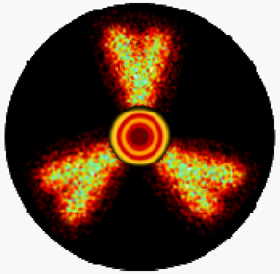
Particle radioactivity of exotic nuclei



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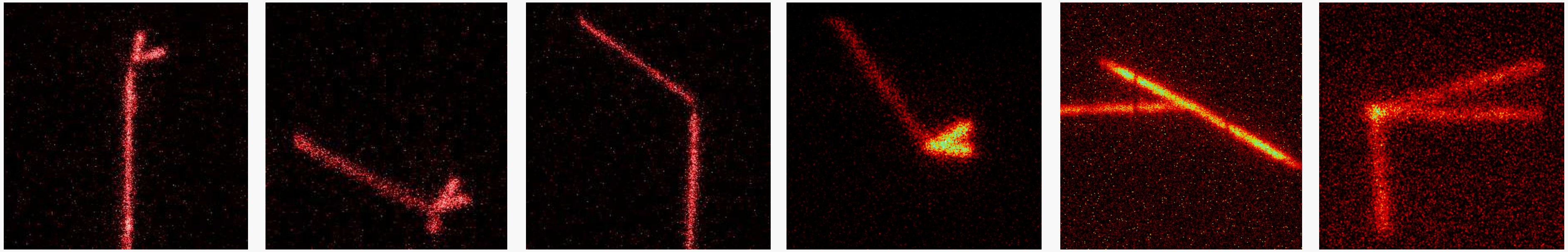
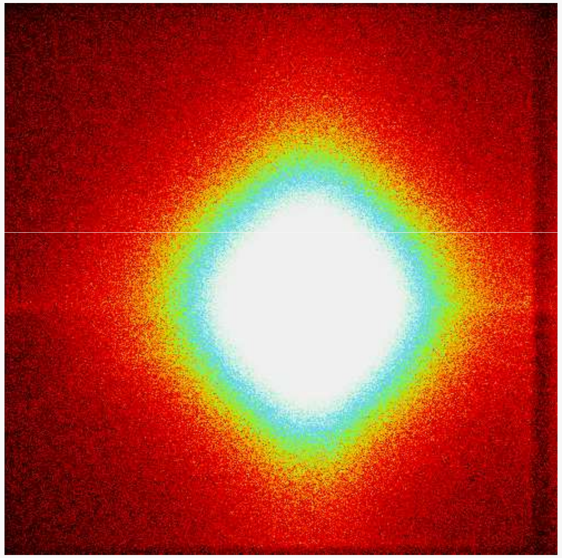
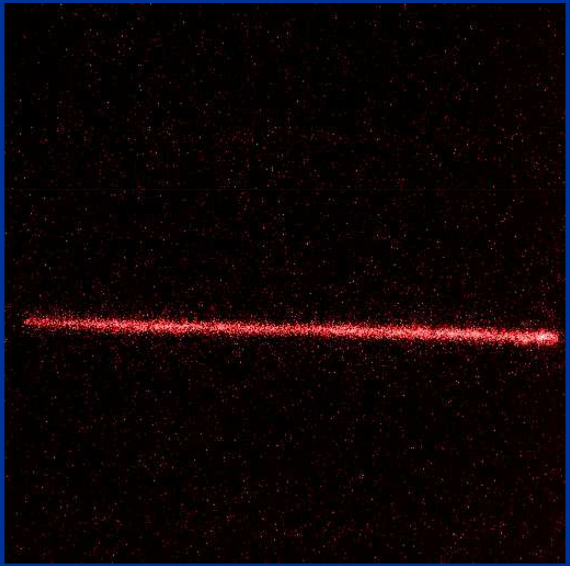


Outline



- Basic concepts
- In-flight at Coulomb barrier
  - Proton radioactivity
  - Alpha emission
- In-flight above Fermi energy
  - Two-proton radioactivity
  - Neutron radioactivity?

Basic concepts



Gamow picture

- Early puzzle of α decay: half-life is extremely dependent of on energy

  Solution by Gamow (1928) was a triumph of quantum mechanics!

Geiger-Nutall (1912)

$$\log T = a + \frac{b}{\sqrt{E_\alpha}}$$

→ Radioactive process is so slow (decaying state so narrow) that it can be approximated by a **stationary** picture:

$$\hat{H}\,\Phi(\vec{r},t) = i\hbar\frac{\partial\Phi(\vec{r},t)}{\partial t}\ ,\ \Phi(\vec{r},t) = \Psi(\vec{r})\,\mathrm{e}^{-iEt/\hbar}$$

but with the complex energy!

$$\hat{H}\,\Psi(\vec{r}) = E\,\Psi(\vec{r}) \qquad E = E_0 - i\,\Gamma/2$$

$$\left|\Phi(\vec{r},t)\right|^2 = \left|\Psi(\vec{r})\right|^2 \mathrm{e}^{-i\Gamma t/\hbar}$$

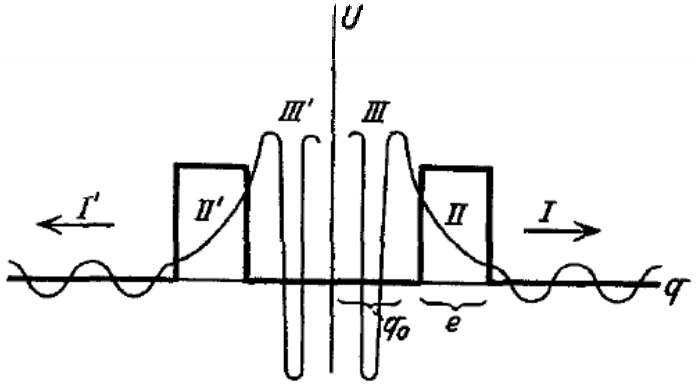
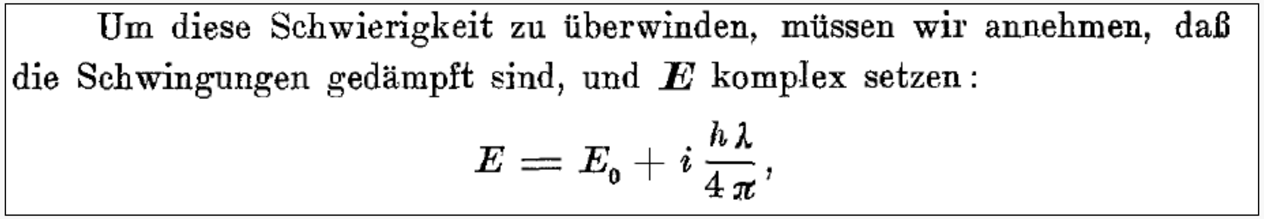


Fig. 3.



Um diese Schwierigkeit zu überwinden, müssen wir annehmen, daß die Schwingungen gedämpft sind, und E komplex setzen:

$$E = E_0 + i\,\frac{h\,\lambda}{4\,\pi},$$

Gamow, Z. Phys. 51 (1928) 204

Particle radioactivity

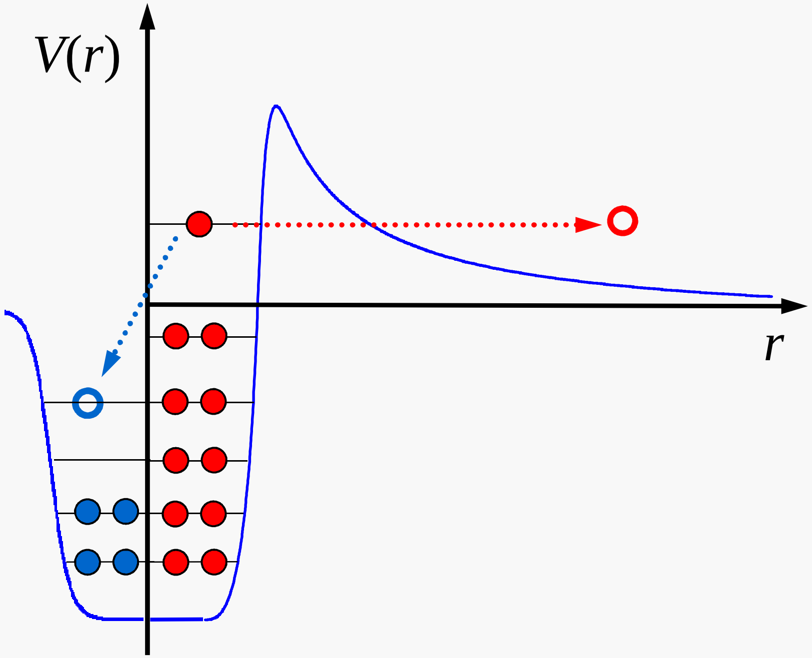
- The fundamental concept: **potential barrier**

→ The (Coulomb) barrier stops an unbound object (α, p, 2p, ^{14}C,..) from flying out immediately.

→ Neutrons can still be hampered by the centrifugal barrier.

→ Beyond proton drip-line, there is always competition with β decay!

Particle observable if $\boxed{T^{p}_{1/2} \leq T^{\beta}_{1/2}}$



- In spherical case, WKB-like method:

$$\boxed{\Gamma/\hbar = S\,\nu \exp\left\{-\frac{2}{\hbar}\cdot\int_{r_{in}}^{r_{out}}\sqrt{2\mu[V(r)-Q_p]}\cdot dr\right\}}$$

ν – frequency of assaults

S – spectroscopic factor (p)
preformation factor (α)

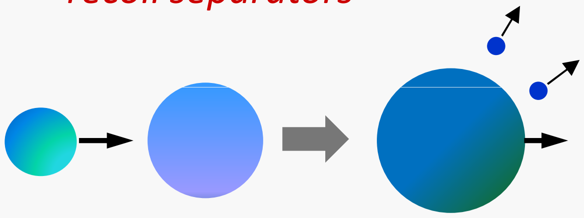
→ This simple approach works surprizingly good and is still frequently used in the analysis of proton and α radioactivity.

Gurvitz and Kalbermann, PRL 59 (1987) 262

Production methods

- To produce short-lived and very proton-rich radioactive nuclei in-flight techniques proved advantageous.

● Fusion-evaporation
reactions between heavy-ions
GSI, Argonne, Oak Ridge, Jyväskylä,...
recoil separators

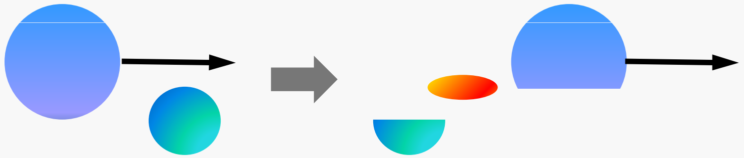


Low energy: ≈ Coulomb barrier

● large beam intensity
● thin target
identification by decays

p and α radioactivity

● Fragmentation
of relativistic heavy-ions
GSI, NSCL, GANIL, RIKEN,...
fragment separators

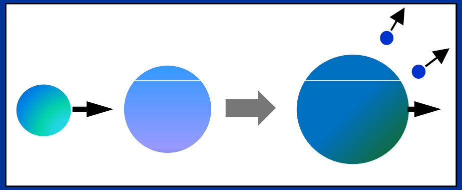


High energy: ≈ above Fermi energy

● lower beam intensity
● thick target
identification in-flight
single ion sensitivity

2p radioactivity

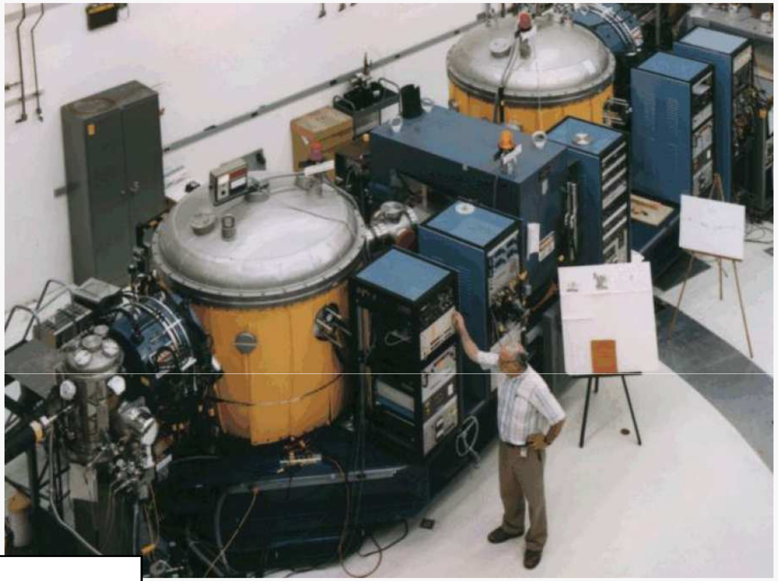
In-flight technique at Coulomb barrier

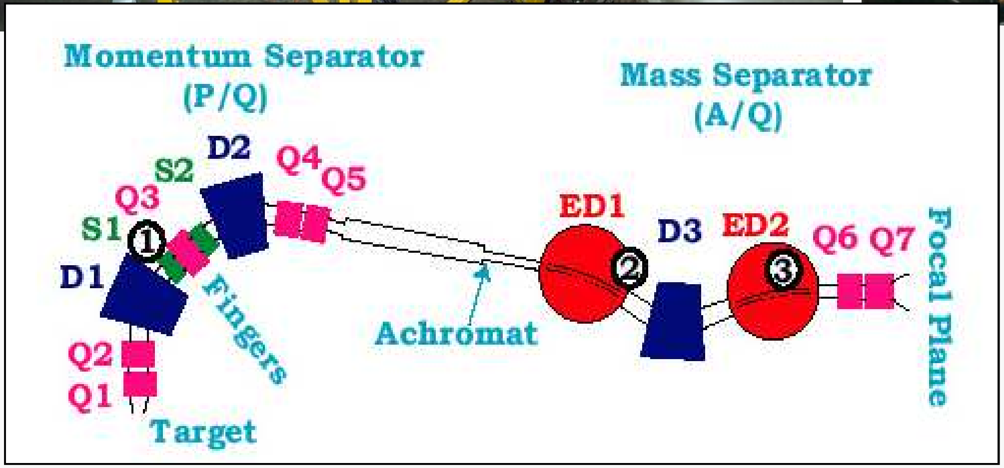


Recoil separators

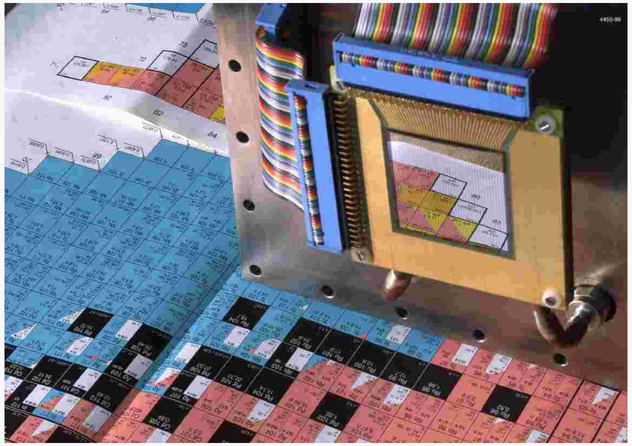
Recoil Mass Separator @ ORNL

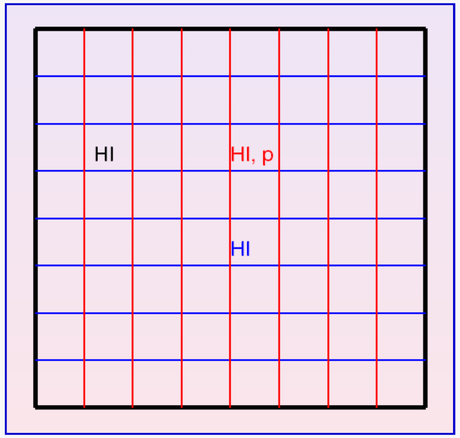
Fragment Mass Analyser @ ANL





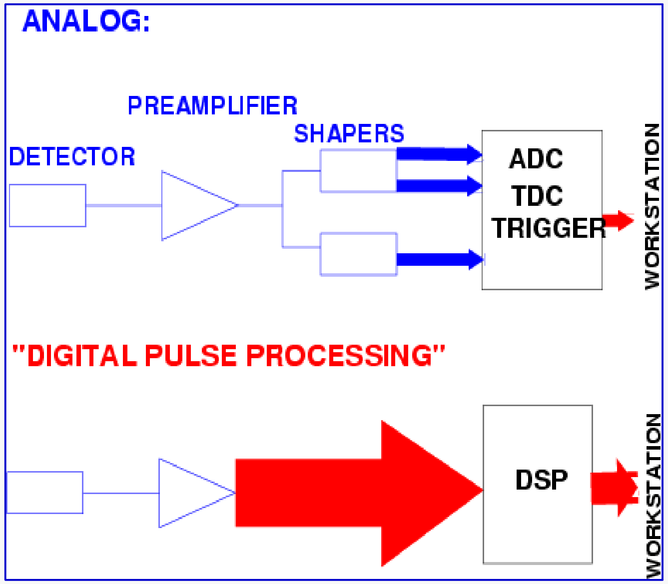
DSSSD and Digital





DSSSD – Double Sided
Silicon Strip Detector

- Correlations between ion-implantation and its decay in space and in time



ANALOG:

PREAMPLIFIER

SHAPERS

DETECTOR

ADC
TDC
TRIGGER

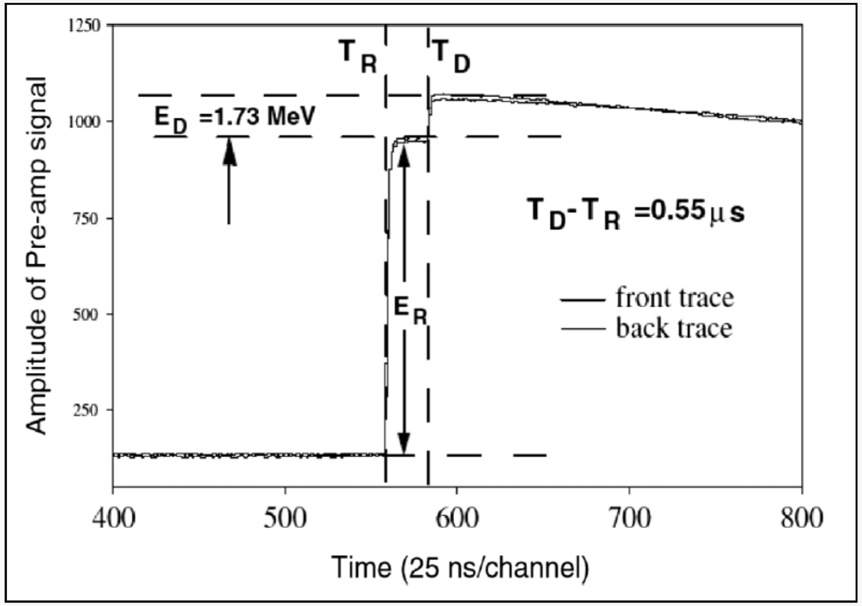
WORKSTATION

"DIGITAL PULSE PROCESSING"

