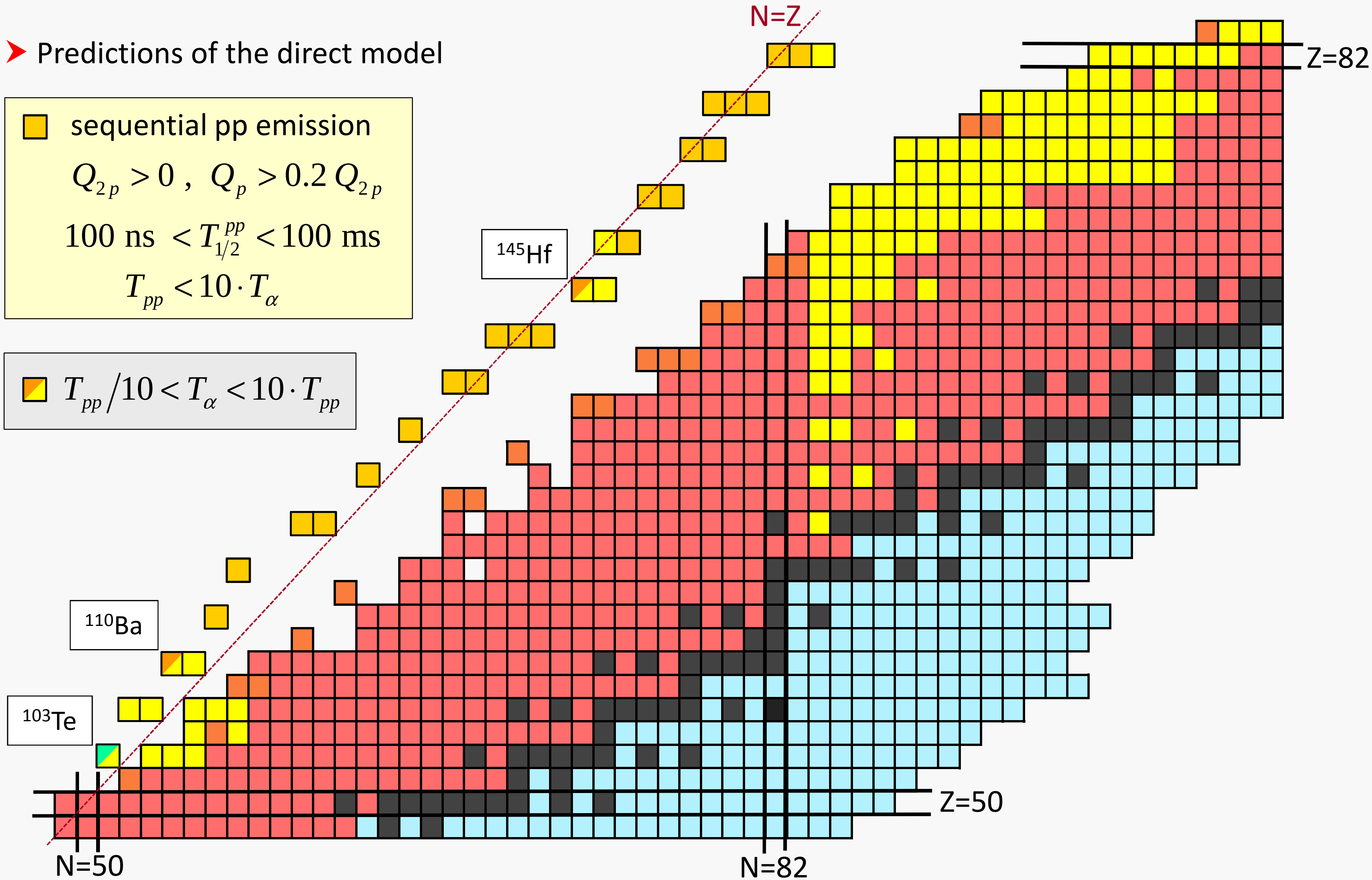
Hafnium


Hafnium isotopes (Z=72)
Decay energy [MeV]
Neutron number
Q_α
Q_{2p}
Q_{1p}
$Q_p > 0.2\,Q_{2p}$
sequential 2p
$Q_p < 0.2\,Q_{2p}$

