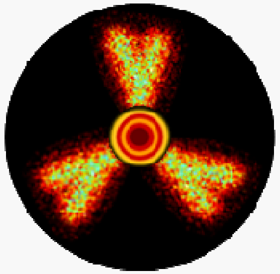
Landscape of two-proton radioactivity



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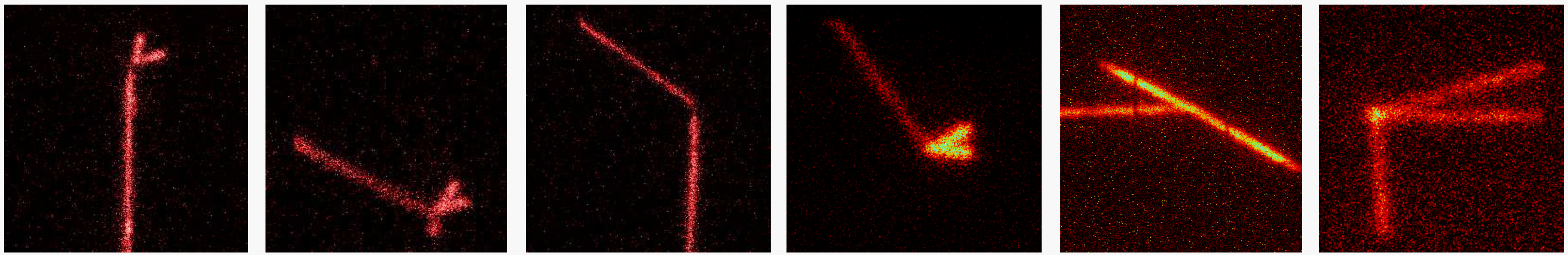
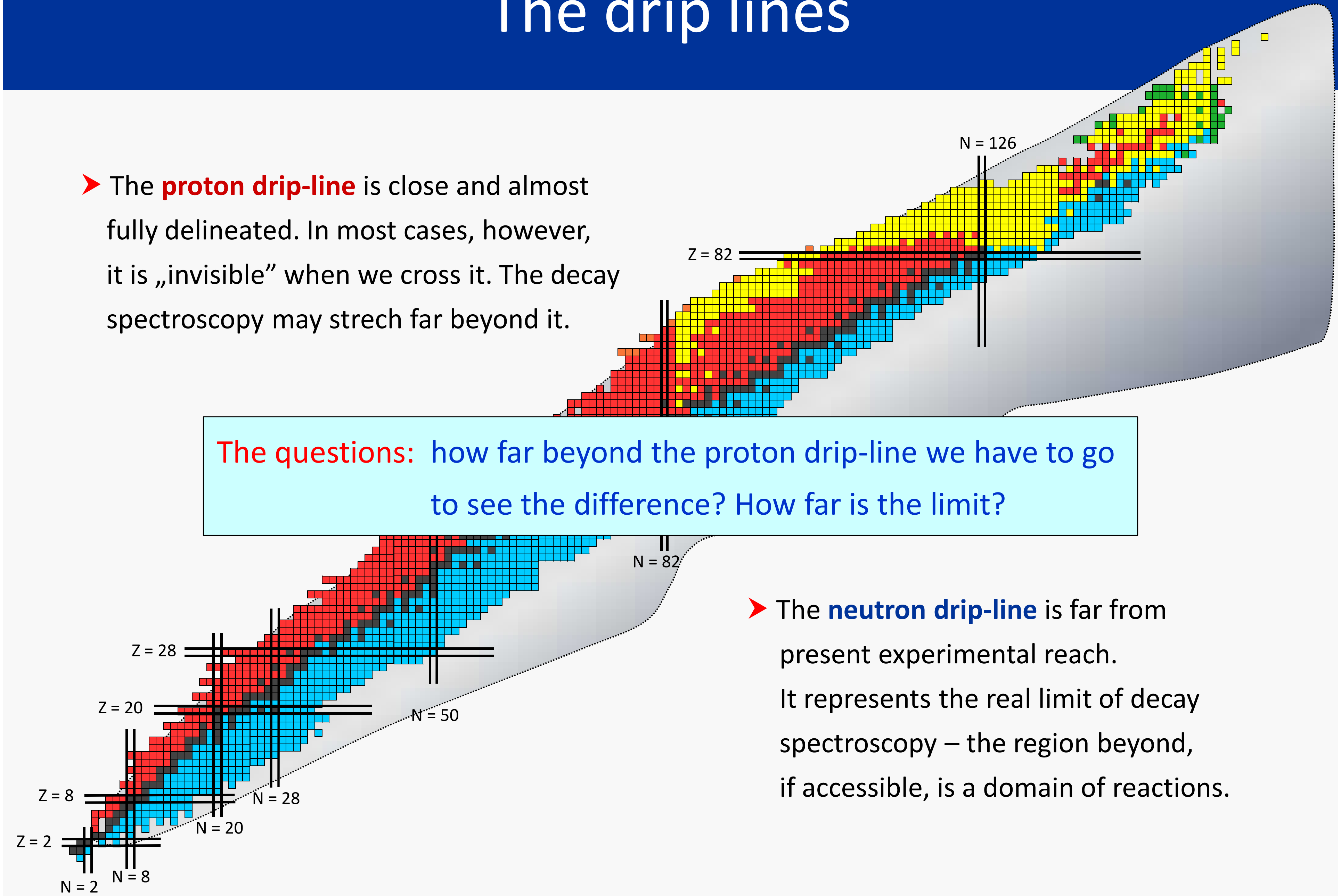


The drip lines

- 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 strech far beyond it.

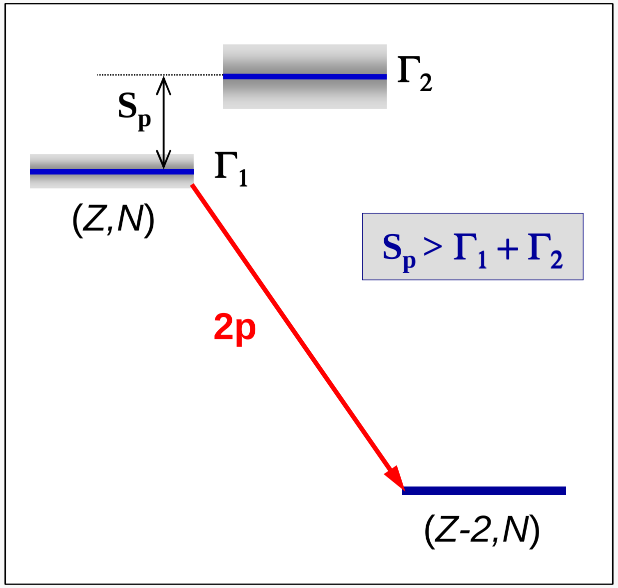


The questions: how far beyond the proton drip-line we have to go to see the difference? How far is the limit?

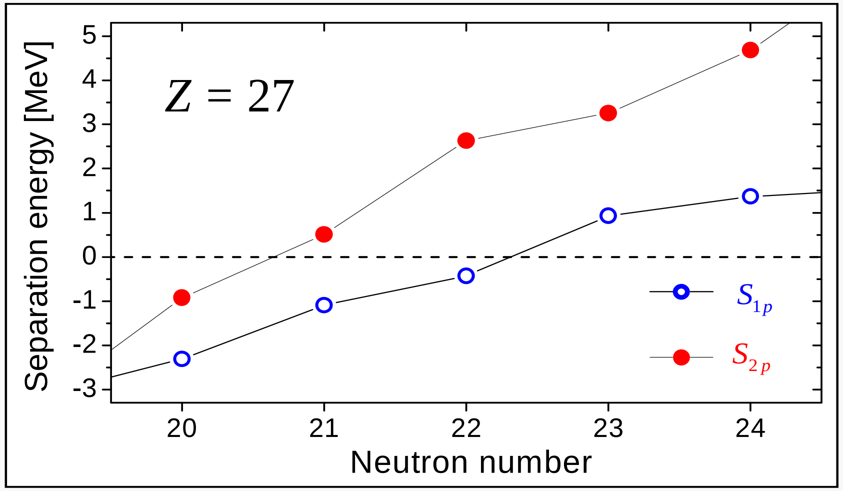
- The **neutron drip-line** is far from present experimental reach. It represents the real limit of decay spectroscopy – the region beyond, if accessible, is a domain of reactions.