DSP

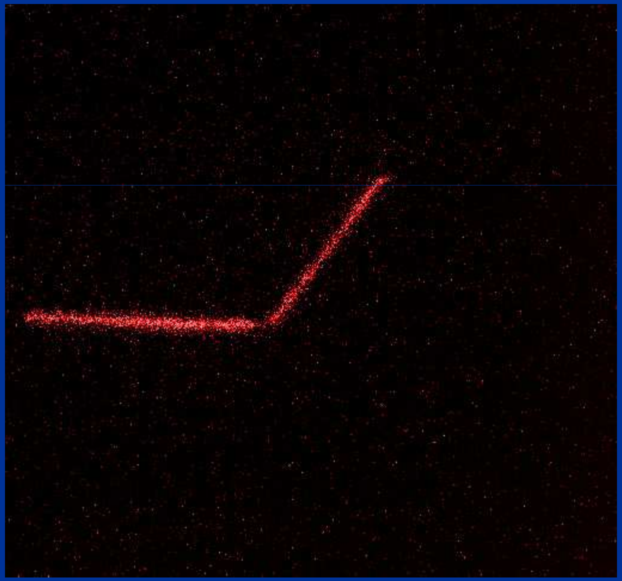
WORKSTATION

Grzywacz, NIM B 234(2007)

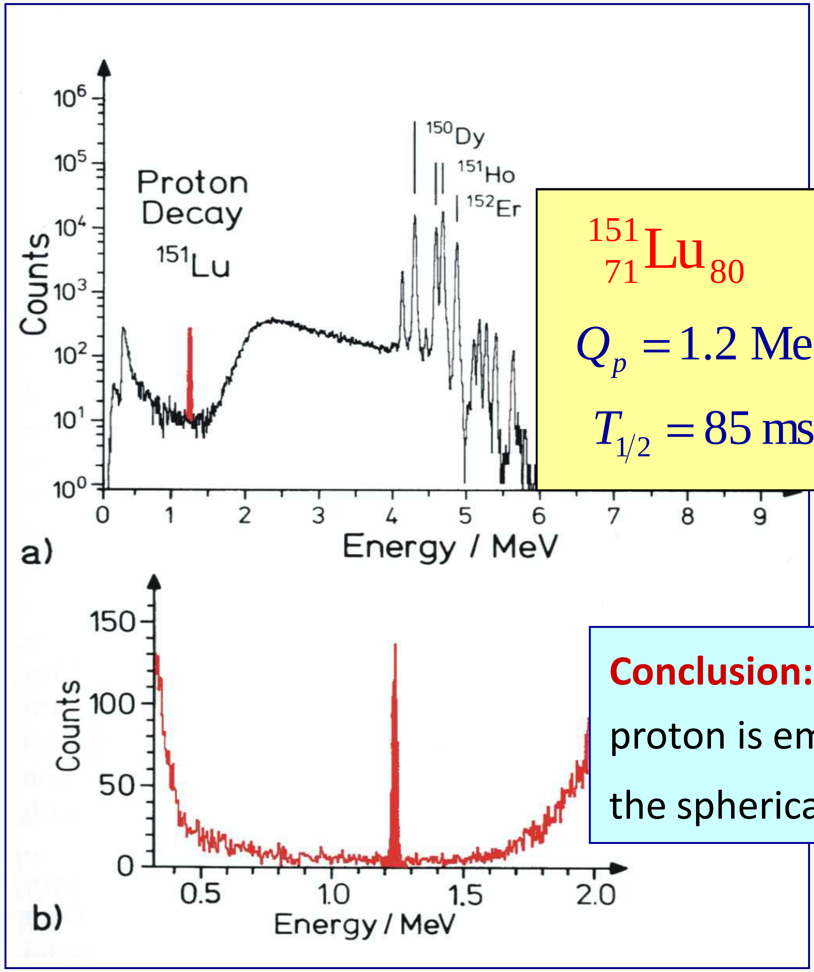


Karny *et al.*, Phys. Rev. Lett. 90 (2003) 012502

Proton radioactivity



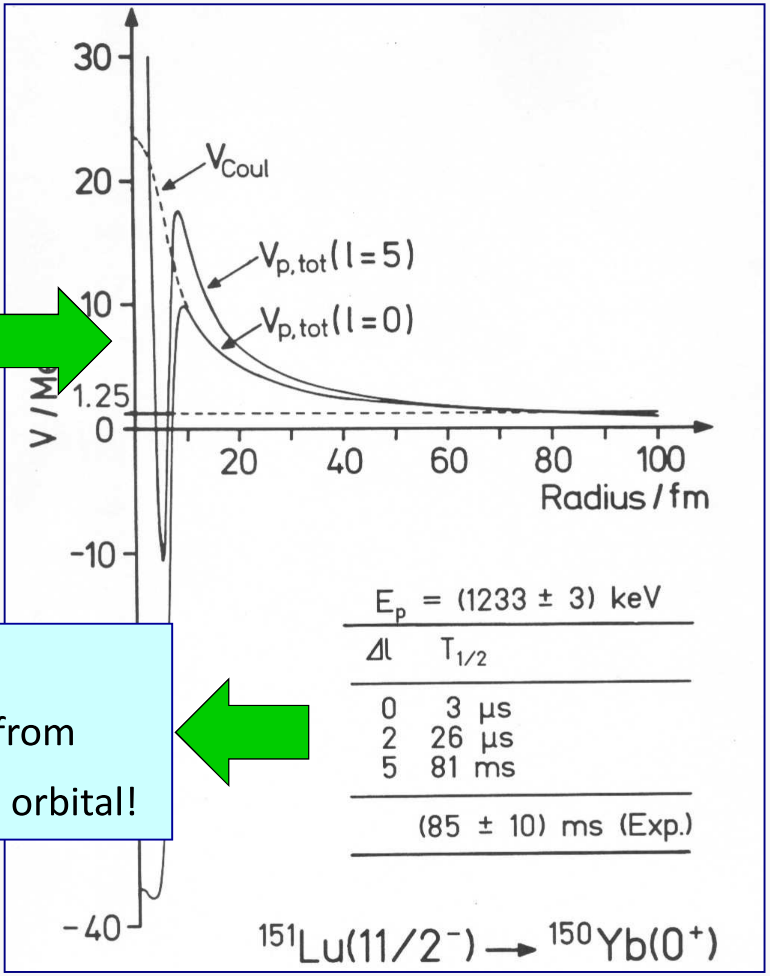
p radioactivity – the first case



$$^{151}_{71}\mathrm{Lu}_{80}$$

$$Q_p = 1.2\ \mathrm{MeV}$$

$$T_{1/2} = 85\ \mathrm{ms}$$



Conclusion:

proton is emitted from

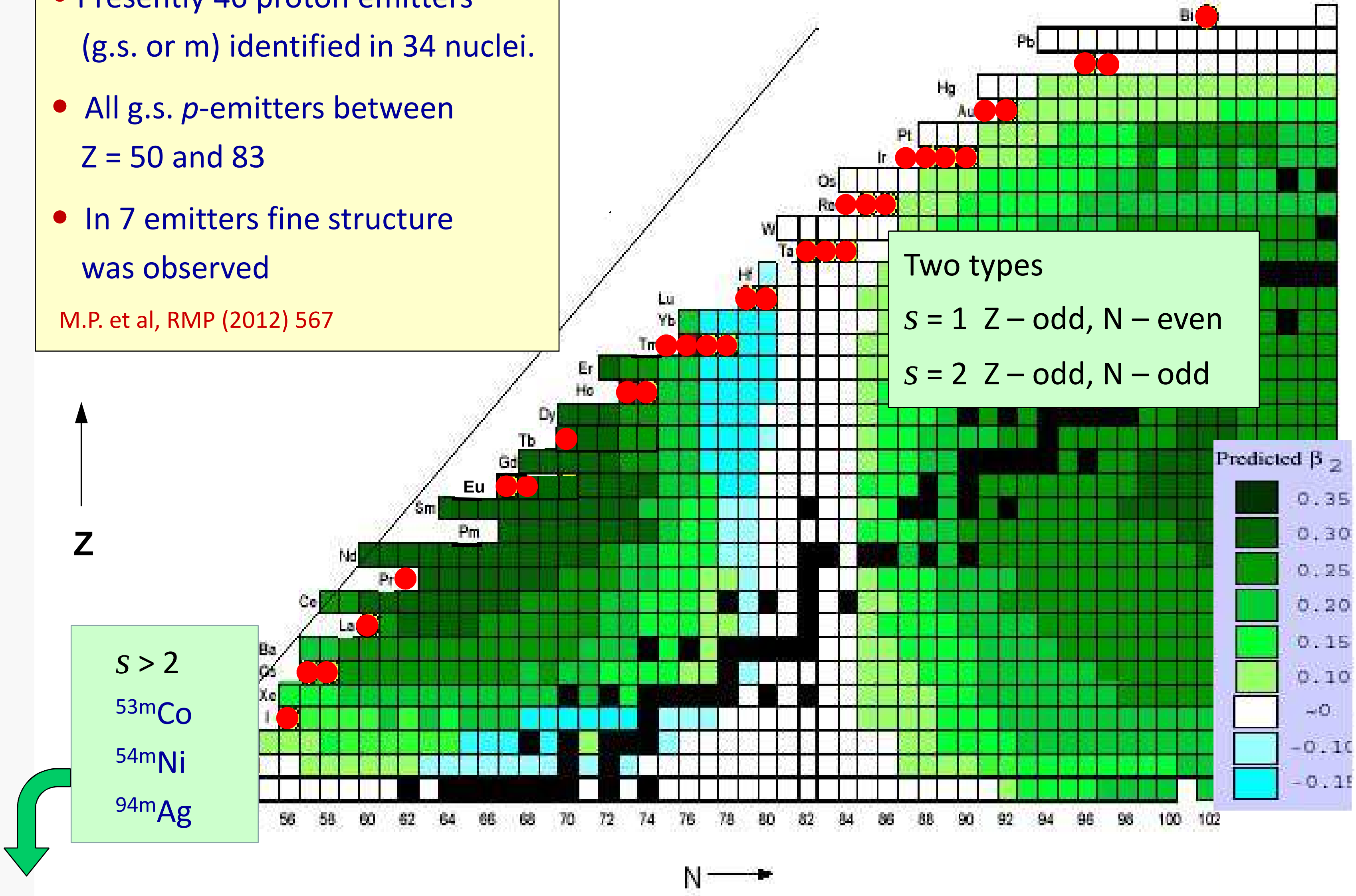
the spherical $h_{11/2}$ orbital!

Hofmann et al., Z. Phys. A 305 (1982) 111

p radioactivity – the status

- Presently 46 proton emitters (g.s. or m) identified in 34 nuclei.
- All g.s. *p*-emitters between Z = 50 and 83
- In 7 emitters fine structure was observed

M.P. et al, RMP (2012) 567



Two types

$s = 1$ Z – odd, N – even

$s = 2$ Z – odd, N – odd

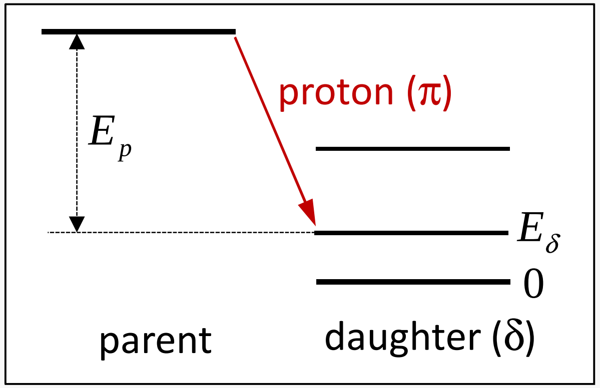
$s > 2$

^{53m}Co

^{54m}Ni

^{94m}Ag

More general model



- Cluster approximation (proton moves in the (deformed) potential of the daughter
- Parent wave function:

$$\Psi_{JM}(\vec{r}) = \frac{1}{r} \sum_{\alpha=\{\pi,\delta\}} u_\alpha(r) [\mathcal{Y}_\pi \otimes \Phi_\delta]_{JM}$$

radial part of relative motion   angular part

→Schrödinger equation, integration over angles:

$$\left[\frac{d^2}{dr^2} - \frac{l_p(l_p+1)}{r^2} + \frac{2\mu}{\hbar^2} E_p \right] u_\alpha(r) = \frac{2\mu}{\hbar^2} \sum_{\alpha'} \left(\hat{V}_{\alpha,\alpha'} \right) u_{\alpha'}(r)$$

(coupled channels)

- Solutions must fulfill conditions:

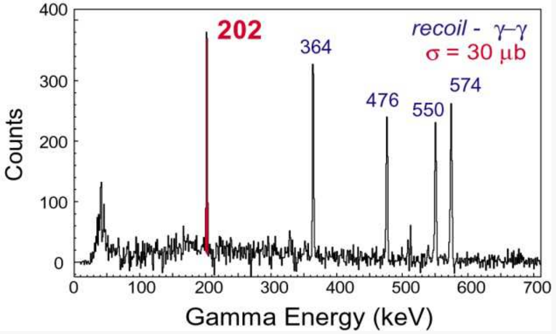
$$u_\alpha(r) \underset{r\to 0}{\longrightarrow} 0 \,, \qquad u_\alpha(r) \underset{r\to\infty}{\longrightarrow} \sim G_{l_p}(\eta, kr) + i\, F_{l_p}(\eta, kr)$$

(outgoing Coulomb wave)

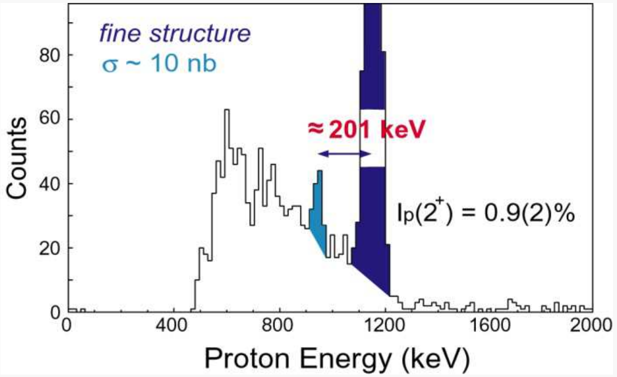
→From radial functions the width: $u_\alpha(r) \Rightarrow \Gamma_\alpha \,, \; \Gamma = \sum_\alpha \Gamma_\alpha \,, \; \Gamma_\delta = \sum_{\{\pi\}} \Gamma_{\{\pi,\delta\}}$

Proton emission from deformed ^{141}Ho

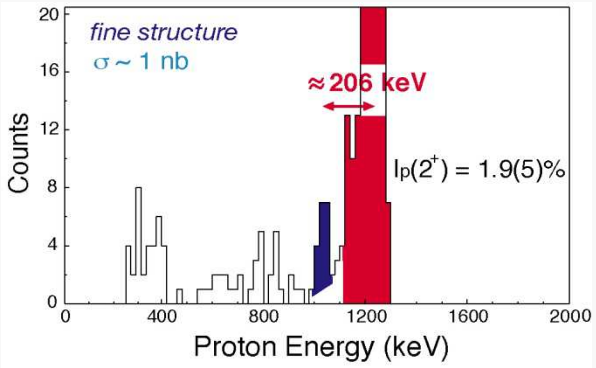
7 µs ^{140m}Dy isomeric decay

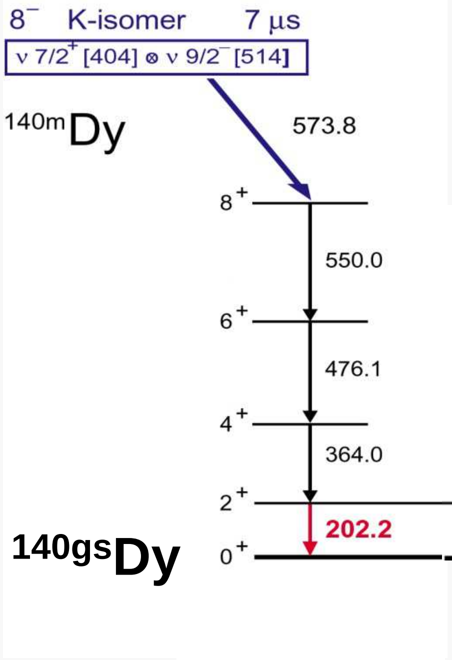


4 ms ^{141gs}Ho proton decay



7.2 µs ^{141m}Ho proton decay



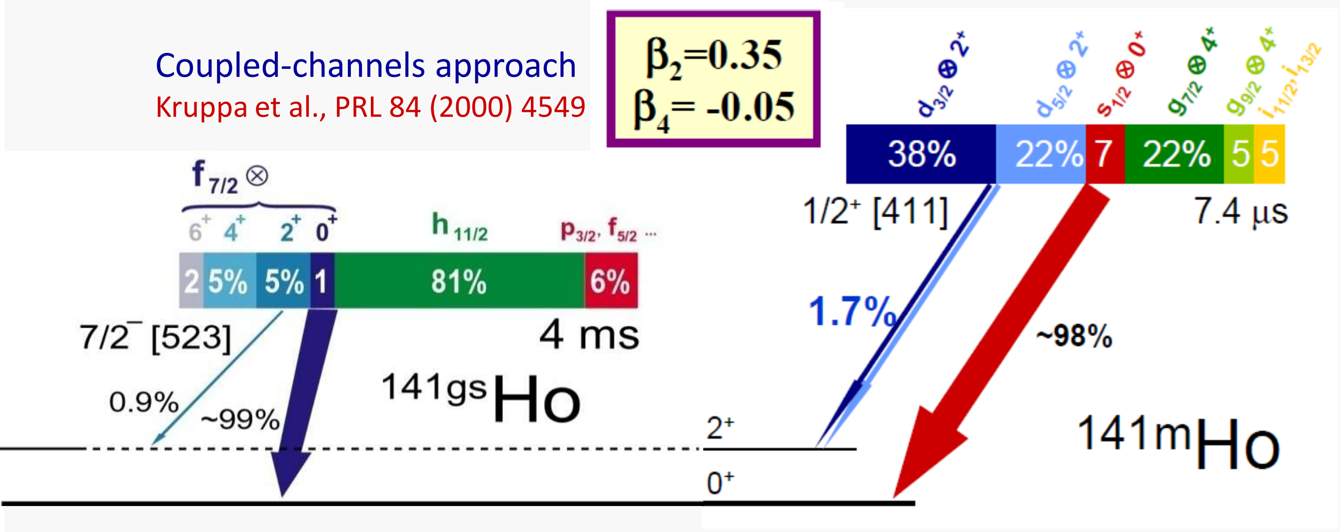


Coupled-channels approach

Kruppa et al., PRL 84 (2000) 4549

$\beta_2 = 0.35$

$\beta_4 = -0.05$



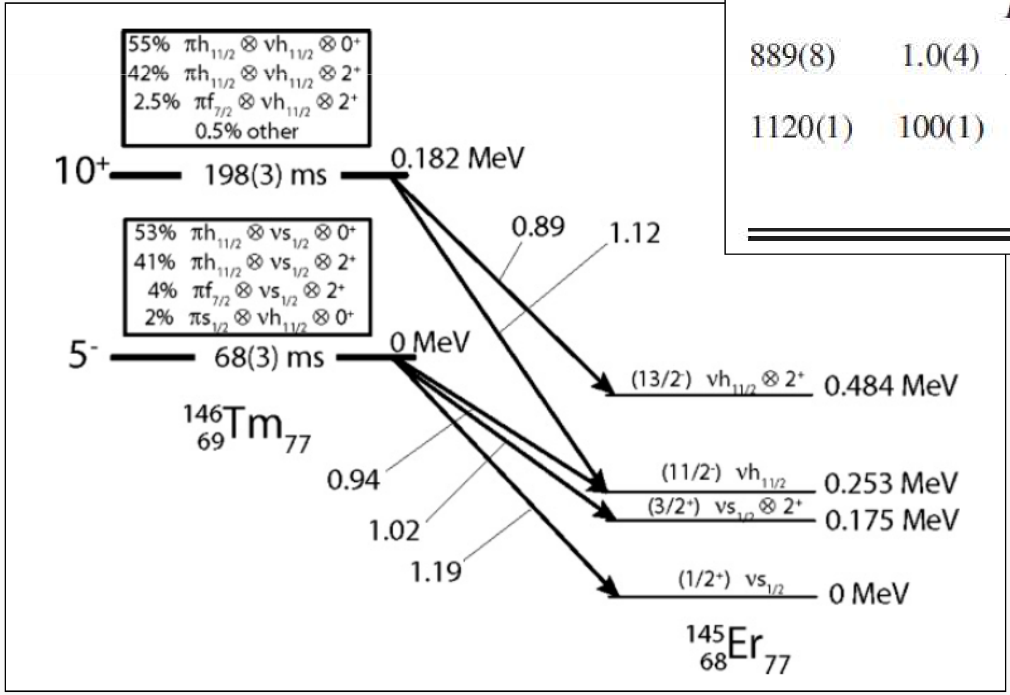
M. Karny et al., Phys. Lett. B664 (2008) 52

Odd-odd example: ^{146}Tm

- The richest emitter known:
  5 proton lines observed!

