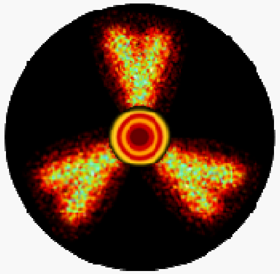
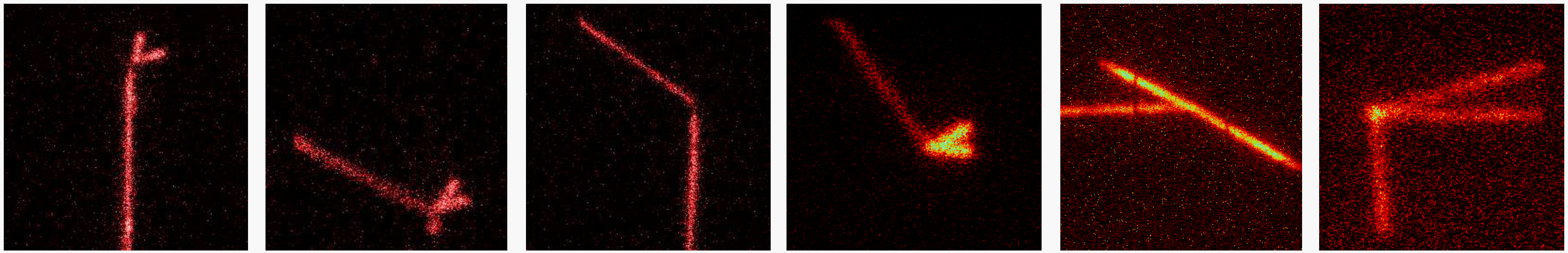
# Particle radioactivity

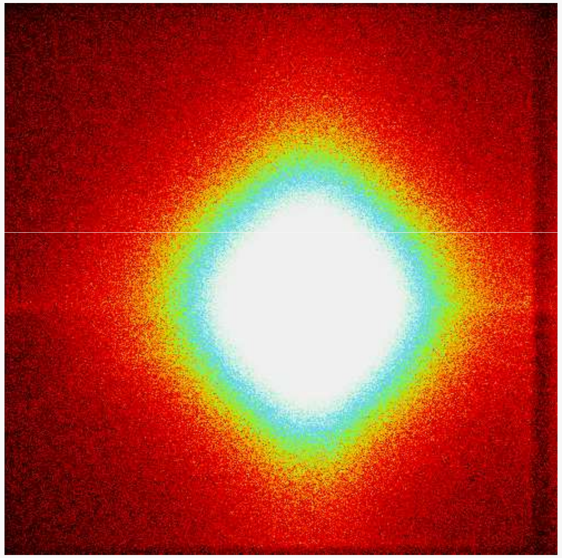


Marek Pfützner

Faculty of Physics, University of Warsaw



# Outline

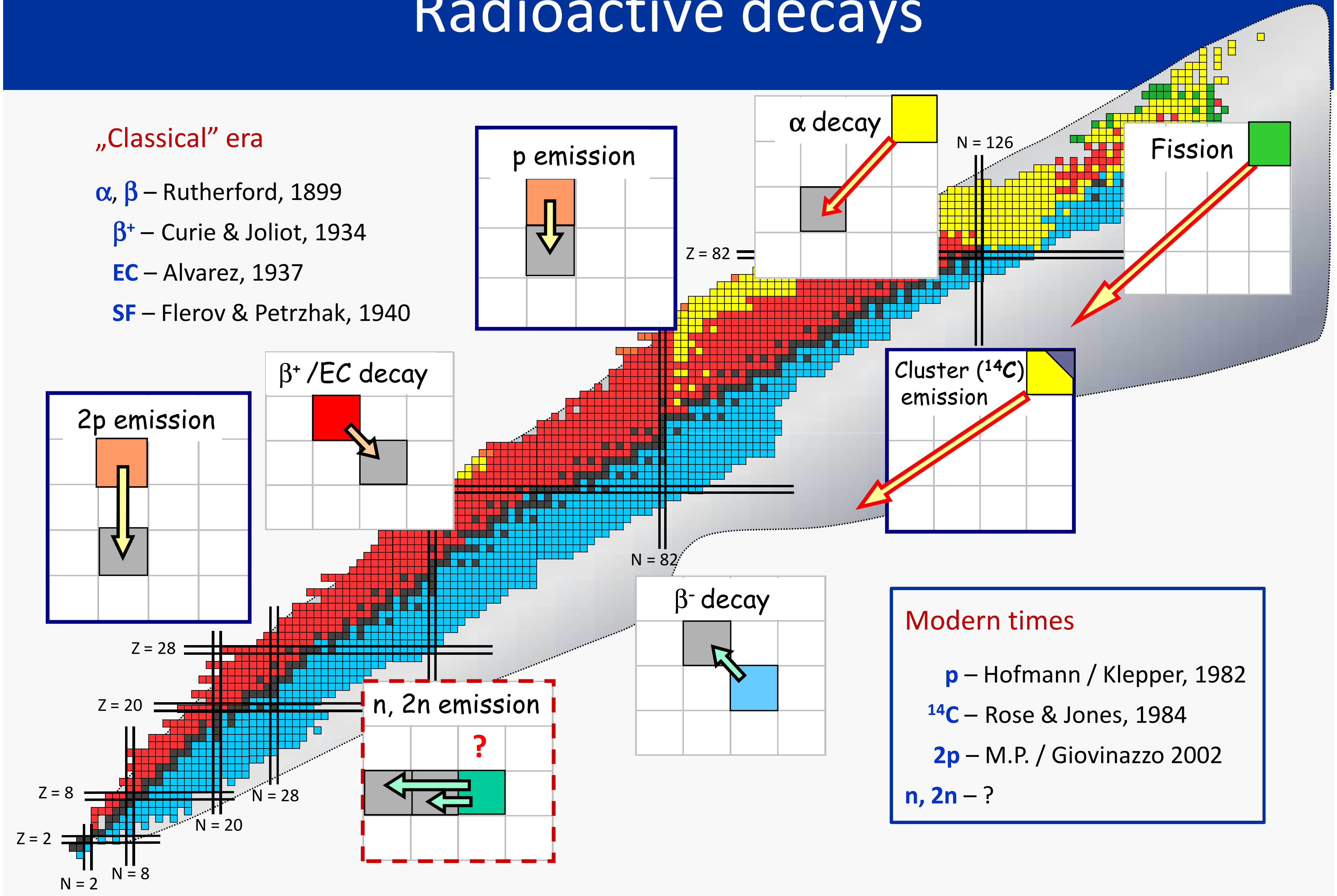


- Basic concepts
- In-flight at Coulomb barrier
  - Proton radioactivity
  - Alpha emission
- In-flight above Fermi energy
  - Two-proton radioactivity
  - Neutron radioactivity?