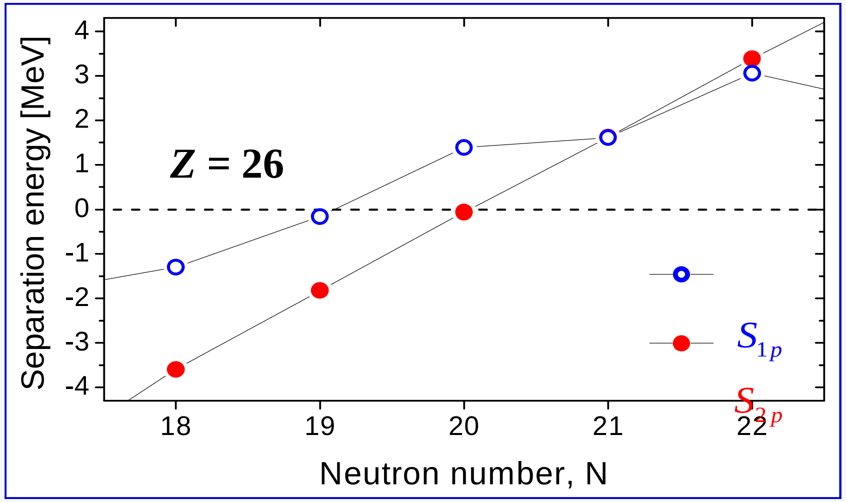
The answer for even Z

➤ It is possible that pair of protons is unbound while each of individual proton is bound!



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



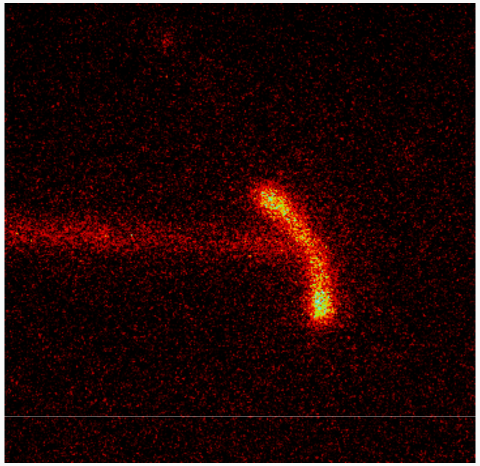


→ True 2p decay is an essentially three-body phenomenon

→ It offers more information: in addition to energy and half-life, there is a distribution of protons' momenta

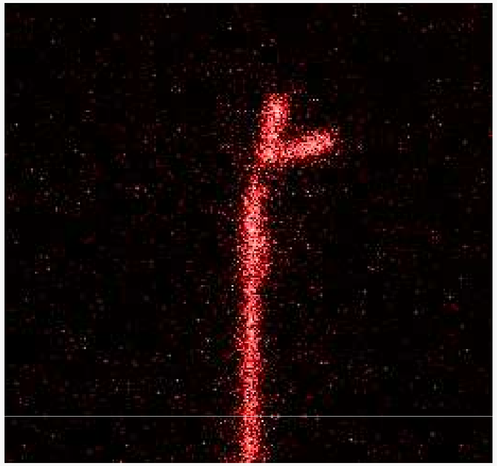
Three cases around Z=28

^{45}Fe



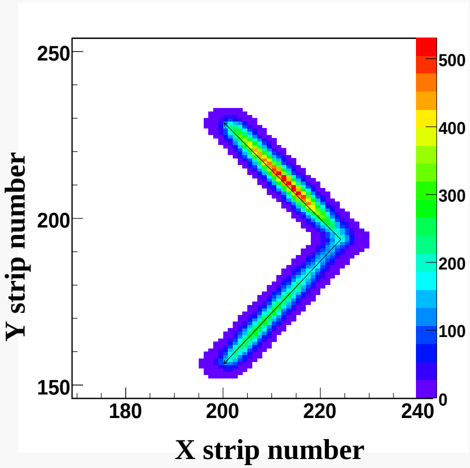
K. Miernik et al., PRL 99 (07) 192501

^{48}Ni

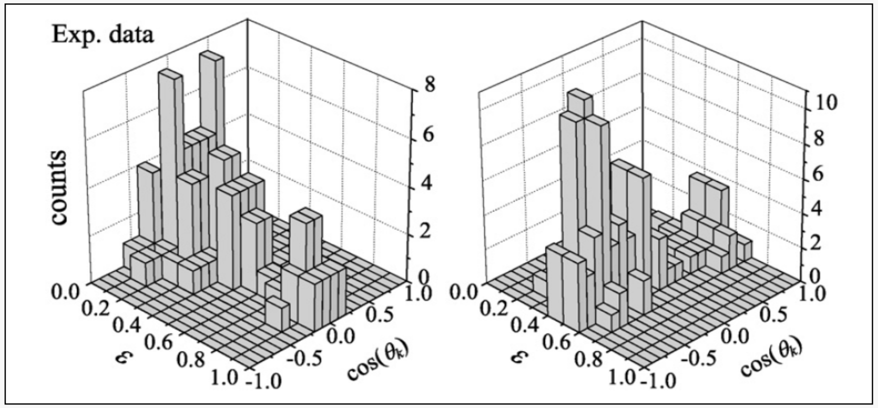


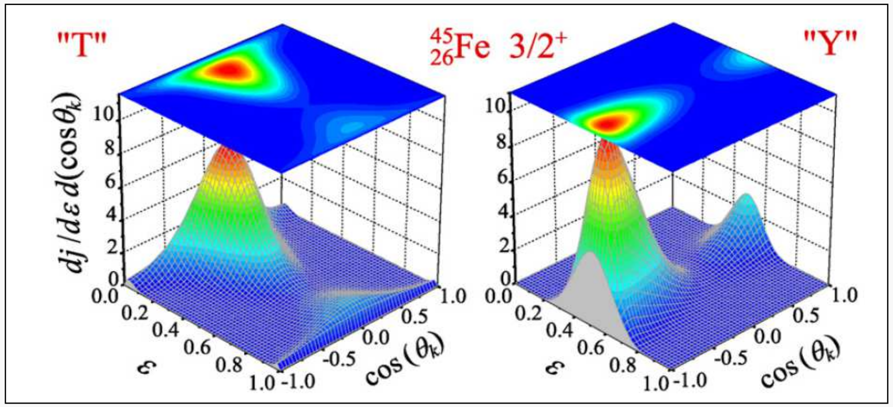
Pomorski et al., PRC 83 (2011) 061303(R)