→ In Z – odd, N – odd (s=2)
nucleus the proton radioactivity
provides data on neutron levels!

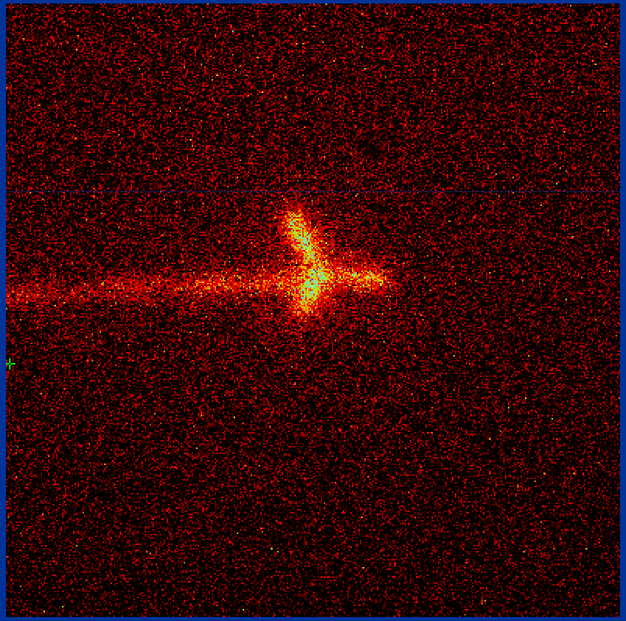
E_p	I_p^{exp} (%)	Wave function composition	I_p^{cal}	Δl	E_f
		Ground state $I^\pi = 5^-, T_{1/2} = 68(5)$ ms			
938(4)	13.8(9)	2% $\pi s_{1/2} \otimes \nu h_{11/2} \otimes 0^+$	$(15)^{\mathrm{a}}$	0	253
1016(4)	18.3(11)	4% $\pi f_{7/2} \otimes \nu s_{1/2} \otimes 2^+$	15	3	175
		41% $\pi h_{11/2} \otimes \nu s_{1/2} \otimes 2^+$	0.003	5	175
1191(1)	68.1(19)	53% $\pi h_{11/2} \otimes \nu s_{1/2} \otimes 0^+$	70	5	0
		Isomeric state $I^\pi = 10^+, T_{1/2} = 198(3)$ ms			
889(8)	1.0(4)	2.5% $\pi f_{7/2} \otimes \nu h_{11/2} \otimes 2^+$	1.2	3	484
		42% $\pi h_{11/2} \otimes \nu h_{11/2} \otimes 2^+$	0.04	5	484
1120(1)	100(1)	55% $\pi h_{11/2} \otimes \nu h_{11/2} \otimes 0^+$	98.6	5	253
		0.1% $\pi h_{9/2} \otimes \nu h_{11/2} \otimes 0^+$	0.2	5	253
		0.4% $\pi(l > 5) \otimes \nu h_{11/2}$			



- Good agreement with the model assuming coupling of a particle to core vibrations (the c-c scheme)

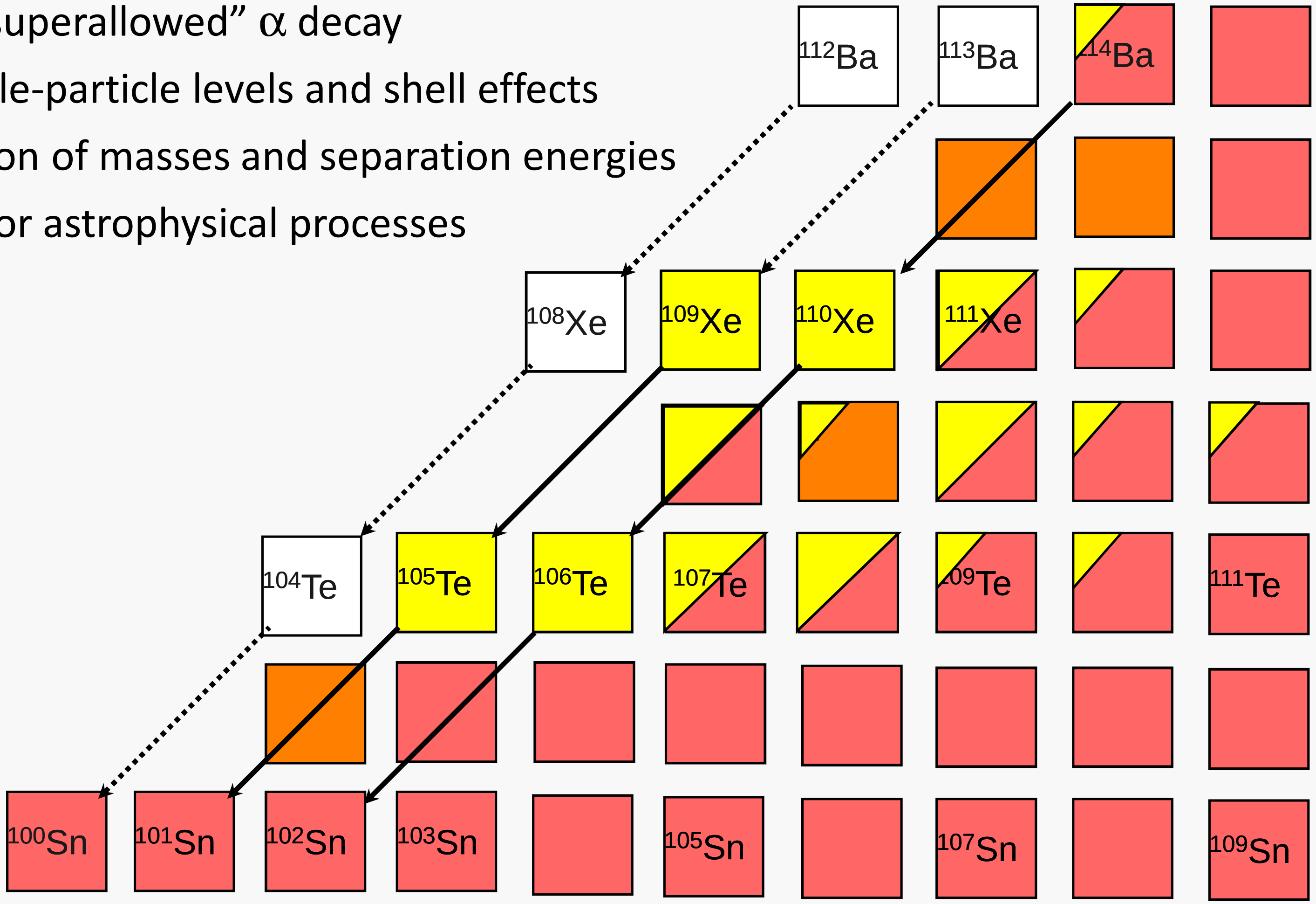
Tantawy *et al.*, Phys. Rev. C 73 (2006) 024316
Hagino, Phys. Rev. C64 (2001) 041304(R)

Alpha radioactivity



Island of α emitters above ^{100}Sn

- Search for „superallowed” α decay
- Probing single-particle levels and shell effects
- Determination of masses and separation energies
- Conditions for astrophysical processes

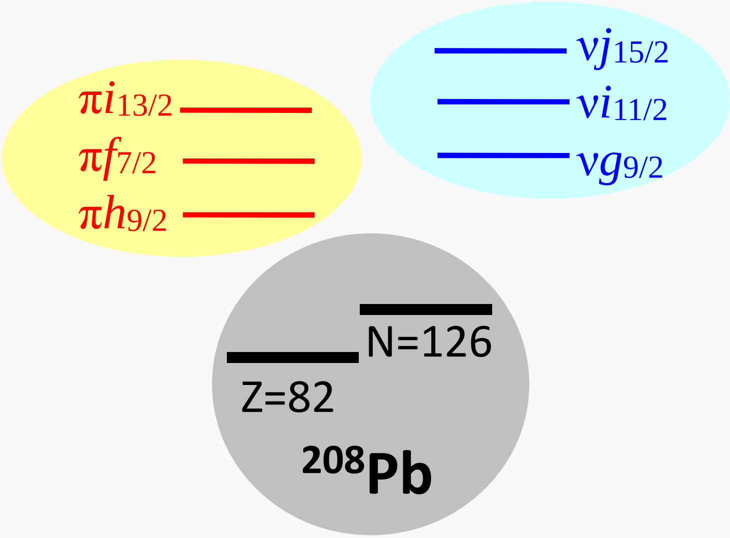


Superallowed α decay?

- Present α-decay reference: ^{212}Po

$^{212}\mathrm{Po} = {}^{208}\mathrm{Pb} + \alpha$

α made of protons and neutrons
from different orbitals of opposite parity

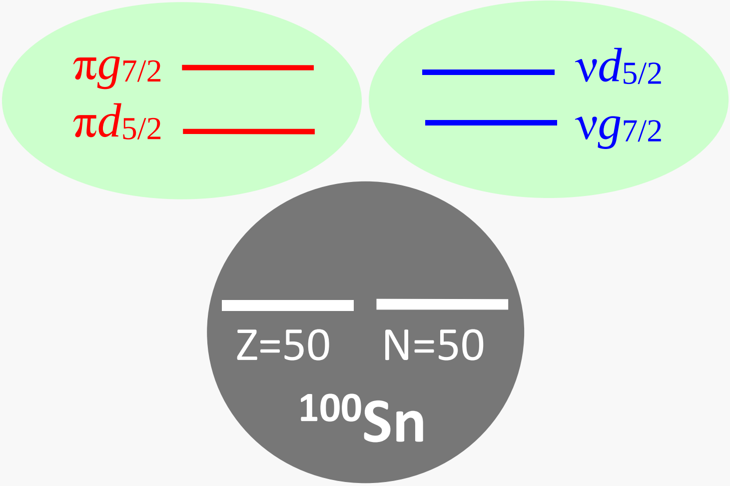


- Expected standard: ^{104}Te

Macfarlane and Siivola, PRL 14 (1965) 114

$^{104}\mathrm{Te} = {}^{100}\mathrm{Sn} + \alpha$

α formed by protons and neutrons
in the same orbitals



Predictions for ^{104}Te → ^{100}Sn decay

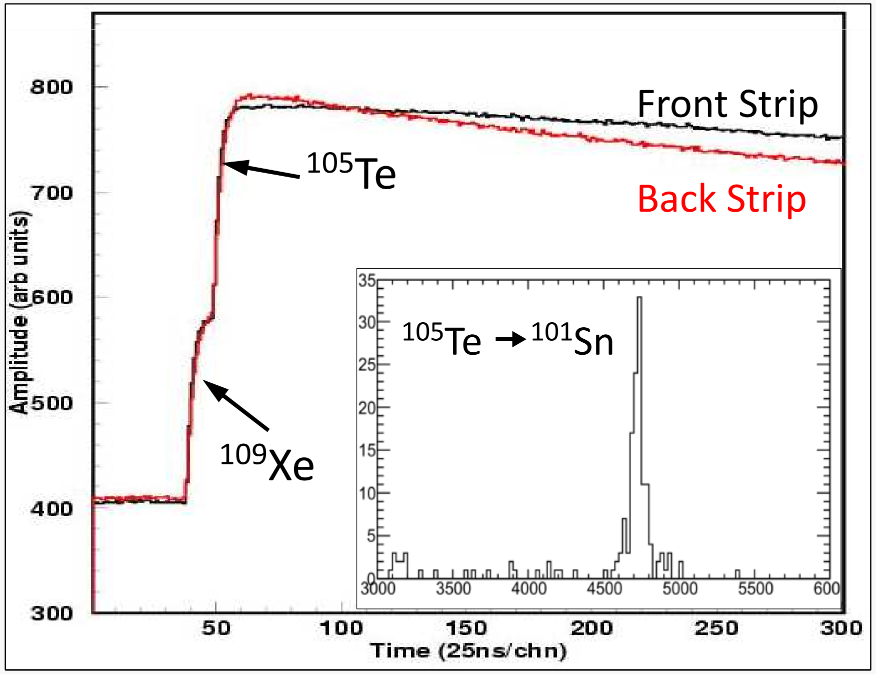
$E_\alpha > 5$ MeV, $T_{1/2} < 50$ ns !

α decay of ^{105}Te

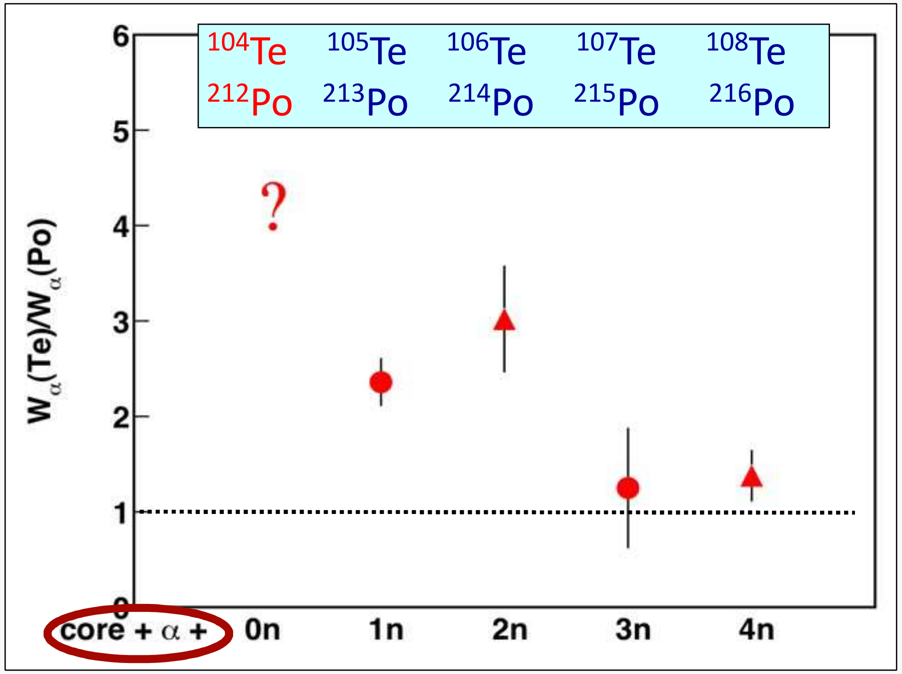
- Decay of ^{105}Te studied:
  - directly at FMA (Argonne) using ^{50}Cr(^{58}Ni, 3n)^{105}Te and fast recovery electronics
  - via decay of ^{109}Xe at HRIBF (ORNL) by ^{54}Fe(^{58}Ni, 3n)^{109}Xe and DSP

→ ^{105}Te decay: E_α = 4.7 MeV, $T_{1/2}$ = 0.6 μs

Seweryniak et al., PRC 73(2006) 061301(R)
S.N. Liddick et al., PRL 97 (2006) 082501
I.G. Darby et al. PRL 105 (2010) 162502

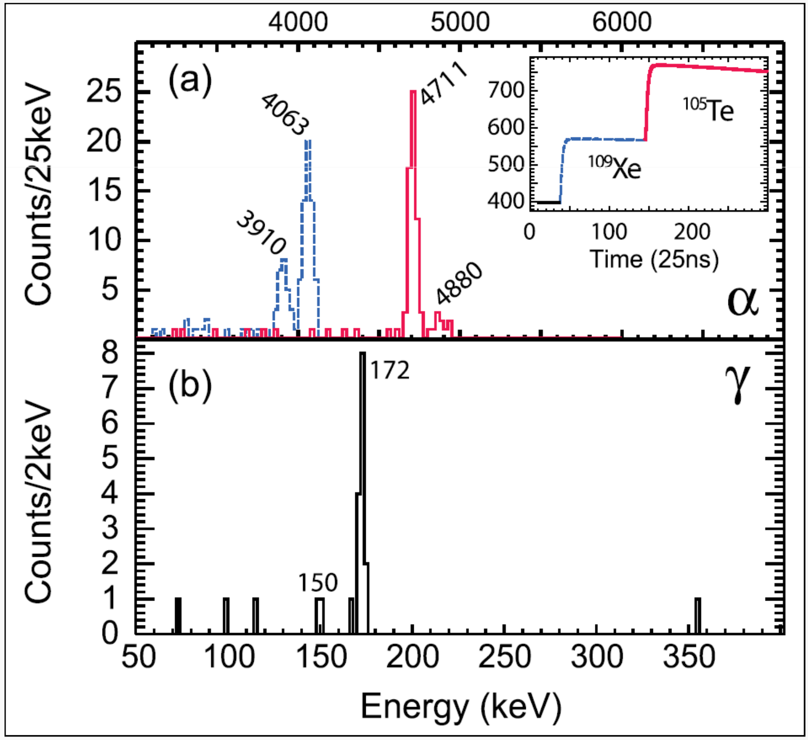


Renormalized α decay width (l = 0 transitions)

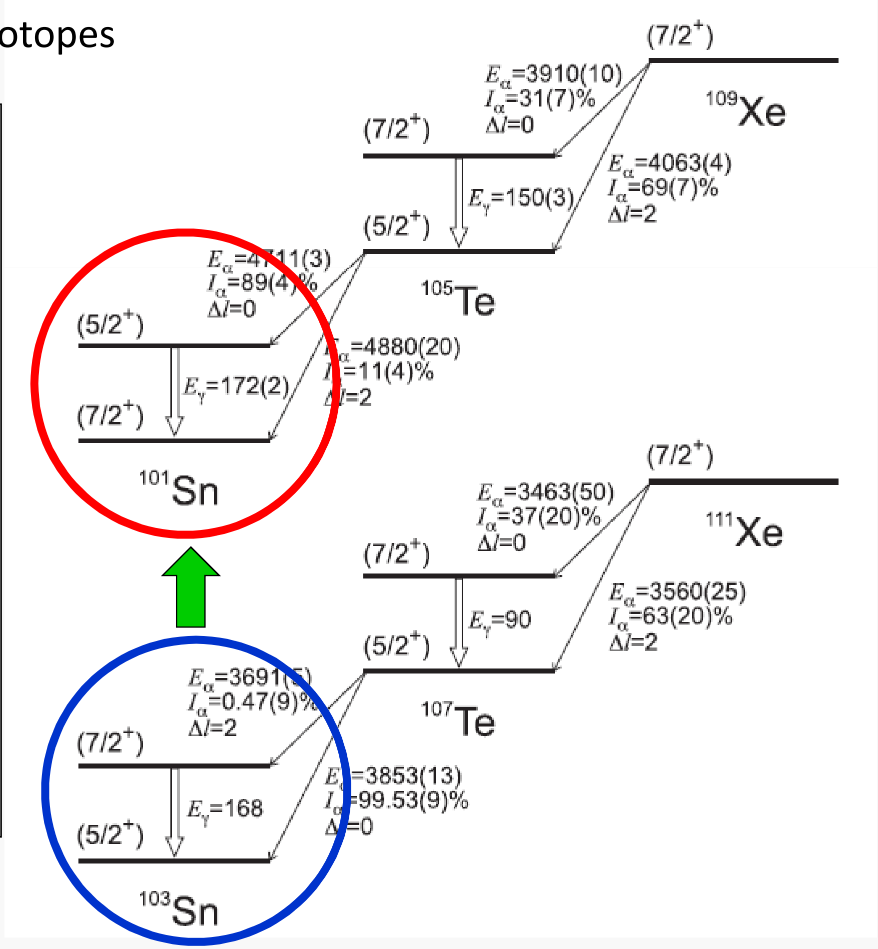


Single particle states in ^{101}Sn

- Details of α decay of ^{109}Xe (fine structure) yield surprizing result on ^{101}Sn!
  5/2$^+$ and 7/2$^+$ levels are reversed between ^{103}Sn and ^{101}Sn
- → Orbital dependent pairing, stronger for $(g_{7/2})^2$ then for $(d_{5/2})^2$, is responsible
  for 5/2$^+$ g.s of ^{103}Sn and heavier odd tin isotopes