# 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 – ?

# Particle radioactivity

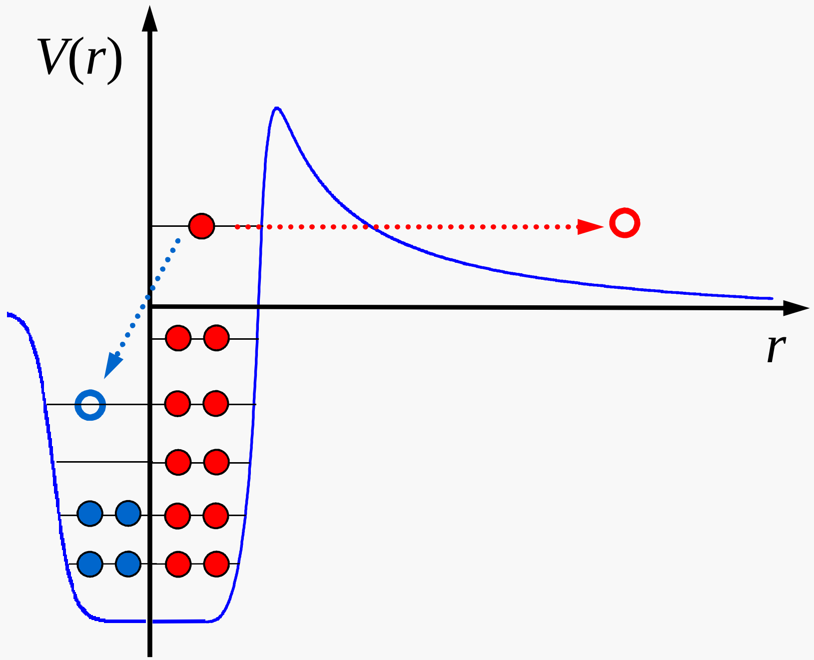
- The fundamental concept: **potential barrier**

→ 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 $T^{p}_{1/2} \leq T^{\beta}_{1/2}$




- In spherical case, WKB-like method:

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

$\nu$ – frequency of assaults

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

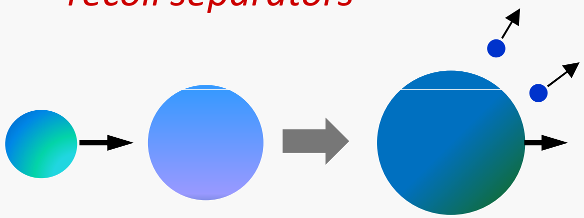
→ This simple approach works surprizingly good and is still frequently used in the analysis of proton and α radioactivity.