^{54}Zn



Ascher et al., PRL 107 (2011) 102502

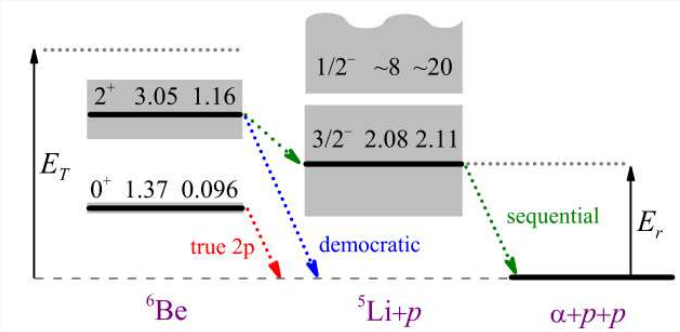


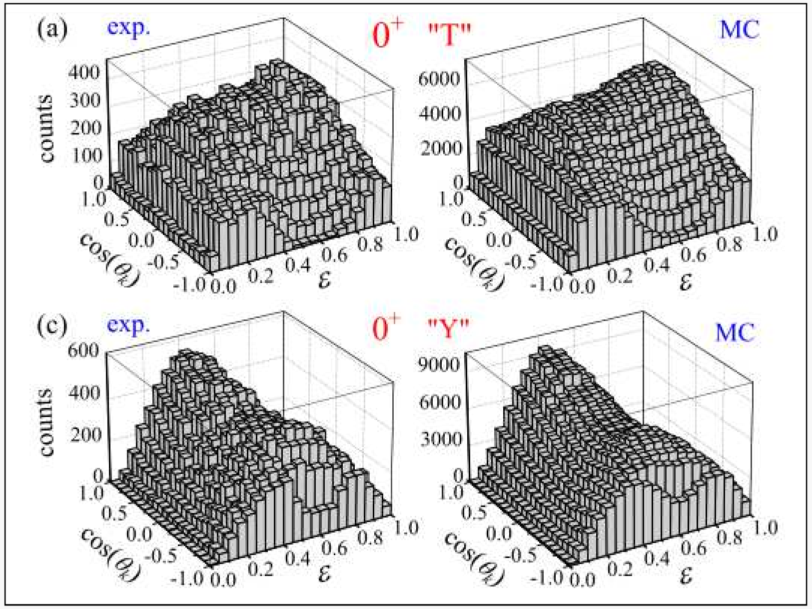


Grigorenko *et al.*, PLB 677 (2009) 30

^{6}Be and ^{19}Mg

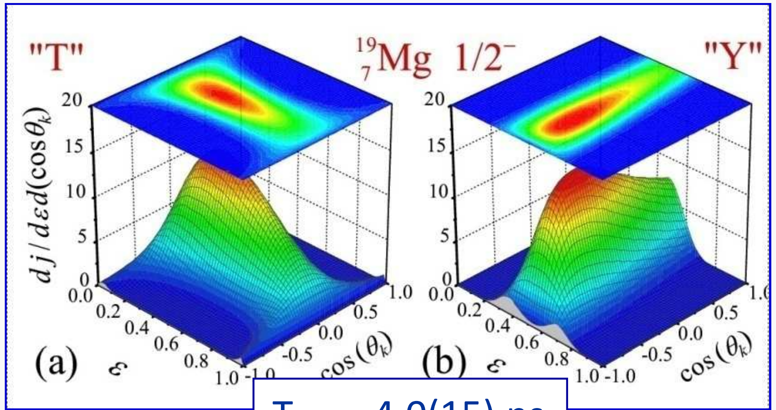
^{7}Be + Be → ^{6}Be @ NSCL



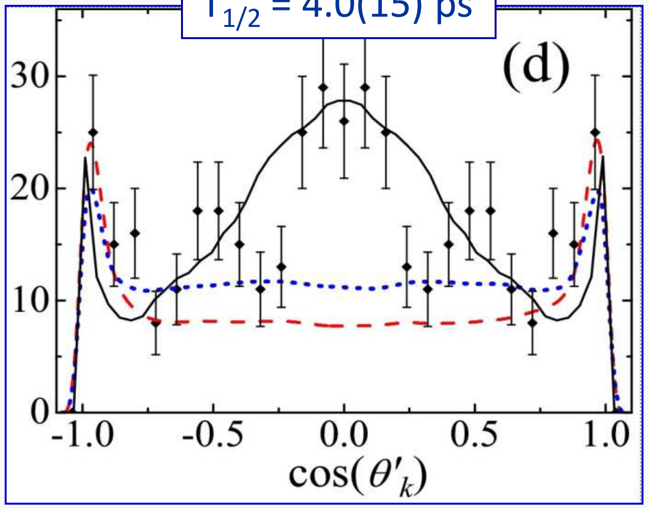


Egorova *et al.*, PRL 109 (2012) 202502

^{20}Mg + Be → ^{19}Mg @ GSI



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

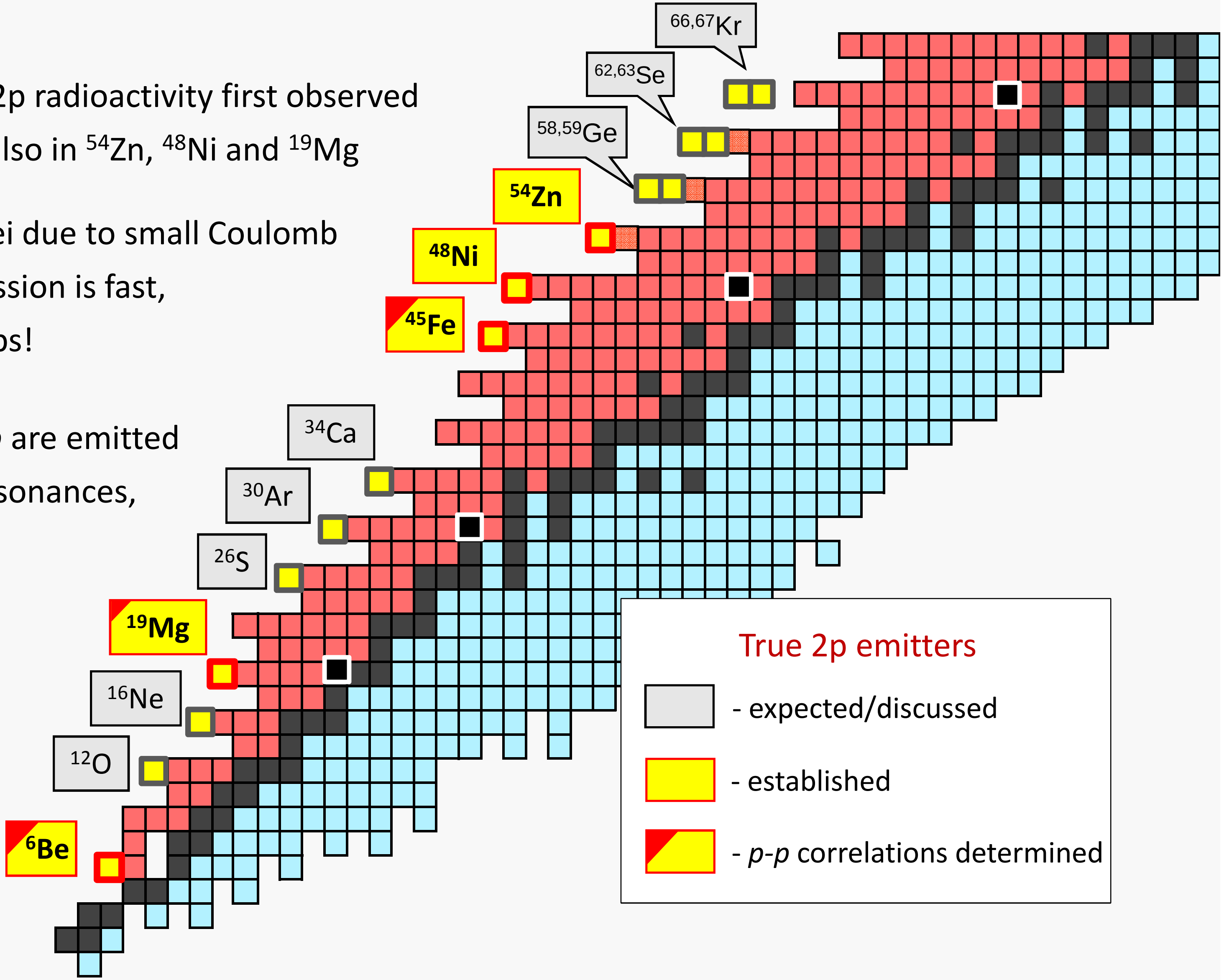


Mukha et al., PRL 99 (2007) 182501

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

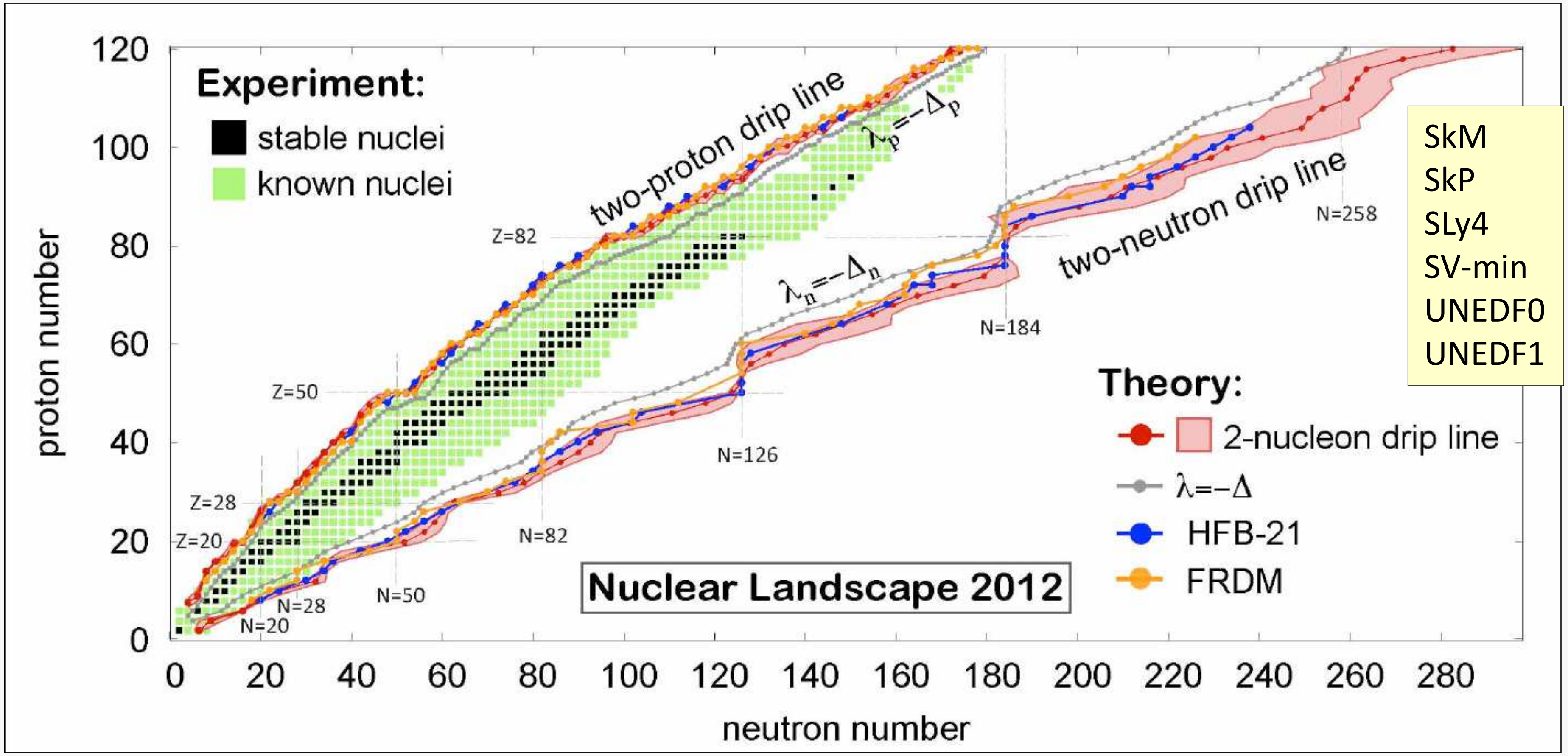
									Sr 71 -0.02 (15) -2.06 (14)	Sr 72 1.18 (15) -0.60 (19)	Sr 73 0.87 (78) 0.99 (19) 0.10 (34)	Sr 74 1.75 (70) 1.69 (21) 1.14 (29)	Sr 75 2.21 (78) 1.90 (73) 4.03 (17)	Sr 76 4.46 (30)
									Rb 70 -2.04 (15) -0.93 (18)	Rb 71 -1.38 (64) -1.78 (19) 0.36 (15)	Rb 72 -0.69 (58) -0.89 (35) 0.93 (39)	Rb 73 -0.59 (55) -0.55 (32) 4.26 (35)	Rb 74 2.13 (73)	
							Kr 67 -0.05 (14) -1.76 (14)	Kr 68 1.28 (14) -0.62 (14)	Kr 69 0.70 (74) 1.11 (18) 0.40 (18)	Kr 70 1.86 (51) 2.14 (19) 1.41 (34)	Kr 71 1.80 (47) 1.81 (48) 4.39 (32)	Kr 72 4.81 (40)		
					Br 64 -2.89 (14) -2.78 (14)	Br 65 -2.85 (14) -1.74 (14)	Br 66 -1.72 (14) -0.62 (14)	Br 67 -1.63 (58) -1.90 (14) 0.54 (17)	Br 68 -0.31 (57) -0.71 (20) 1.36 (25)	Br 69 -0.45 (43) -0.73 (32) 4.06 (15)	Br 70 2.58 (37)			
				Se 62 -0.10 (14) -2.76 (14)	Se 63 0.11 (14) -1.51 (14)	Se 64 1.11 (14) -0.29 (14)	Se 65 0.69 (70) 1.09 (14) 0.81 (17)	Se 66 1.96 (49) 2.43 (18) 2.00 (27)	Se 67 1.96 (28) 2.07 (25) 4.77 (17)	Se 68 4.79 (31)				
			As 60 -3.31 (66) -2.74 (14) -2.55 (14)	As 61 -2.43 (64) -2.66 (14) -1.60 (14)	As 62 -1.48 (42) -1.61 (14) -0.26 (14)	As 63 -1.13 (52) -1.40 (14) 1.13 (14)	As 64 -0.10 (41) -0.28 (17) 2.10 (10)	As 65 -0.08 (46) -0.43 (29) 4.59 (17)	As 66 2.70 (22)					
