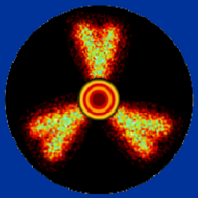


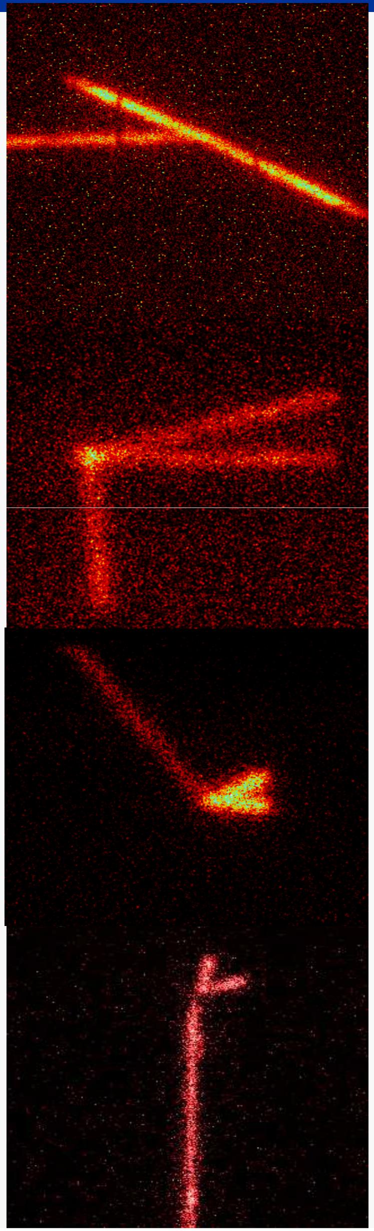
Promieniotwórczość dwuprotonowa status i perspektywy

Marek Pfützner

ZAKŁAD FIZYKI JĄDROWEJ
UNIWERSYTET WARSZAWSKI

Katedra Fizyki Teoretycznej, IF UMCS, Lublin, 10 stycznia 2017

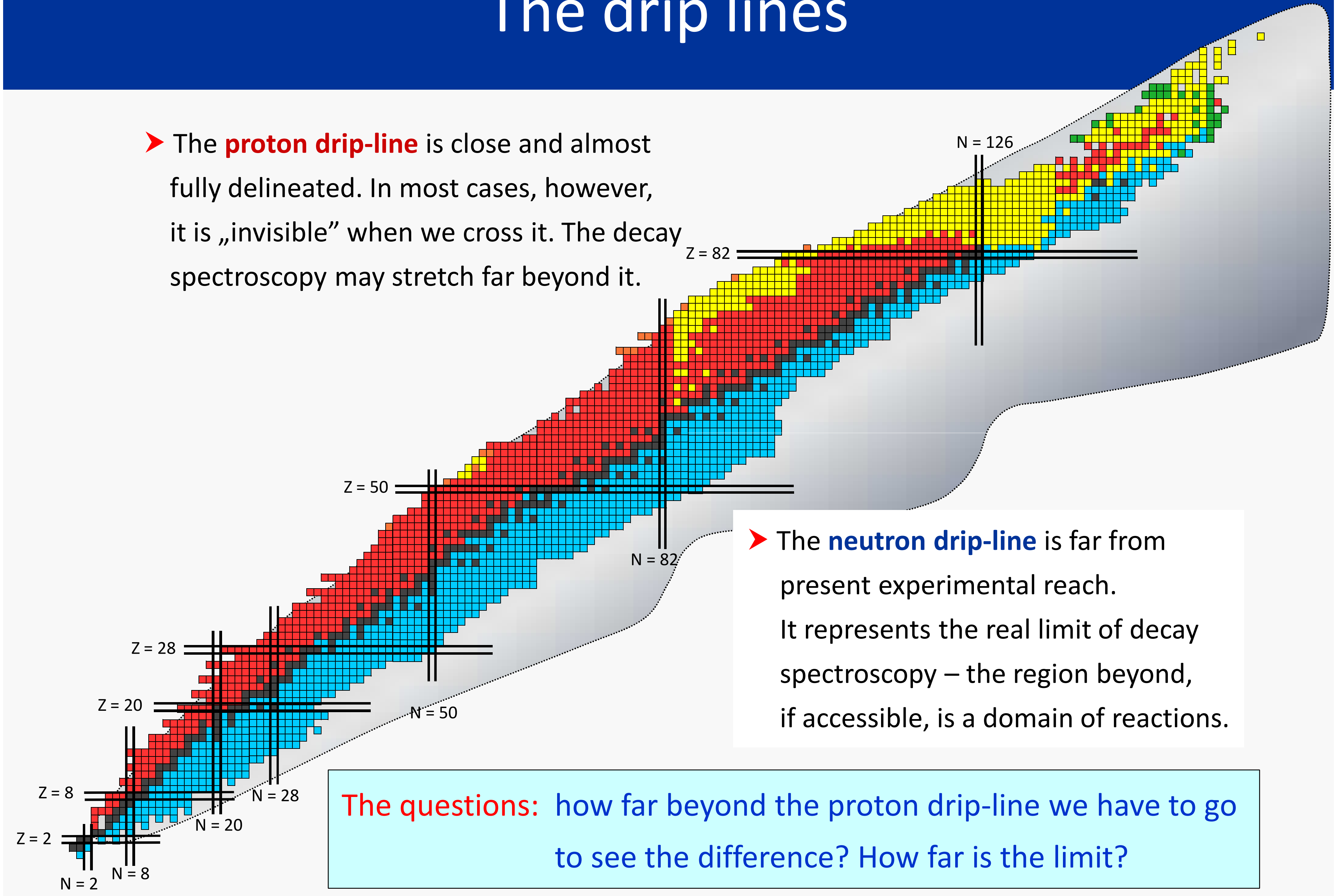
Plan



- ❑ **Wstęp**
  - Mapa nuklidów i granice spektroskopii
  - Emisja dwóch protonów (2p) – stan obecny
- ❑ **Eksperymenty**
  - Potrzeba dokładnych mas
  - Pierwsze obserwacje: energia i czas rozpadu
  - Detektor warszawski i korelacje p-p
  - Najnowsze wyniki
- ❑ **Modele**
  - Model trójciałowy (Grigorenko – Zhukov)
  - Przybliżenia dwuciałowe (direct i diproton)
  - Globalne przewidywania
- ❑ **Podsumowanie**

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.

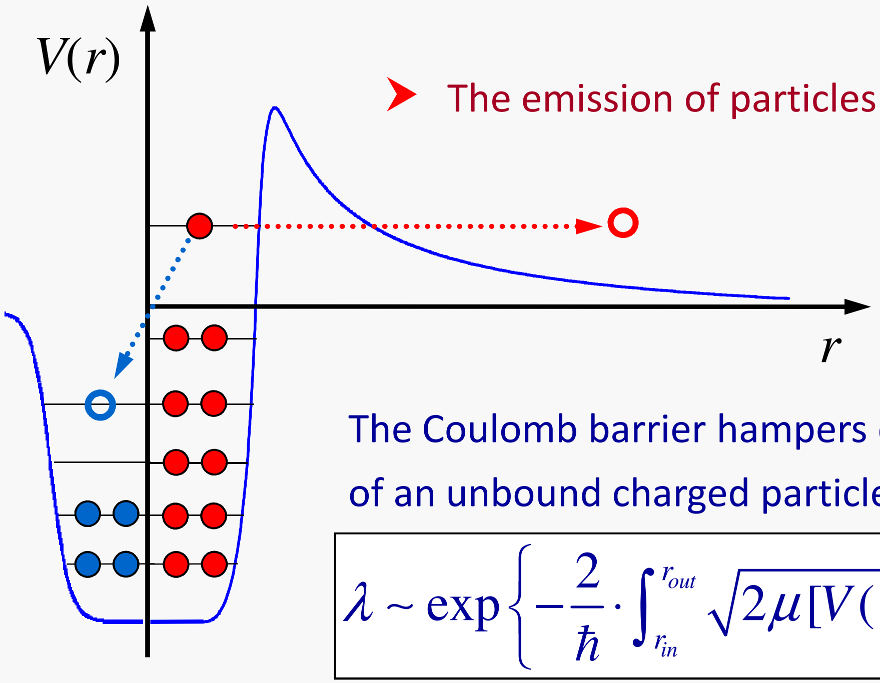


- The **neutron drip-line** is far from present experimental reach. It represents the real limit of decay spectroscopy – the region beyond, if accessible, is a domain of reactions.

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

Beyond the proton drip-line

Competition between two decay modes



- The β^+ decay

Probability of transition:

$$\boxed{\lambda \sim Q^5}$$

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

$$\boxed{T_{1/2} > 1\ \mathrm{ms}}$$

- The emission of particles

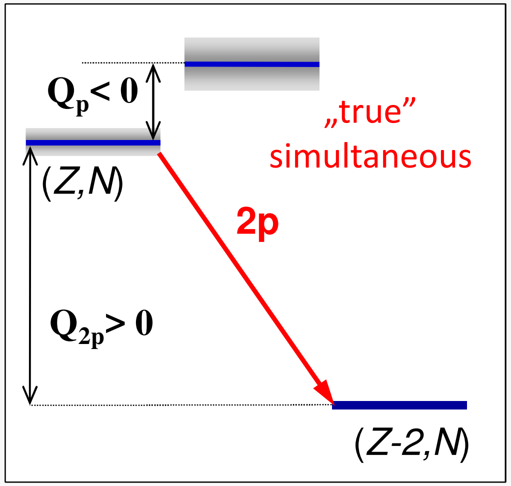
The Coulomb barrier hampers emission
of an unbound charged particle (α, p, 2p,…)

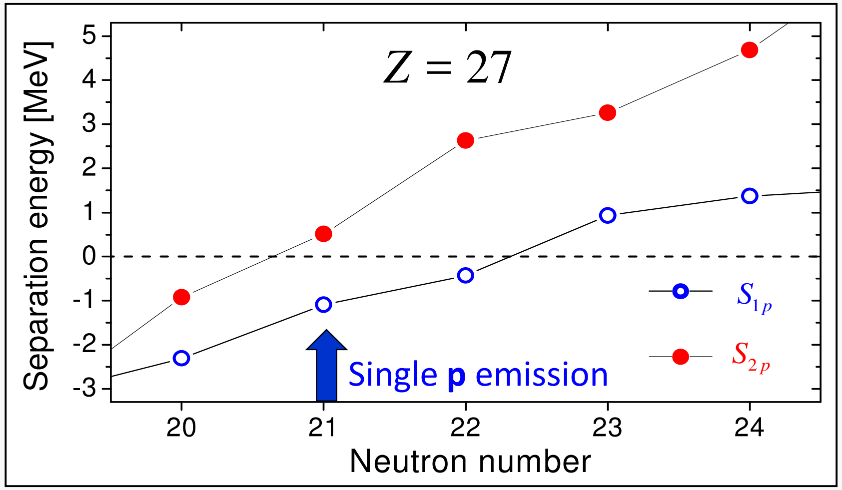
$$\boxed{\lambda \sim \exp\left\{-\frac{2}{\hbar}\cdot\int_{r_{in}}^{r_{out}}\sqrt{2\mu[V(r)-Q]}\cdot dr\right\}}$$

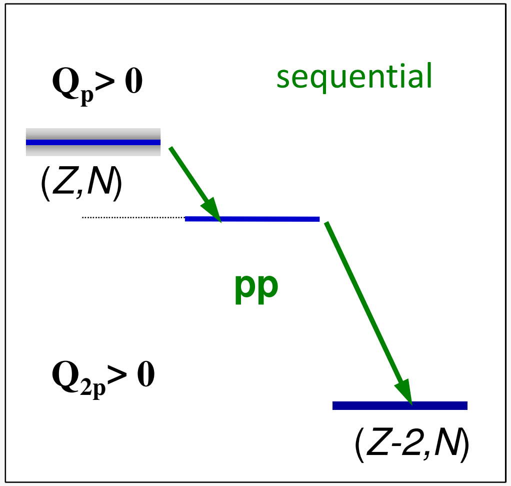
→ To find where the drip-line actually is and to predict which decay will happen,
we need: *a*) atomic masses, *b*) decay models

p drip-line is not a limit!

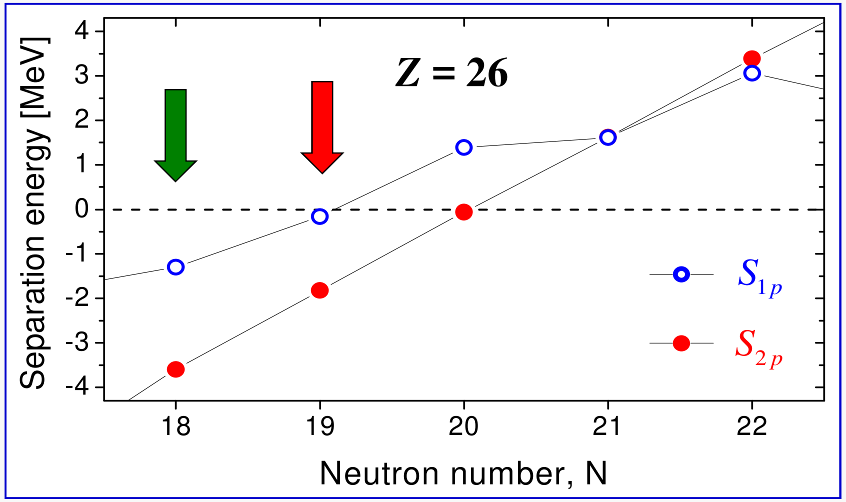
- The limit of „existence” beyond the proton drip-line is determined by emission of protons