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*



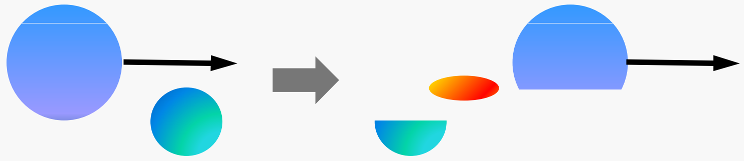
Low energy: ≈ Coulomb barrier

- 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

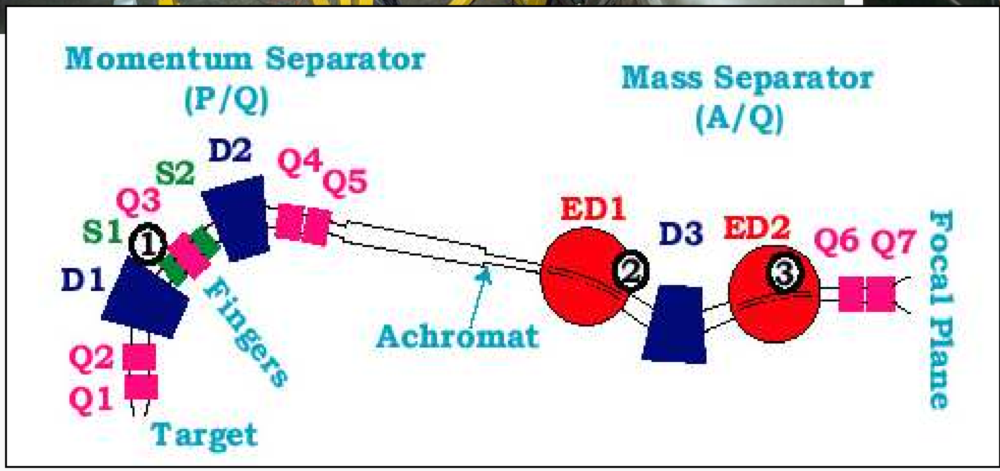
single ion sensitivity

*2p* radioactivity

# Recoil separators

Recoil Mass Separator @ ORNL

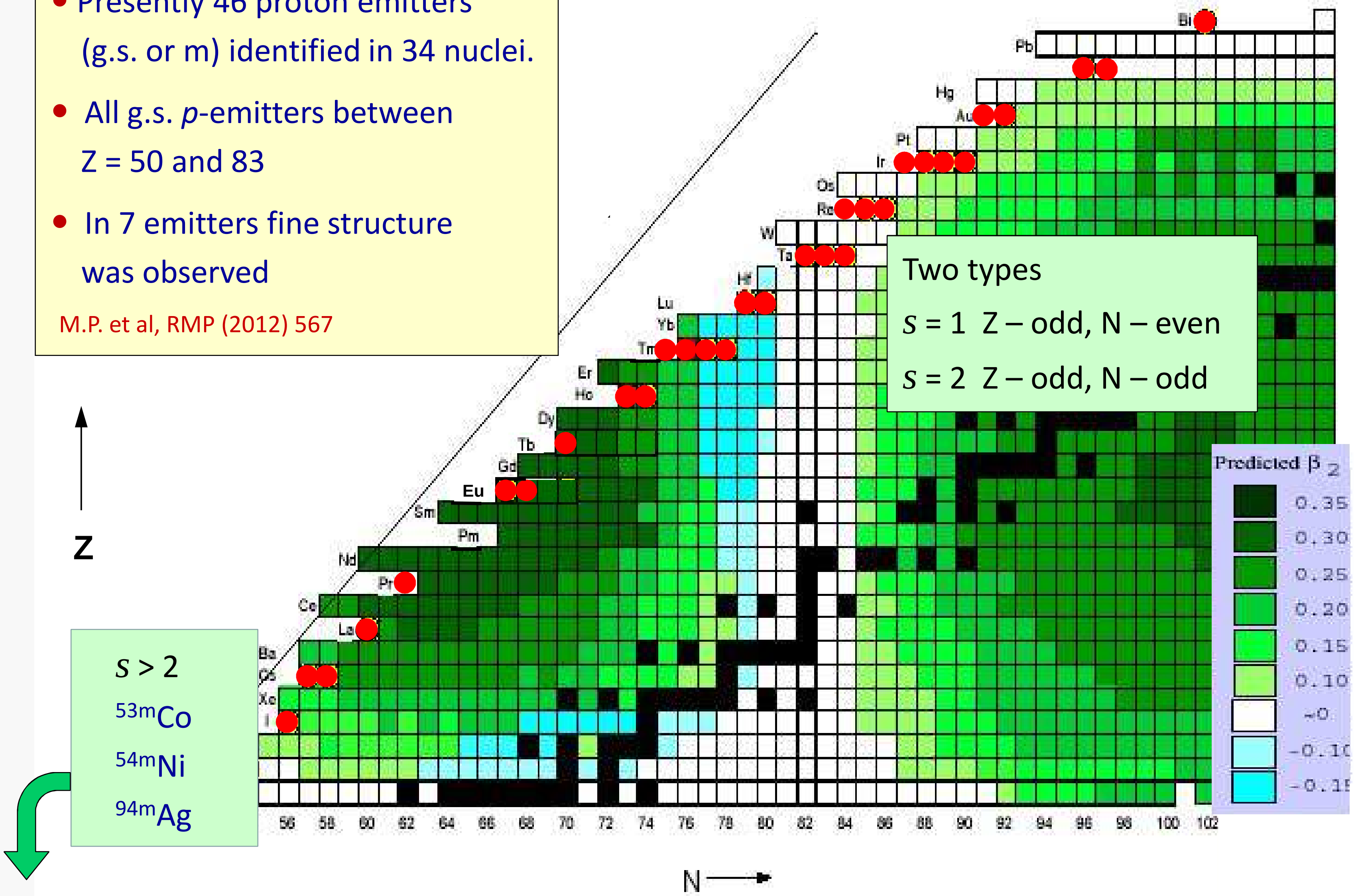
Fragment Mass Analyser @ ANL



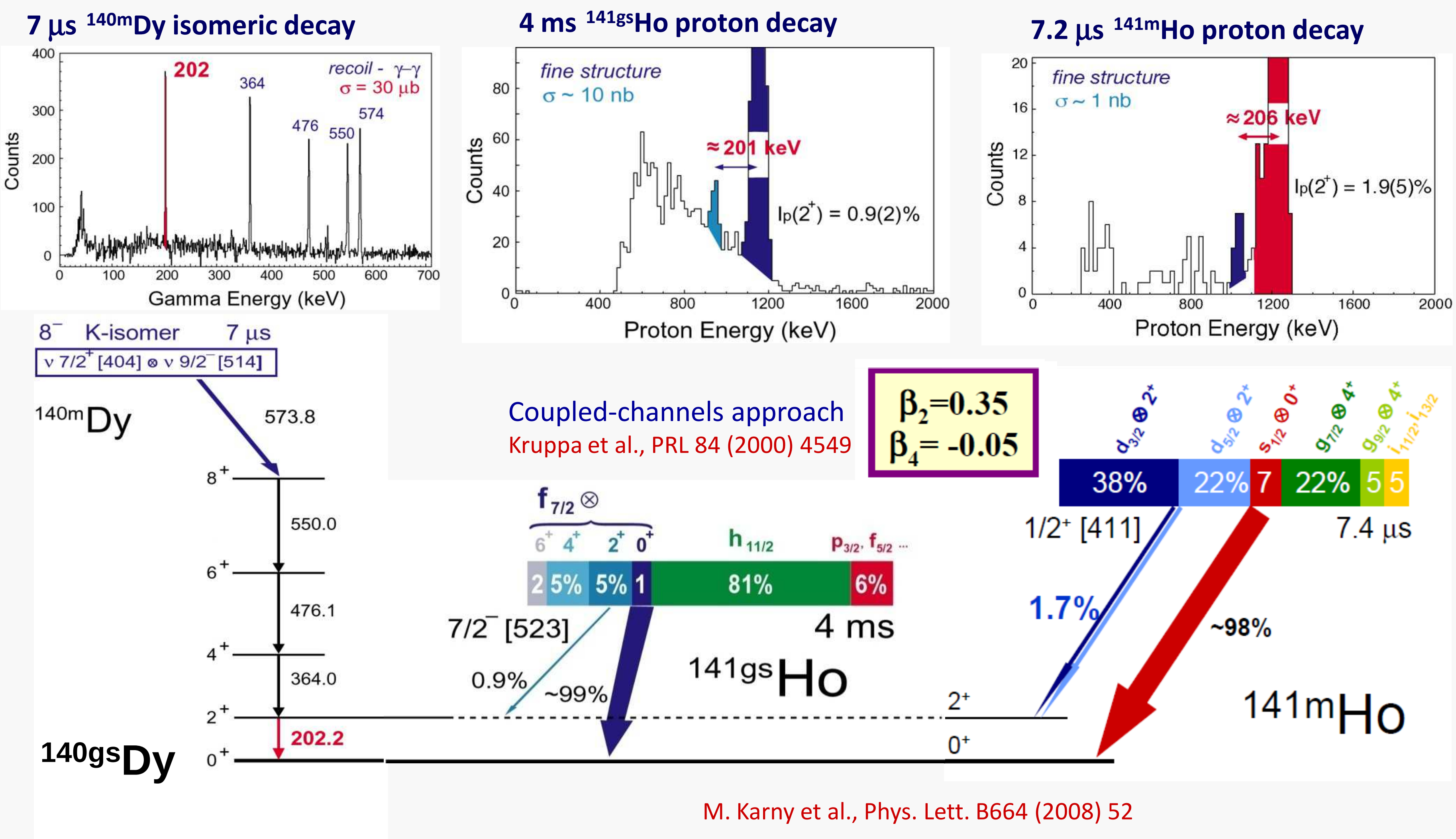
# *p* radioactivity – the status

- 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

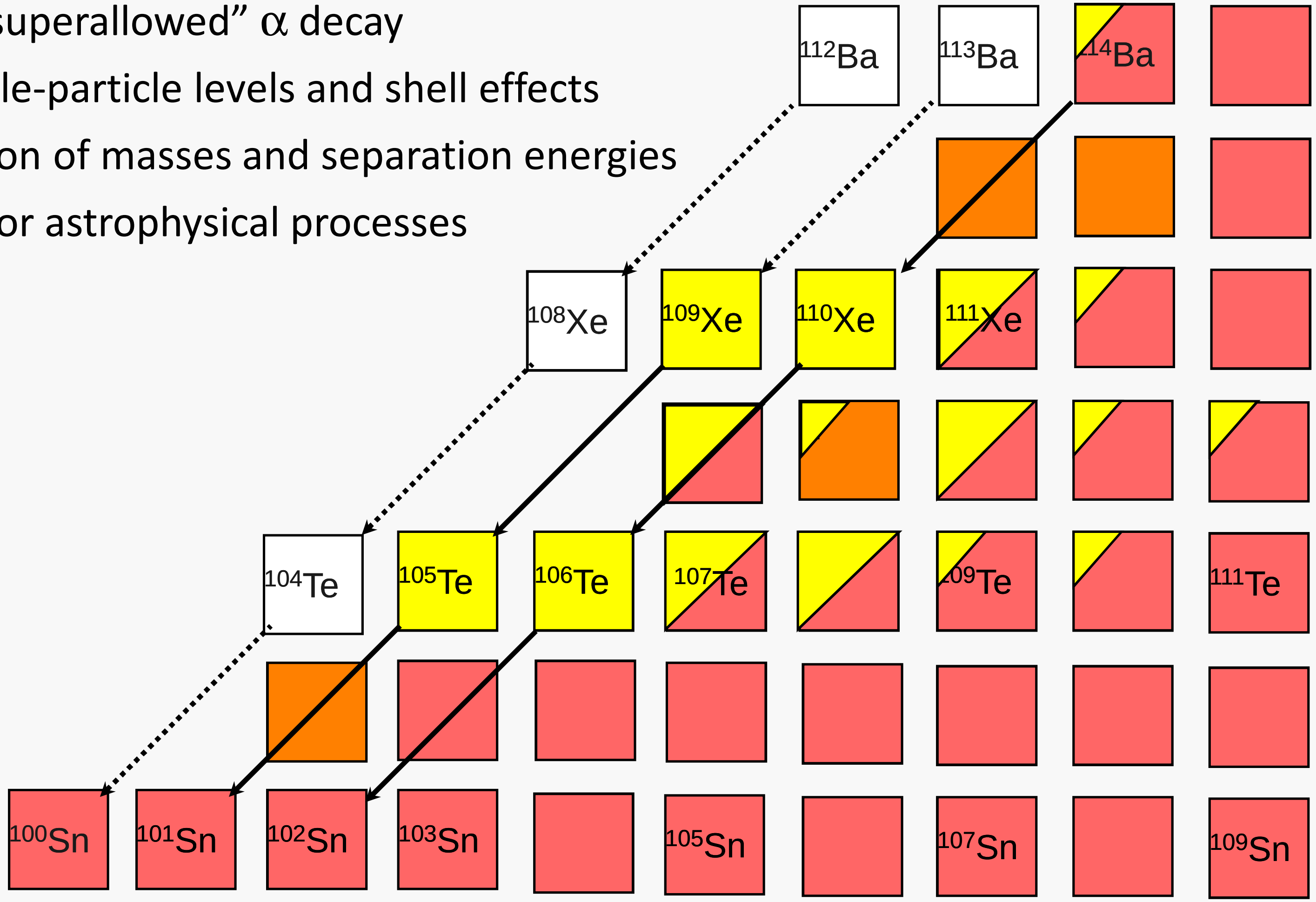