I.G. Darby et al. PRL 105 (2010) 162502

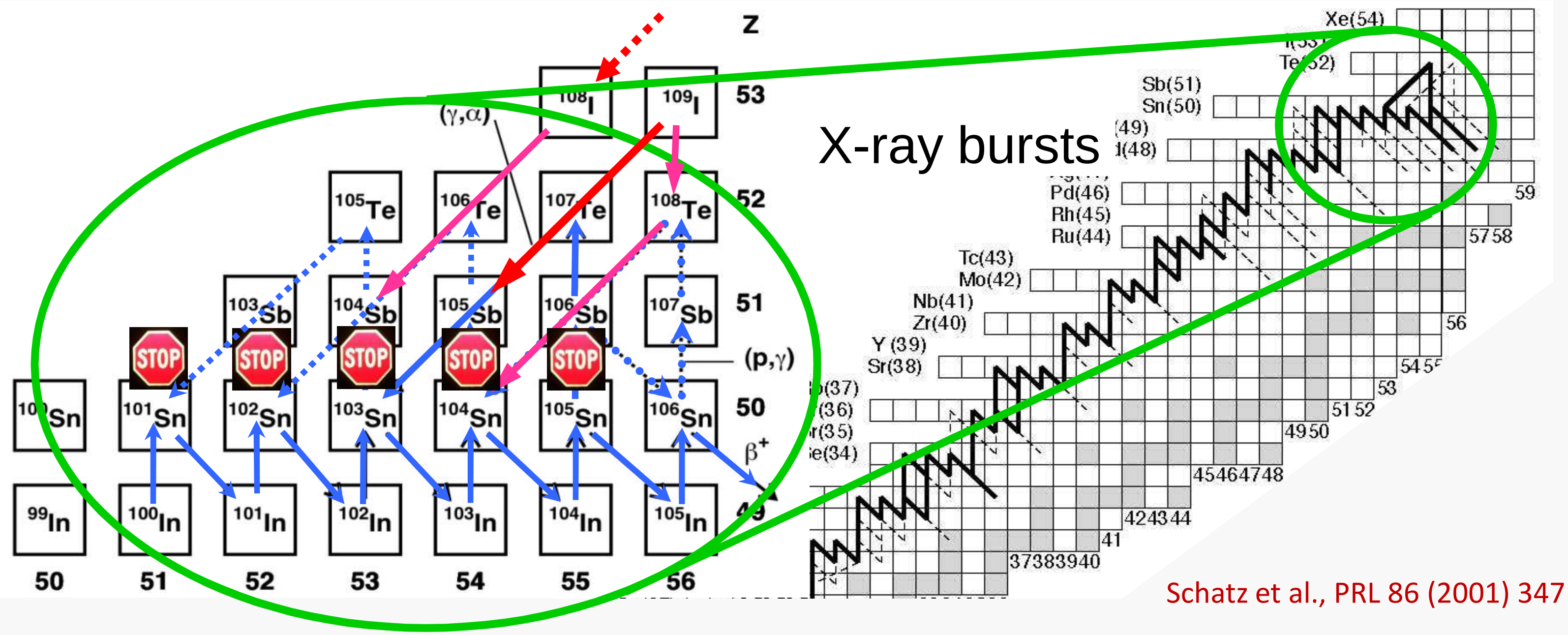


Termination of *rp*-process

- In some conditons *rp*-process could terminate by Sn-Sb-Te cycle. The details of this cycle depend critically on Q_p values of Sb-isotopes.
  - α-decay of ^{109}I yielded the Q_p = 356 keV for ^{105}Sb solving an old controversy.
  - Similarly, the search for α-decay of ^{112}Cs produced a limit Q_p > 150 keV for ^{104}Sb.
  - The Q_p values of ^{106}Sb and heavier isotopes were measured in JYFLTRAP.

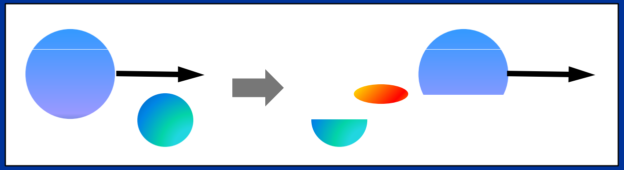
→ The *rp*-process most likely dies out before reaching the Sn-Sb-Te cycle.

Mazzocchi et al., PRL 98 (2007) 212501 Cartegni et al., PRC 85 (2012) 014312 Elomaa et al., PRL 102 (2009) 252501

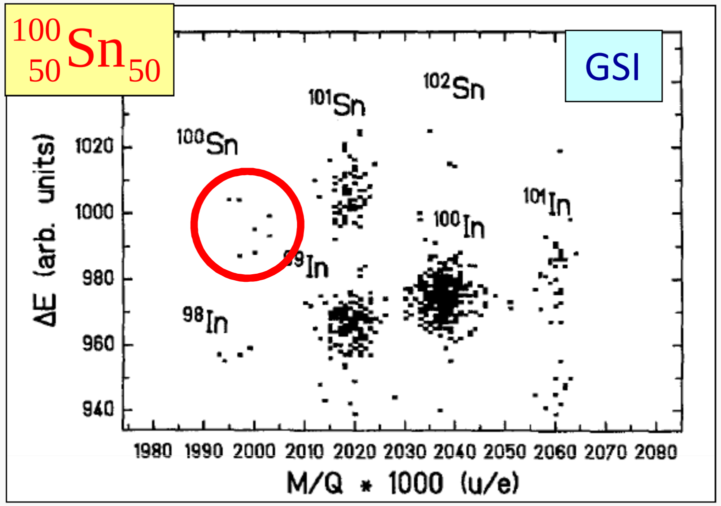


Schatz et al., PRL 86 (2001) 3471

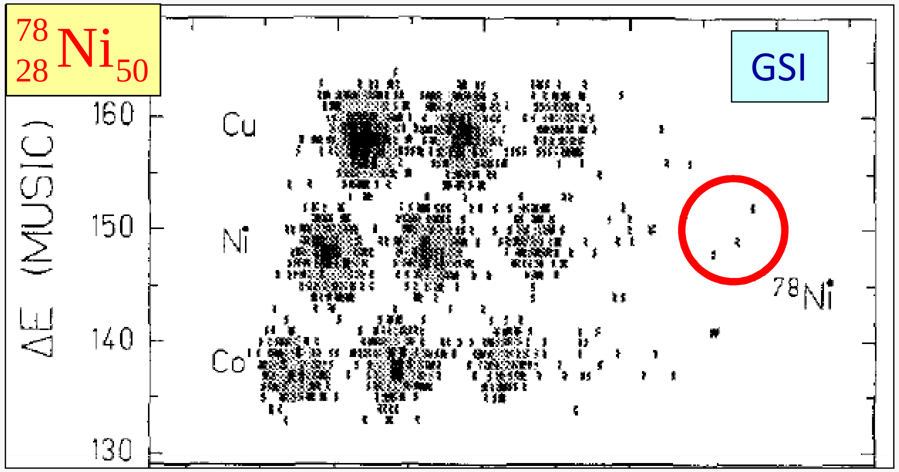
In-flight technique above Fermi energy



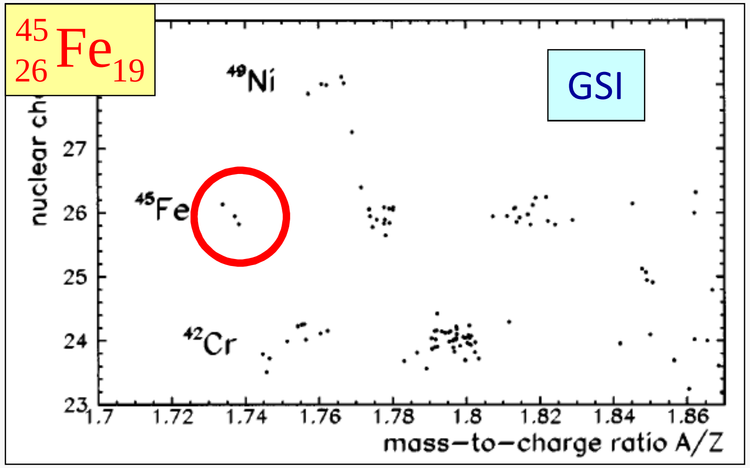
Fragmentation milestones



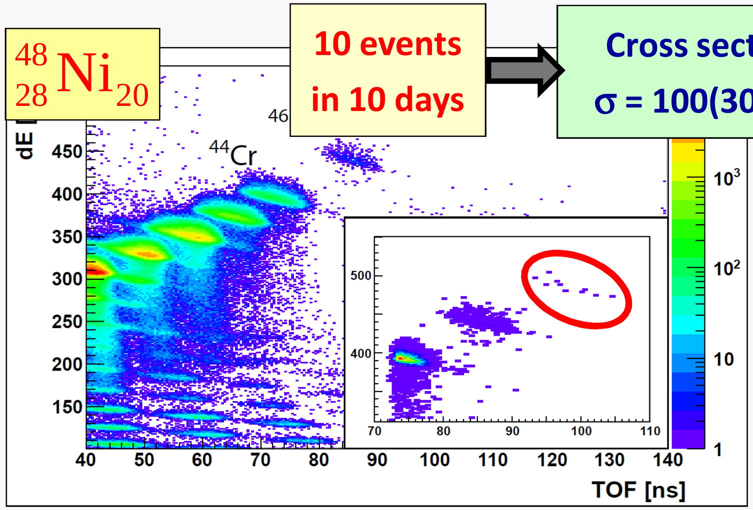
Schneider et al., Z. Phys. A 348 (1994) 241



Engelmann et al., Z. Phys. A352 (1995) 351



Blank et al., PRL 77 (1996) 2893

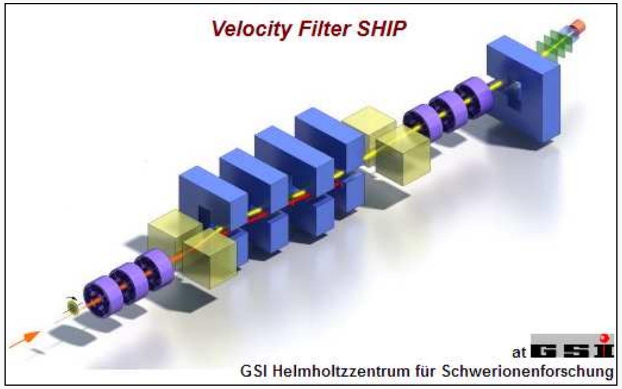


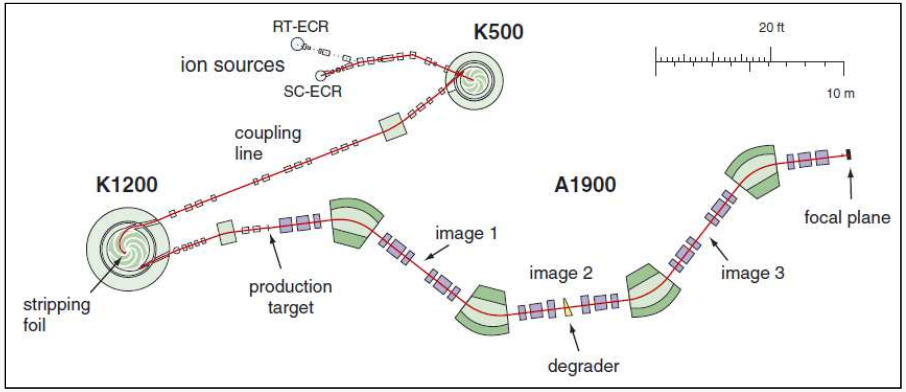
10 events in 10 days

Cross section: σ = 100(30) fb !

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

Sensitivity





- Hunt for element 120 at SHIP

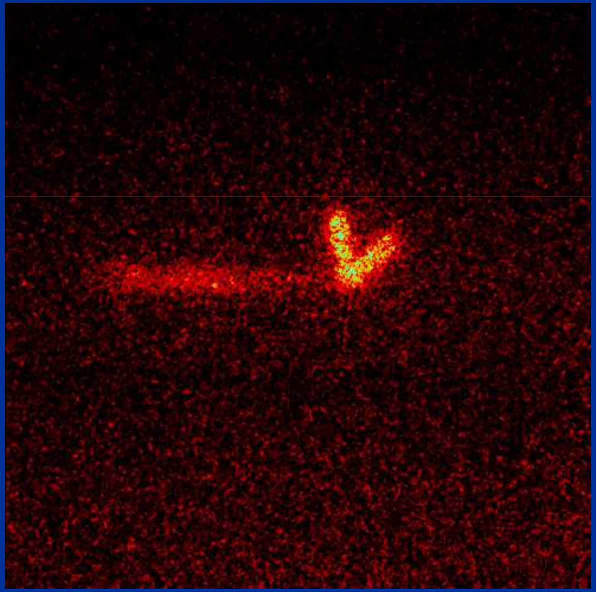
fusion $^{54}\mathrm{Cr} + {}^{248}\mathrm{Cm} \rightarrow {}^{302}120^{*}$

- Production of ^{48}Ni at NSCL

fragmentation $^{58}\mathrm{Ni} + {}^{\mathrm{nat}}\mathrm{Ni} \rightarrow {}^{48}\mathrm{Ni}$

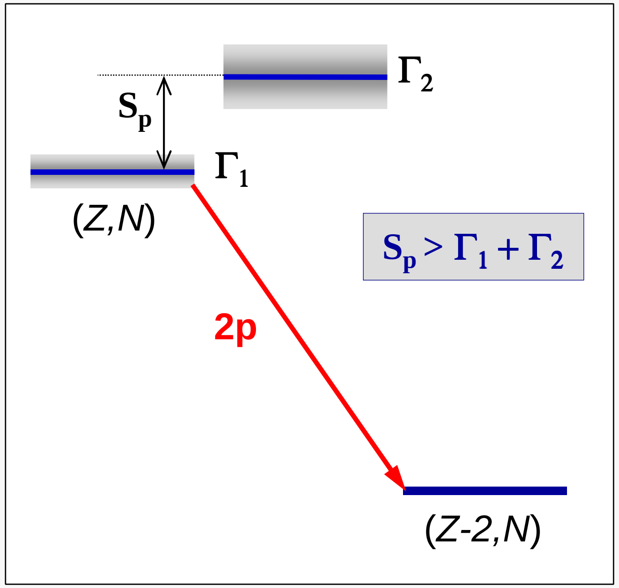
Cross section:	≈ 90 fb	≈ 100 fb	
Beam intensity:	750 pnA	20 pnA	38 times weaker
Running time (1 event):	≈100 days	≈1 day	100 times shorter
Total dose:	≈ $4 \cdot 10^{19}$ part.	≈ $1 \cdot 10^{16}$ part.	4000 times smaller
Target thickness:	0.5 mg/cm^2	580 mg/cm^2	

Two-proton radioactivity



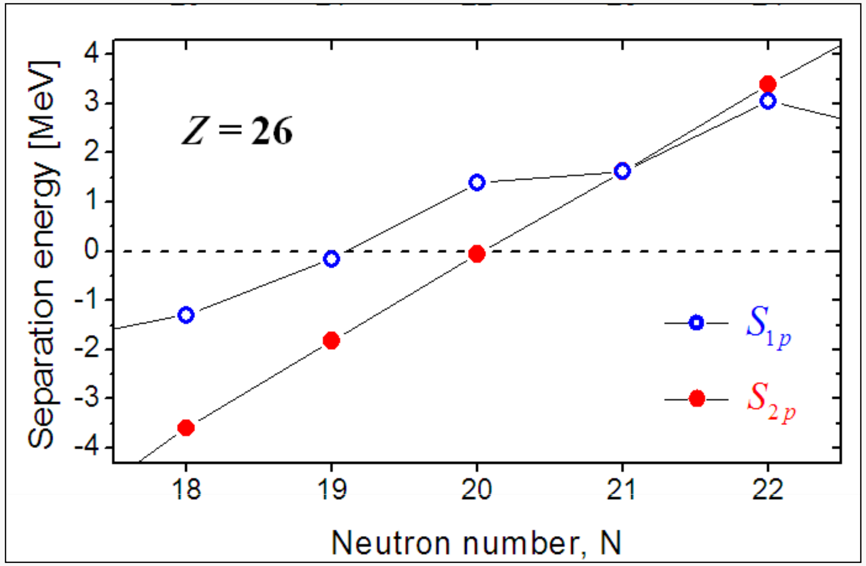
Two protons can be unbound!

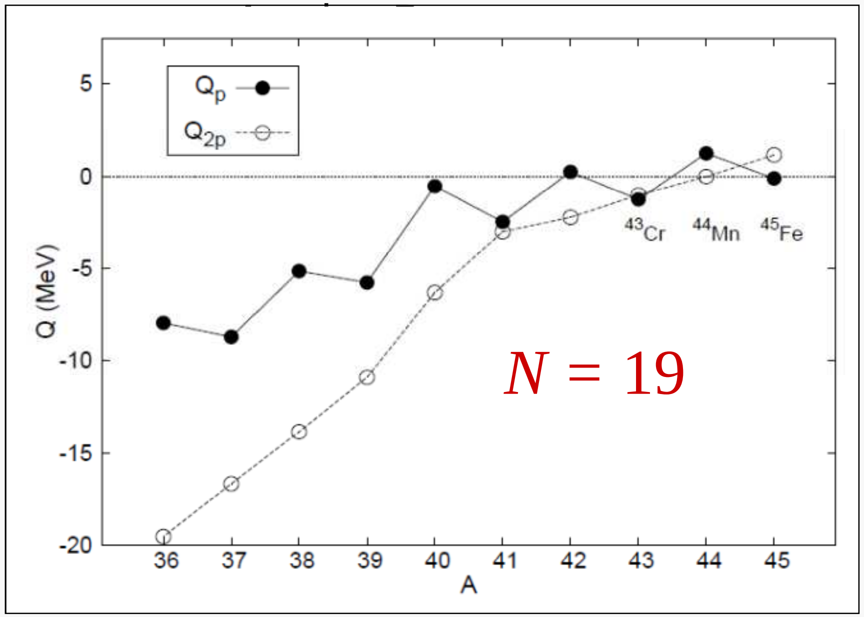
- It is possible that pair of protons is unbound while each of individual proton is bound!