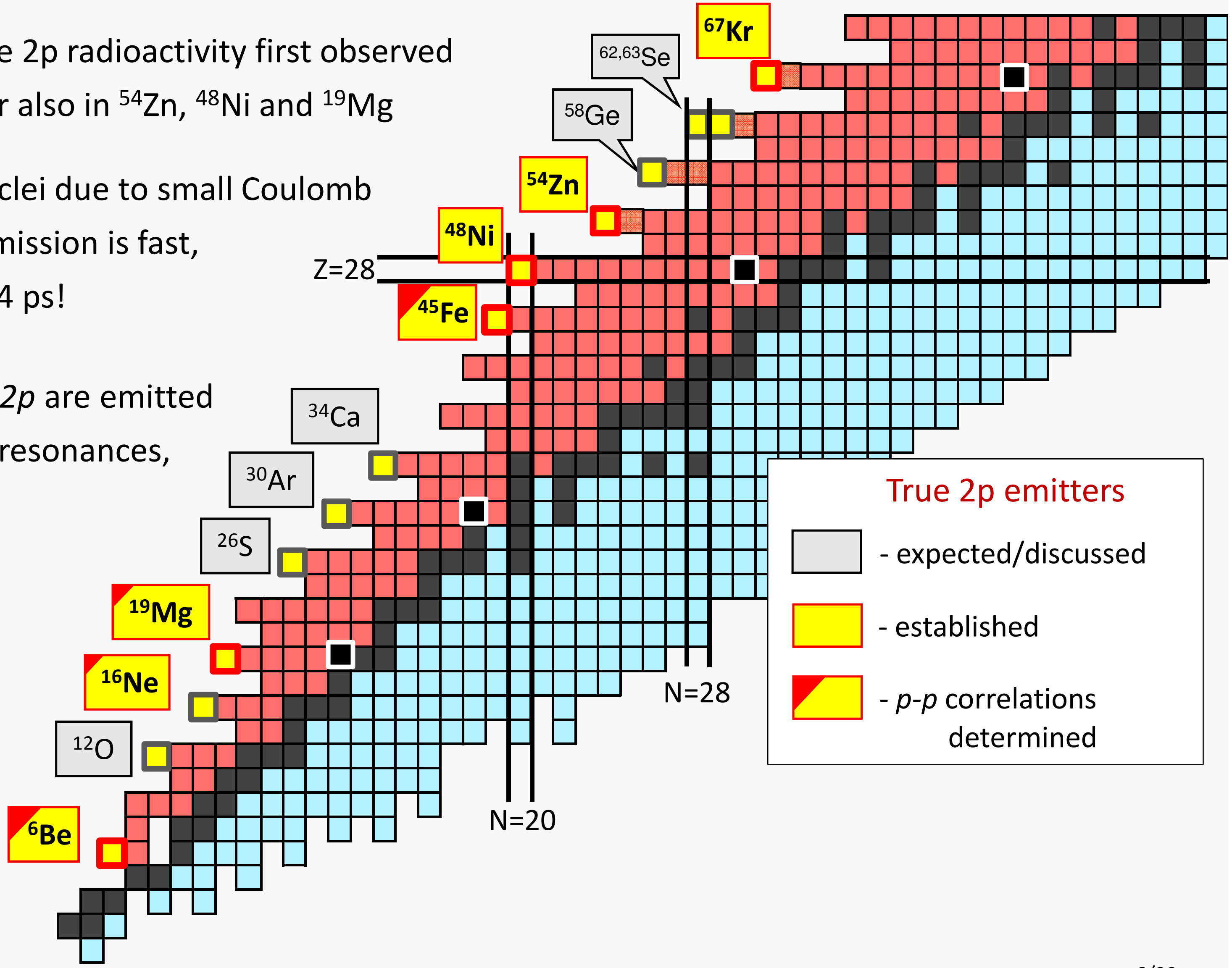


V.I. Goldanskii, Nucl. Phys. 19 (60) 482



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



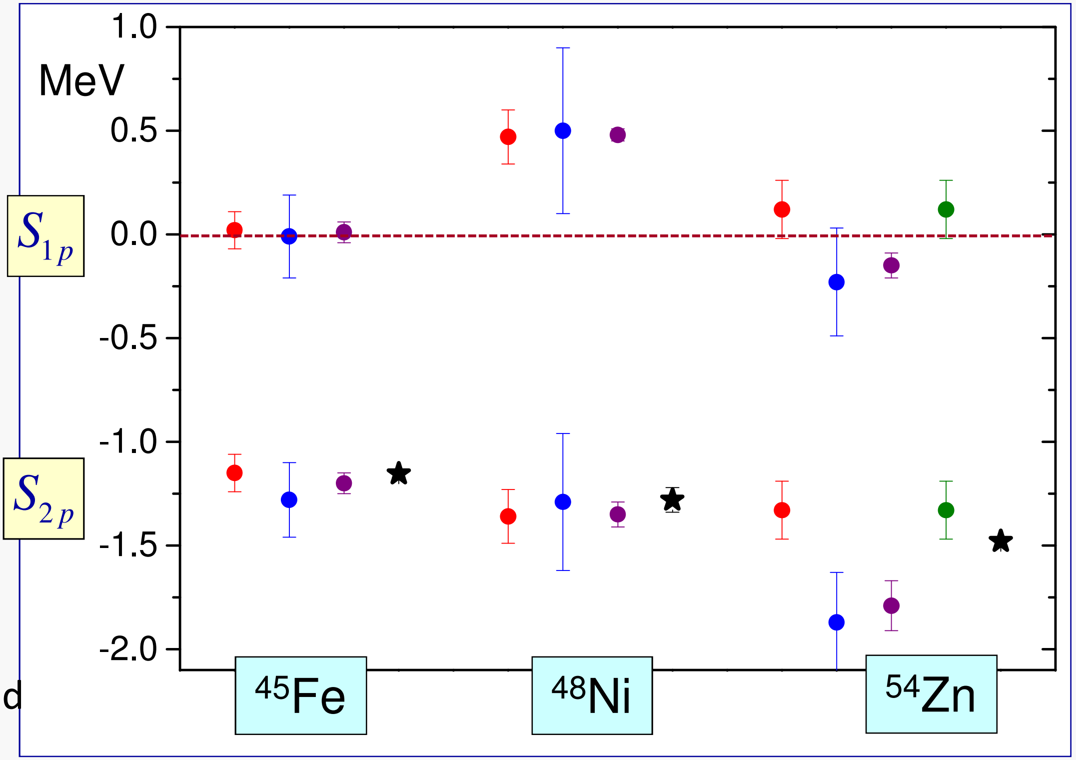
First 2p candidates

- 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

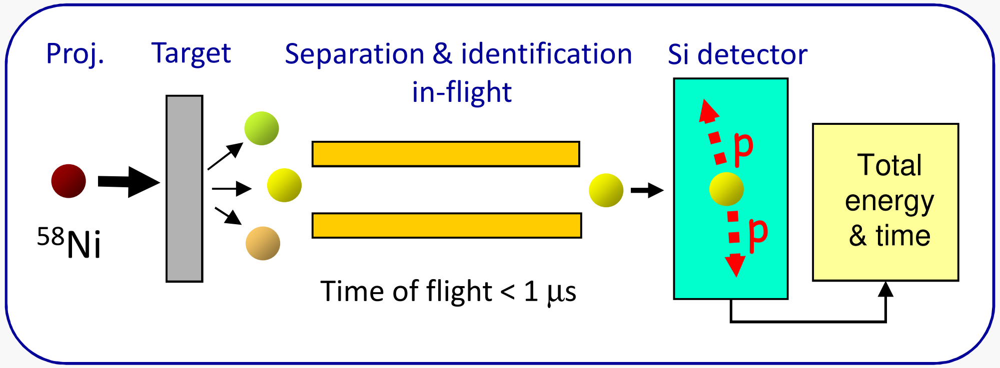
● Cole, PRC 54 (96) 1240

● Brown *et al.*, PRC 65 (02) 045802

★ exp

First evidence for 2p emission

Main idea of experiment



Proj.

Target

Separation & identification in-flight

Si detector

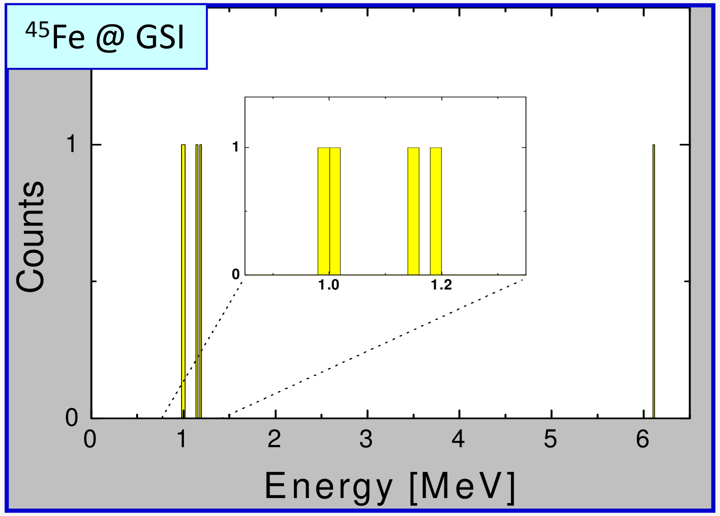
^{58}Ni

p

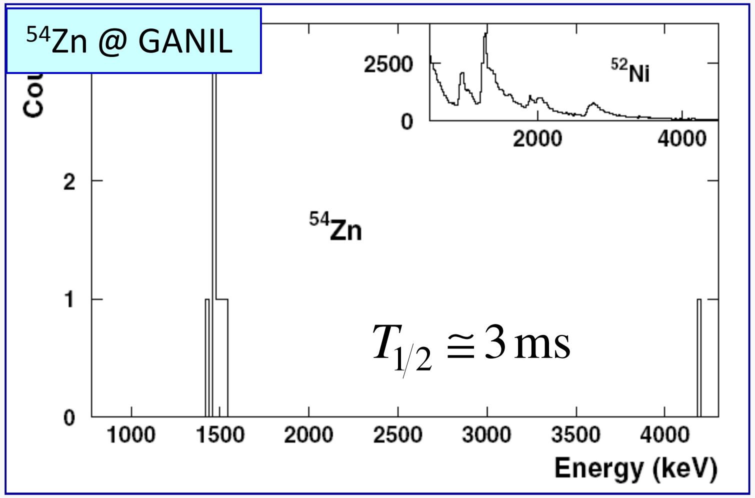
p

Total energy & time

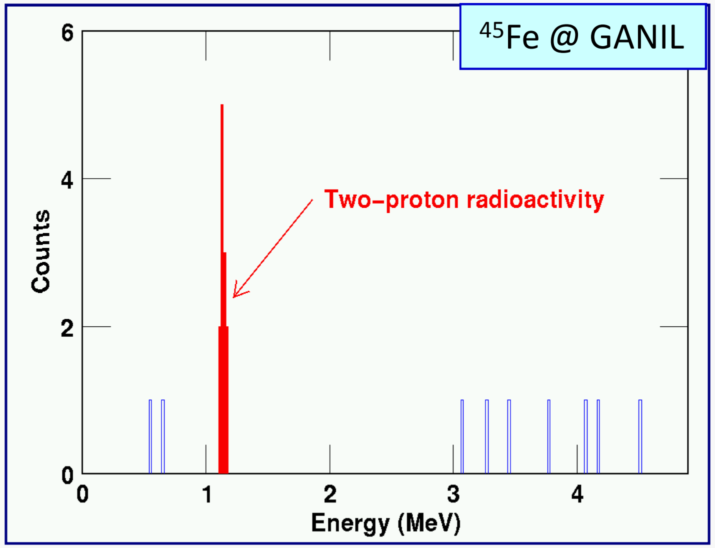
Time of flight < 1 μs



MP et al., EPJ A 14 (2002) 279



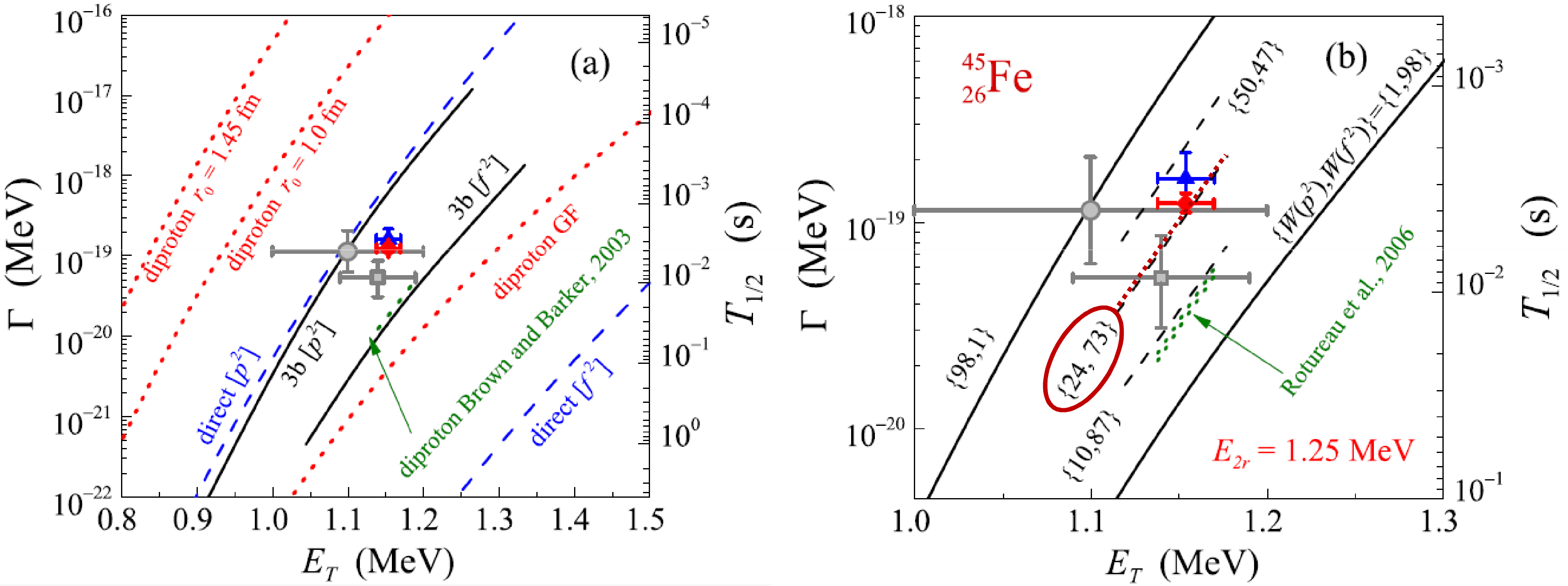
Blank et al., PRL 94 (2005) 232501



Giovinazzo et al., PRL 89 (2002) 102501

Total decay energy and time

- The decay energy and the lifetime are enough to establish the 2p decay.
  Most models used for comparison are based on two-body approximations.

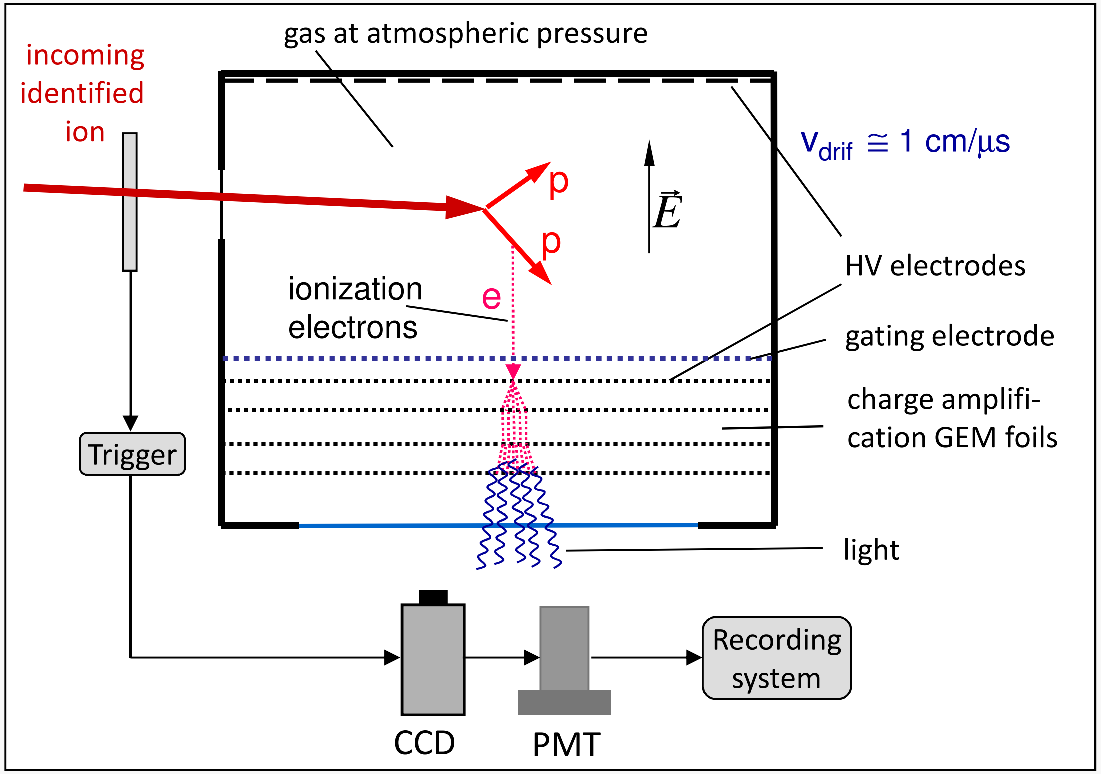


→ To explore fully the physics of the process, the correlations between proton's momenta must be determined! New detection technique is needed and a model capturing the three-body kinematics.

New idea – TPC with optical readout

OTPC – Optical Time Projection Chamber

Wojciech Dominik, HEP Warsaw

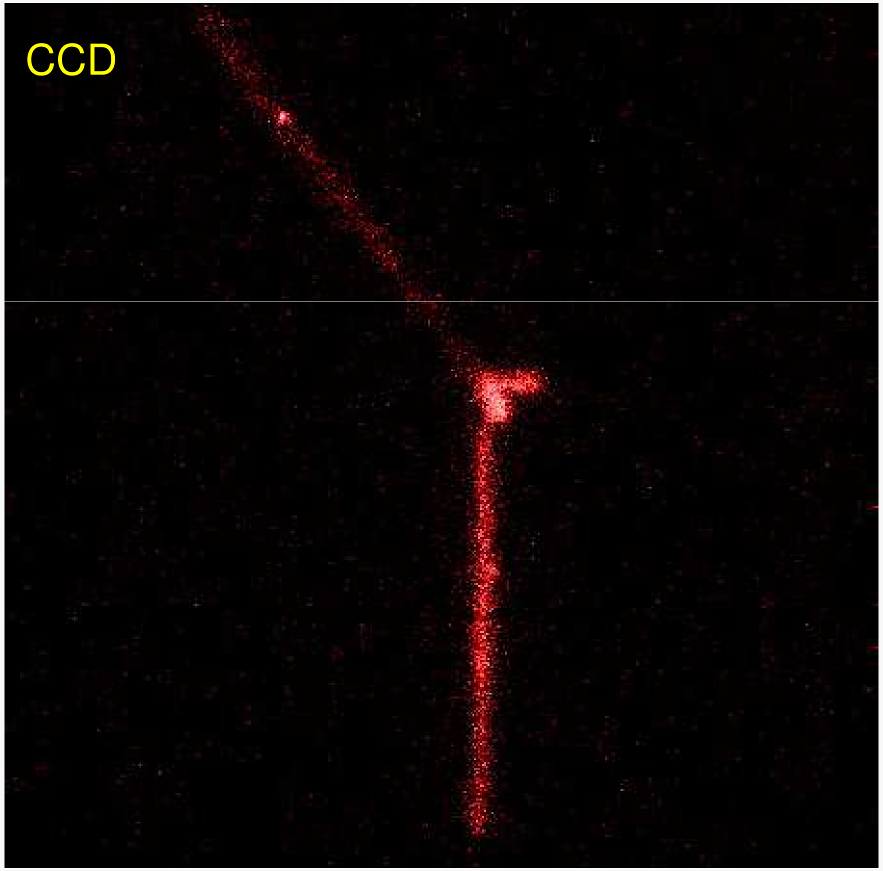


Miernik et al., NIM A581 (2007) 194

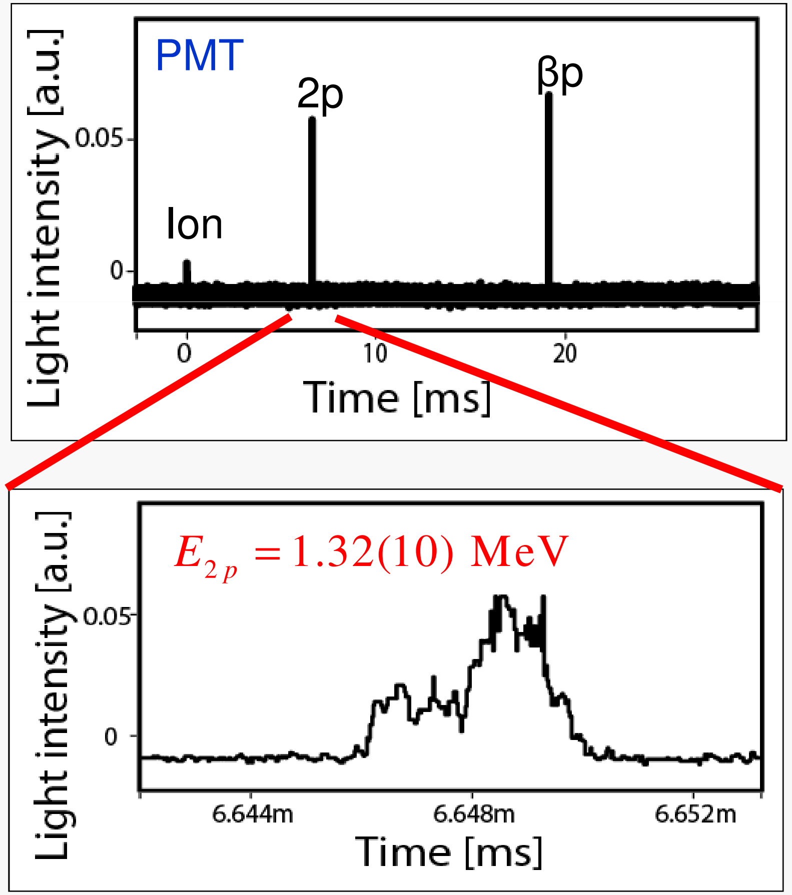
OTPC operation

- The CCD picture yields 2D projection of tracks of particles

- The PMT provides information on sequence, timing, and z-coordinate

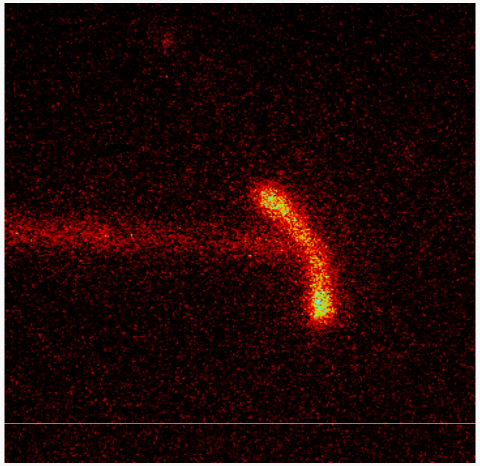


Pomorski et al., PRC 83 (2011) 061303(R)