# Proton emission from deformed $^{141}$Ho



# 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

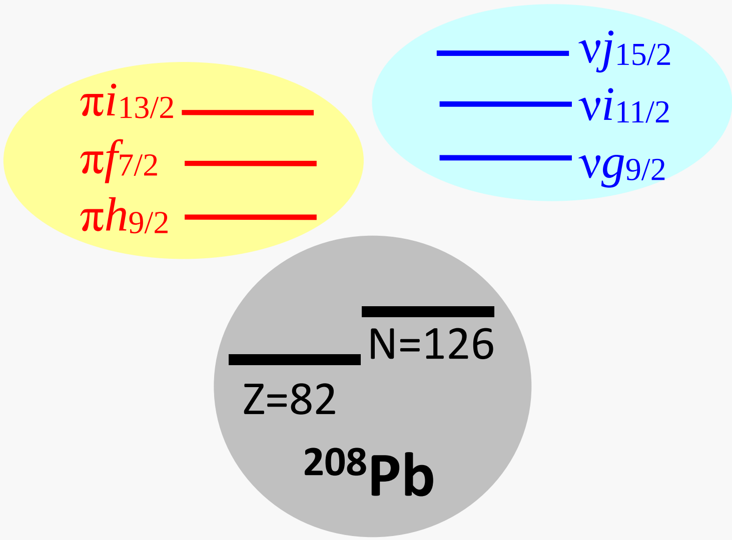


# Superallowed α decay?

- Present α-decay reference: $^{212}$Po

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

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

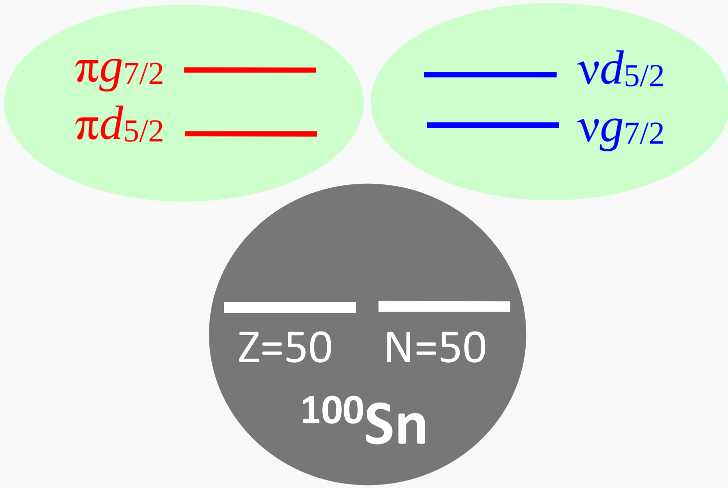



- Expected standard: $^{104}$Te

Macfarlane and Siivola, PRL 14 (1965) 114

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

α formed by protons and neutrons
in the same orbitals




Predictions for $^{104}Te \rightarrow ^{100}Sn$ decay

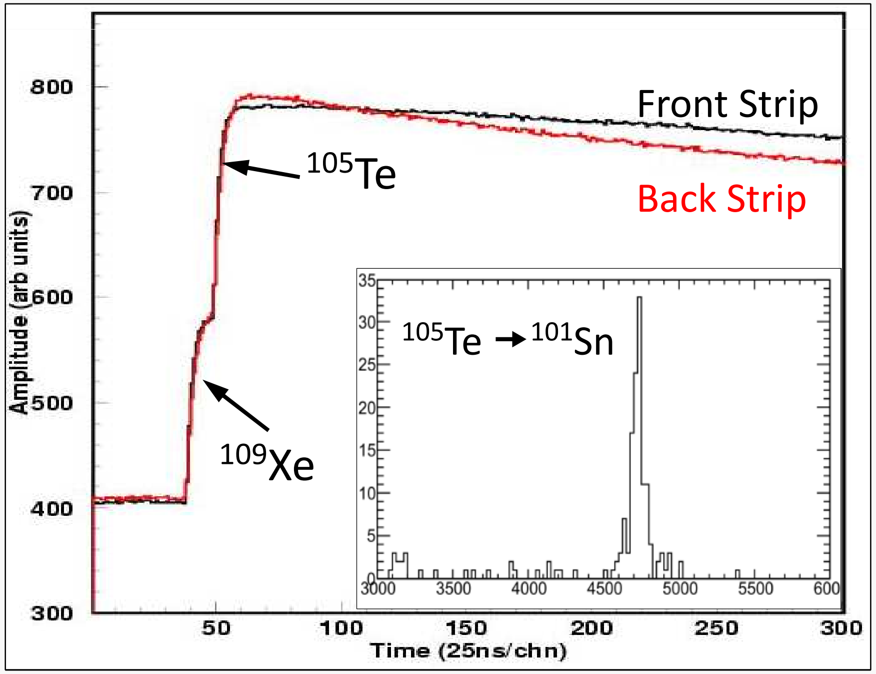
$E_\alpha$ > 5 MeV, $T_{1/2}$ < 50 ns !