- → 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

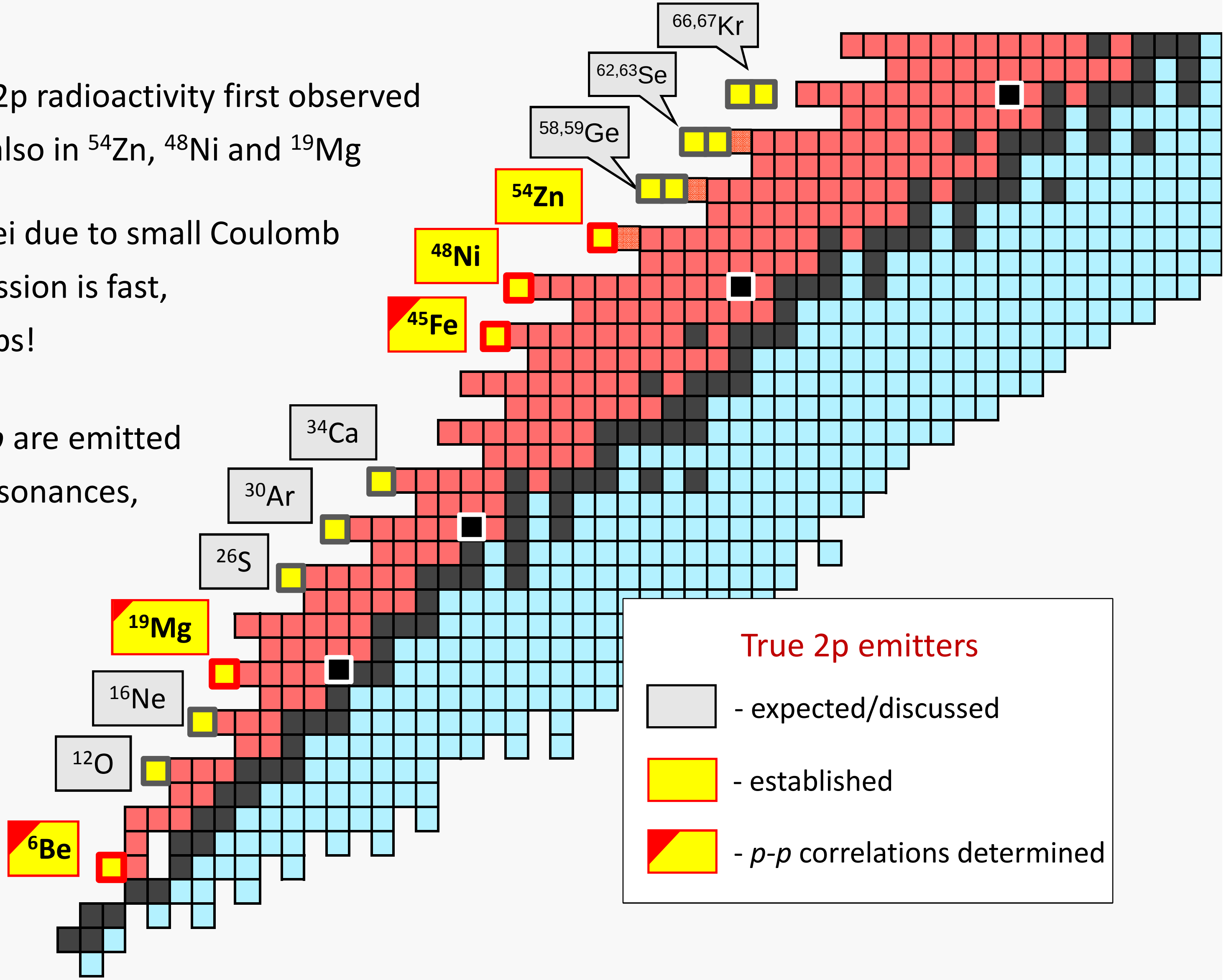
Goldansky, Nucl. Phys. 19 (1960) 482



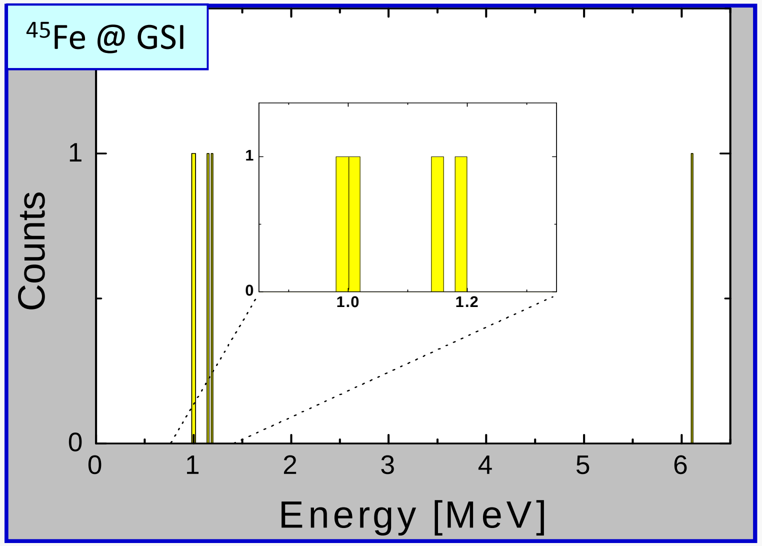


True *2p* emitters

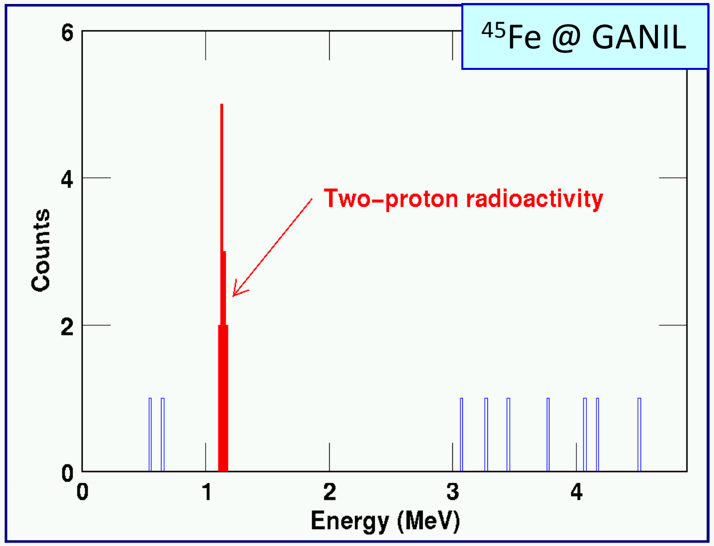
- Ground-state 2p radioactivity first observed in ^{45}Fe. Later also in ^{54}Zn, ^{48}Ni and ^{19}Mg
- In lighter nuclei due to small Coulomb barrier *2p* emission is fast, $T_{1/2}(^{19}\mathrm{Mg}) = 4$ ps!
- Below ^{19}Mg *2p* are emitted from broad resonances, like ^{6}Be



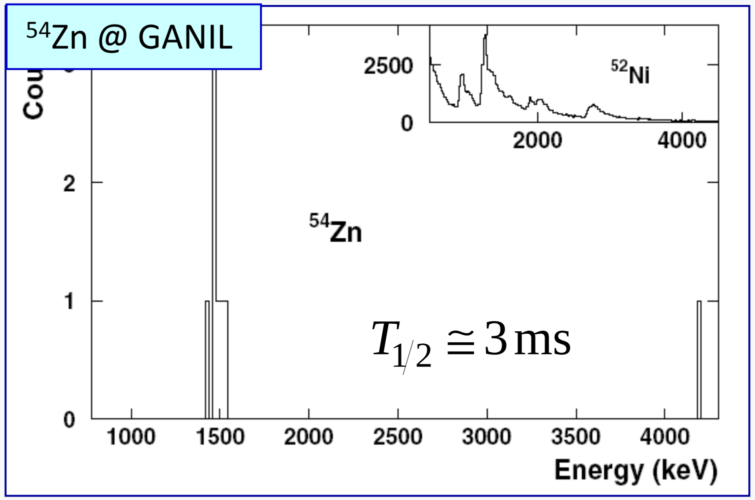
First, with silicon detectors



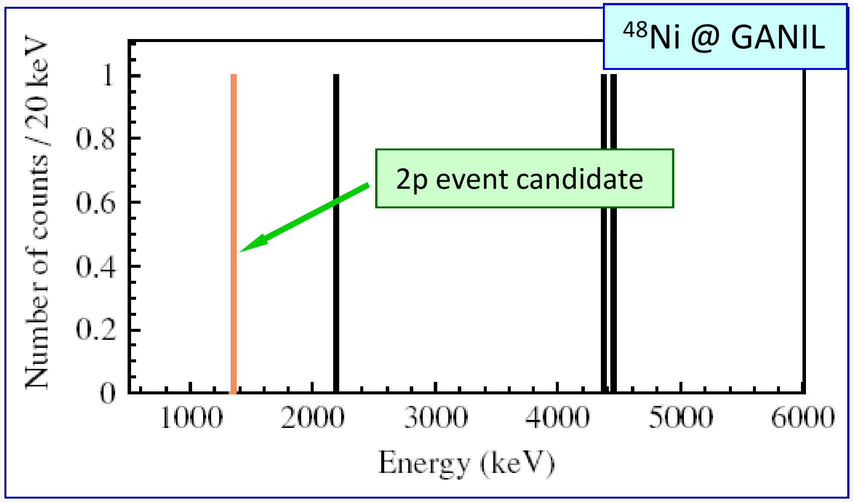
MP et al., EPJ A 14 (2002) 279



Giovinazzo et al., PRL 89 (2002) 102501



Blank et al., PRL 94 (2005) 232501

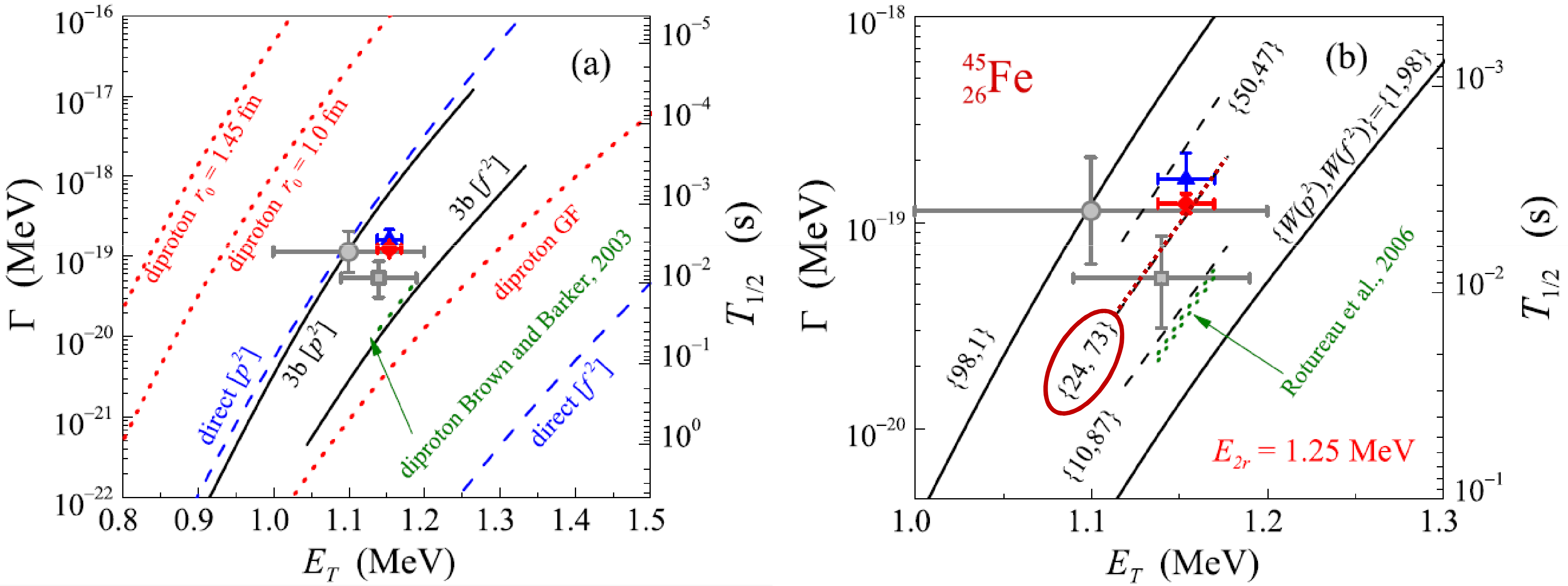


Dossat et al., PRC 72 (2005) 054315

Decay energy and time

- The decay energy and the lifetime are enough to establish the 2p decay.

  Most models used for comparison, however, are based on two-body approximations.

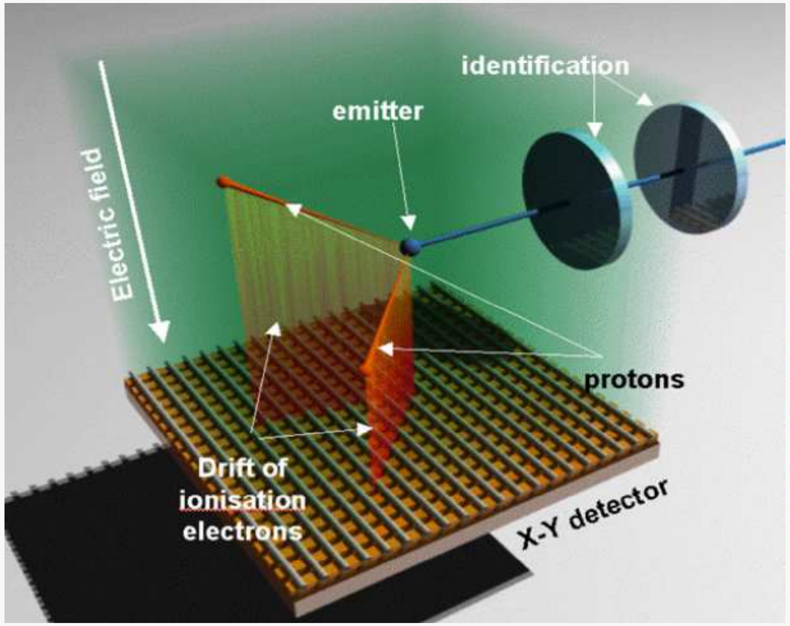


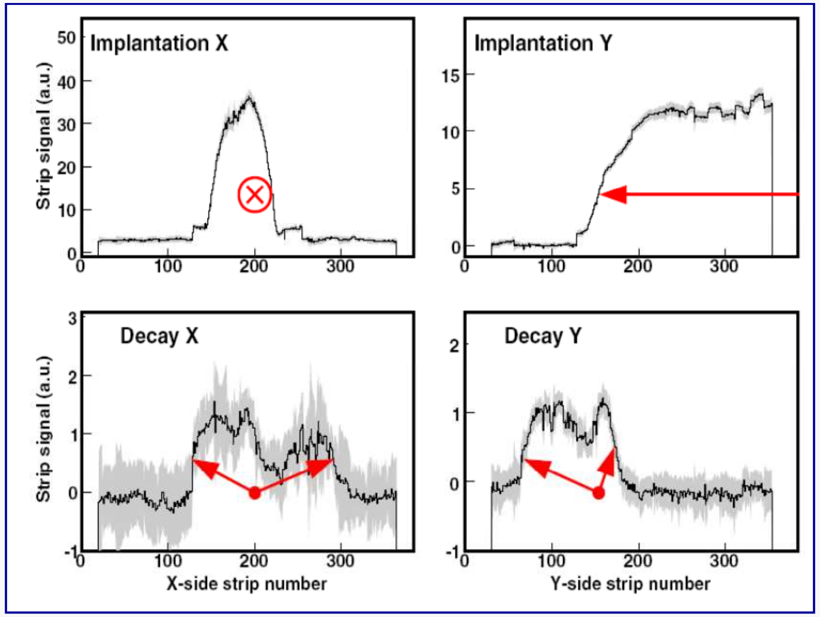
→ To explore fully the physics of the process, the correlations between proton's momenta must be determined! New detection technique is needed and a model capturing the three-body kinematics.

TPC principle

- A „classical" Time Projection Chamber (TPC) constructed at CEN Bordeaux.

  It has fully electronic readout.The position on the *x-y* plane is detected by two ortogonal sets of 768 strips readout by ASIC-type electronics.