Three cases around Z=28

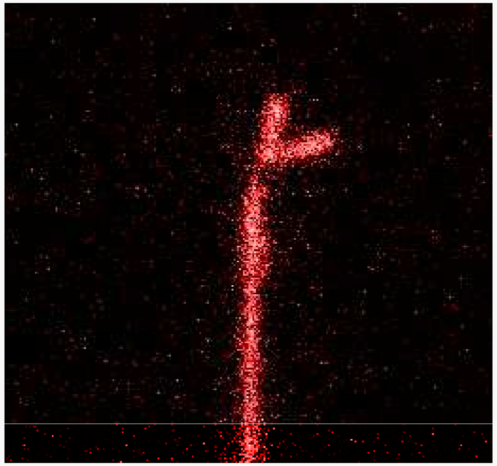
^{45}Fe



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

≈ 80 events

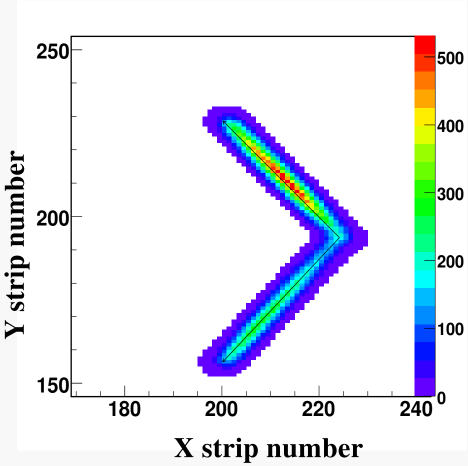
^{48}Ni



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

4 events

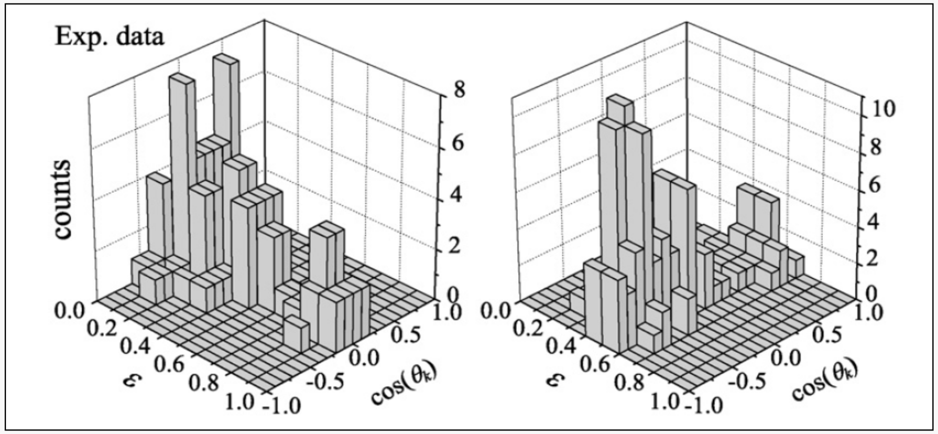
^{54}Zn



Ascher et al., PRL 107 (2011) 102502

7 events

For ^{45}Fe the p-p momentum correlations has been established

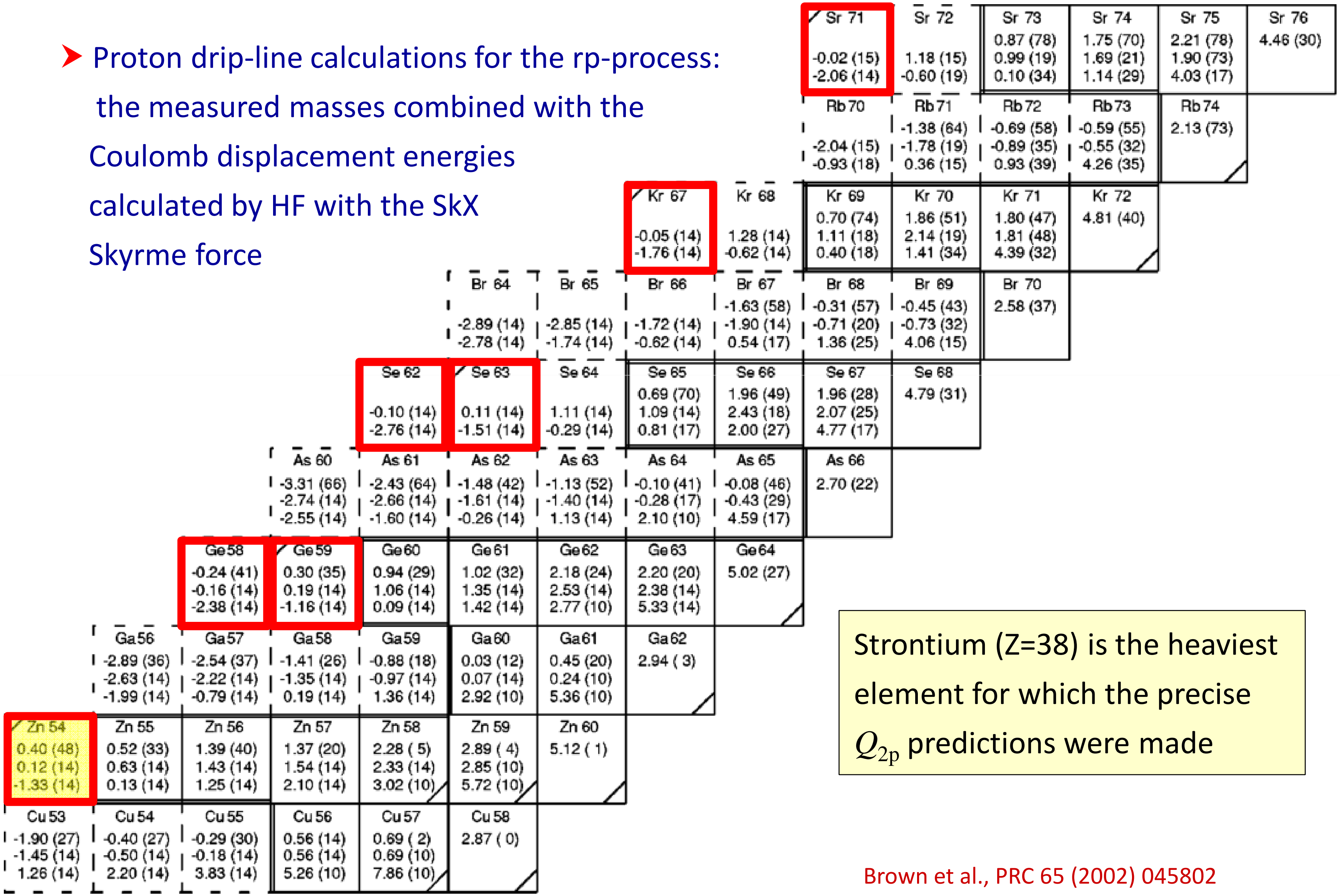


Grigorenko *et al*., PLB 677 (09) 30

M.P. et al., Rev. Mod. Phys. 84 (2012) 567

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



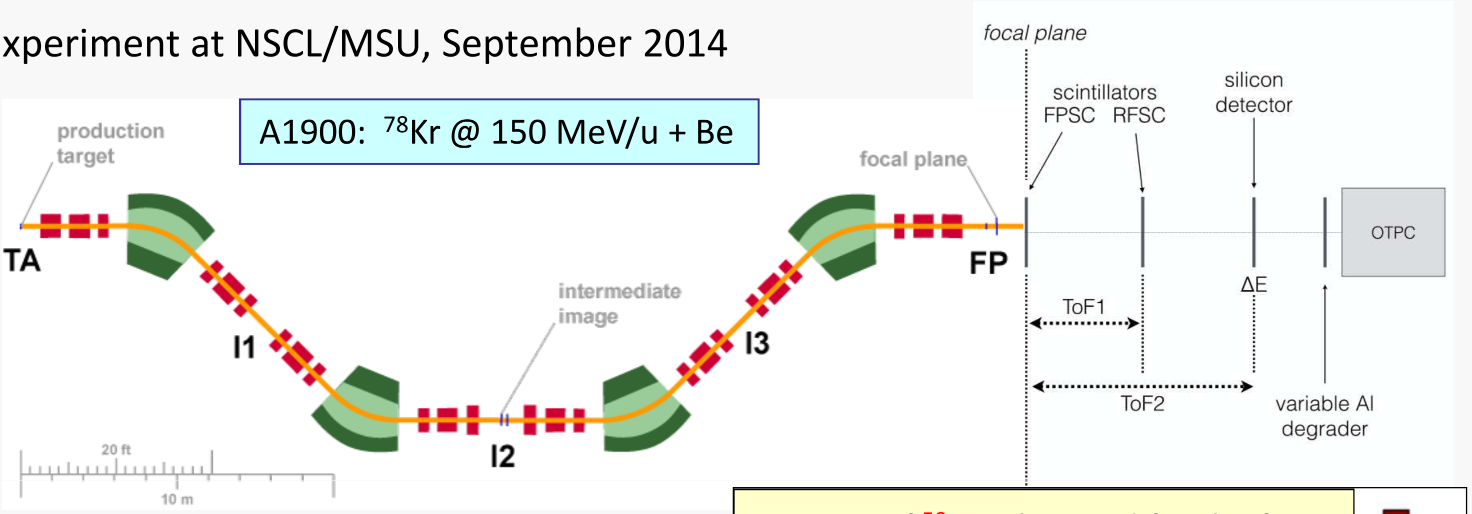
									Sr 71 -0.02 (15) -2.06 (14)	Sr 72 1.18 (15) -0.60 (19)	Sr 73 0.87 (78) 0.99 (19) 0.10 (34)	Sr 74 1.75 (70) 1.69 (21) 1.14 (29)	Sr 75 2.21 (78) 1.90 (73) 4.03 (17)	Sr 76 4.46 (30)
									Rb 70 -2.04 (15) -0.93 (18)	Rb 71 -1.38 (64) -1.78 (19) 0.36 (15)	Rb 72 -0.69 (58) -0.89 (35) 0.93 (39)	Rb 73 -0.59 (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)					
		Ge58 -0.24 (41) -0.16 (14) -2.38 (14)	Ge59 0.30 (35) 0.19 (14) -1.16 (14)	Ge60 0.94 (29) 1.06 (14) 0.09 (14)	Ge61 1.02 (32) 1.35 (14) 1.42 (14)	Ge62 2.18 (24) 2.53 (14) 2.77 (10)	Ge63 2.20 (20) 2.38 (14) 5.33 (14)	Ge64 5.02 (27)						
	Ga56 -2.89 (36) -2.63 (14) -1.99 (14)	Ga57 -2.54 (37) -2.22 (14) -0.79 (14)	Ga58 -1.41 (26) -1.35 (14) 0.19 (14)	Ga59 -0.88 (18) -0.97 (14) 1.36 (14)	Ga60 0.03 (12) 0.07 (14) 2.92 (10)	Ga61 0.45 (20) 0.24 (10) 5.36 (10)	Ga62 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

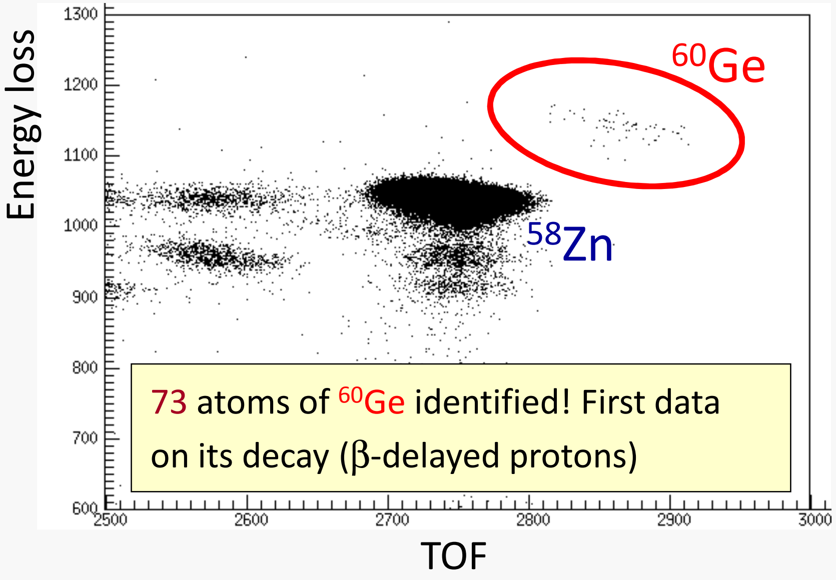
Brown et al., PRC 65 (2002) 045802

First observation of ^{59}Ge

- Experiment at NSCL/MSU, September 2014

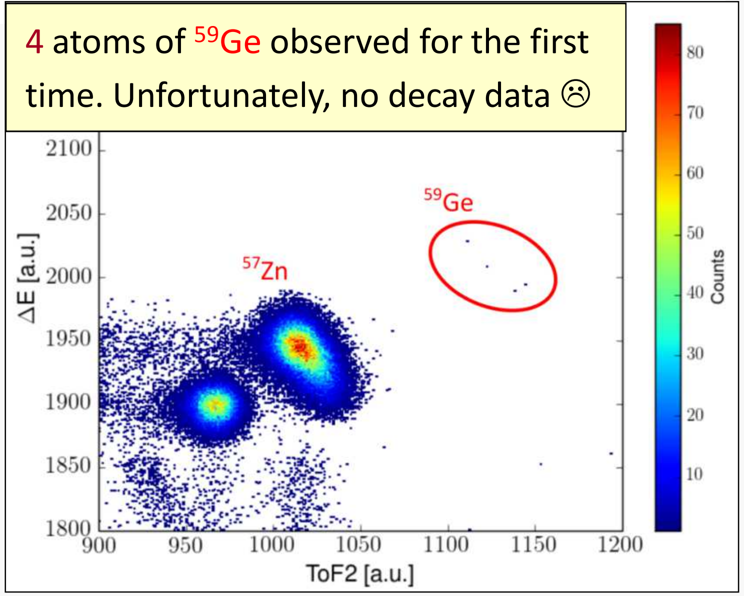


A1900: ^{78}Kr @ 150 MeV/u + Be



73 atoms of ^{60}Ge identified! First data on its decay (β-delayed protons)