# α decay of $^{105}$Te

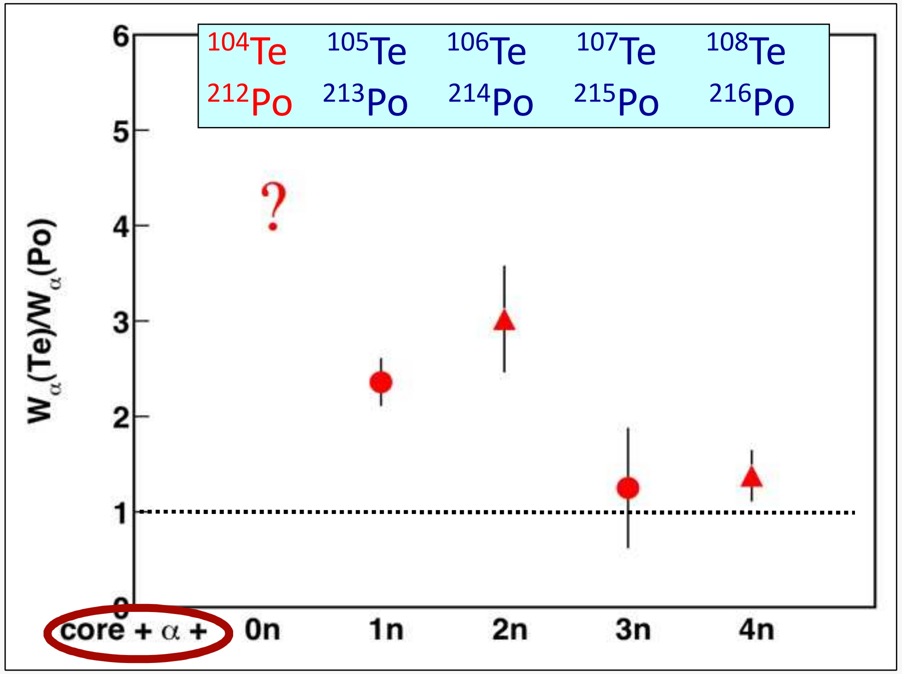
- Decay of $^{105}$Te studied:
  - directly at FMA (Argonne) using $^{50}$Cr($^{58}$Ni, 3n)$^{105}$Te and fast recovery electronics
  - via decay of $^{109}$Xe at HRIBF (ORNL) by $^{54}$Fe($^{58}$Ni, 3n)$^{109}$Xe and DSP

→ $^{105}$Te decay: $E_\alpha$ = 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

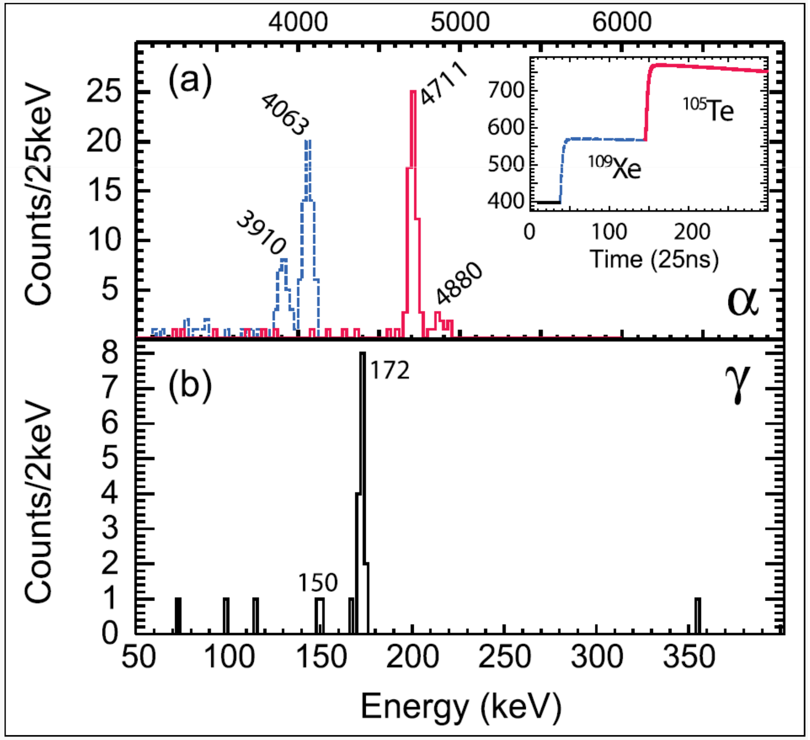



Renormalized α decay width ($l$ = 0 transitions)