		Ge 58 -0.24 (41) -0.16 (14) -2.38 (14)	Ge 59 0.30 (35) 0.19 (14) -1.16 (14)	Ge 60 0.94 (29) 1.06 (14) 0.09 (14)	Ge 61 1.02 (32) 1.35 (14) 1.42 (14)	Ge 62 2.18 (24) 2.53 (14) 2.77 (10)	Ge 63 2.20 (20) 2.38 (14) 5.33 (14)	Ge 64 5.02 (27)						
	Ga 56 -2.89 (36) -2.63 (14) -1.99 (14)	Ga 57 -2.54 (37) -2.22 (14) -0.79 (14)	Ga 58 -1.41 (26) -1.35 (14) 0.19 (14)	Ga 59 -0.88 (18) -0.97 (14) 1.36 (14)	Ga 60 0.03 (12) 0.07 (14) 2.92 (10)	Ga 61 0.45 (20) 0.24 (10) 5.36 (10)	Ga 62 2.94 (3)							
Zn 54 0.40 (48) 0.12 (14) -1.33 (14)	Zn 55 0.52 (33) 0.63 (14) 0.13 (14)	Zn 56 1.39 (40) 1.43 (14) 1.25 (14)	Zn 57 1.37 (20) 1.54 (14) 2.10 (14)	Zn 58 2.28 (5) 2.33 (14) 3.02 (10)	Zn 59 2.89 (4) 2.85 (10) 5.72 (10)	Zn 60 5.12 (1)								
Cu 53 -1.90 (27) -1.45 (14) 1.26 (14)	Cu 54 -0.40 (27) -0.50 (14) 2.20 (14)	Cu 55 -0.29 (30) -0.18 (14) 3.83 (14)	Cu 56 0.56 (14) 0.56 (14) 5.26 (10)	Cu 57 0.69 (2) 0.69 (10) 7.86 (10)	Cu 58 2.87 (0)									

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**



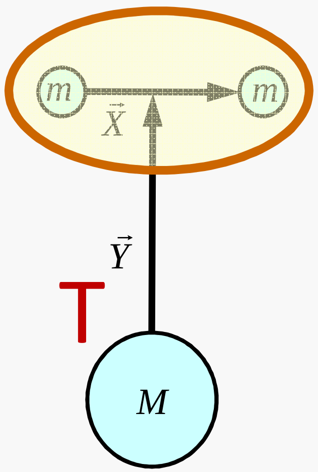
→ There are 6900 ± 500 nuclei bound with Z ≤ 120

Erler et al., Nature 486 (2012) 509

Diproton model

- By simplifying interactions in the *core+p+p* system, the three-body decay can be reduced to the combination of two-body processes.

Jacobi T system → **diproton model**



The WKB approximation

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

$$\mathcal{N}\int_{r_1}^{r_{in}} \frac{dr}{2k(r)} = 1 \qquad k(r) = \sqrt{2\mu\left|Q_{2p} - 2V_p(r)\right|}$$

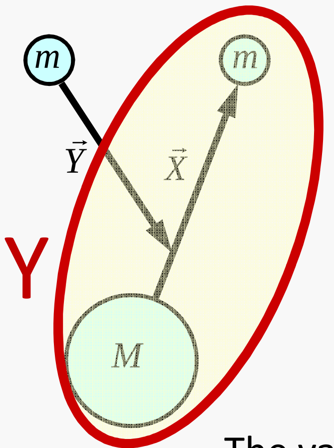
$$\theta^2_{\mathrm{dipr}} = \frac{(2n)!}{2^{2n}(n!)^2}\left[\frac{A}{A-2}\right]^{2n} \mathcal{O}^2 \qquad n \approx (3Z)^{1/3} - 1$$