Ciemny et al., EPJ A52 (2016) 89



4 atoms of ^{59}Ge observed for the first time. Unfortunately, no decay data ☹

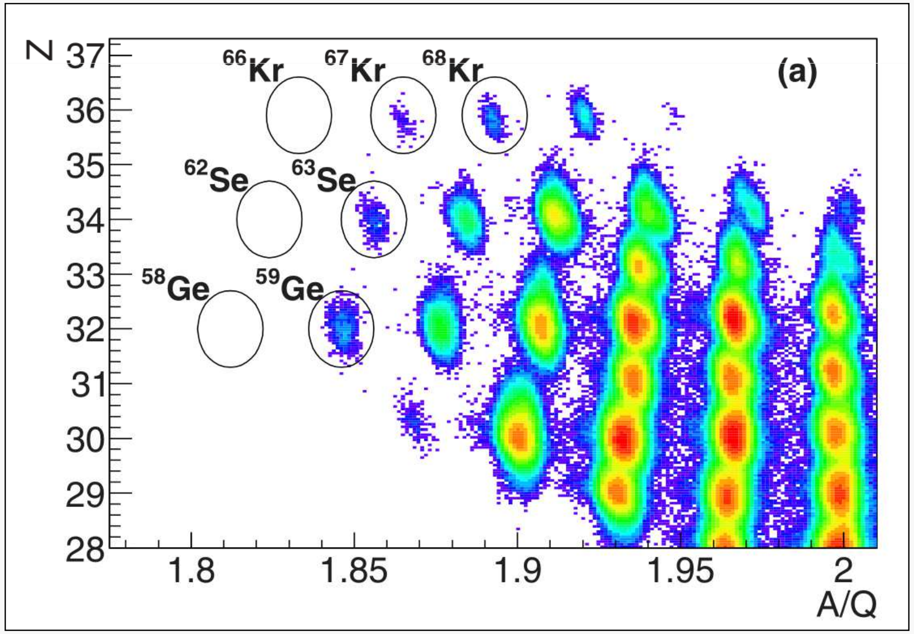
Ciemny et al., PRC 92 (2015) 014622

New results from RIKEN

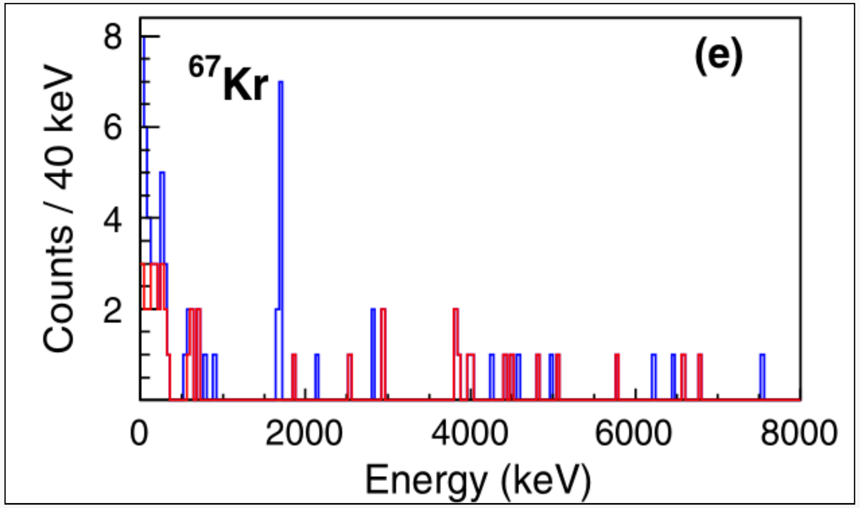
- French group at RIKEN, spring 2015

BigRIPS: ^{78}Kr @ 345 MeV/u + Be

  - First observation of ^{63}Se, ^{67}Kr, and ^{68}Kr
  - 1220 events of ^{59}Ge (!) and none for ^{58}Ge ➞ unbound
  - 2p emission in ^{67}Kr clearly observed ➞ $Q_{2p} = 1690(17)$ keV, $T_{1/2} = 7.4(30)$ ms, $b_{2p} = 37(14)\%$



Blank et al., PRC 93 (2016) 061301(R)

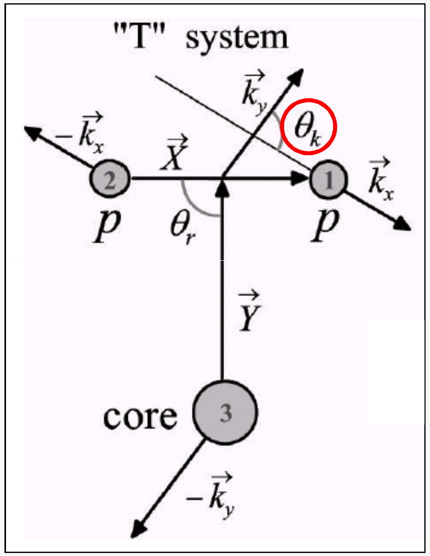


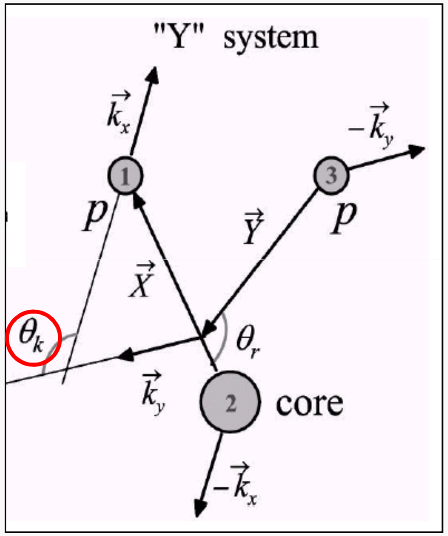
Goigoux et al., PRL 117 (2016) 162501

Jacobi coordinates

- Three-body kinematics is simpler in Jacobi coordinates.

  The *p*-*p* correlations are fully described by two variables: $\varepsilon = E_X / E_T$ and θ_k





Transition from CM to
Jacobi „T” system

$\vec{k}_1, \vec{k}_2$ - protons' momenta in CM

$$E_X = \left(\vec{k}_1 - \vec{k}_2\right)^2 / 4\, m_p$$

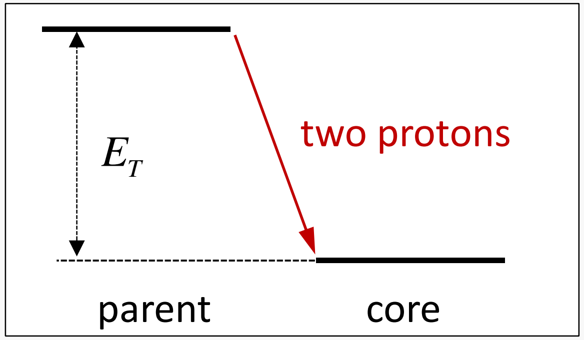
θ_k is the angle between vectors:

$\left(\vec{k}_1 - \vec{k}_2\right)$ and $\left(\vec{k}_1 + \vec{k}_2\right)$

- In place of radius and solid angle we introduce the *hyperradius* and *hyper solid angle*:

$$r,\ \Omega \ \rightarrow\ \rho,\ \Omega_5 \qquad \Omega_5 = \left\{\theta_\rho, \Omega_X, \Omega_Y\right\} \qquad \rho = \frac{A_1 A_2 A_3}{A_1 + A_2 + A_3}\left(\frac{\vec{r}_{12}^{\,2}}{A_3} + \frac{\vec{r}_{23}^{\,2}}{A_1} + \frac{\vec{r}_{31}^{\,2}}{A_2}\right)$$

Three-body model



- Cluster approximation (two protons and the core)
- Parent wave function:

$$\Psi_{JM}(\rho,\Omega_5)=\frac{1}{\rho^{5/2}}\sum_{\alpha=\{K,\ldots\}}\chi_\alpha(\rho)\,\mathcal{J}_\alpha^{JM}(\Omega_5)$$

radial functions hyperspherical harmonics

→Schrödinger equation, integration over angles:

$$\left[\frac{d^2}{d\rho^2}-\frac{\mathcal{L}_K(\mathcal{L}_K+1)}{\rho^2}+\frac{2\mu}{\hbar^2}E_T\right]\chi_\alpha(\rho)=\frac{2\mu}{\hbar^2}\sum_{\alpha'}\left(\hat{V}_{\alpha,\alpha'}\right)\chi_{\alpha'}(\rho)$$

(coupled channels)

- Main problem: the asymptotic form of radial functions is not known!

Solution of Grigorenko and Zhukov:

$$\chi_\alpha^+(\rho)\xrightarrow[\rho\to\infty]{}\sim\sum_{\alpha'}\hat{A}_{\alpha,\alpha'}\left[G_{\mathcal{L}_0}(\eta_{\alpha'},\kappa\rho)+i\,F_{\mathcal{L}_0}(\eta_{\alpha'},\kappa\rho)\right]$$

$\hat{A}_{\alpha,\alpha'}$ is the matrix which diagonalizes the Coulomb part of $\hat{V}_{\alpha,\alpha'}$

→From radial functions the width and correlations :

$$\chi_\alpha^+(\rho)\Rightarrow\Gamma\,,\quad dj/d\varepsilon\,d(\cos\theta_k)$$

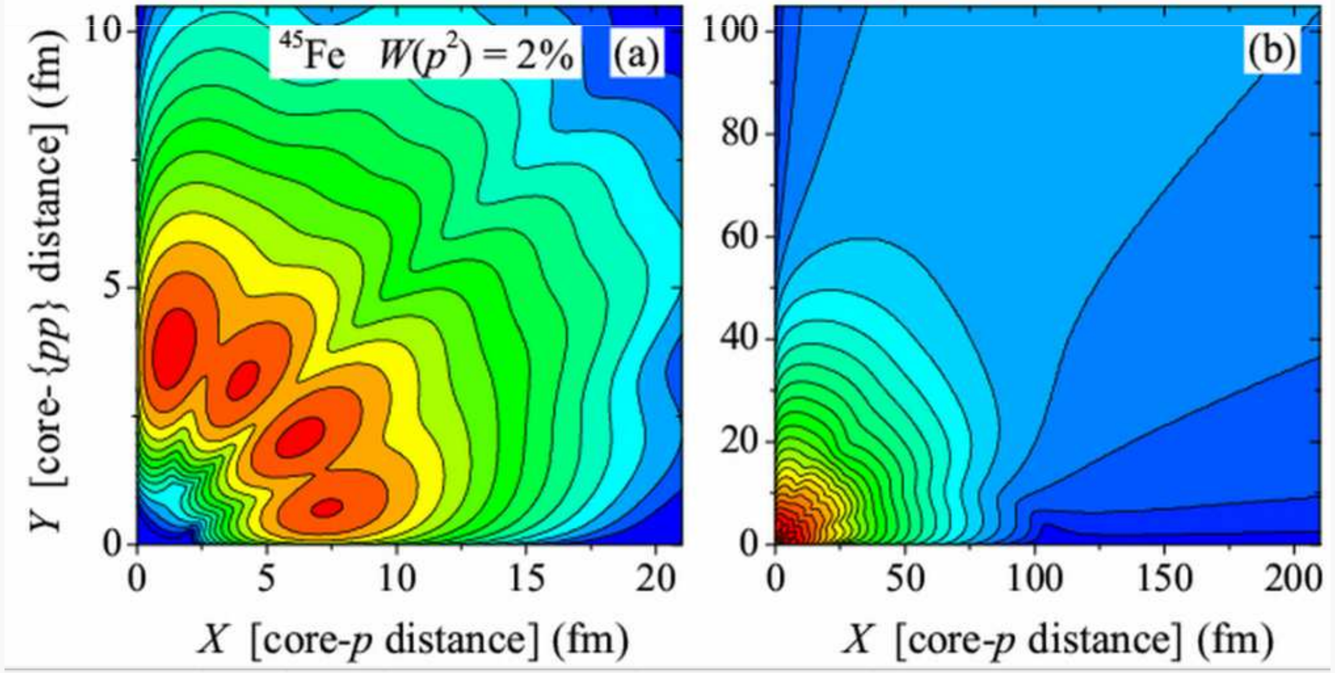
Grigorenko and Zhukov, PRC 68 (03) 054005
M.P. et al, RMP (2012) 567

^{45}Fe: the wave function

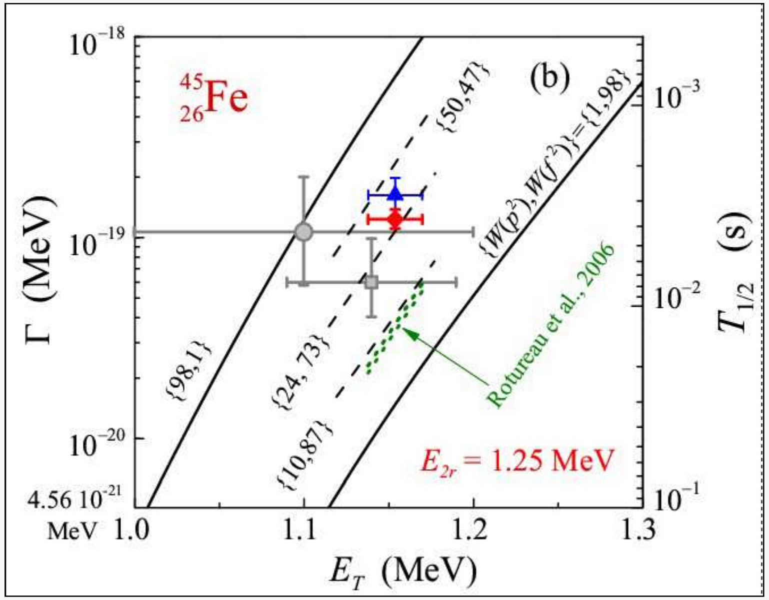
- The 3-body wave function can be expressed as a sum of terms having defined l^2 configuration: $$\Psi_{JM} = \sum_i W_i \left[l_i^2 \right]_0$$

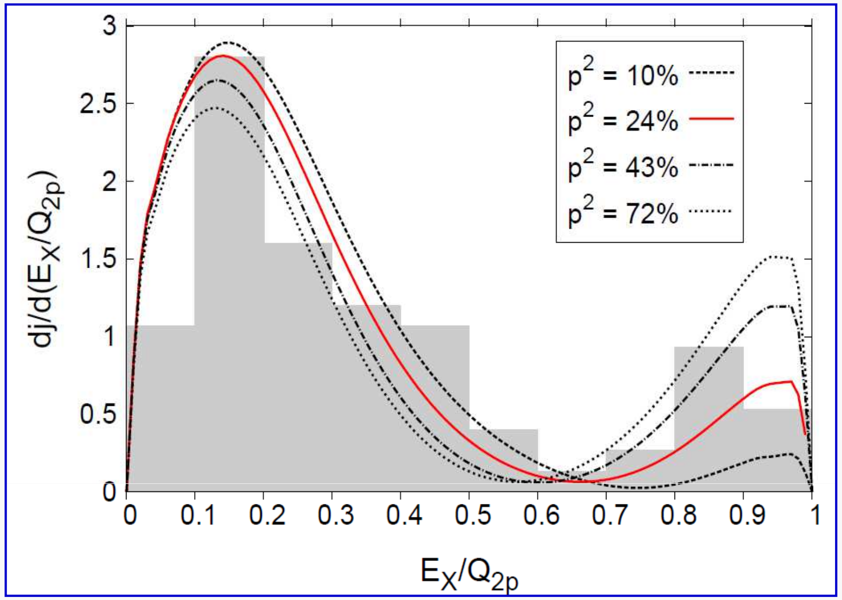
  By adjusting the potentials, the weights of different l^2 configurations can be modified

The ^{45}Fe wave function density $|\Psi|^2$ in the T system for $W(f^2) = 98\%$, $W(p^2) = 2\%$



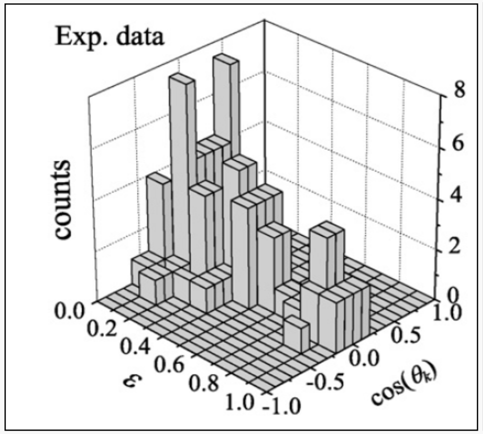
p-p correlations in ^{45}Fe

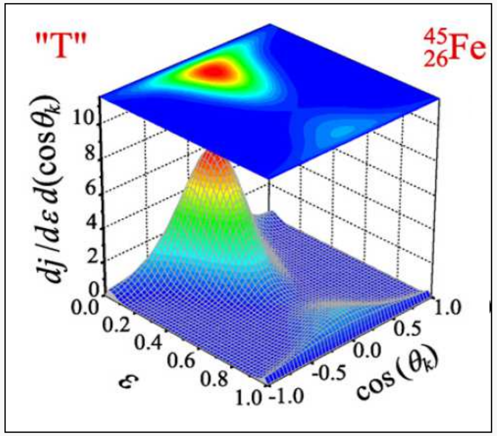




Result for ^{45}Fe: $W(p^2) = 0.3\pm0.1$

- All observables are well reproduced by the 3-body model
- The picture seems to depend on the composition of the initial wave function