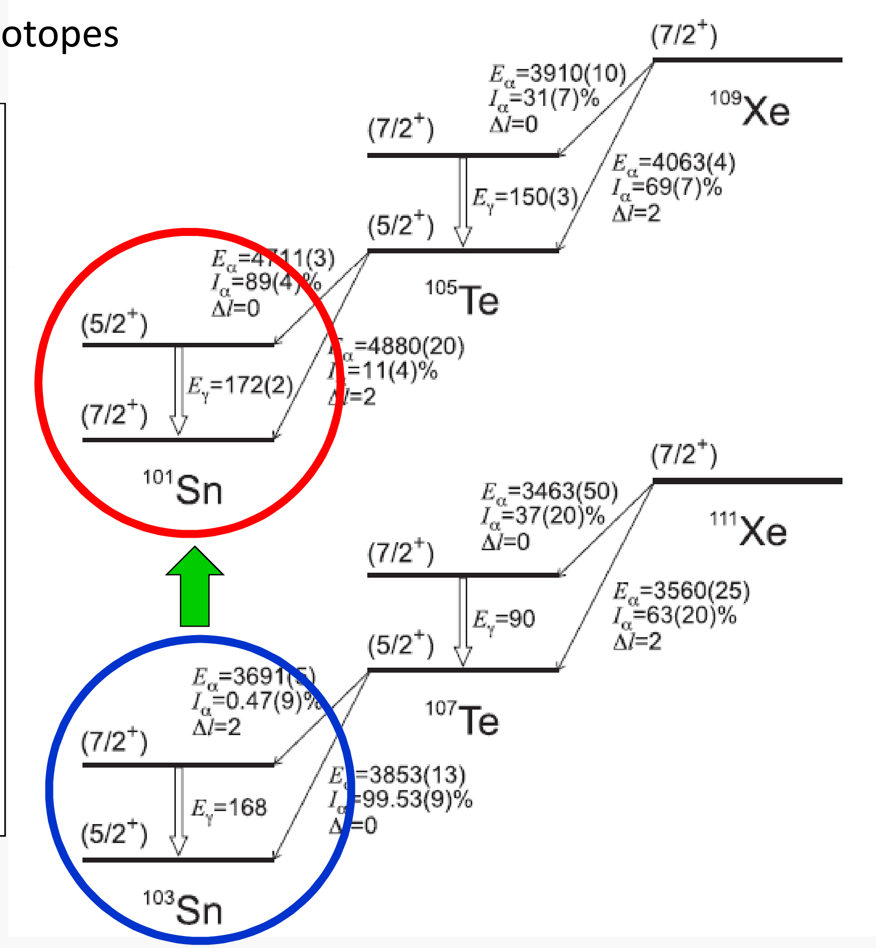


# Single particle states in $^{101}$Sn

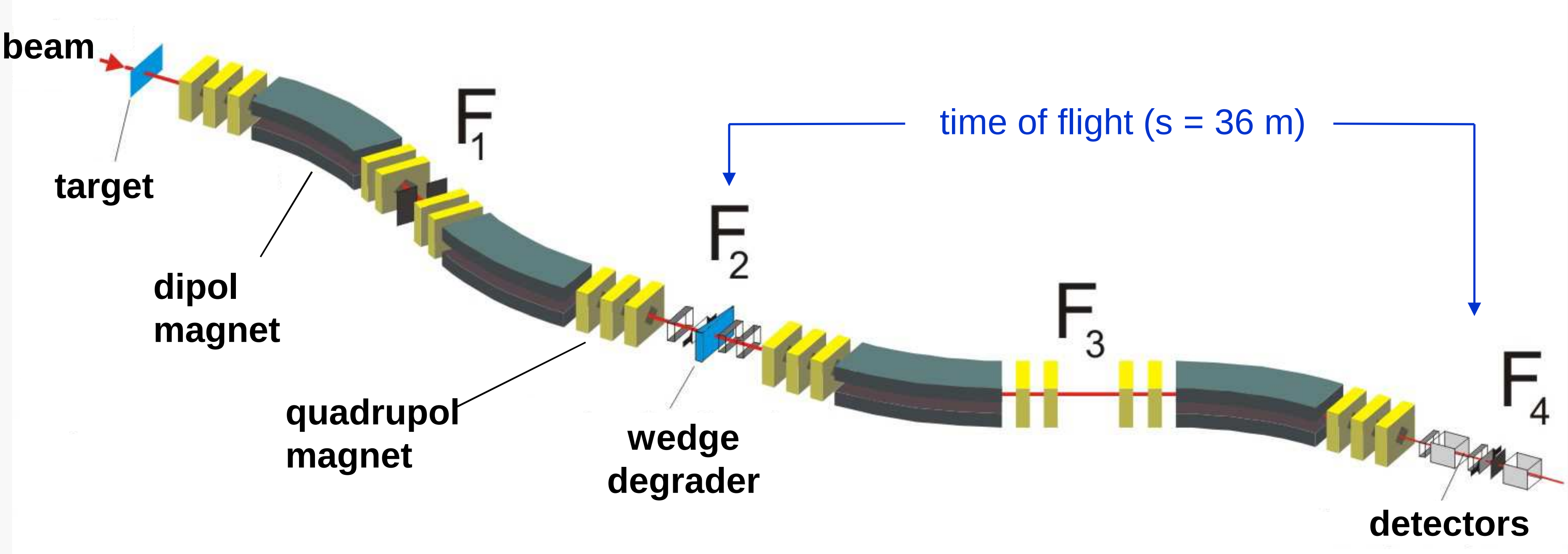
- ➤ Details of $\alpha$ decay of $^{109}$Xe (fine structure) yield surprising result on $^{101}$Sn!
  5/2$^+$ and 7/2$^+$ levels are reversed between $^{103}$Sn and $^{101}$Sn
- → Orbital dependent pairing, stronger for $(g_{7/2})^2$ then for $(d_{5/2})^2$, is responsible for 5/2$^+$ g.s of $^{103}$Sn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




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



# Fragment separators



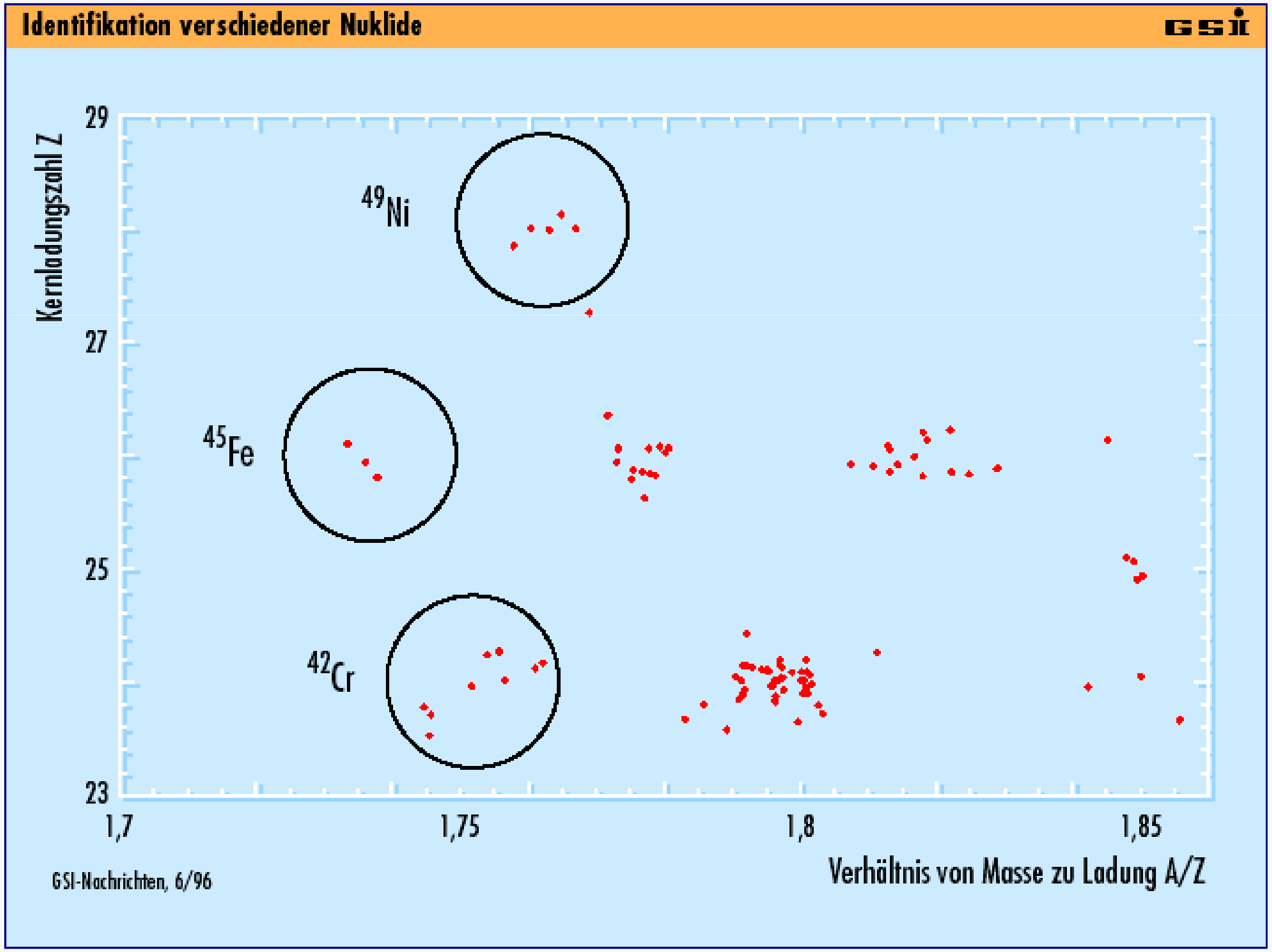

Time-of-flight → v
Positions + B field → Bρ
} → A/q ≈ **A/Z**

Energy loss ΔE in ionization chamber → **Z**

# Example of identification

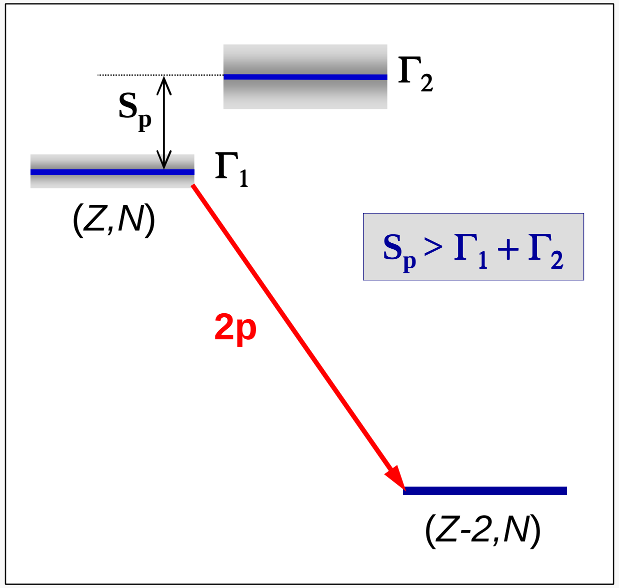
- First observation of three new nuclides : $^{42}$Cr, $^{45}$Fe i $^{49}$Ni