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

Direct model

Jacobi Y system → **direct model**

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

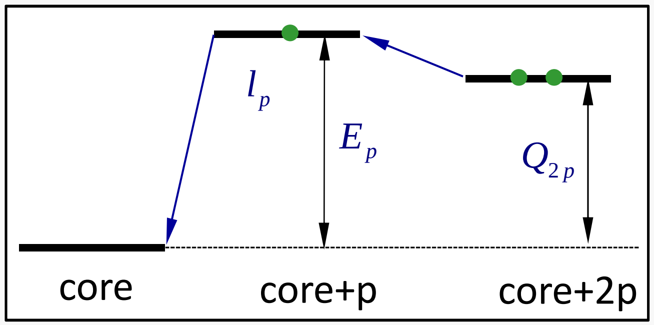


Γ_i is the width of the two-body subsystem: $\Gamma_i\left(E\right) = 2\gamma_i^2 P_{l_p}\left(E,R,Z_i\right)$

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

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

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

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

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

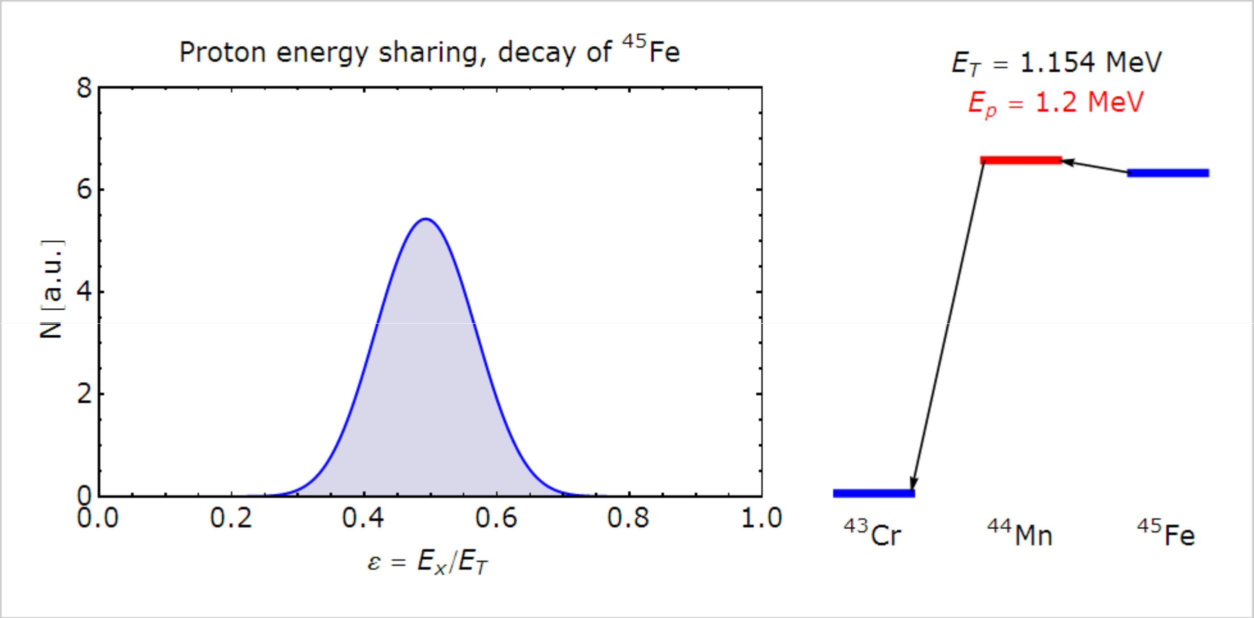
$l_p = 0$

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

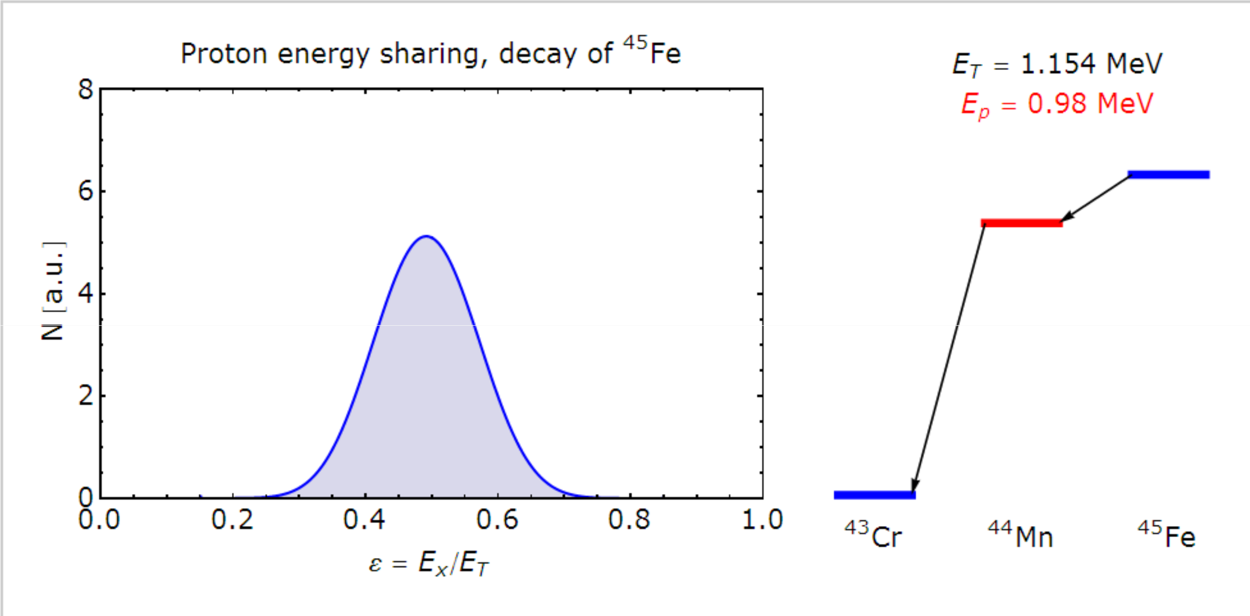
- In the direct model we can investigate how the proton's energy spectrum depends on the position of the intermediate state



$Q_{2p} = 1.15\ \mathrm{MeV},\ \ Q_{1p} = -0.05\ \mathrm{MeV}$ ➡ 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