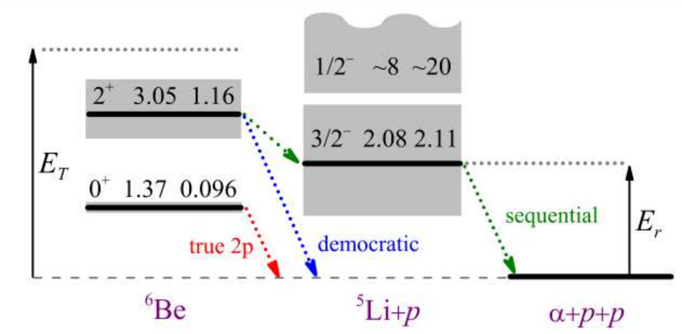


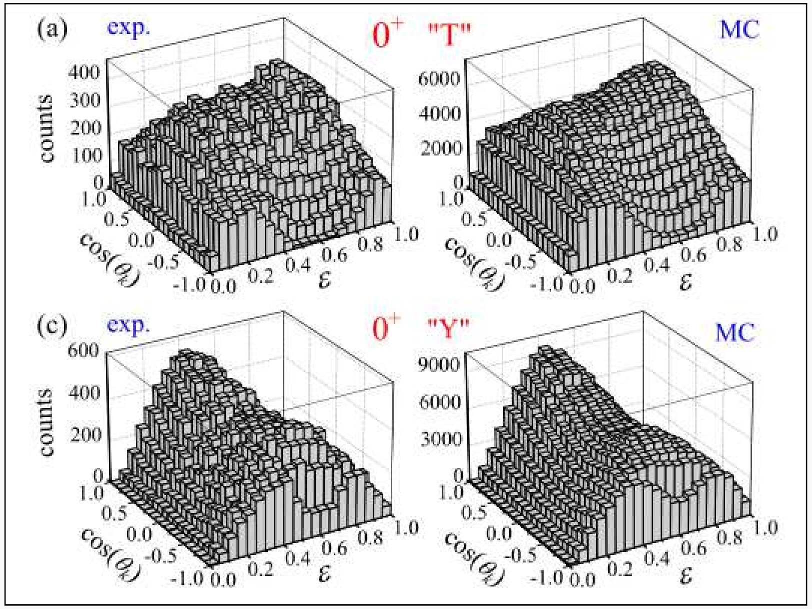
Grigorenko *et al*., PLB 677 (2009) 30

M.P. et al., Rev. Mod. Phys. 84 (2012) 567

^{6}Be and ^{19}Mg

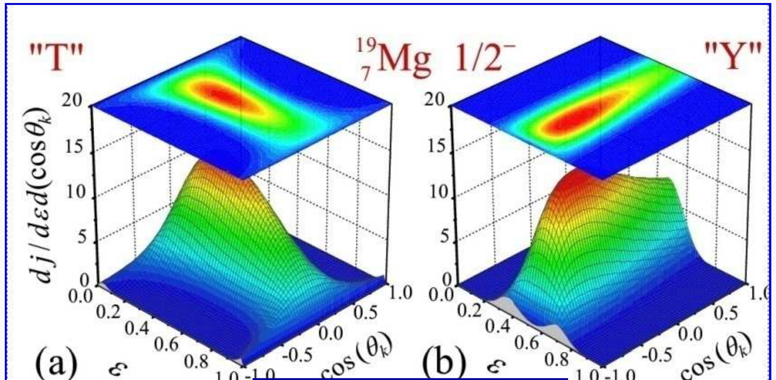
^{7}Be + Be → ^{6}Be @ NSCL



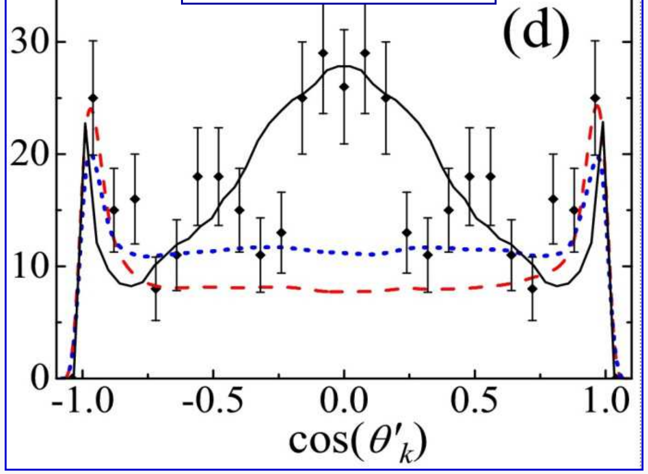


Egorova *et al.*, PRL 109 (2012) 202502

^{20}Mg + Be → ^{19}Mg @ GSI



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



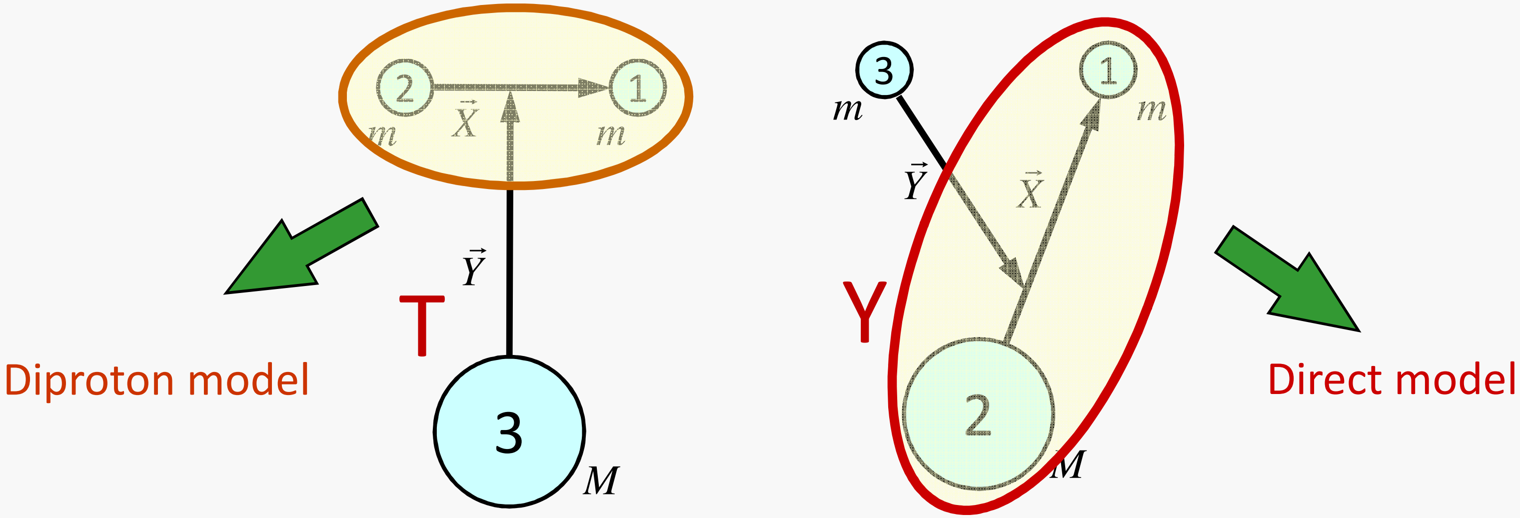
Mukha et al., PRL 99 (2007) 182501

Mukha et al., EPJA 42 (2009) 421

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.

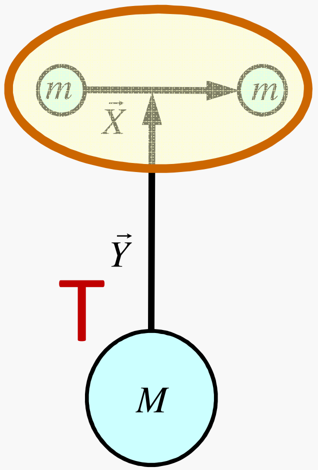
Diproton model

- Jacobi T system → **diproton model**

The WKB approximation

$$\boxed{\Gamma_{2p,dipr} = \theta^2_{dipr} \mathcal{N} \frac{\hbar^2}{4\mu} \exp\left[-2\int_{r_2}^{r_3} k(r)\, dr\right]}$$

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



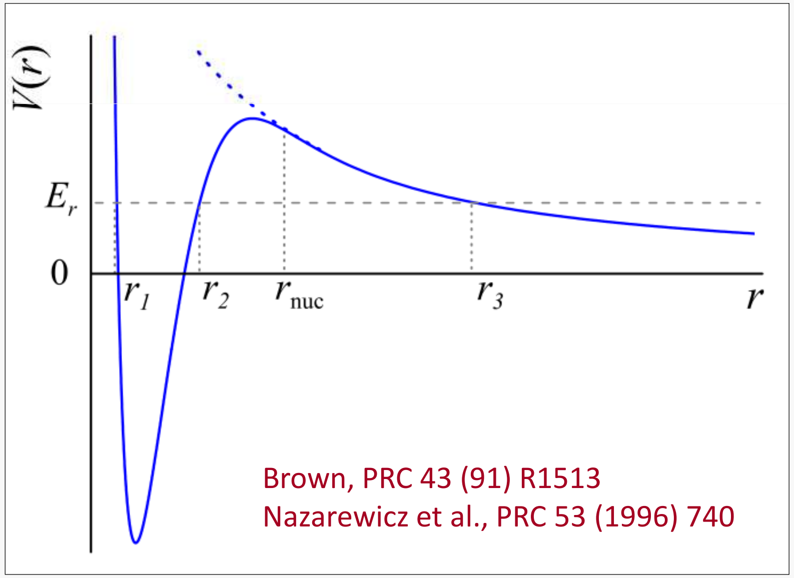
$$\mathcal{N}\int_{r_1}^{r_2} \frac{dr}{2k(r)} = 1$$

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

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

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

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



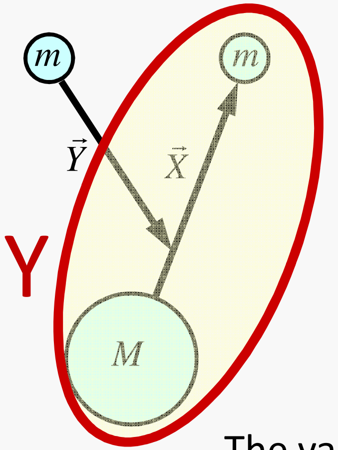
Brown, PRC 43 (91) R1513
Nazarewicz et al., PRC 53 (1996) 740

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

Direct model

- Jacobi Y system → **direct model**

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

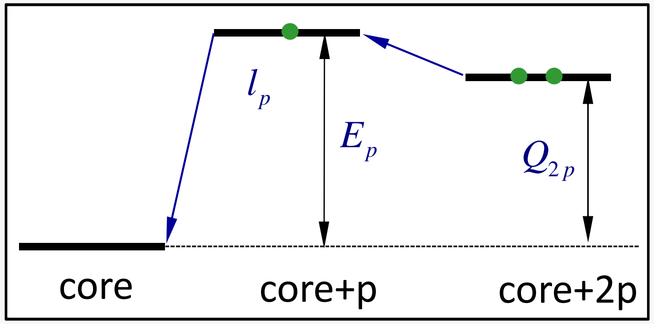


Γ_i is the width of the two-body subsystem: $\Gamma_i(E)=2\gamma_i^2 P_{l_p}(E,R,Z_i)$

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

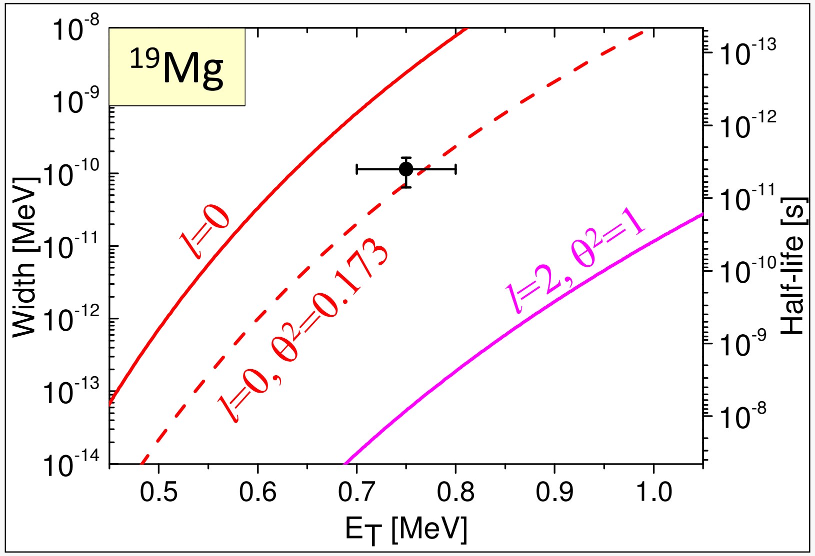
reduced width: $\gamma_i^2=\dfrac{\hbar^2}{2\mu_i R^2}\theta_i^2$

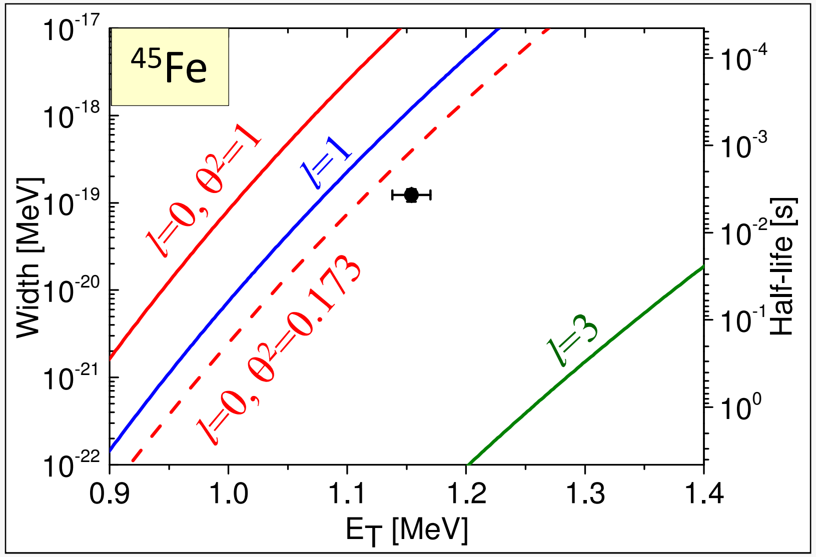
The value of spectroscopic factor determined from the experimental half-lives of known 2p emitters: ^{19}Mg, ^{45}Fe, ^{48}Ni, and ^{54}Zn, assuming $l_\mathrm{p}=0$ ⇨ $\boxed{\theta_x^2=\theta_y^2=0.173}$

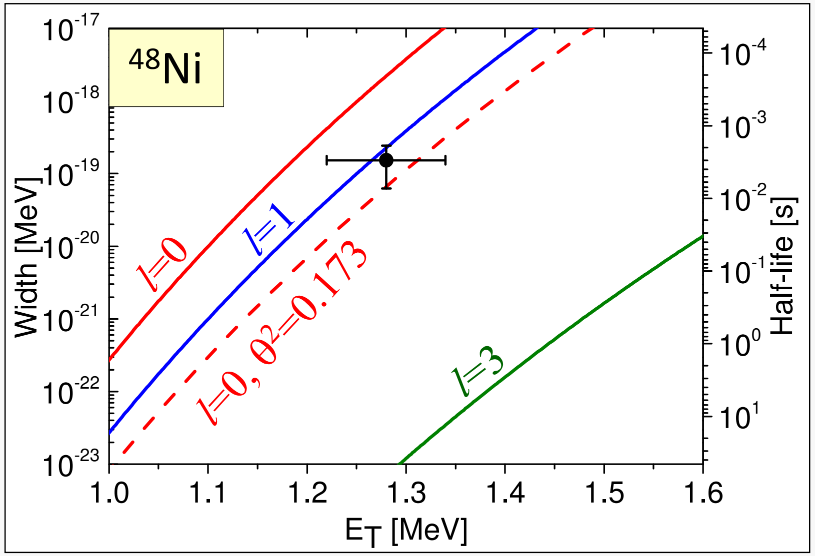


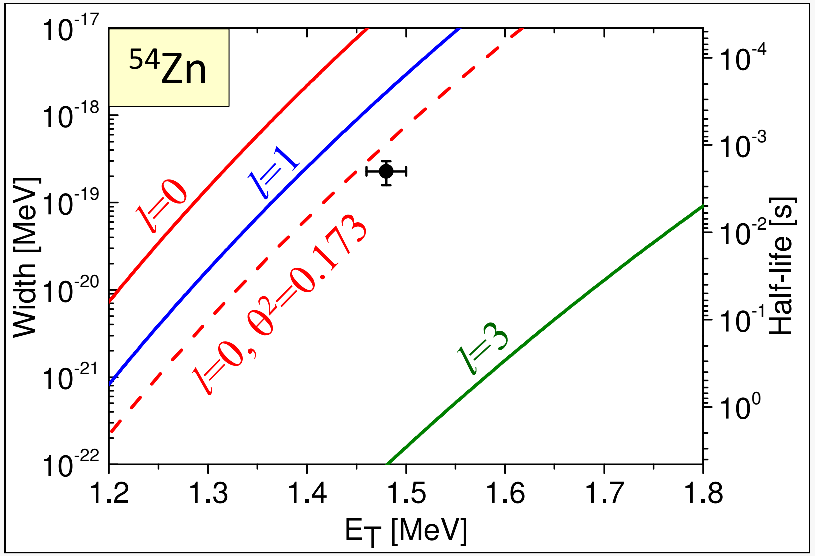
Grigorenko and Zhukov, PRC 76 (07) 014009
M.P. et al, RMP (2012) 567