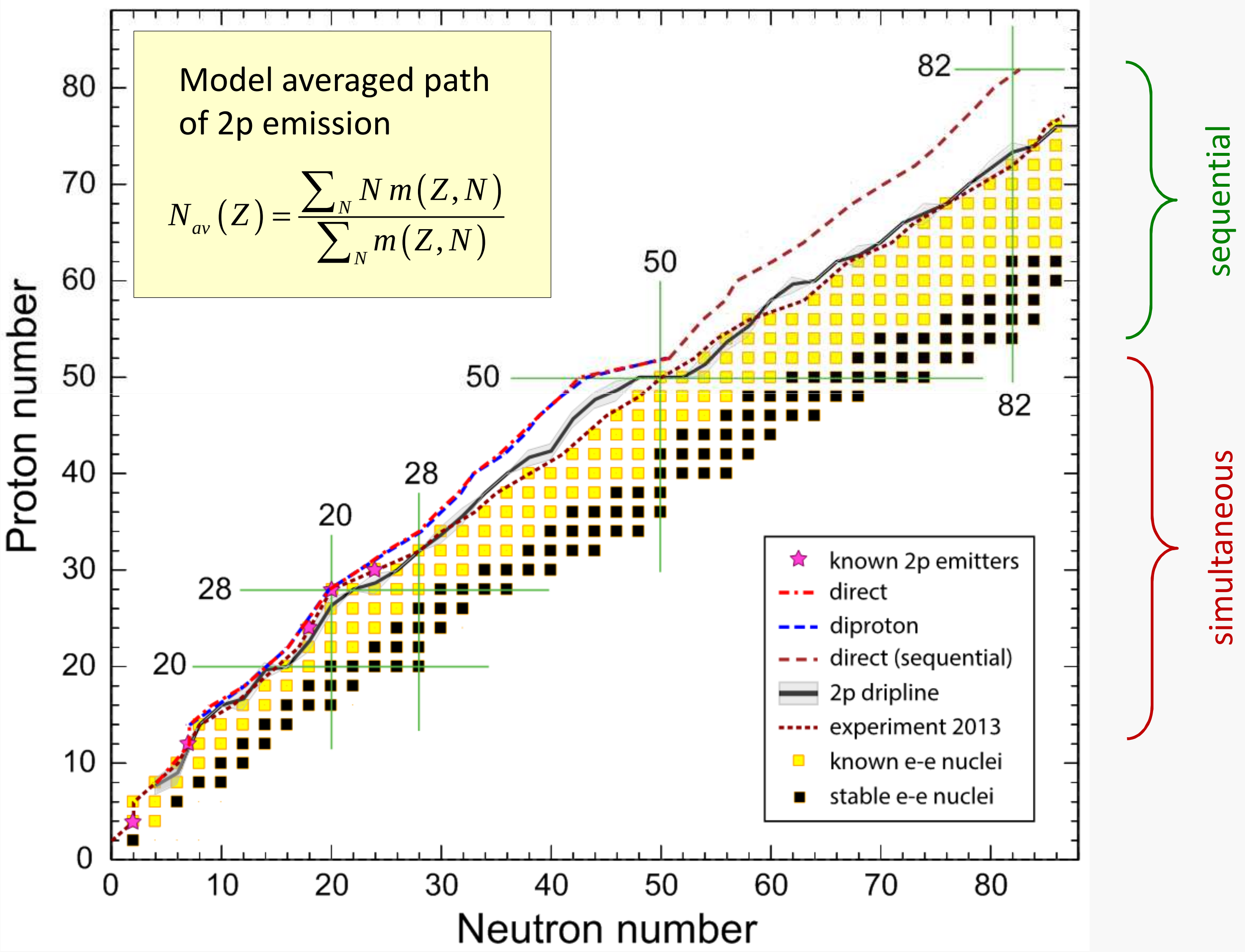

Hafnium isotopes (Z=72)
Half-lives [s]
Neutron number
2p seq.
α
100 ns < $T_{1/2}$ < 100 ms

Between tellurium and lead

- Predictions of the direct model



Full 2p landscape



Summary

- The direct (simultaneous) ground-state ***2p* emission established** for
  ^{6}Be, ^{19}Mg, ^{45}Fe, ^{48}Ni, and ^{54}Zn.
  The hunt for other cases continues: ^{30}Ar, ^{59}Ge,… .

- For every even-Z element between zinc and tellurium (Z=52) the isotopes decaying by *2p* radioactivity in the time window $100\ \text{ns} < T_{1/2} < 100$ ms are predicted.

- In **^{103}Te** the competition between simultaneous *2p*, sequential *pp*, and α emission may occur. For **^{145}Hf** the competition between α and sequential *pp* is predicted.

- Above tellurium the limit of decay spectroscopy is represented by sequential pp emission, except for xenon (Z=54) where α decay dominates.

- Above lead (Z=82) α decay dominates, no *2p* emission is expected to be observed.

Thank you!