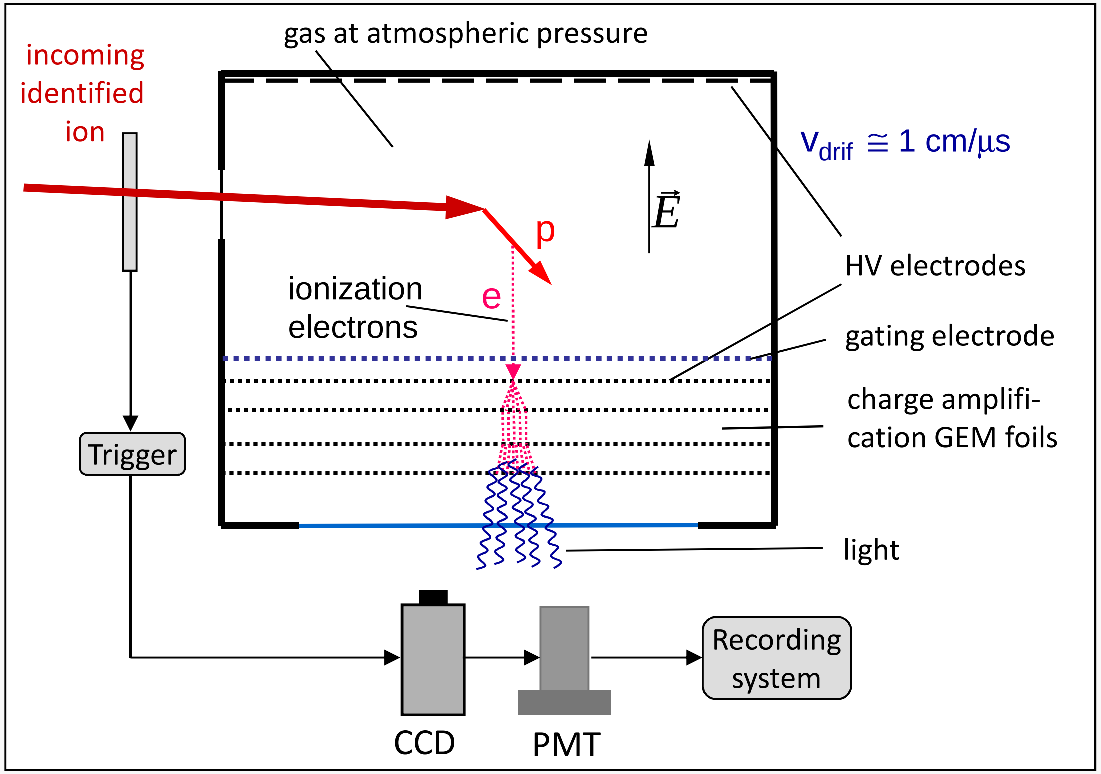
A decay event of ^{45}Fe

→ Expensive and difficult to handle. Problems with information on *z* coordinate

Giovinazzo et al., PRL 99 (2007) 102501

New idea – TPC with optical readout

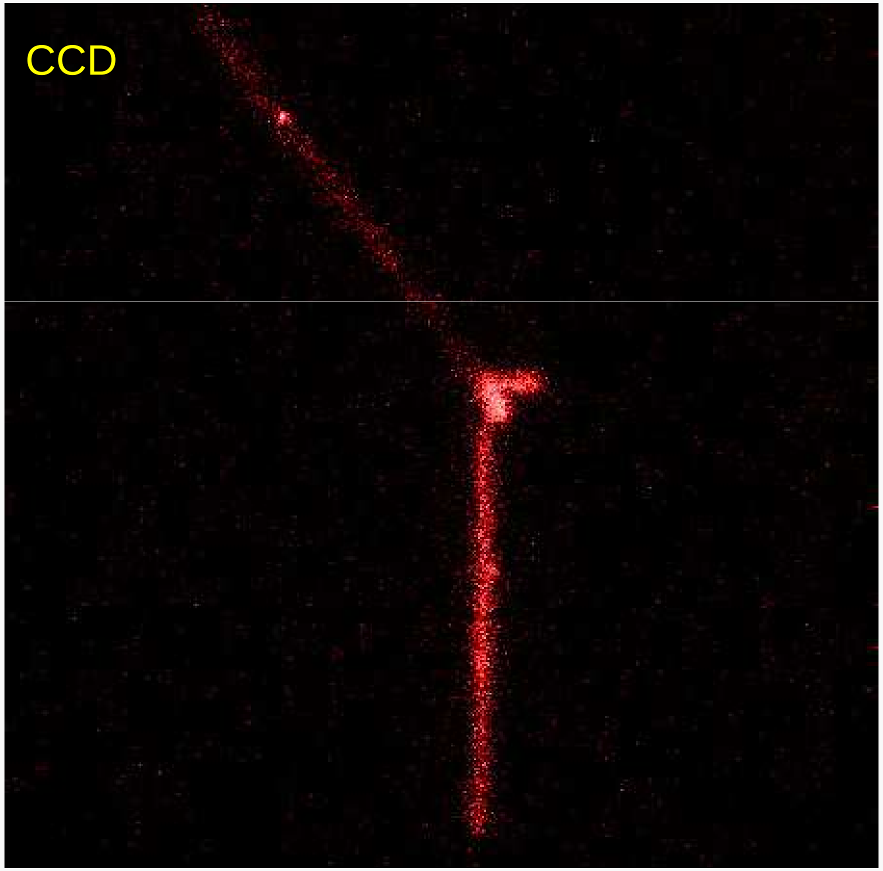
OTPC – Optical Time Projection Chamber

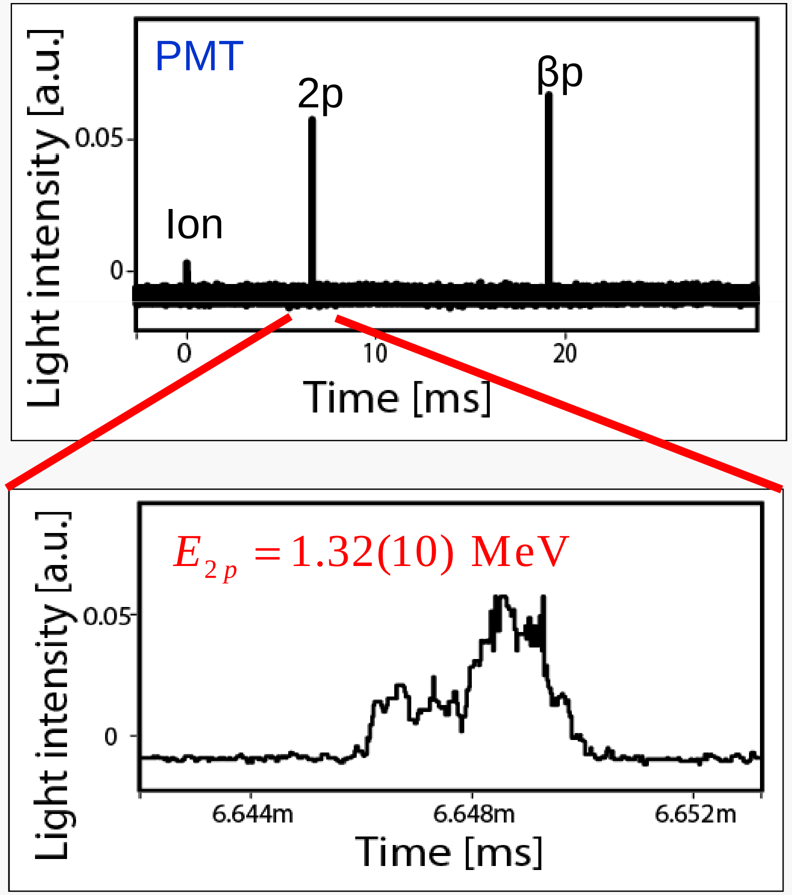


Miernik et al., NIM A581 (2007) 194

OTPC operation

- The CCD picture yields 2D projection of tracks of particles
- The PMT provides information on sequence, timing, and z-coordinate

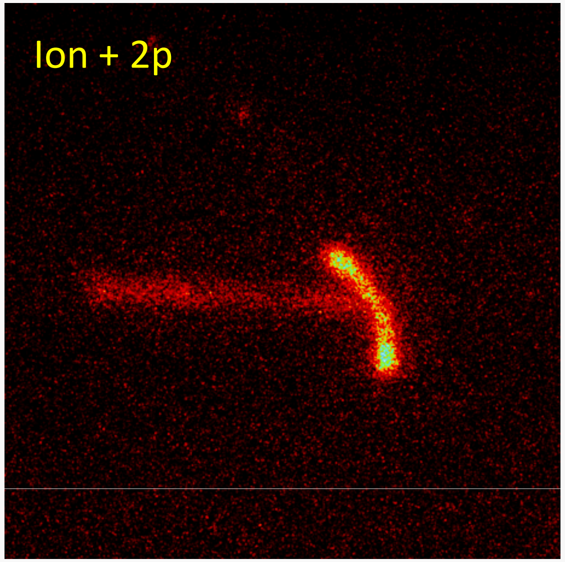


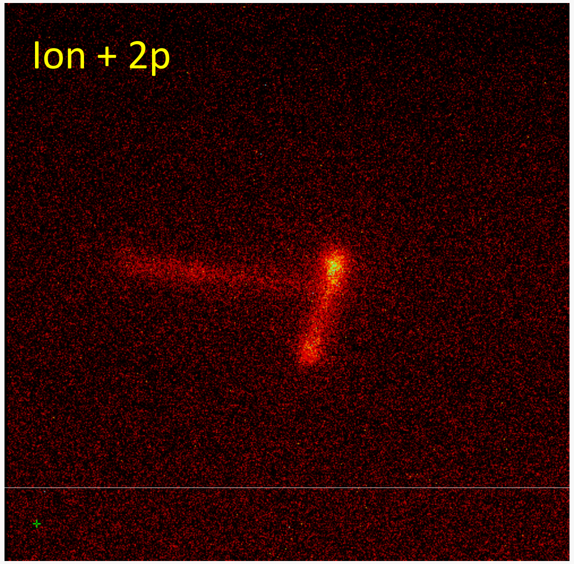


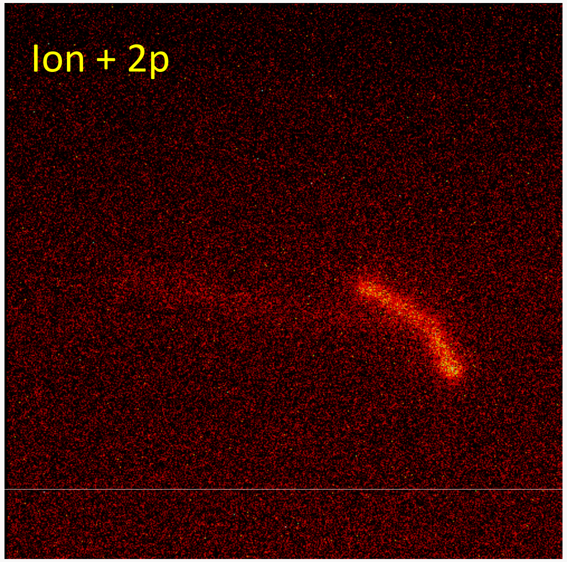
$E_{2p} = 1.32(10)$ MeV

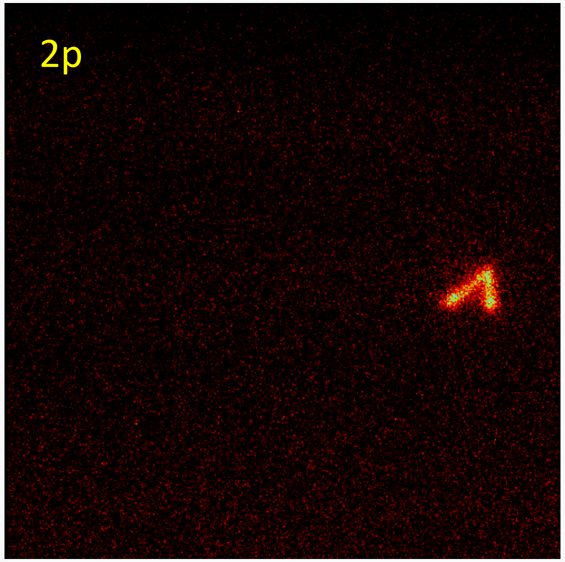
Pomorski et al., PRC 83 (2011) 061303(R)

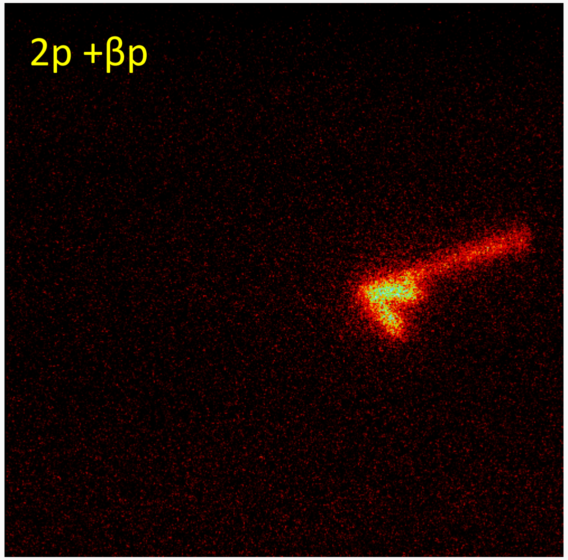
2p decays of ^{45}Fe

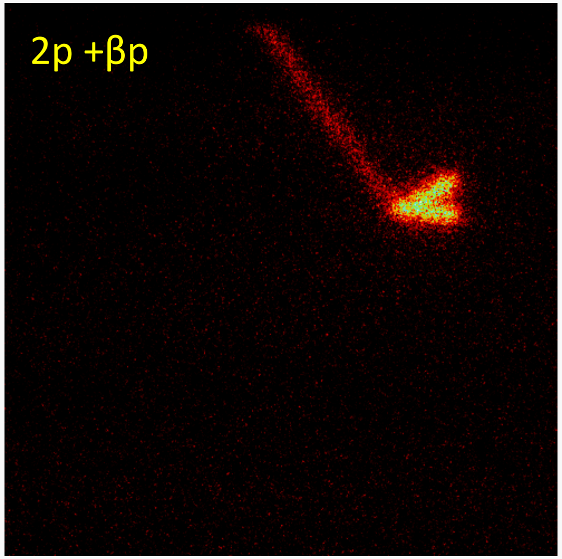










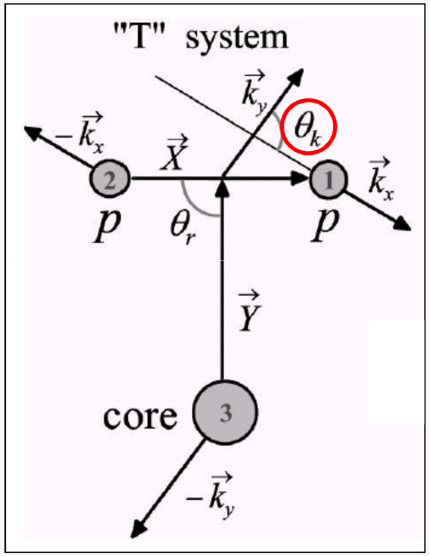


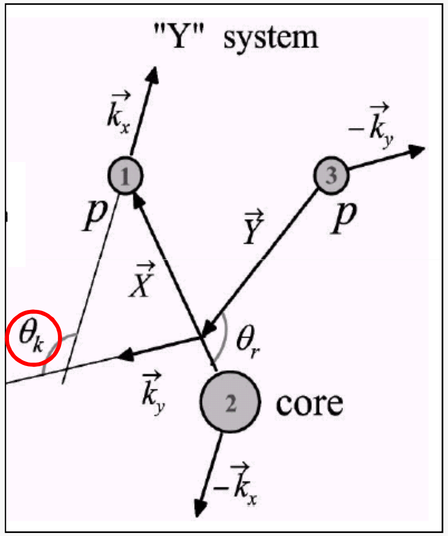
Miernik et al., PRL 99 (2007) 192501

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

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

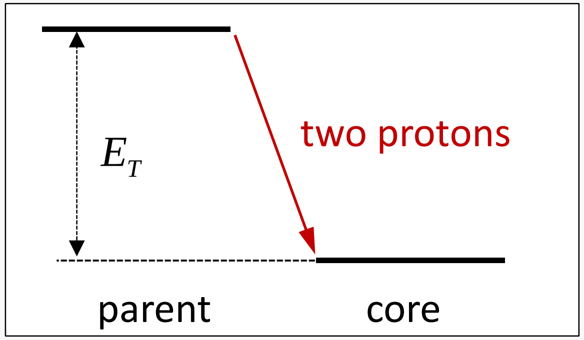
θ_k is the angle between vectors:

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

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

→Schrödinger equation, integration over angles:

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

(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 $\hat{V}_{\alpha,\alpha'}$

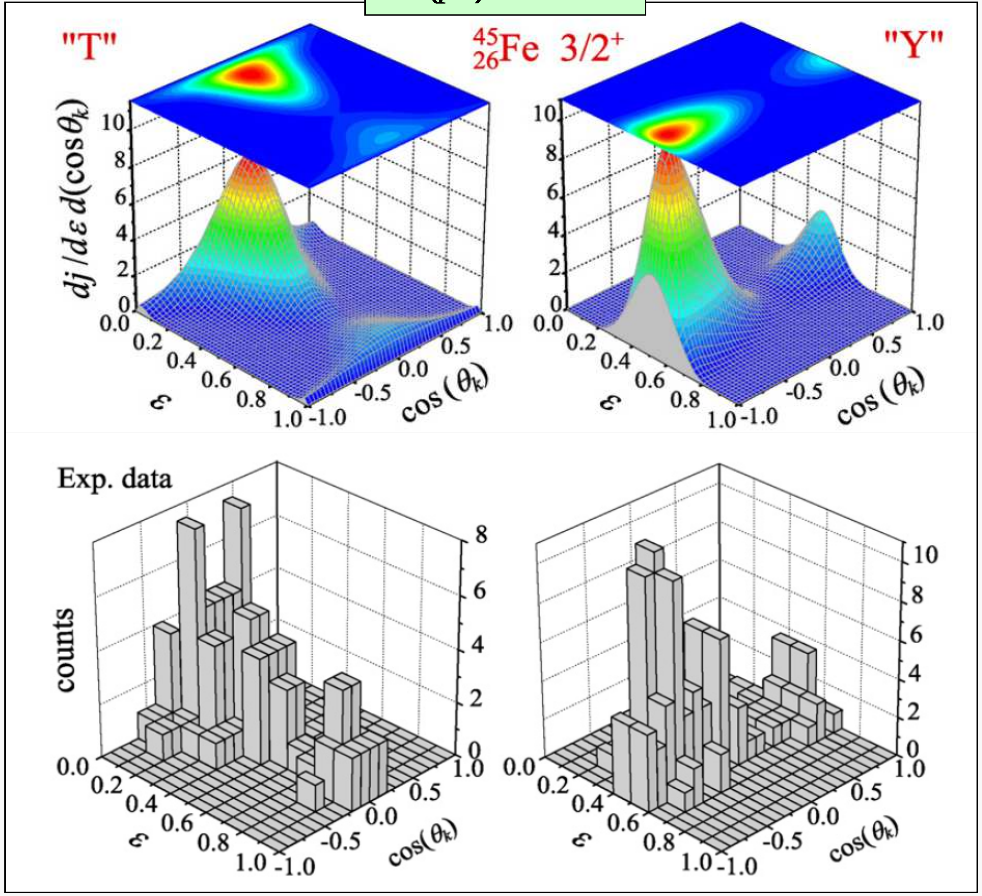
→From radial functions the width and correlations :

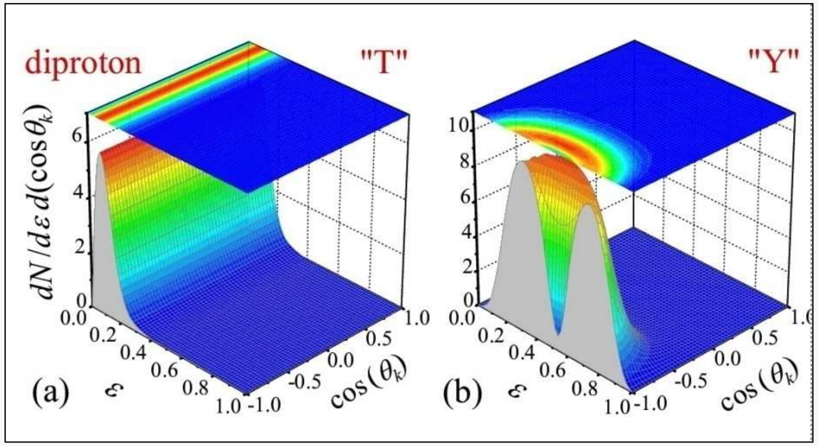
$$\chi_\alpha(\rho) \Rightarrow \Gamma\ ,\quad d\,j/d\varepsilon\, d\left(\cos\theta_k\right)$$

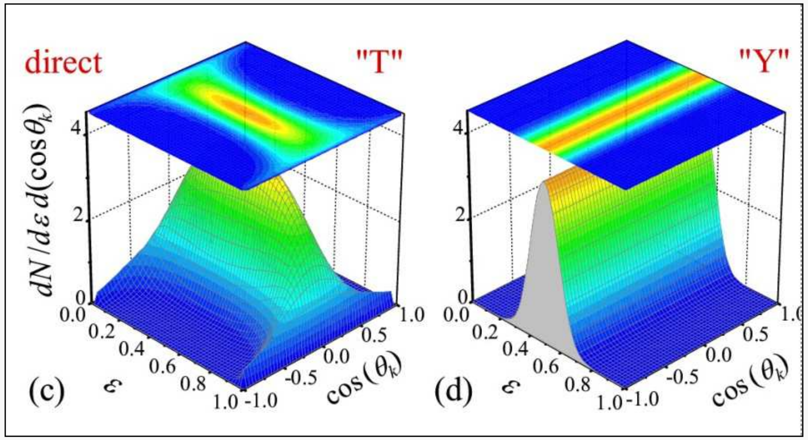
Grigorenko and Zhukov, PRC 68 (03) 054005
M.P. et al, RMP (2012) 567