Direct model for known 2p emitters



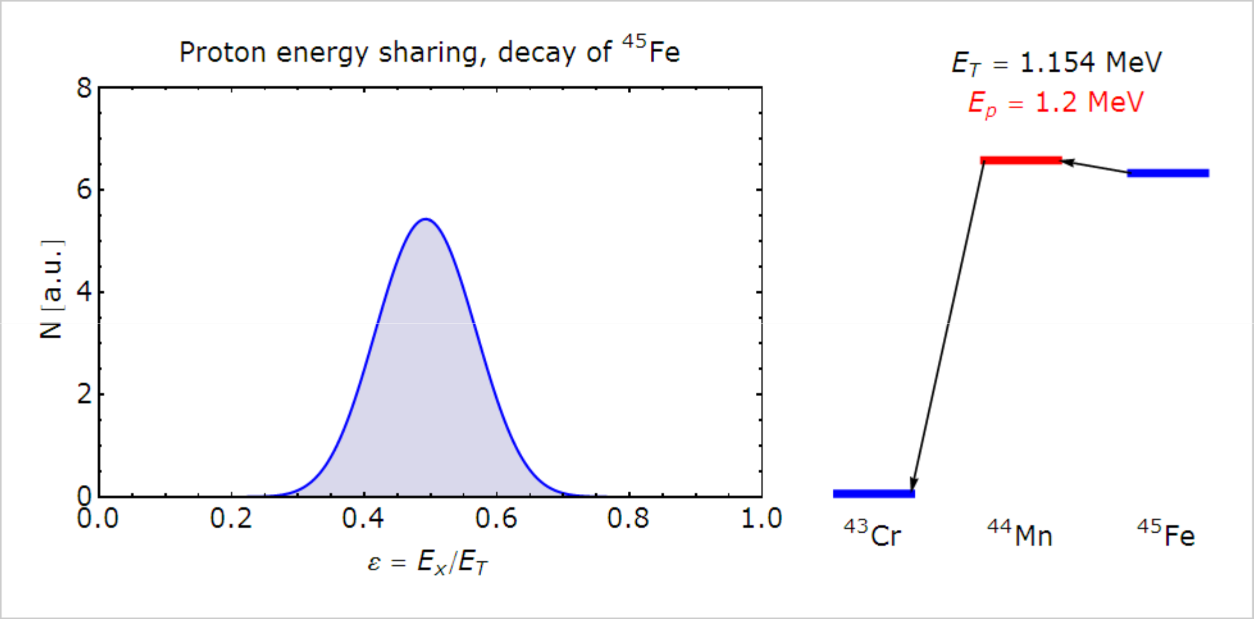






Simultaneous vs. sequential

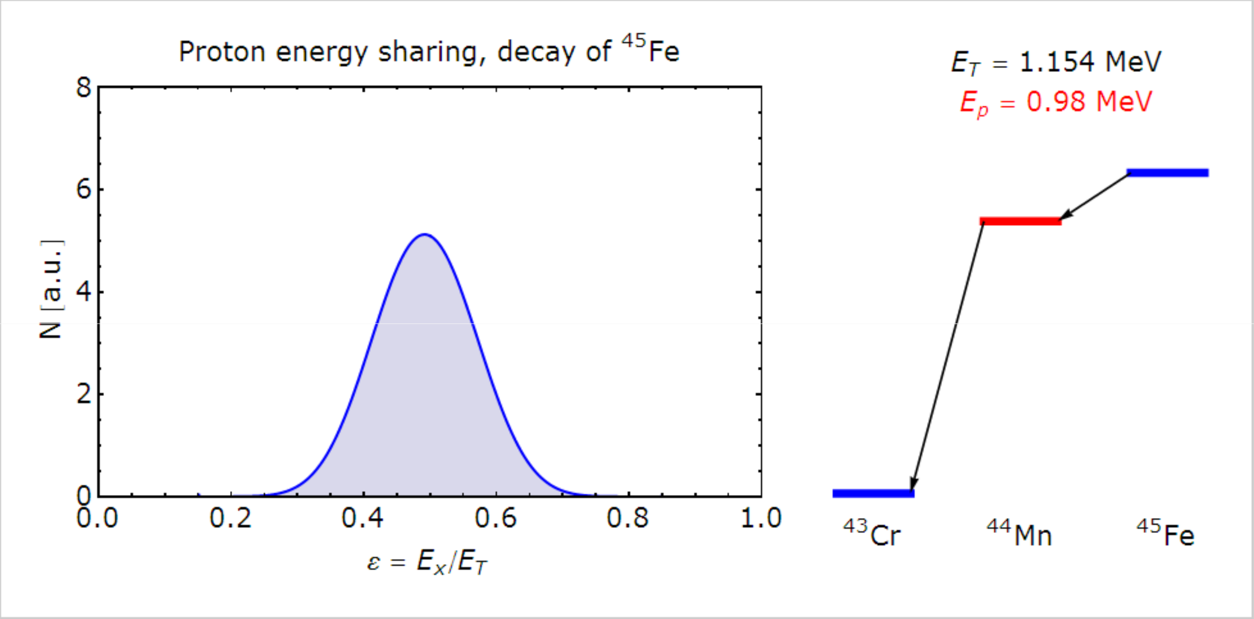
- In the direct model we can investigate how the proton's energy spectrum depends on the position of the intermediate state



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

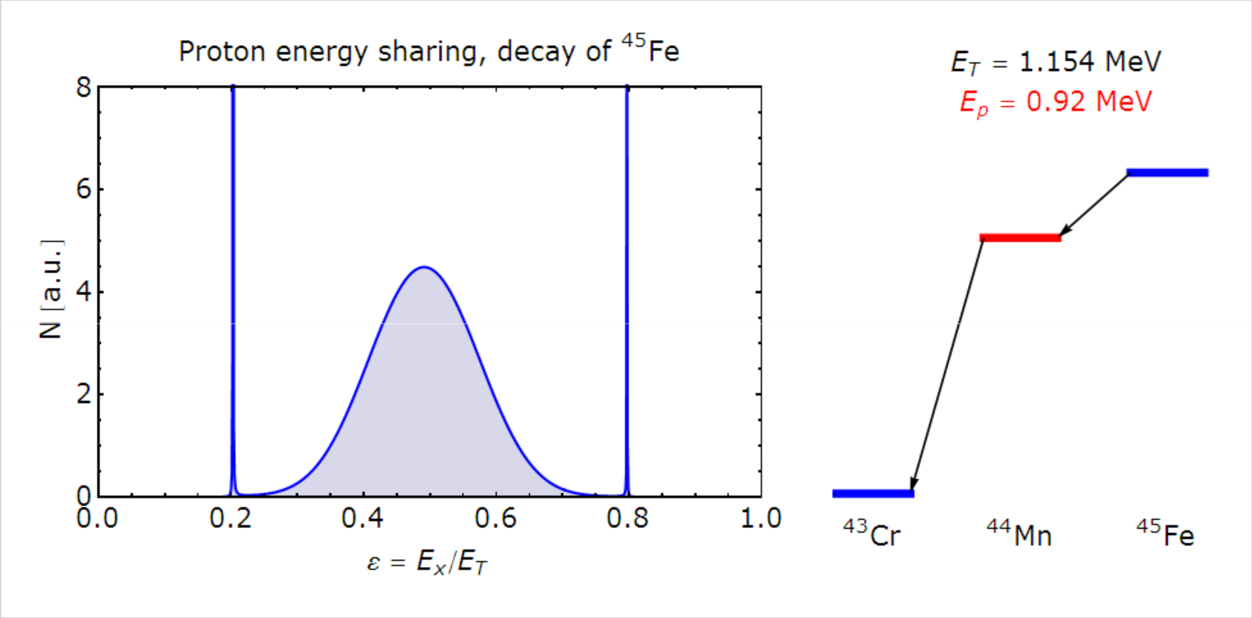


$$\boxed{Q_{2p} = 1.15 \text{ MeV},\ Q_{1p} = 0.17 \text{ MeV}}$$

➡ Still simultaneous 2p!

Simultaneous vs. sequential

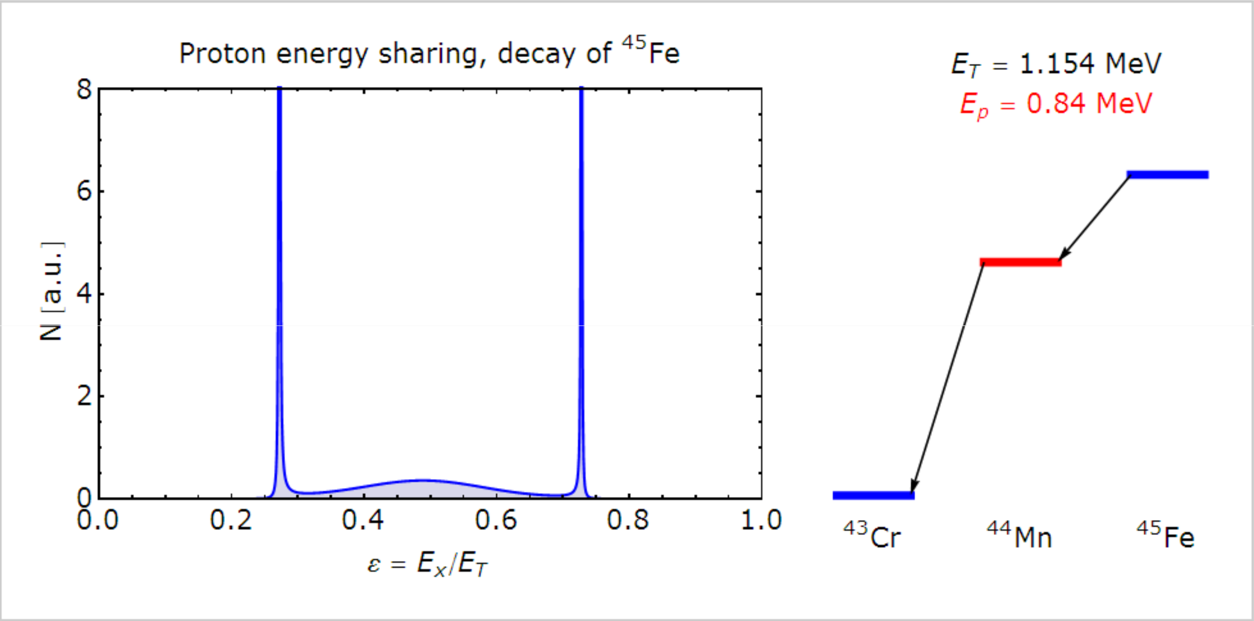
- In the direct model we can investigate how the proton's energy spectrum depends on the position of the intermediate state



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



$\boxed{Q_{2p} = 1.15\ \text{MeV},\ \ Q_{1p} = 0.31\ \text{MeV}}$ ➡ Sequential 2p emission dominates

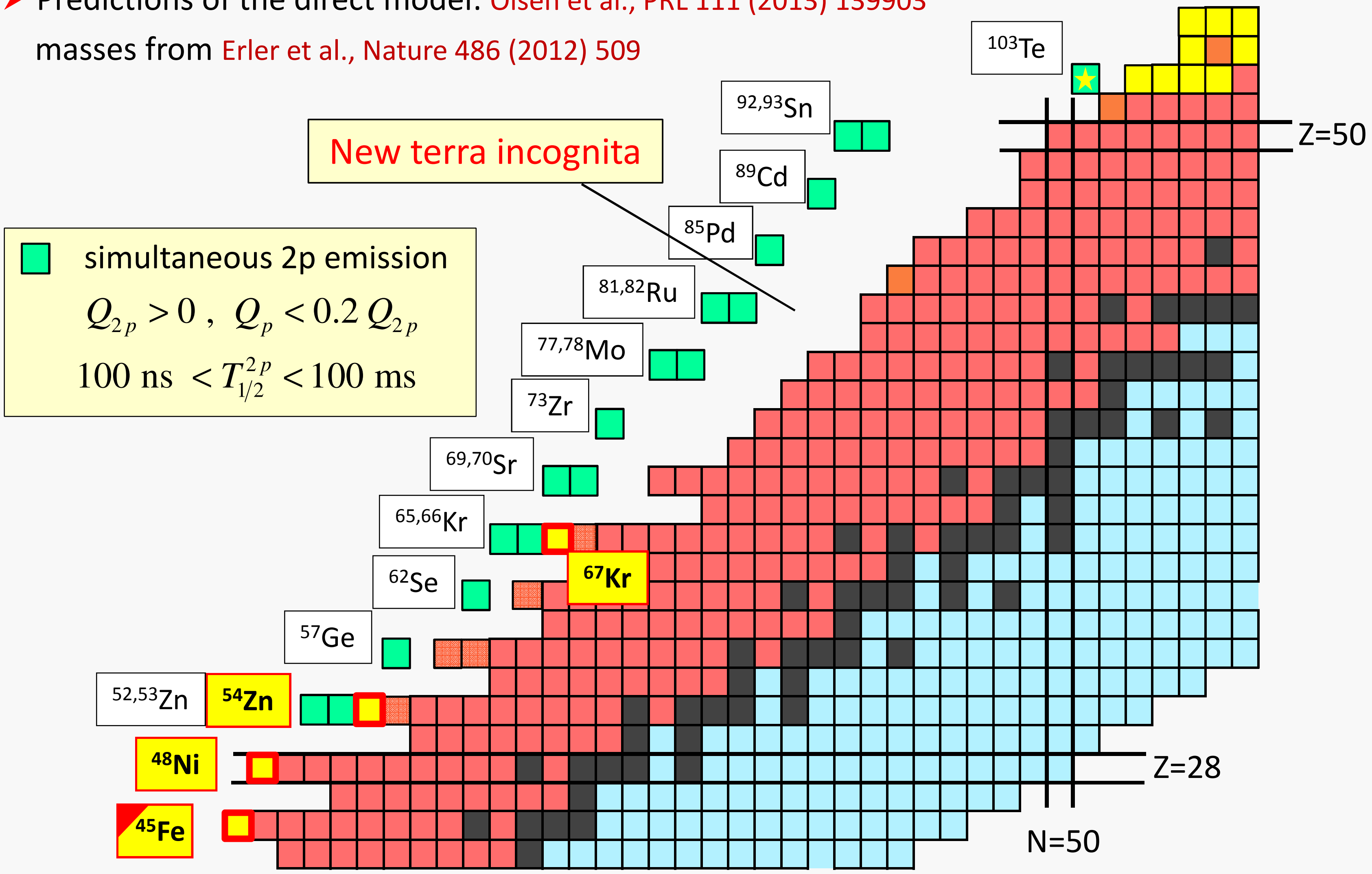
→ Rough criterion: for $Q_p < 0.2\, Q_{2p}$ true, simultaneous 2p decay

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

Up to tellurium

- Predictions of the direct model: Olsen et al., PRL 111 (2013) 139903

  masses from Erler et al., Nature 486 (2012) 509



New terra incognita

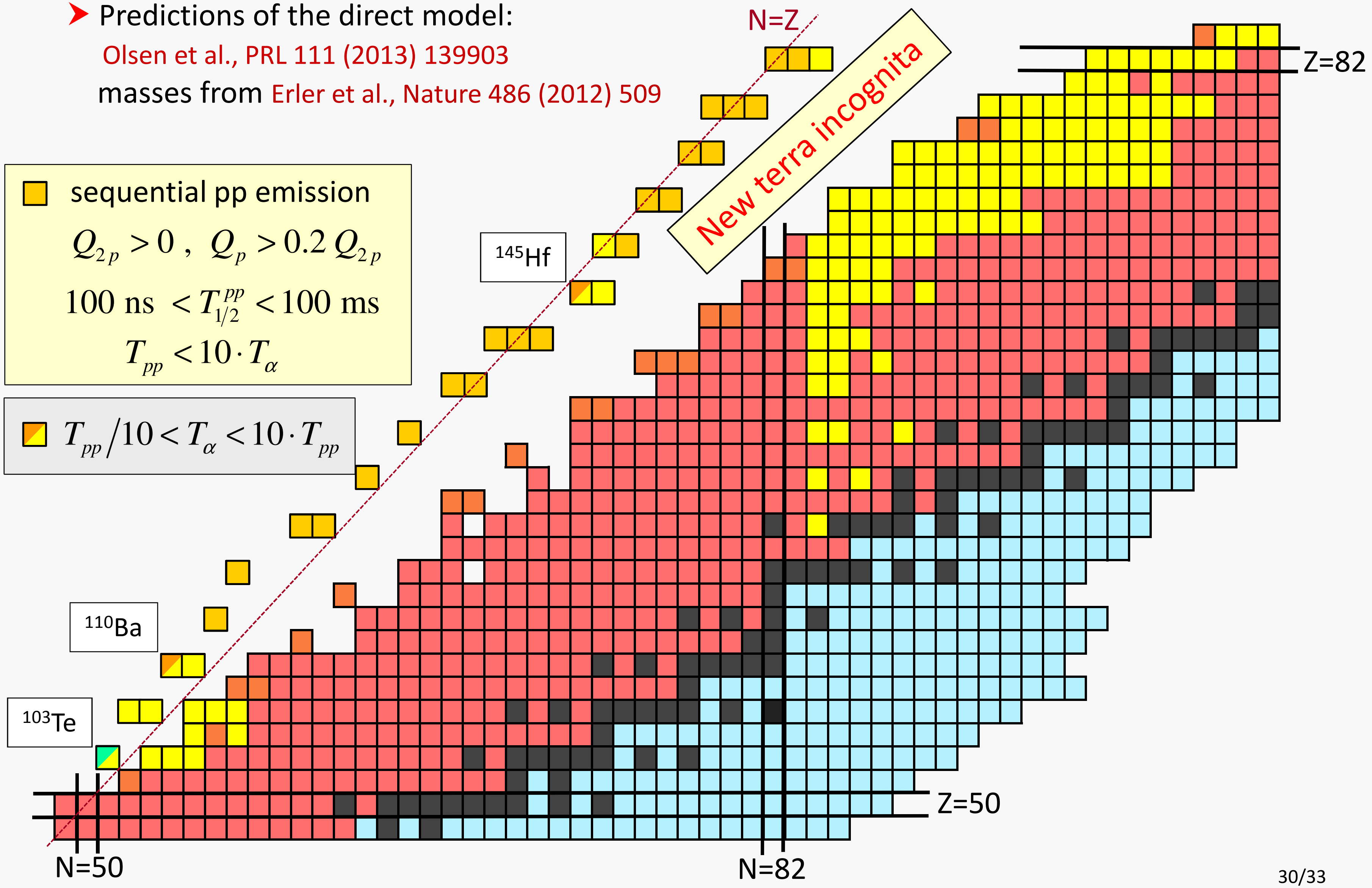
🟩 simultaneous 2p emission

$$Q_{2p} > 0\,,\;\; Q_p < 0.2\,Q_{2p}$$

$$100\ \text{ns} < T_{1/2}^{2p} < 100\ \text{ms}$$

Between tellurium and lead

- Predictions of the direct model:
  Olsen et al., PRL 111 (2013) 139903
  masses from Erler et al., Nature 486 (2012) 509