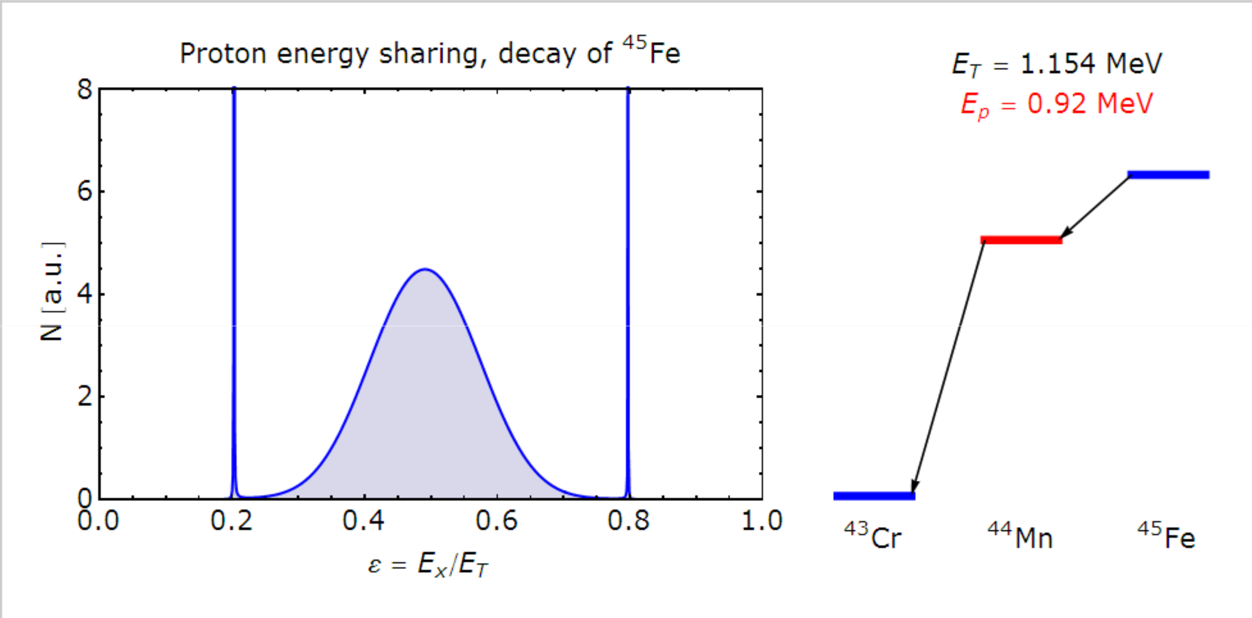


$$Q_{2p} = 1.15 \text{ MeV}, \;\; Q_{1p} = 0.17 \text{ MeV}$$

➡ 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

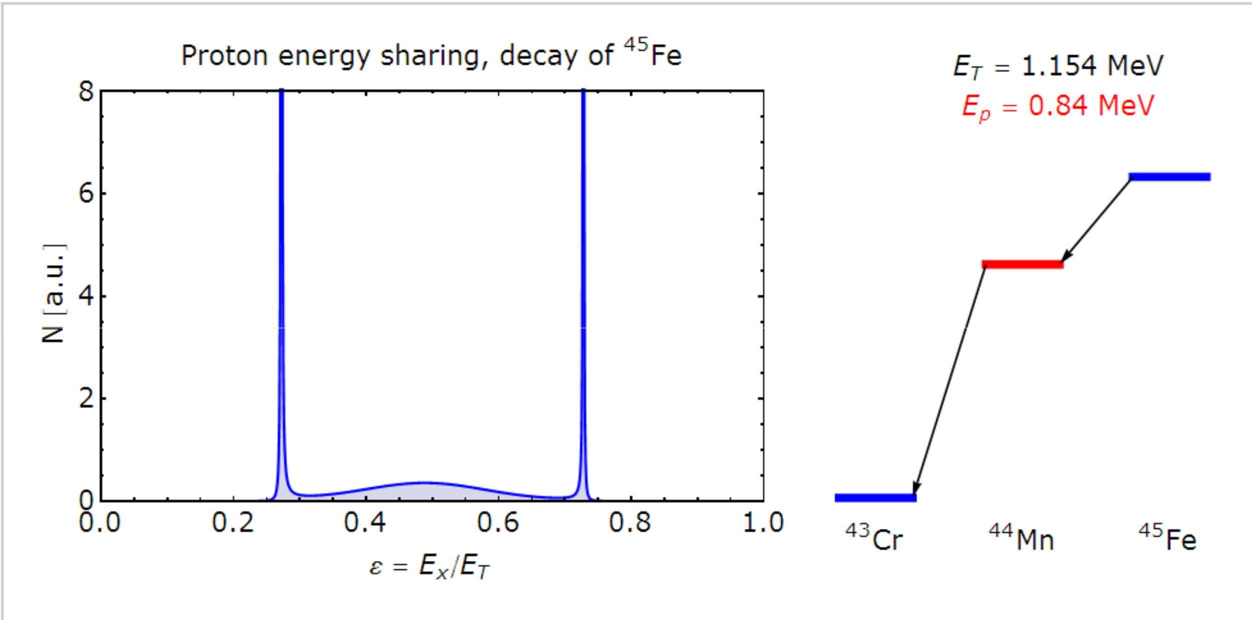


$$Q_{2p} = 1.15 \text{ MeV}, \ Q_{1p} = 0.23 \text{ MeV}$$

➡ 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

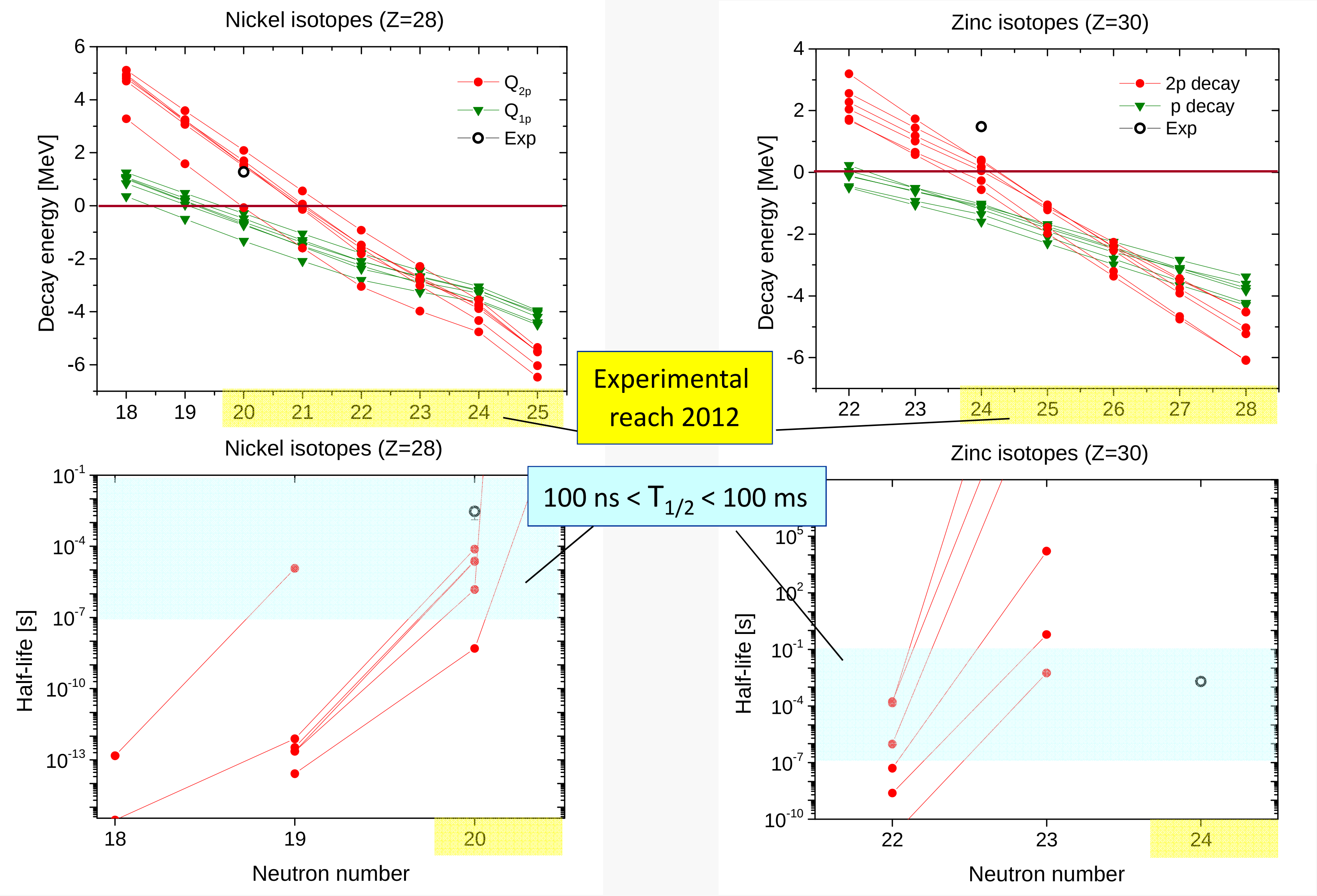
- Nuclear binding energies: deformed DFT with six effective Skyrme interaction plus density-dependent zero-range pairing term (Erler et al., Nature 486 (2012) 509)

- 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

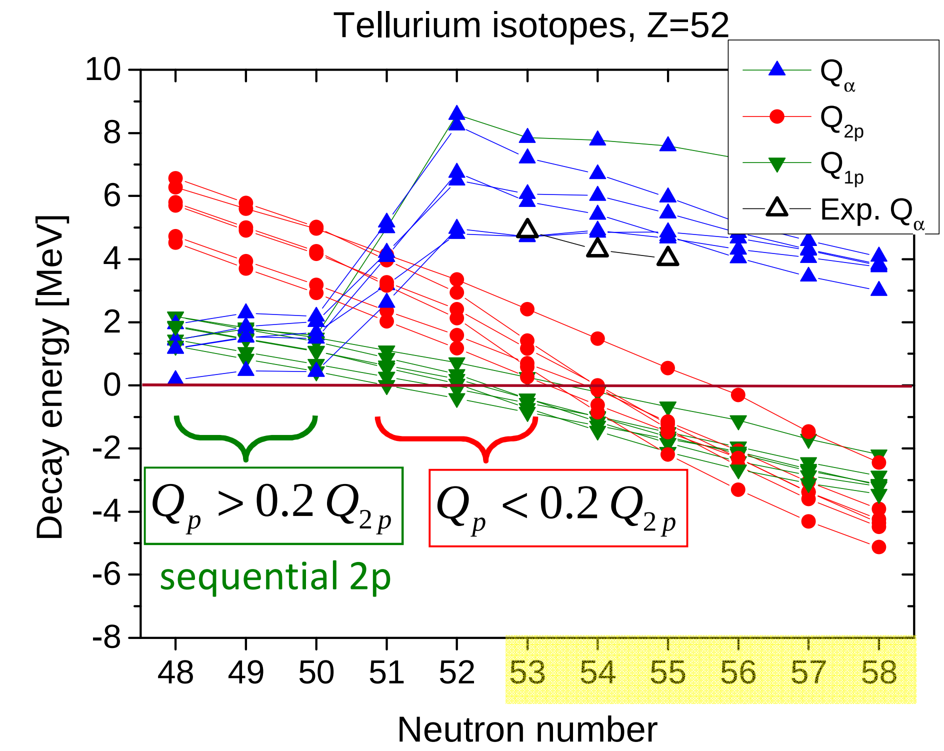
- The adopted decay-time criterion (arbitrary):
  we consider a nucleus to be a **2p decay candidate** predicted by a given mass (and decay) model when 100 ns < $T_{1/2}$ < 100 ms.
  Longer half-life will loose competition with β decay.
  Shorter will be difficult to detect using in-flight separation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