FRS, GSI, 1996



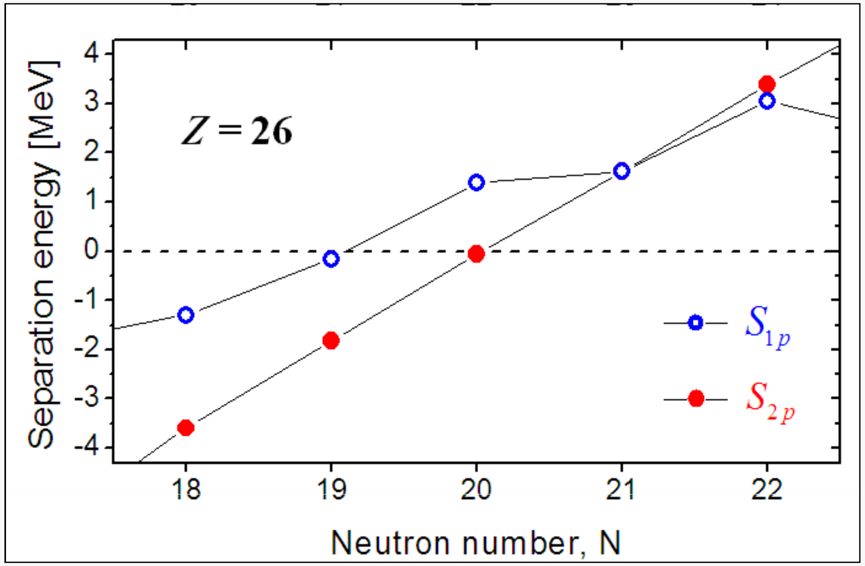
# Two protons can be unbound!

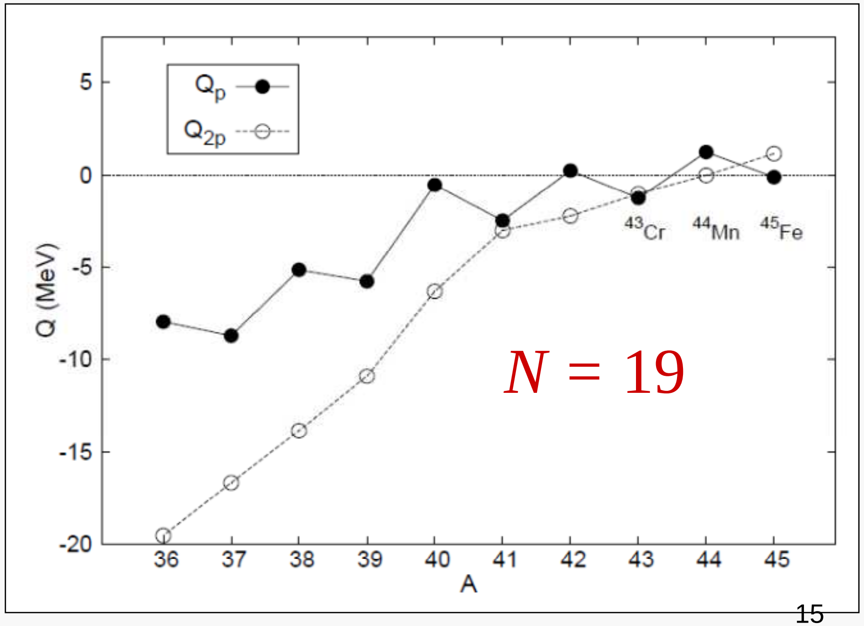
- It is possible that pair of protons is unbound while each of individual proton is bound!