🟨 sequential pp emission

$$Q_{2p} > 0\,,\quad Q_p > 0.2\,Q_{2p}$$

$$100\ \text{ns} < T_{1/2}^{pp} < 100\ \text{ms}$$

$$T_{pp} < 10\cdot T_\alpha$$

◩ $T_{pp}/10 < T_\alpha < 10\cdot T_{pp}$

Models of 2p emission

- **3-body** – Grigorenko & Zhukov; Grigorenko et al., Phys. Rev. C 82 (2010) 014615
- **R-matrix** – Brown & Barker Phys. Rev. C 67 (2003) 041304(R)
- **SMEC** (Shell Model Embedded in Continnum) – Rotureau, Okołowicz, Płoszajczak, Nucl. Phys. A 767 (2006) 13
- **TDM** (Time Dependent Method) – Oishi, Hagino, Sagawa, Phys. Rev. C 90 (2014) 034303
- **SATPE** (simple approach, emission from a BCS pairing state) – Delion, Liotta, Wyss, Phys. Rev. C 87 (2013) 034328
- **RMF+BCS** (only masses for candidates 20 < Z < 40) – Singh & Saxena, Int. J. on Modern Phys. E 21 (2012) 1250076
- **Femtoscopy** in 2p decay – Bertulani, Hussein, Verde, Phys. Lett B 666 (2008) 86

Review papers:

- „Two-proton radioactivity” Blank & Płoszajczak, Rep. Prog. Phys. 71 (2008) 046301
- „Radioactive decays at limits of nuclear stability” MP, Karny, Grigorenko, Riisager, Rev. Mod. Phys. 84 (2012) 567

Summary

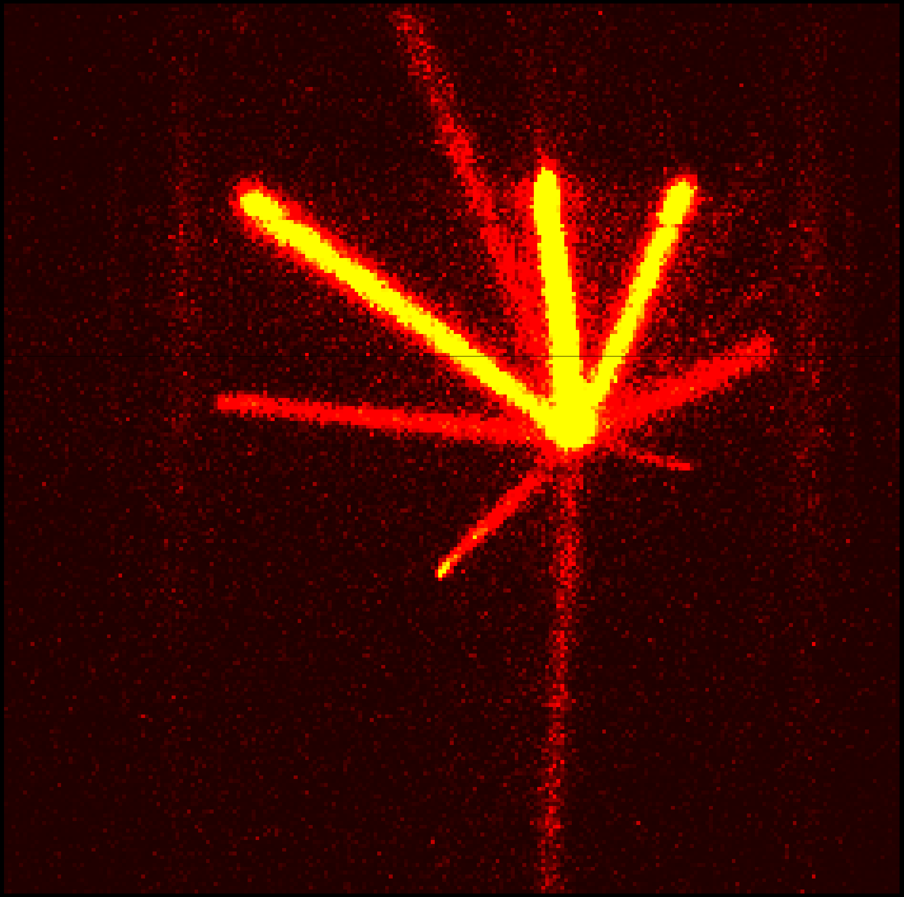
- The simultaneous ground-state ***2p* emission established** for
  ^{6}Be, ^{16}Ne, ^{19}Mg, ^{45}Fe, ^{48}Ni, ^{54}Zn, and ^{67}Kr
  The hunt for other cases continues.

- 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.

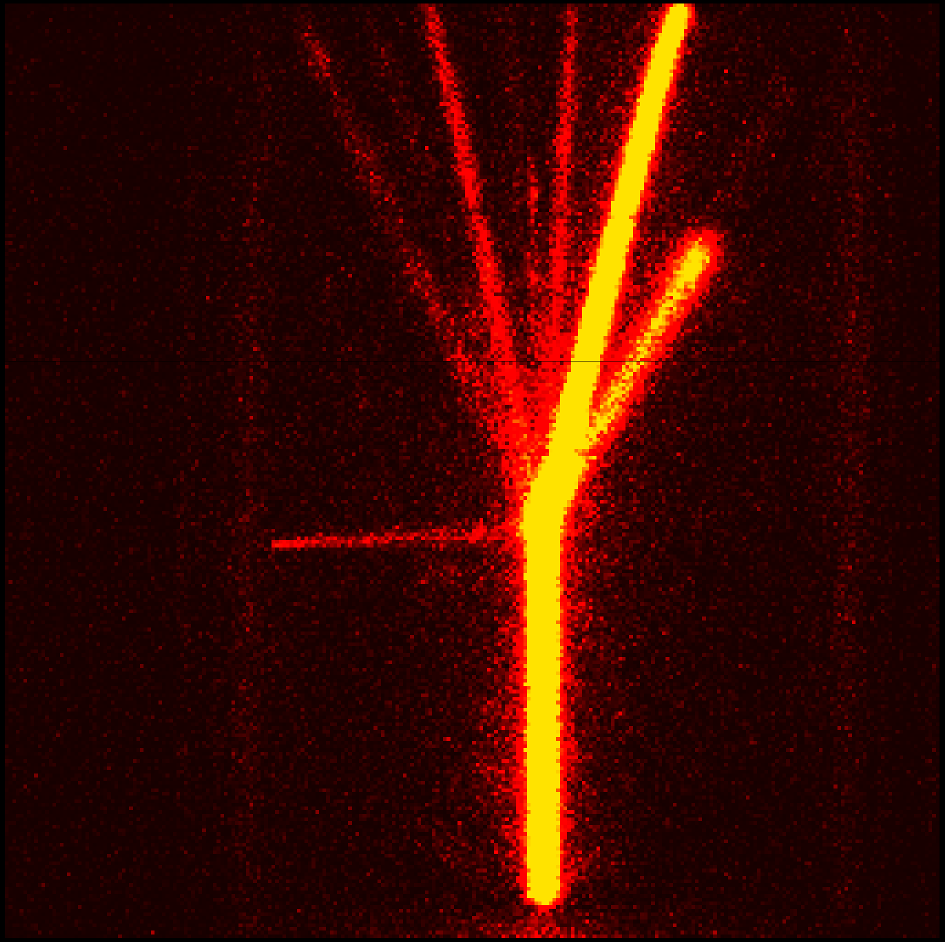
- Correlations between protons offer a new way to investigate nuclear structure. This feature is not yet explored. The only model predicting these correlations suggests the dependence on the initial wave function.

- Better theoretical description of 2p emission is strongly needed!
  It should combine a realistic description of the initial state with the correct 3-body asymptotics.

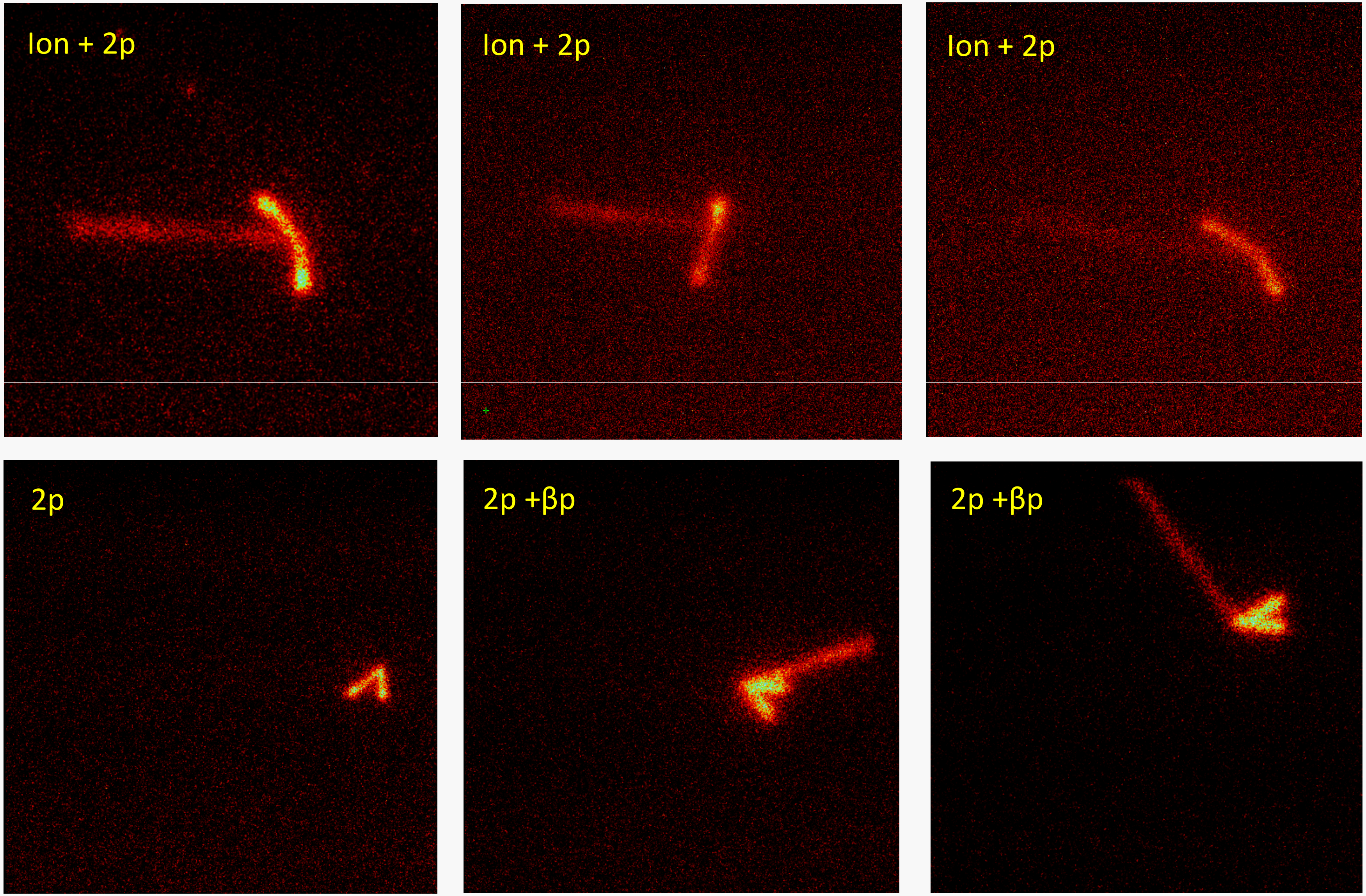
Thank you!



Additional slides



2p decays of ^{45}Fe



Ion + 2p

Ion + 2p

Ion + 2p

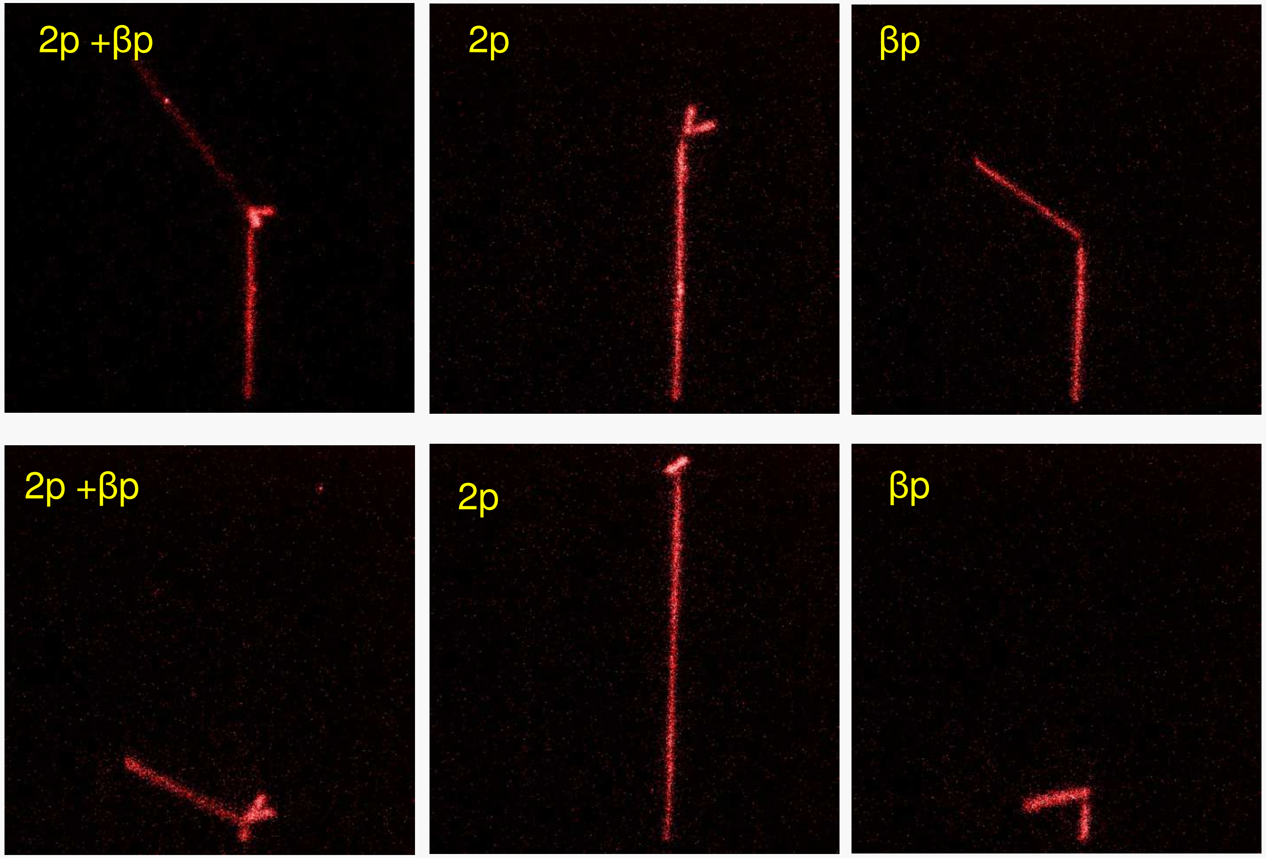
2p

2p +βp

2p +βp

Miernik et al., PRL 99 (2007) 192501

All decays of ^{48}Ni



- Results of the full analysis:

$$Q_{2p} = 1.29(4)\ \text{MeV}$$

Brown [38]	Ormand [39]	Cole [40]
1.36(13)	1.29(33)	1.35(6)

$$T_{1/2} = 2.1^{+1.4}_{-0.6}\ \text{ms}$$

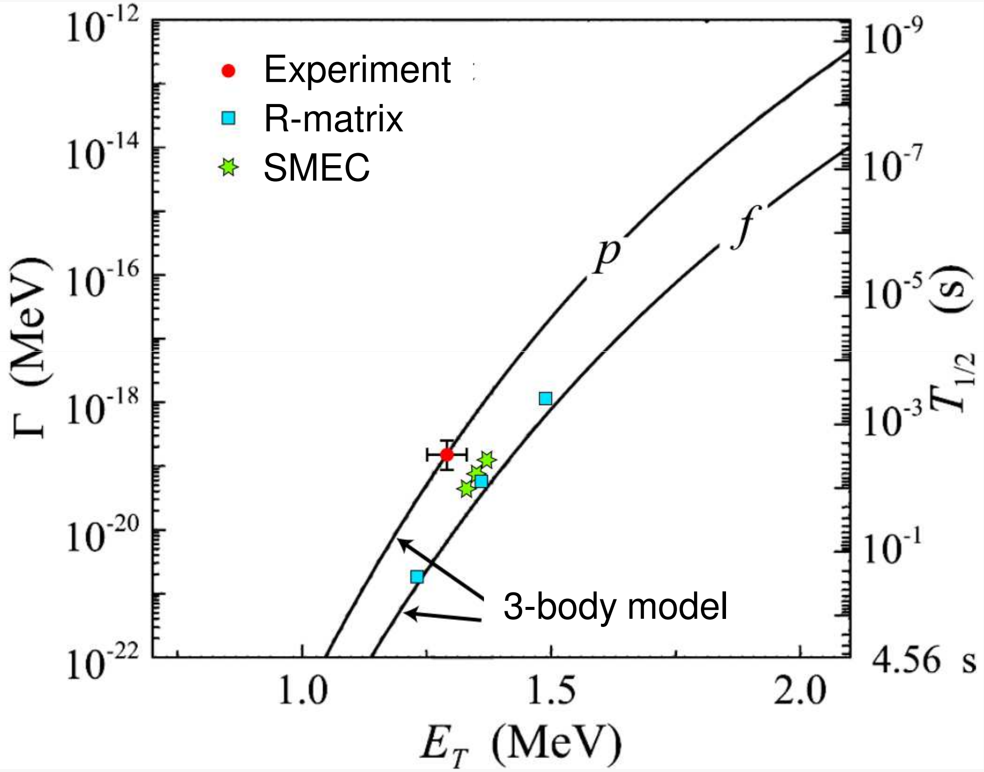
$$b_{2p} = 0.7(2)$$
$$b_{\beta} = 0.3(2)$$