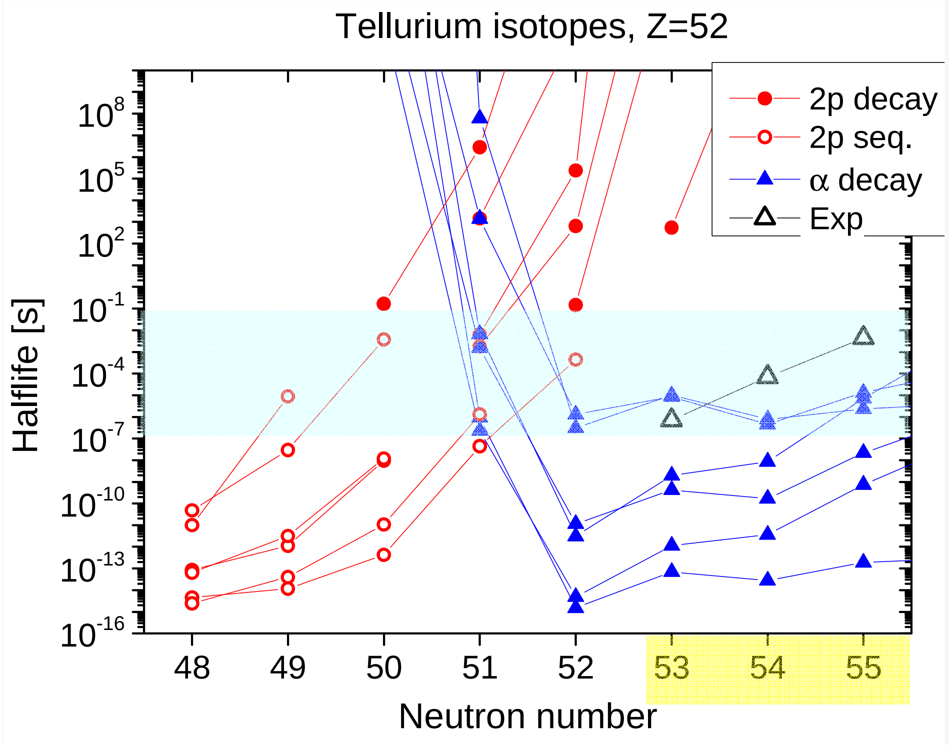
- Counting:
  a candidate has the model multiplicity $m(Z,N) = k$
  when it is predicted by k mass models.

Nickel and zinc in the direct model



Tellurium

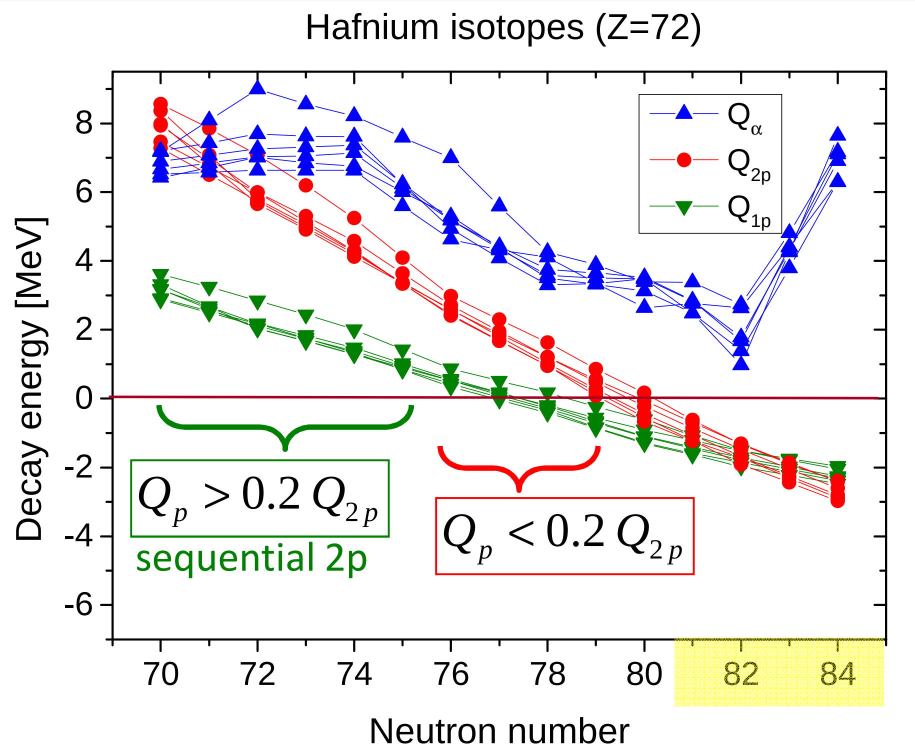


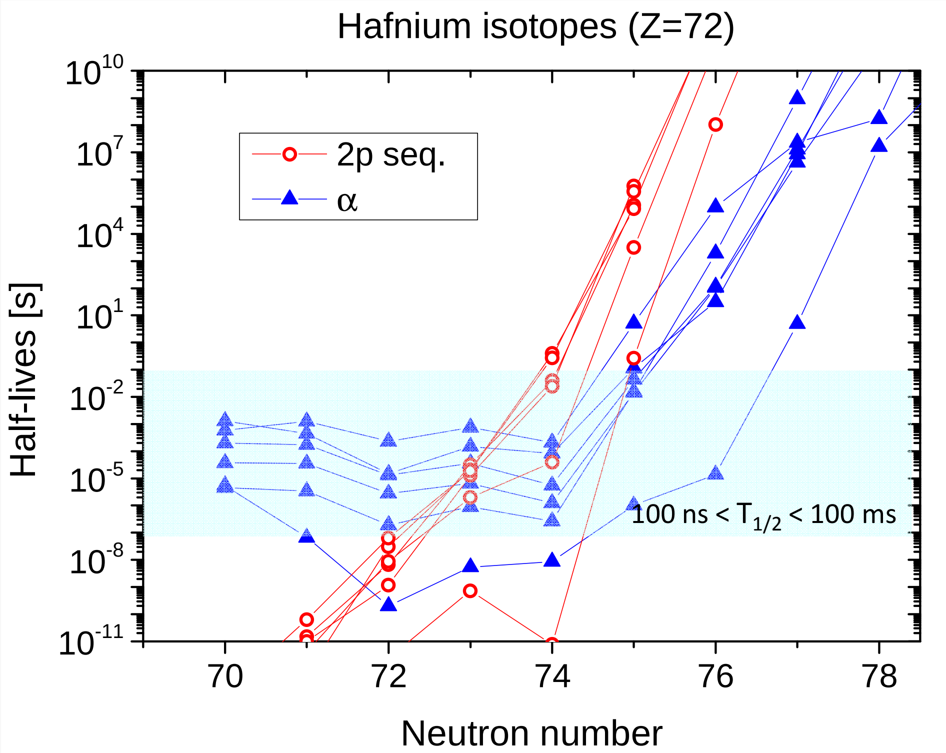


▲ α decay half-lives from the global, fenomenological formula by Koura, J. Nucl. Science and Tech. 49 (2012) 816

- 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!

No 2p above tellurium!?