Full picture for ^{45}Fe

W(p^2) = 24%







- All observables are simultaneously well reproduced by the 3-body model

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

Full picture for ^{6}Be

- Radioactive beam experiment at Texas A&M University

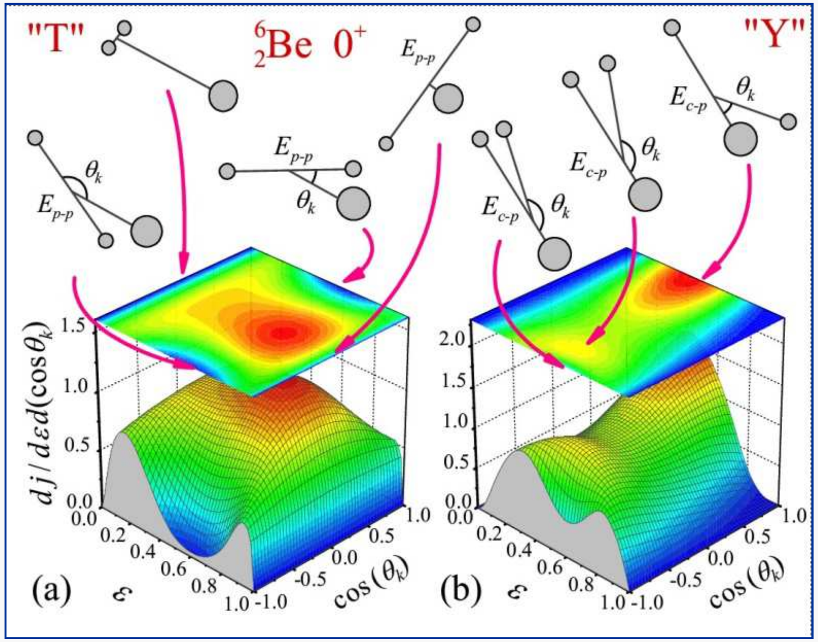
^{10}C inelastic scattering

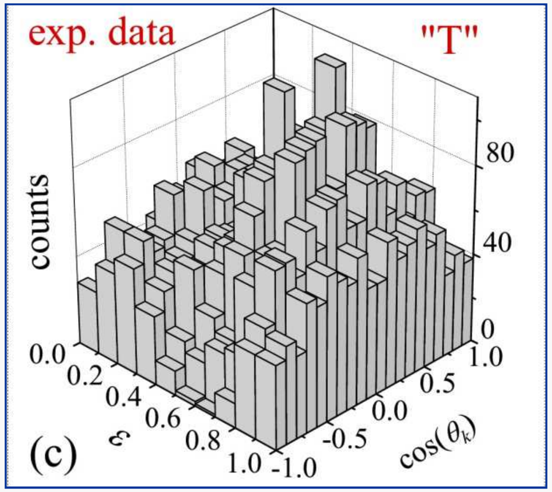
❶ p (^{10}B, ^{10}C) n @15 MeV/u

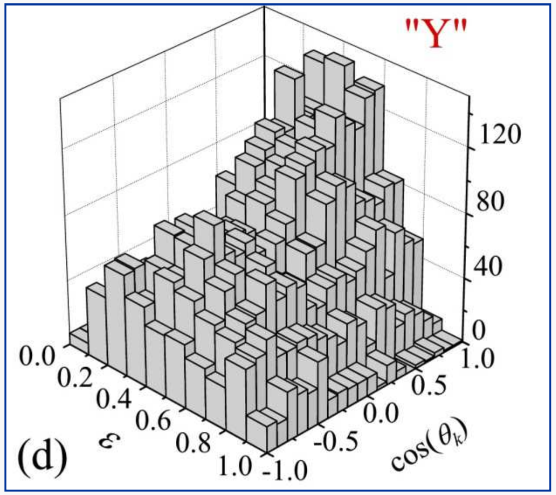
❷ 11 MeV/u ^{10}C + C/Be → ^{10}C*

❸ ^{10}C* → ^{6}Be + α

Mercurio et al., PRC 78 (08) 031602(R)
Grigorenko et al., PLB 677 (2009) 30







Case of ^{19}Mg

- Decay in-flight and tracking for very short-lived *2p* decays at GSI

Radioactive beam experiment

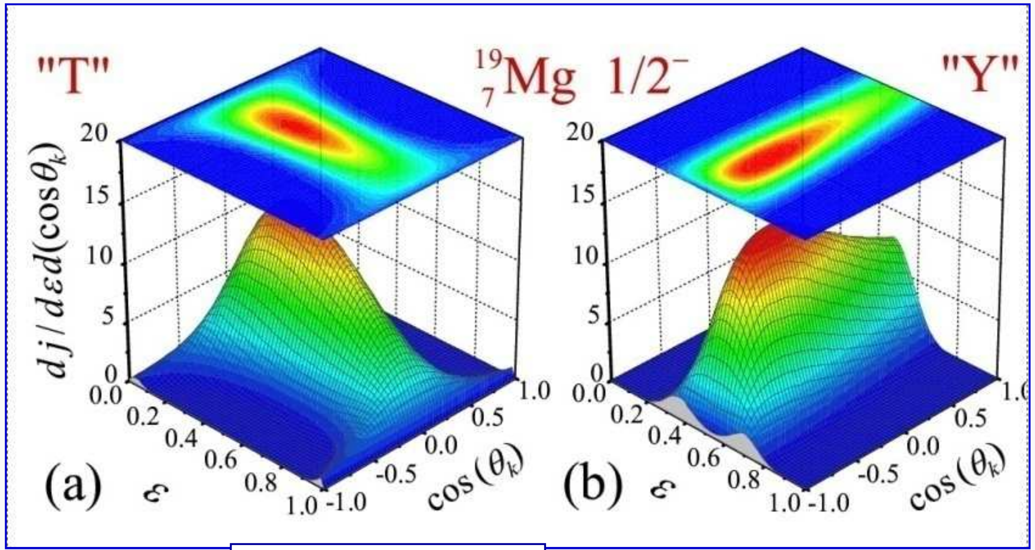
❶ ^{24}Mg @ 600 MeV/u + Be → ^{20}Mg

❷ ^{20}Mg + Be → ^{19}Mg

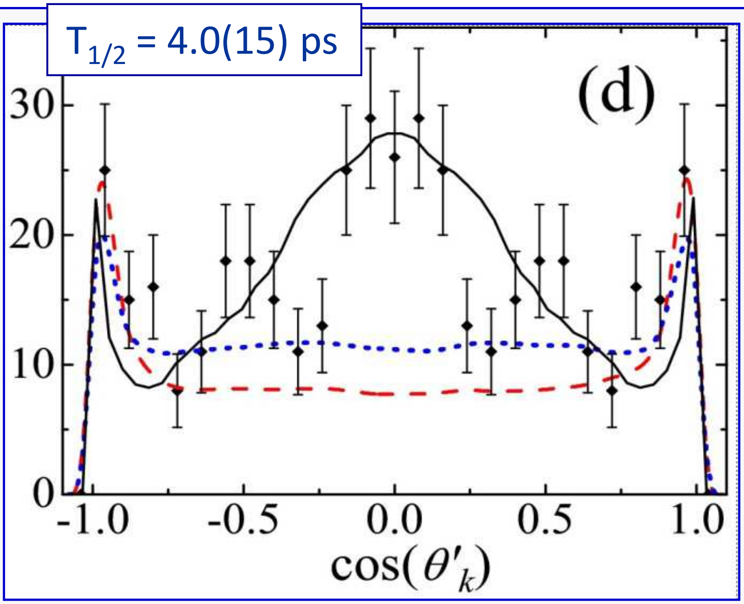
- Only projection of proton's momenta on the plane could be determined.

Mukha et al., PRL. 99 (2007) 182501

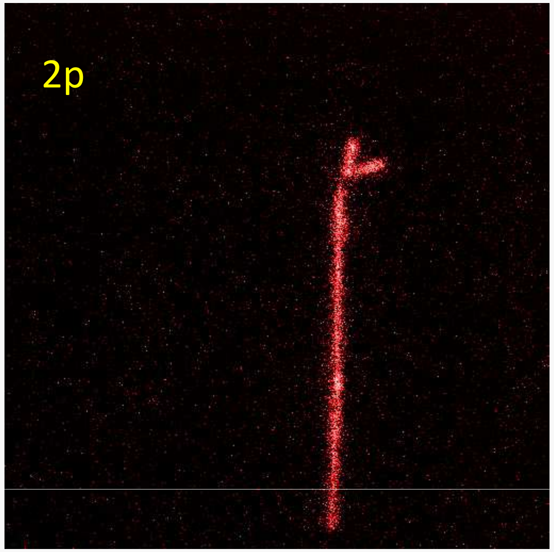
Mukha et al., PR C 77 (2008) 061303(R)

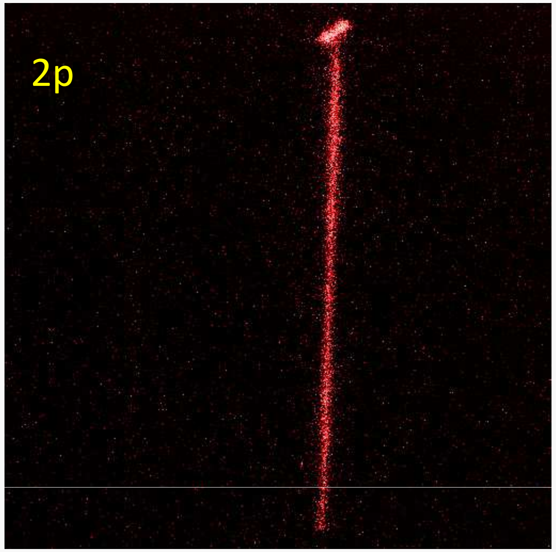


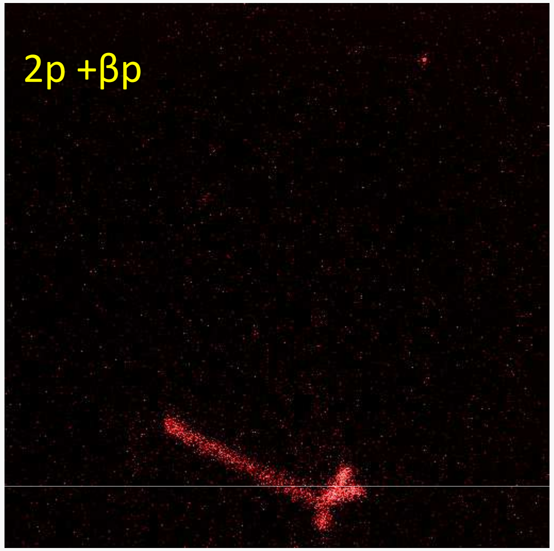
T$_{1/2}$ = 4.0(15) ps

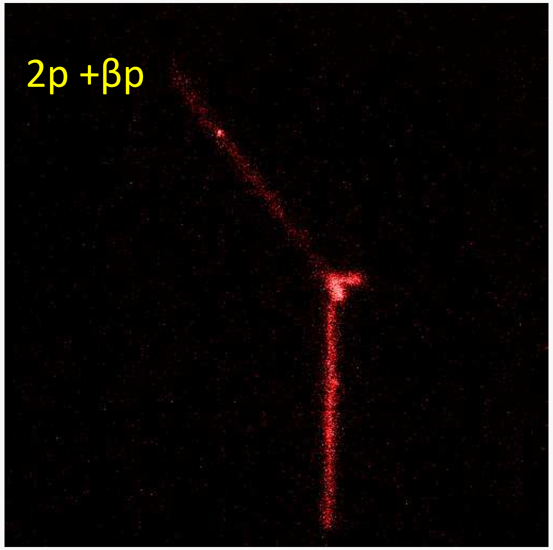


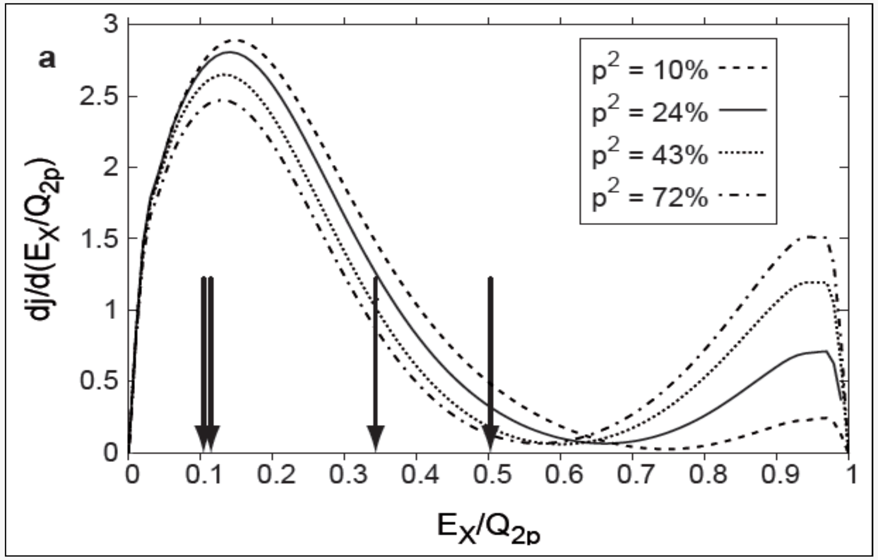
2p decays of ^{48}Ni







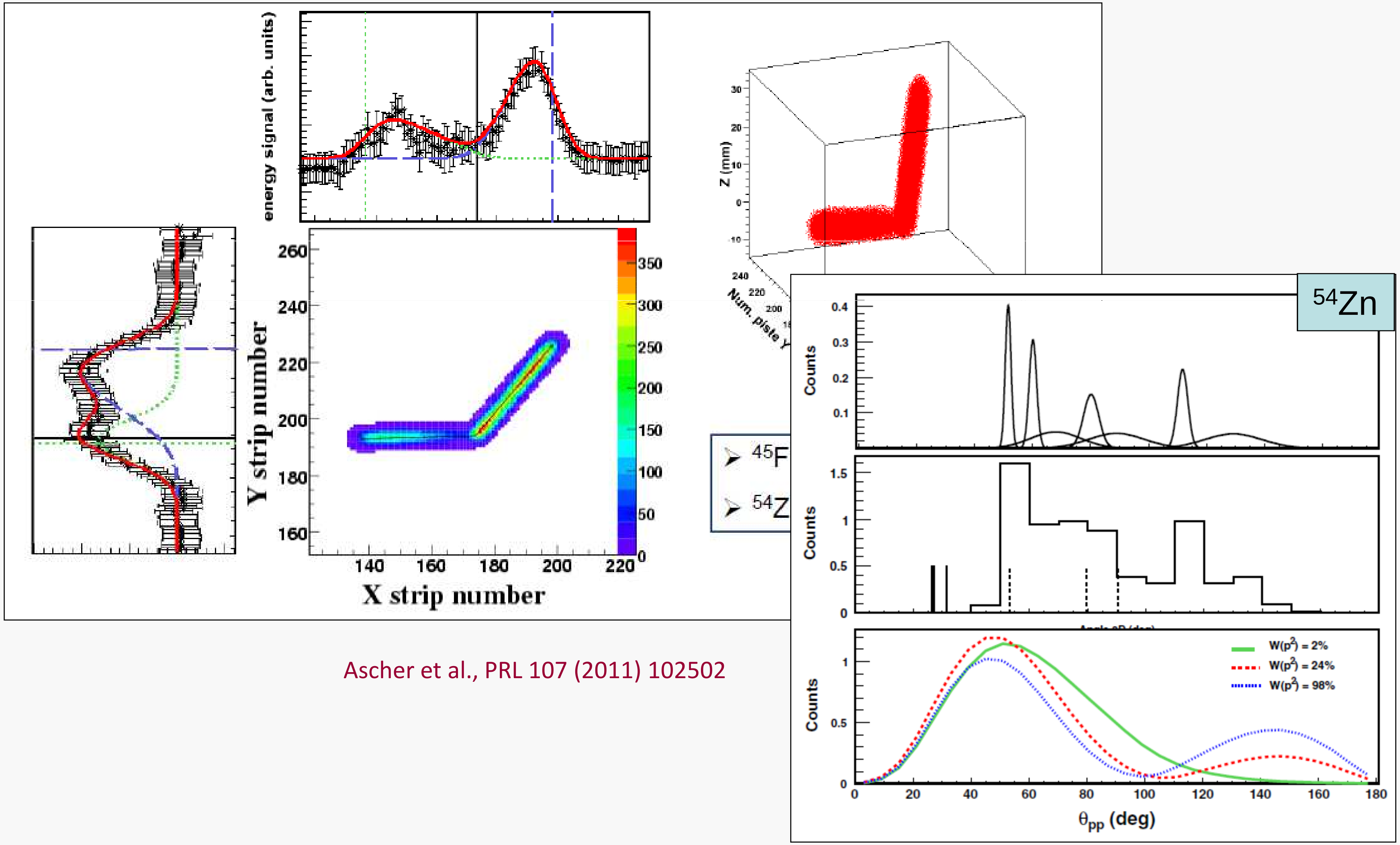




Pomorski et al., Acta Phys. Pol. B 43 (2012) 267

p-*p* correlations in ^{54}Zn

- ^{54}Zn studied at GANIL with the Bordeaux TPC. Seven events reconstructed in 3D

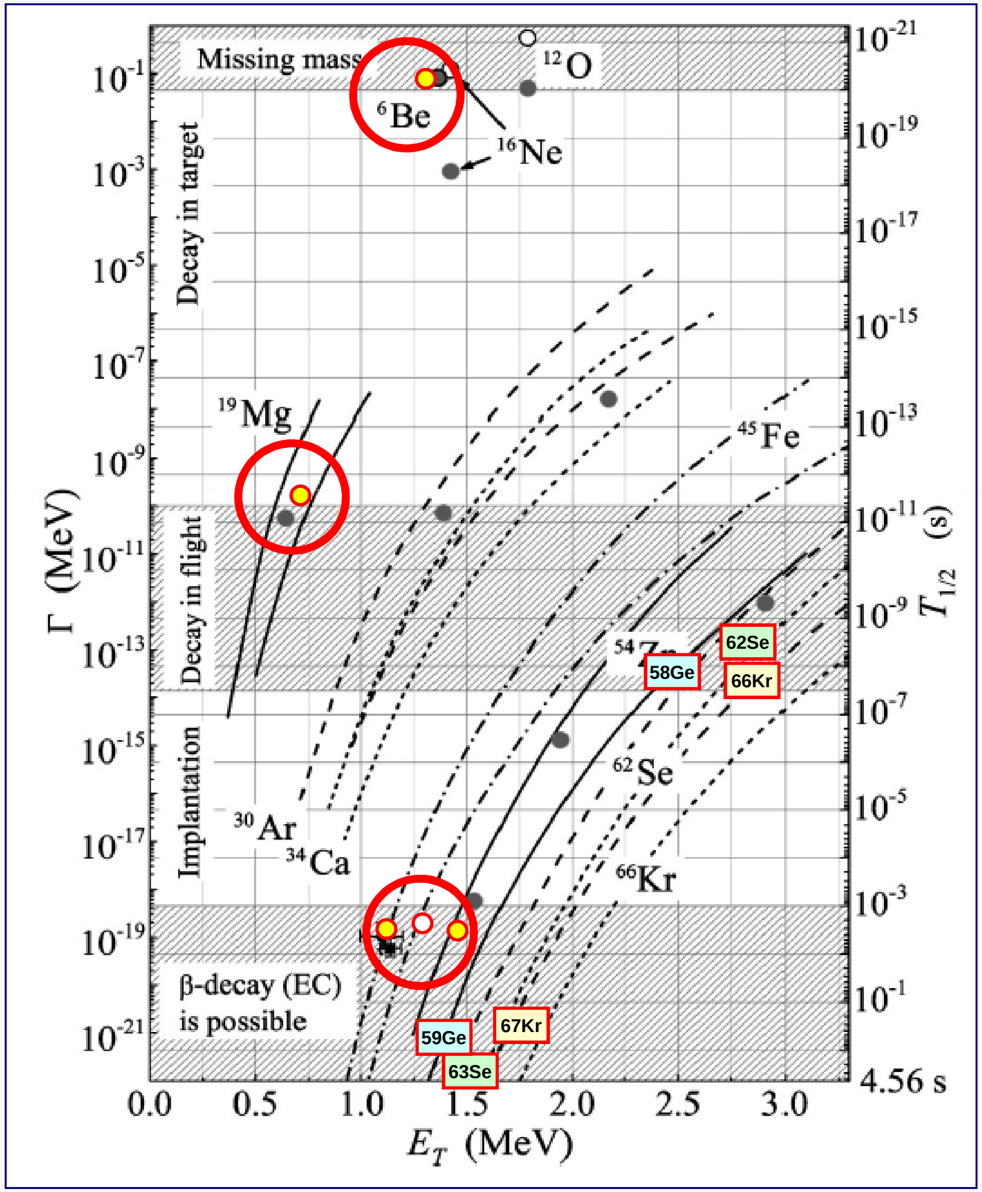


Ascher et al., PRL 107 (2011) 102502

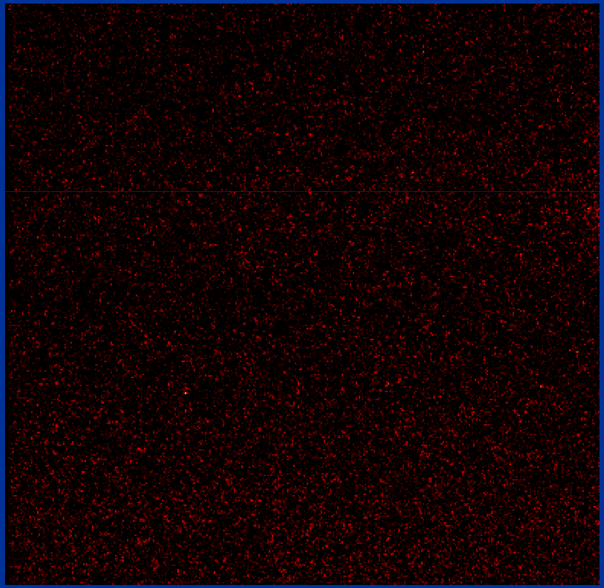
Range of lifetimes

- The three-body model seems to work in the range of half-lives covering 18 orders of magnitude!