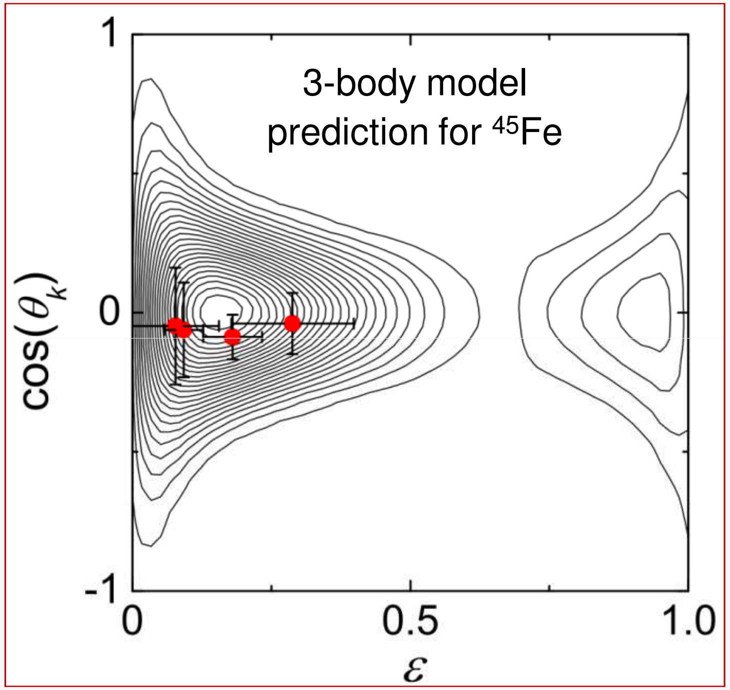
$$\Rightarrow$$

$$T^{2p}_{1/2} = 3^{+2}_{-1}\ \text{ms}$$
$$T^{\beta}_{1/2} = 7^{+7}_{-5}\ \text{ms}$$

2p decay of ^{48}Ni

- Comparison with predictions





Pomorski et al., PRC 90 (14) 014311

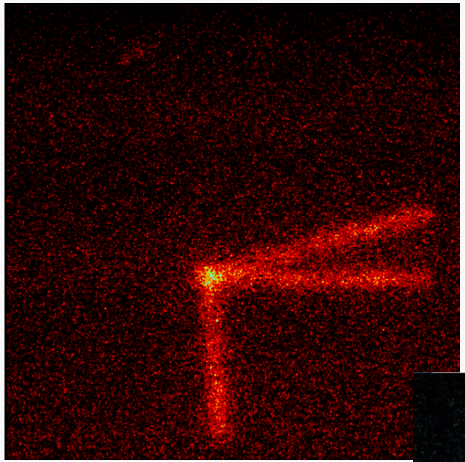
Grigorenko and Zhukov, PRC 68 (2003) 054005

Brown and Barker, PRC 67 (2003) 041304

Rotureau, Okołowicz, Płoszajczak, NPA 767 (2006) 13

→ Unfortunately, there are no predictions for the *p-p* correlations in ^{48}Ni ☹

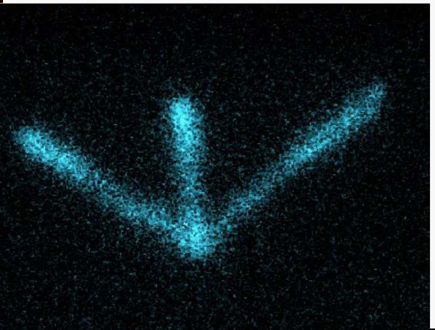
First observation of β3p decay



^{45}Fe, NSCL 2007

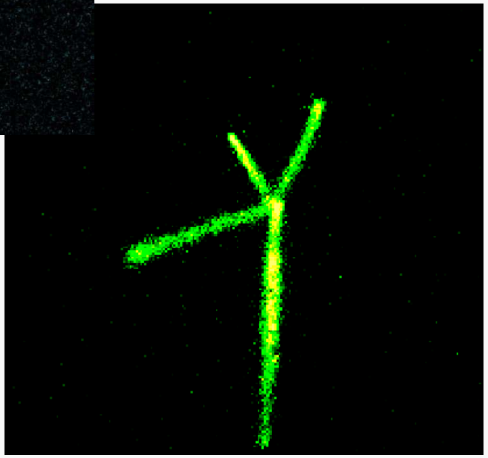
Miernik et al., PRC 76 (07) 041304(R)

The only 3 cases known up to now



^{43}Cr, NSCL 2007

Pomorski et al., PRC 83 (2011) 014306

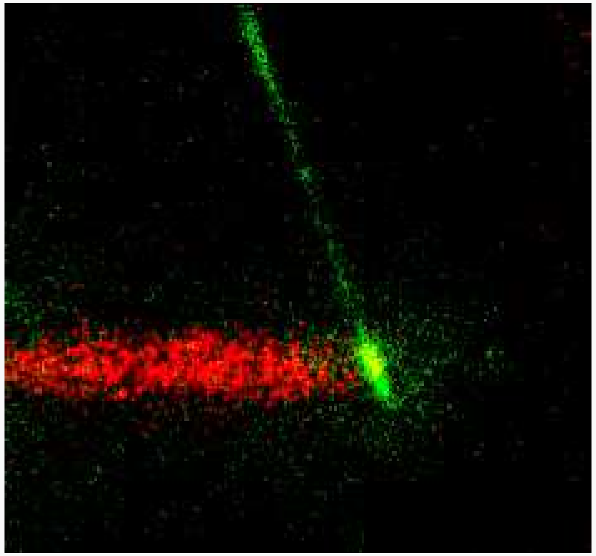


^{31}Ar, GSI 2012

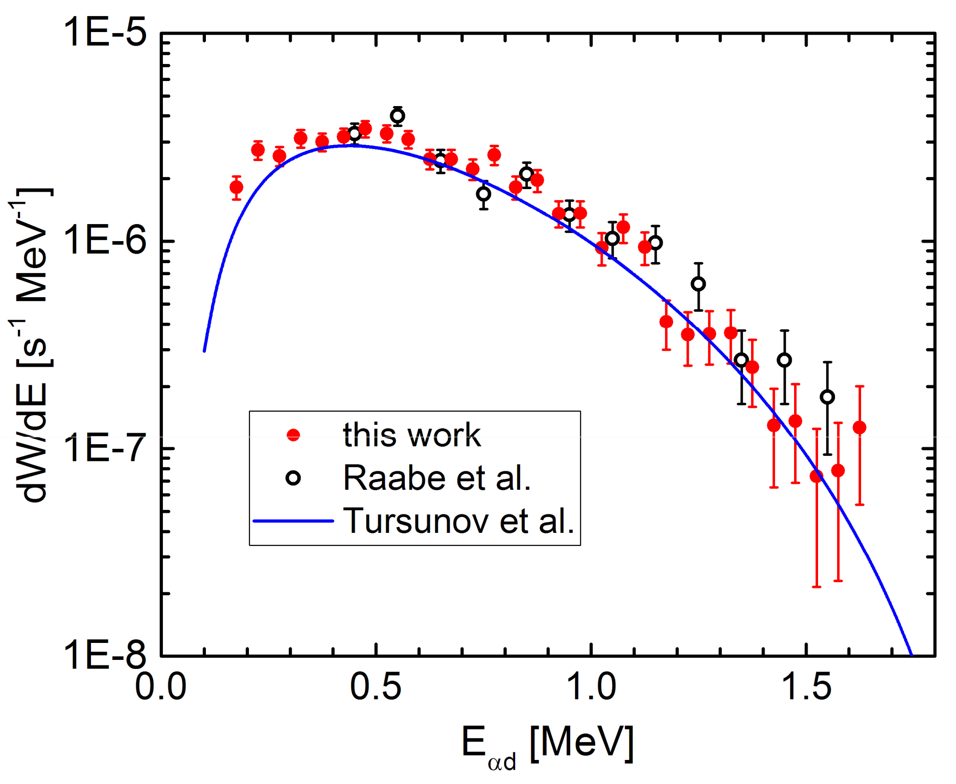
Lis et al., PRC 91, 064309 (2015)

Probing the *2n* halo of ^{6}He

- Weak decay branch (≈10^{-6}) ^{6}He → α + d provides insight into the 2n halo of ^{6}He
- Bunches of ^{6}He ions were delivered by **REX-ISOLDE** and implanted into the OTPC
- Clear images of decay events with tracks of an α particle and a deuteron were recorded by a CCD camera



A CCD image showing a bunch of implanted ^{6}He ions (red) and a ^{6}He → α + d decay (green)



→ The spectrum extended to lower energy, reveals 70% more intensity.

Pfützner et al., PRC 92 (15) 014316

2p-emission half-lives

Direct model

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

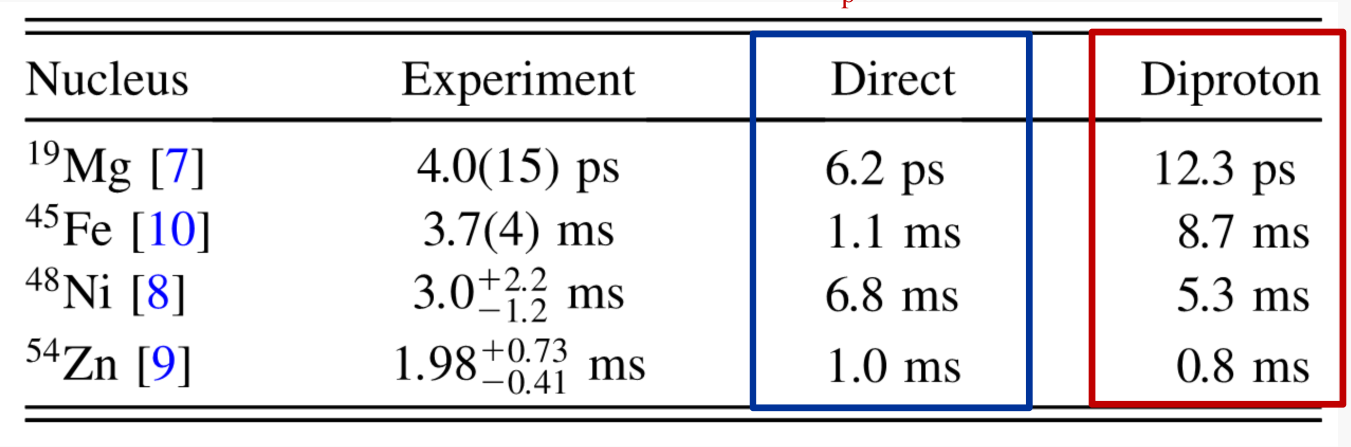
Diproton model

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

- The comparison of predicted half-lives with experiment

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

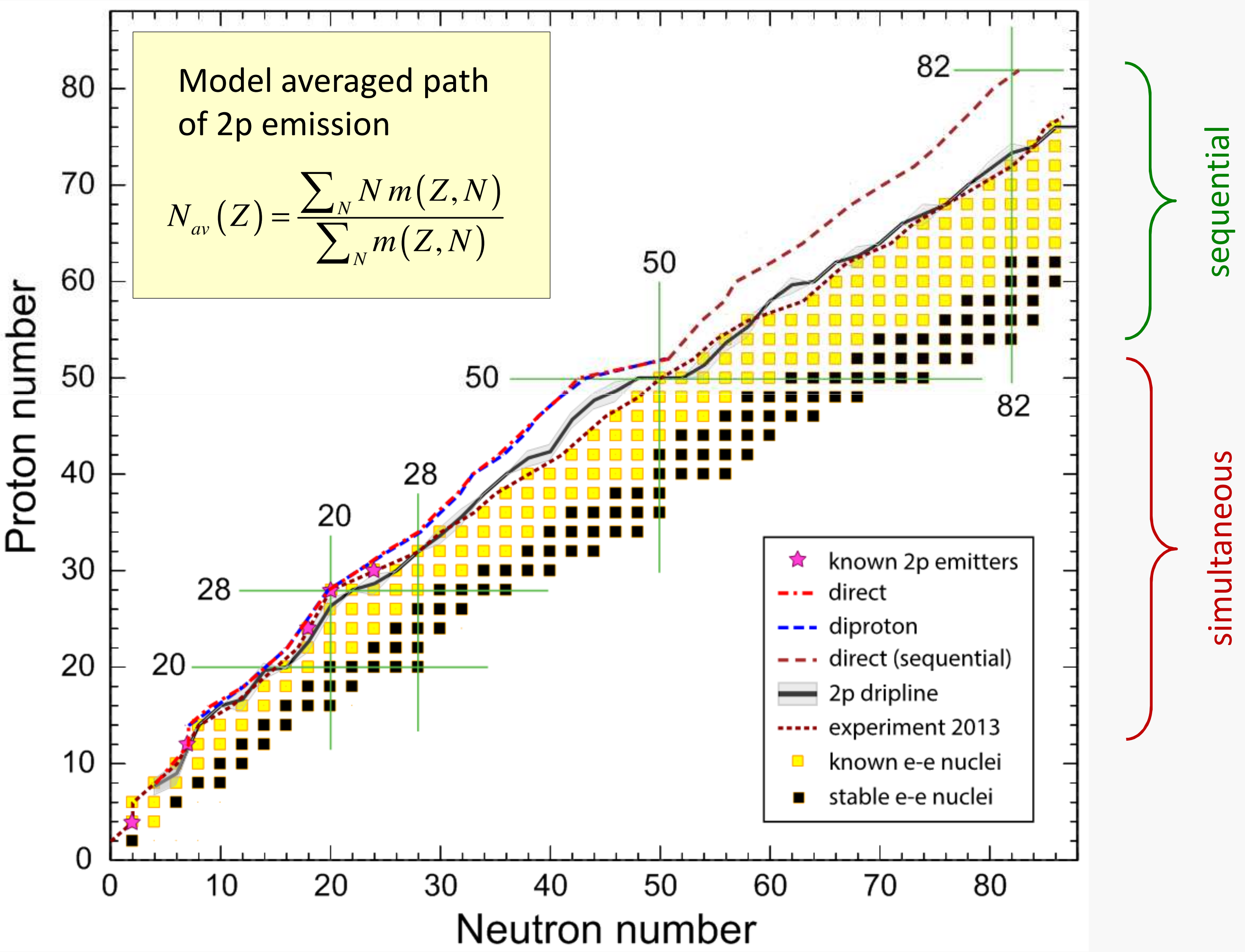
$l_p = 0$



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

Full 2p landscape



Model averaged path of 2p emission

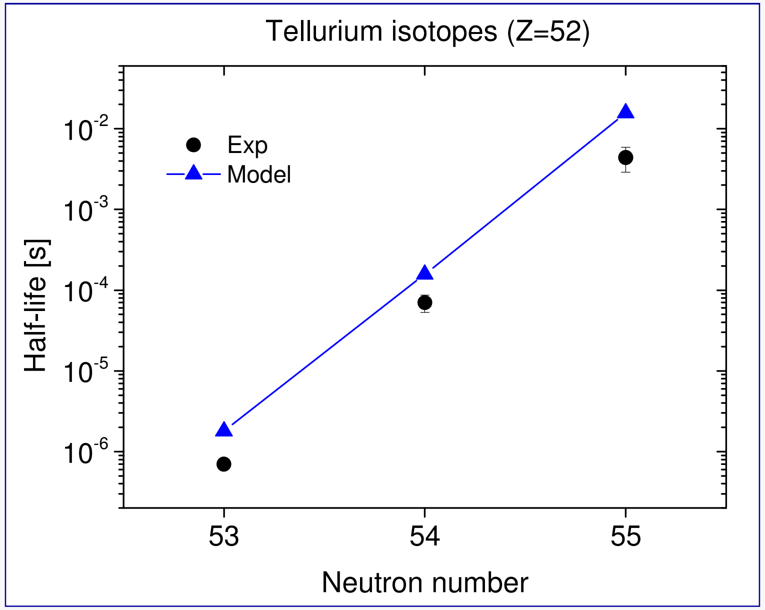
$$N_{av}(Z) = \frac{\sum_N N\, m(Z,N)}{\sum_N m(Z,N)}$$

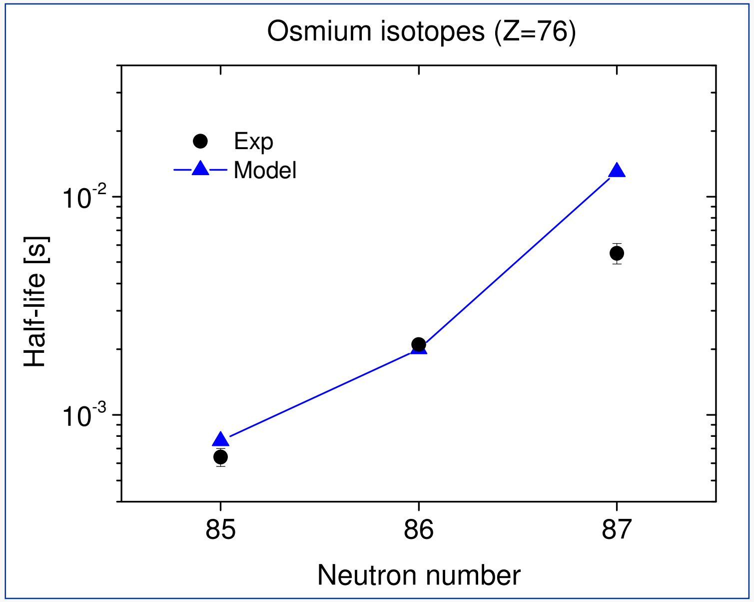
sequential

simultaneous

α -emission

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





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