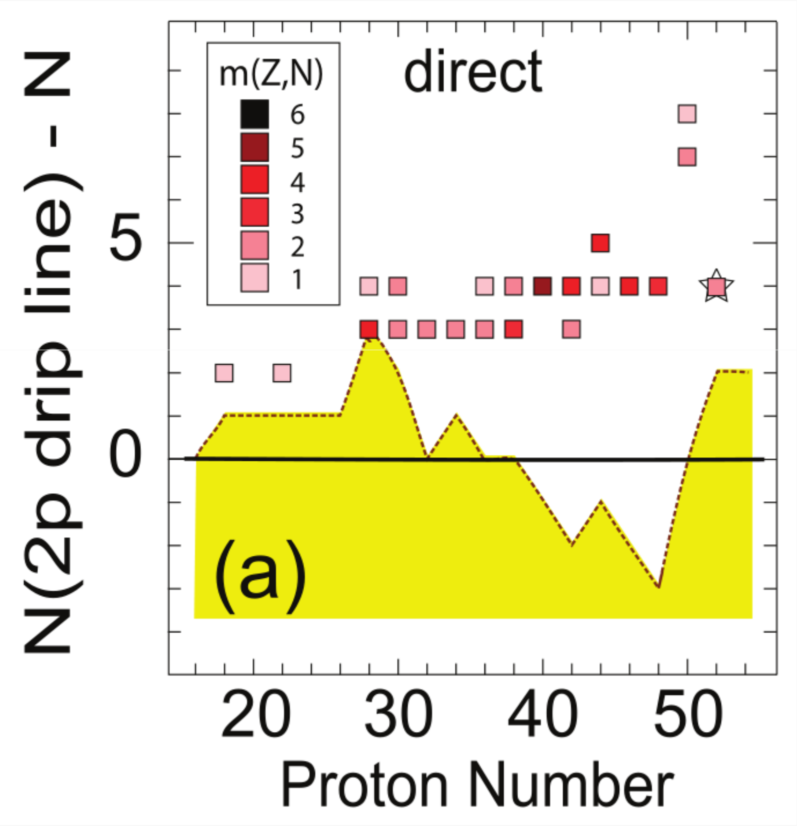


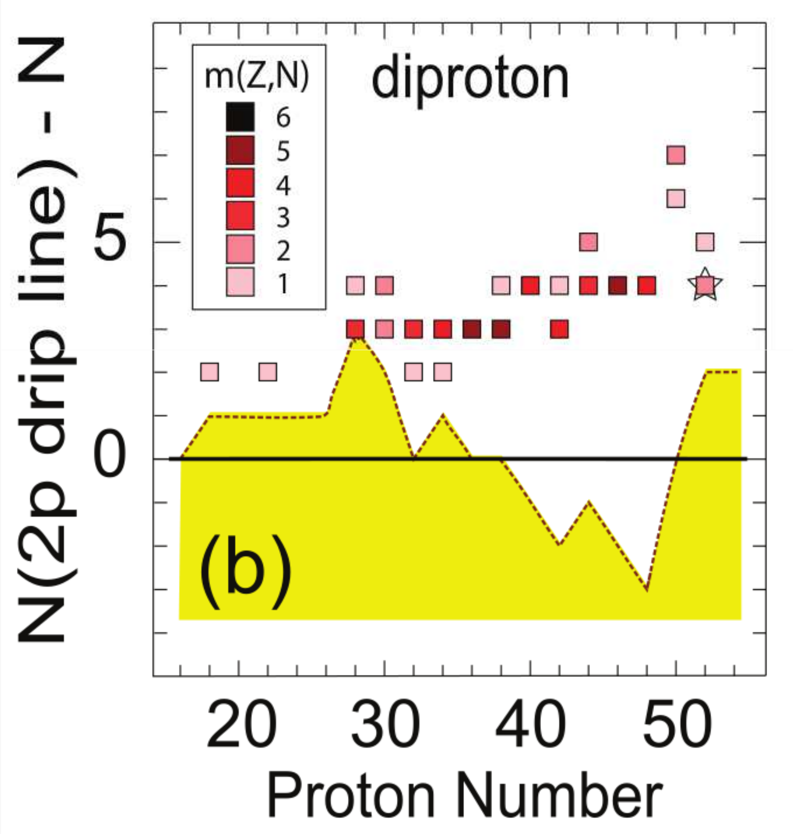


- When the energy condition for the true 2p decay is fulfilled, the predicted half-life is extremely long
- When the fast proton emission becomes possible, it proceeds as the sequential 2p decay

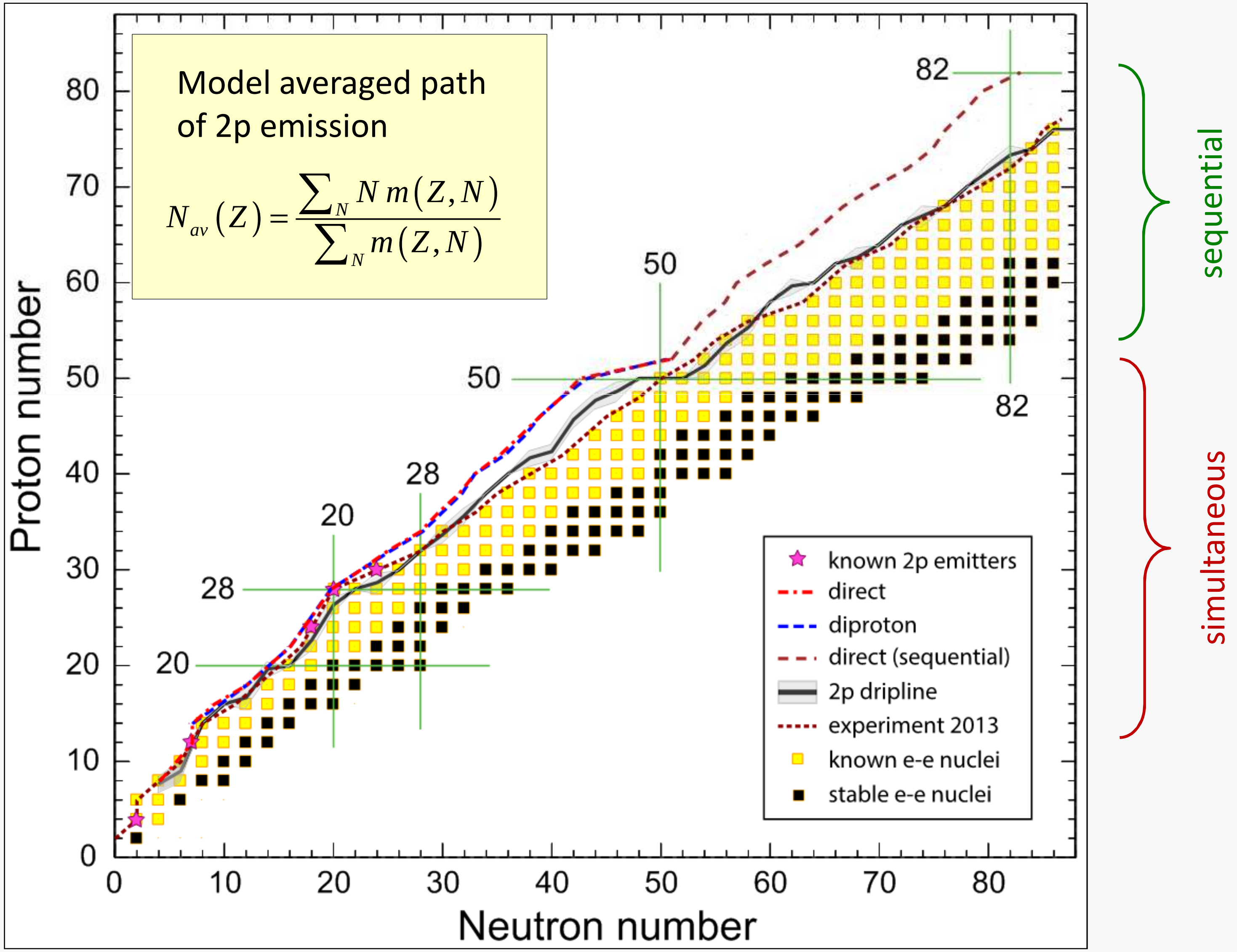
True 2p landscape

- Selection criteria: $100\ \text{ns} < T_{2p} < 100\ \text{ms}$ $T_{2p} < 10 \cdot T_{\alpha}$





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 ns $< T_{1/2} <$ 100 ms are predicted.
- In **^{103}Te** the competition between simultaneous 2p, sequential 2p, and α emission may occur.
- Above tellurium the limit of decay spectroscopy is represented by sequential 2p 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.

PRL 110, 2225… PHYSICAL REVIEW LETTERS week ending 31 MAY 2013

Errata will follow ☹

Landscape of Two-Proton Radioactivity

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Thank you!