  - Invariant mass method for broad resonanses
    $T_{1/2} \leq 10^{-19}$ s
  - In-flight decays
    $T_{1/2}$ = 1 ps – 50 ns
  - Implantation method
    $T_{1/2}$ > 50 ns

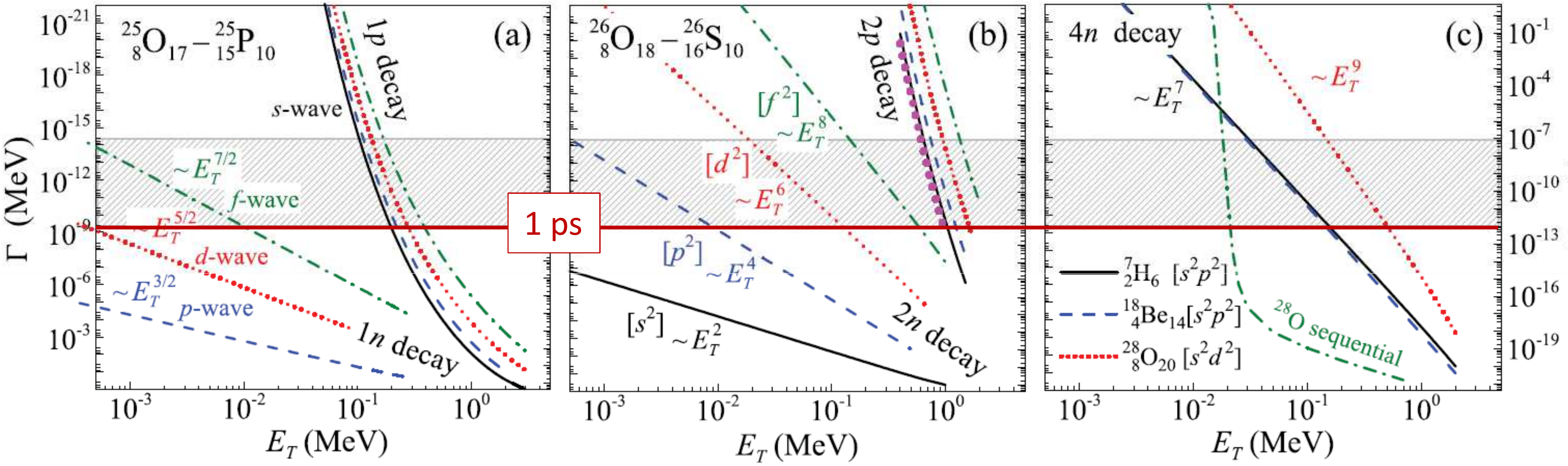


Neutron radioactivity



n, 2n, or 4n?

- The xn emission estimated by a simplified version of 3-body model (direct decay model) and compared to proton emission



● Extremely small decay energy needed for a measurable decay time of 1n emission.

Very unlikely to find a candidate in the *s*-*d* shell.

●● Broader energy window thus higher chances to find a good case.

^{26}O could be a candidate!

●●●● Special energy configuration required (only $S_{4n} < 0$) but not impossible.

^{7}H and ^{28}O are not excluded!

Grigorenko et al., PRC 84 (2011) 021303(R)

Summary

- The particle radioactivity (*p*, α) at the proton drip-line is very **efficient tool** in nuclear spectroscopy. Yield masses (separation energies) of very exotic systems, provides stringent tests for models of nuclear structure.

- More than **40 proton-emitting states** are known. 7 emitters exhibit **fine structure**. Observation of g.s. proton radioactivity for $Z < 50$ remains an experimental challenge.

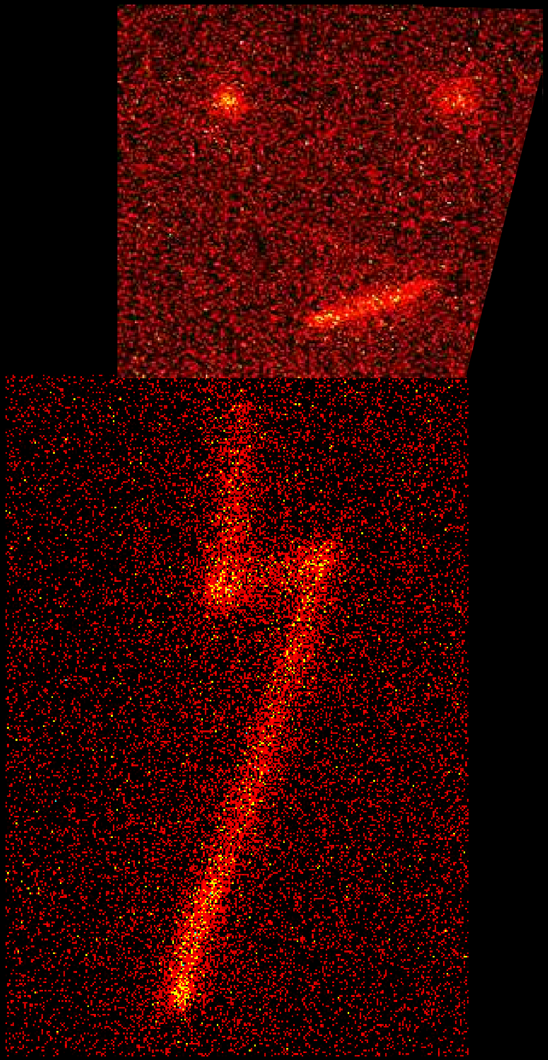
- The observation of „**superallowed**" α-decay ^{104}Te → ^{100}Sn is approaching.

- The direct 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 and ^{59}Ge will be tried soon.

- The observation of **full *p-p* correlation picture** in ^{6}Be and ^{45}Fe was the major breakthrough in the field. The 3-body model of Grigorenko and Zhukov was confirmed and the **influence of nuclear structure** on the *2p* emission was demonstrated. Further theoretical work is needed to elucidate this issue.

- Observation of **two-neutron radioactivity** is probable in nuclei accesible already now.

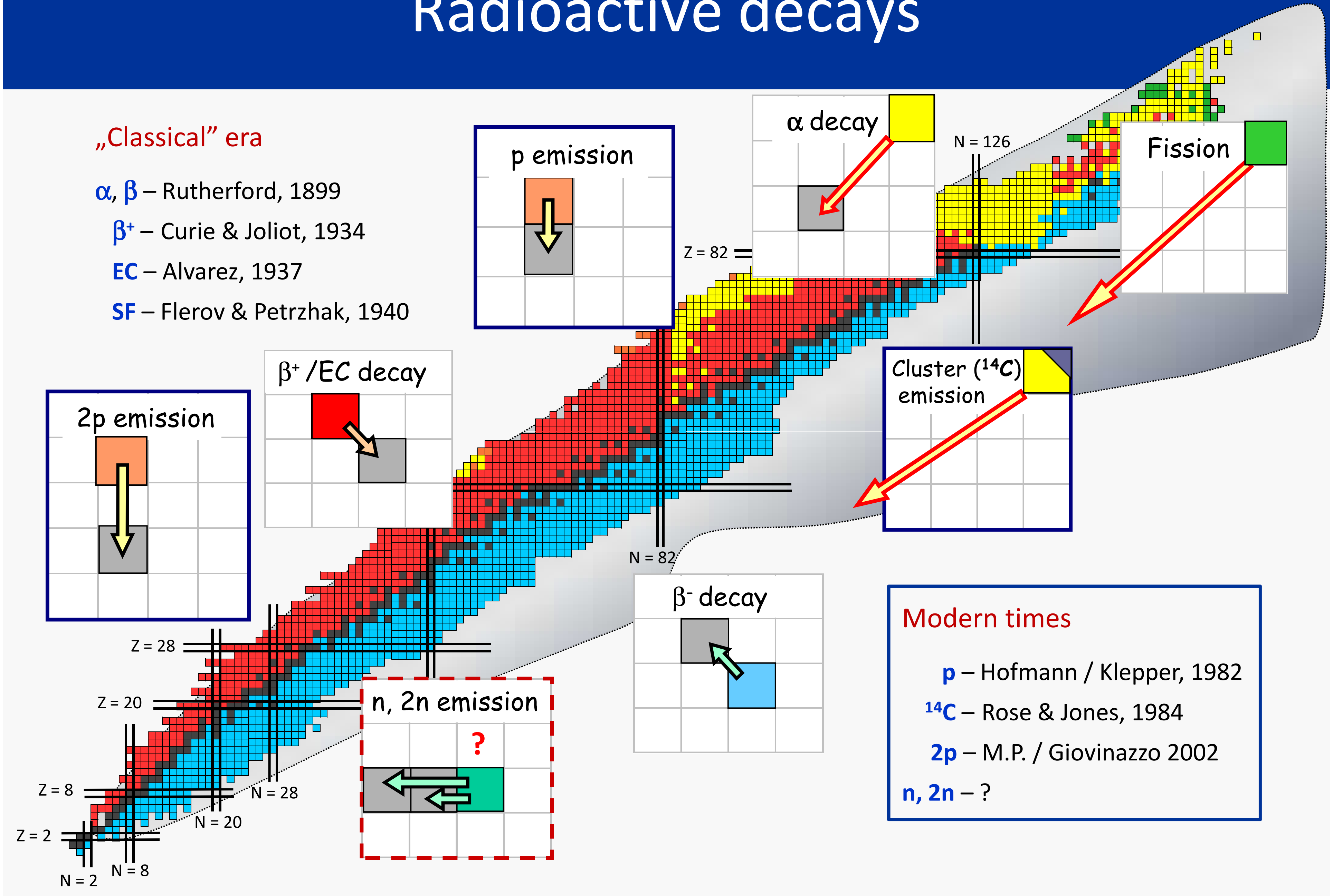
Thank you!



Radioactive decays

„Classical” era

- **α, β** – Rutherford, 1899
- **β^+** – Curie & Joliot, 1934
- **EC** – Alvarez, 1937
- **SF** – Flerov & Petrzhak, 1940



Modern times

- **p** – Hofmann / Klepper, 1982
- **^{14}C** – Rose & Jones, 1984
- **2p** – M.P. / Giovinazzo 2002
- **n, 2n** – ?

What is radioactive?

- ➤ What is plotted on the chart? Present practice: all systems we know something about.
- → Suggestion: plot only long-lived, i.e. **stable** and **radioactive** (those which **exist**!)

Radioactivity

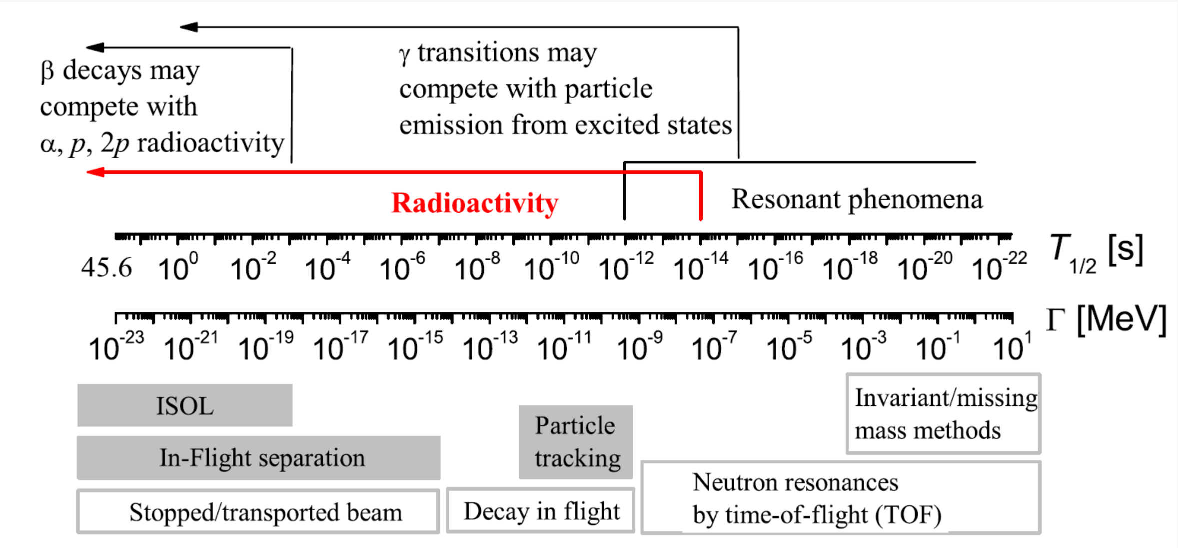
- Slow enough to form neutral atoms
- Characteristic **time** measured directly
- Independent of formation mechanism

$$T_{1/2} \geq 10^{-14}\ \text{s}$$

Reactions/Resonances

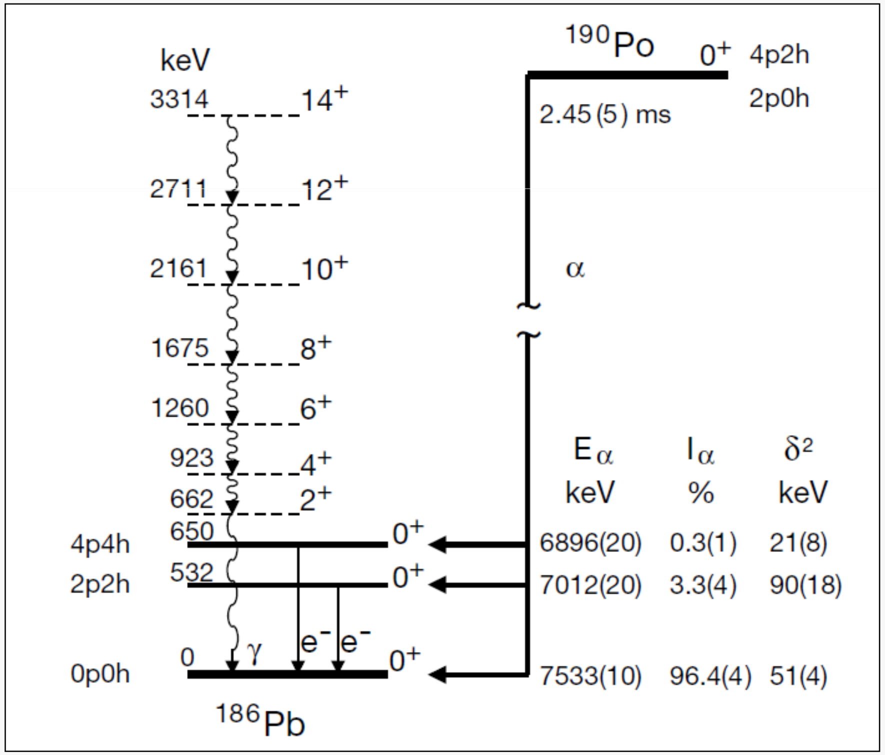
- Fast on atomic scale
- Characteristic **width** measured directly
- Influenced by reaction mechanism

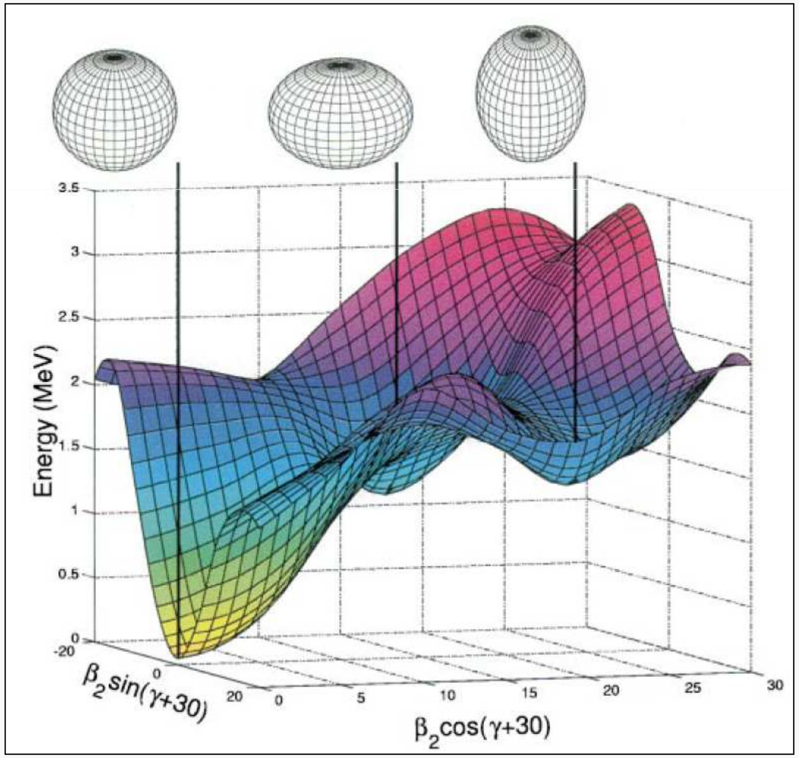
$$\Gamma \geq 1\ \text{meV}$$



Shape coexistence in ^{186}Pb

- Alpha spectroscopy revealed surprizing nature of lowest excitations in ^{186}Pb: the three 0^+ levels with different deformation. A unique case of interaction between proton *p-h* excitations across the closed shell (Z=82) and large number of mid-shell neutrons, N=(82+126)/2.





Andreyev *et al.*, Nature 405 (2000) 430