- 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

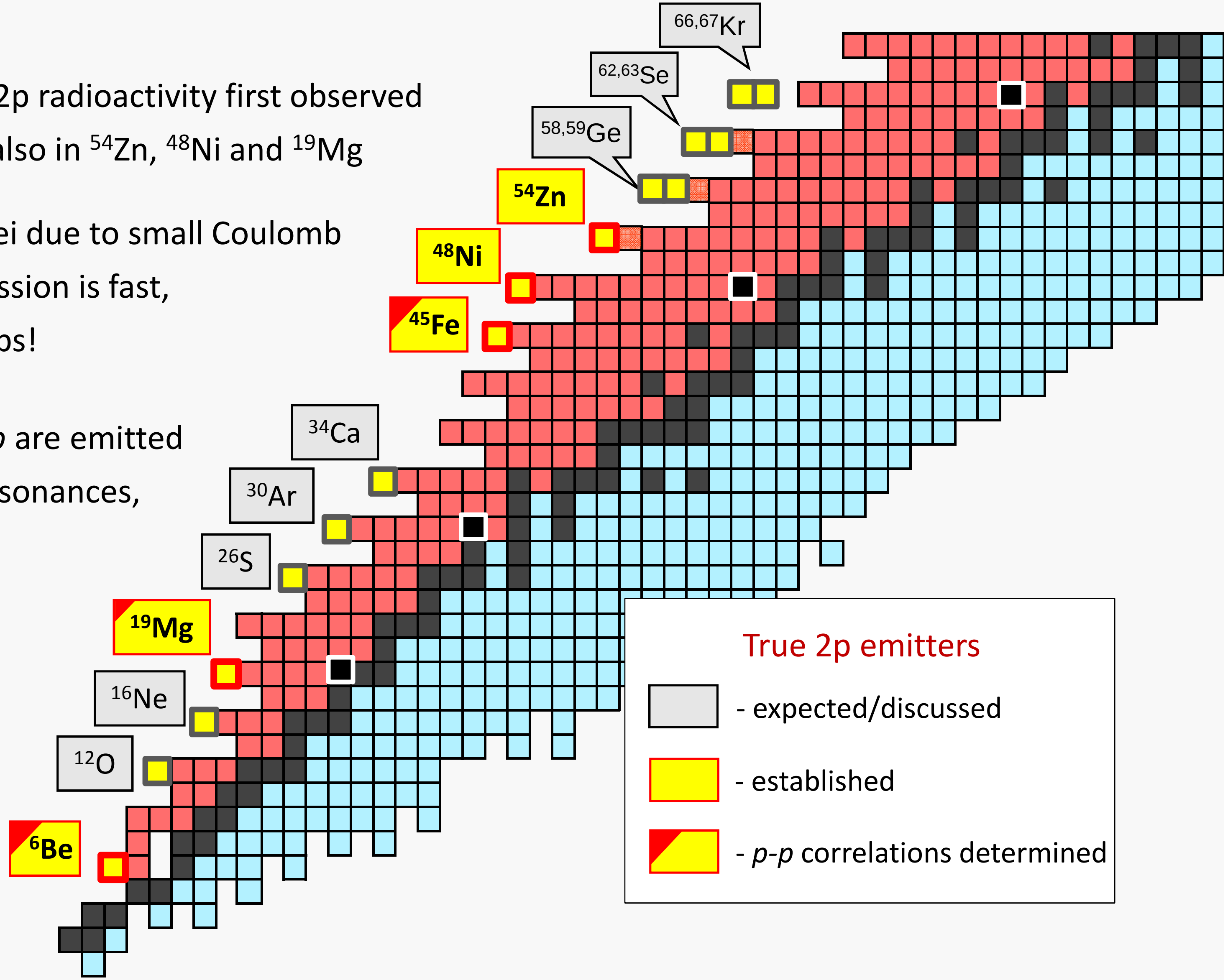
Goldansky, Nucl. Phys. 19 (1960) 482



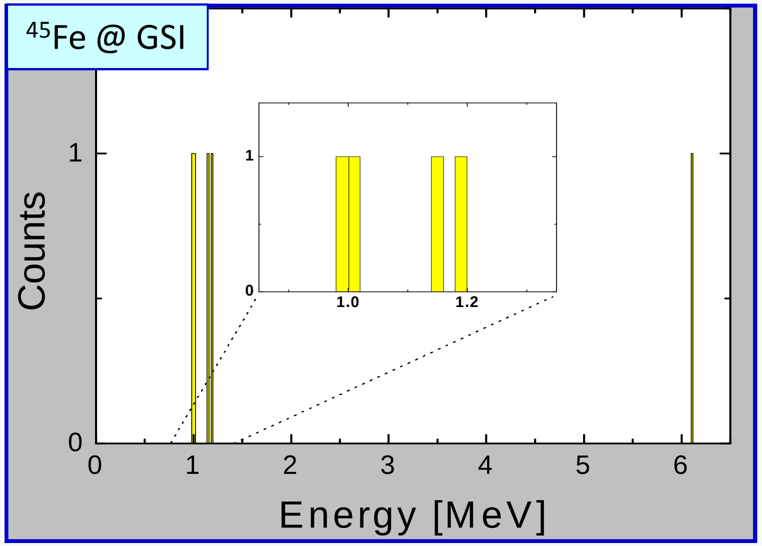



# True *2p* emitters

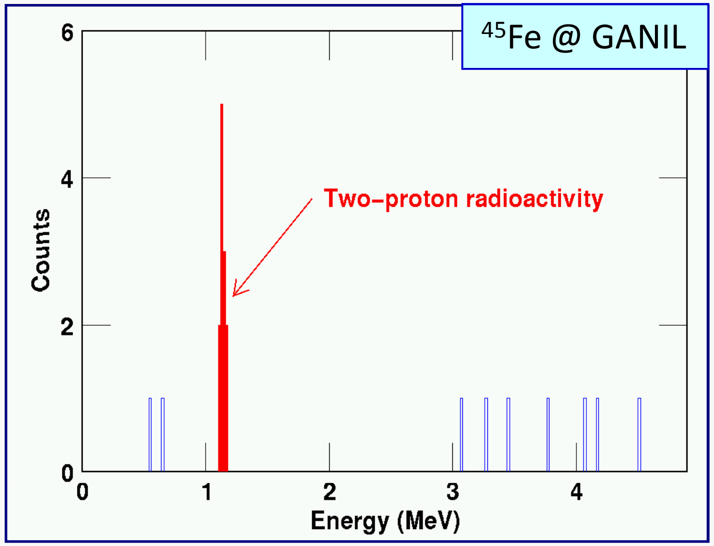
- Ground-state 2p radioactivity first observed in $^{45}Fe$. Later also in $^{54}Zn$, $^{48}Ni$ and $^{19}Mg$
- In lighter nuclei due to small Coulomb barrier *2p* emission is fast, $T_{1/2}(^{19}Mg)$ = 4 ps!
- Below $^{19}Mg$ *2p* are emitted from broad resonances, like $^{6}Be$



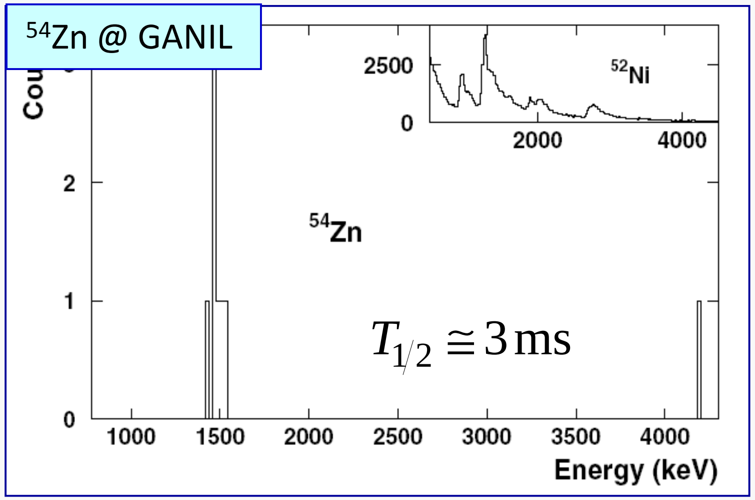
# First, with silicon detectors



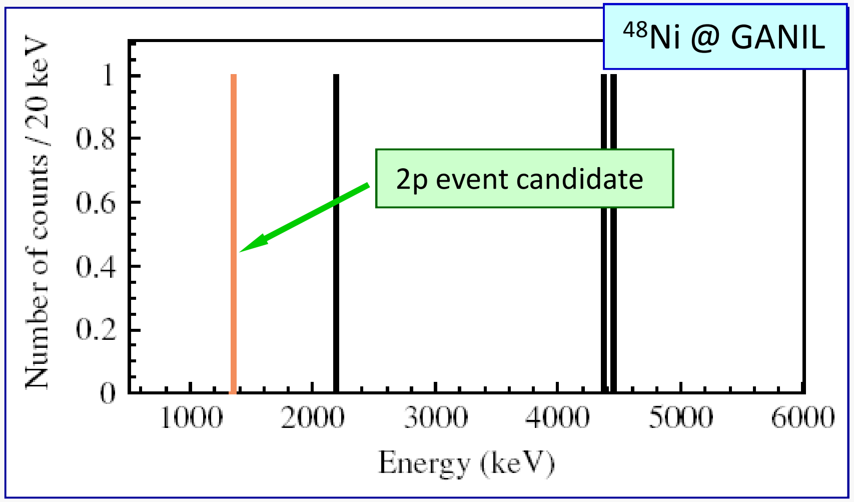

MP et al., EPJ A 14 (2002) 279




Giovinazzo et al., PRL 89 (2002) 102501



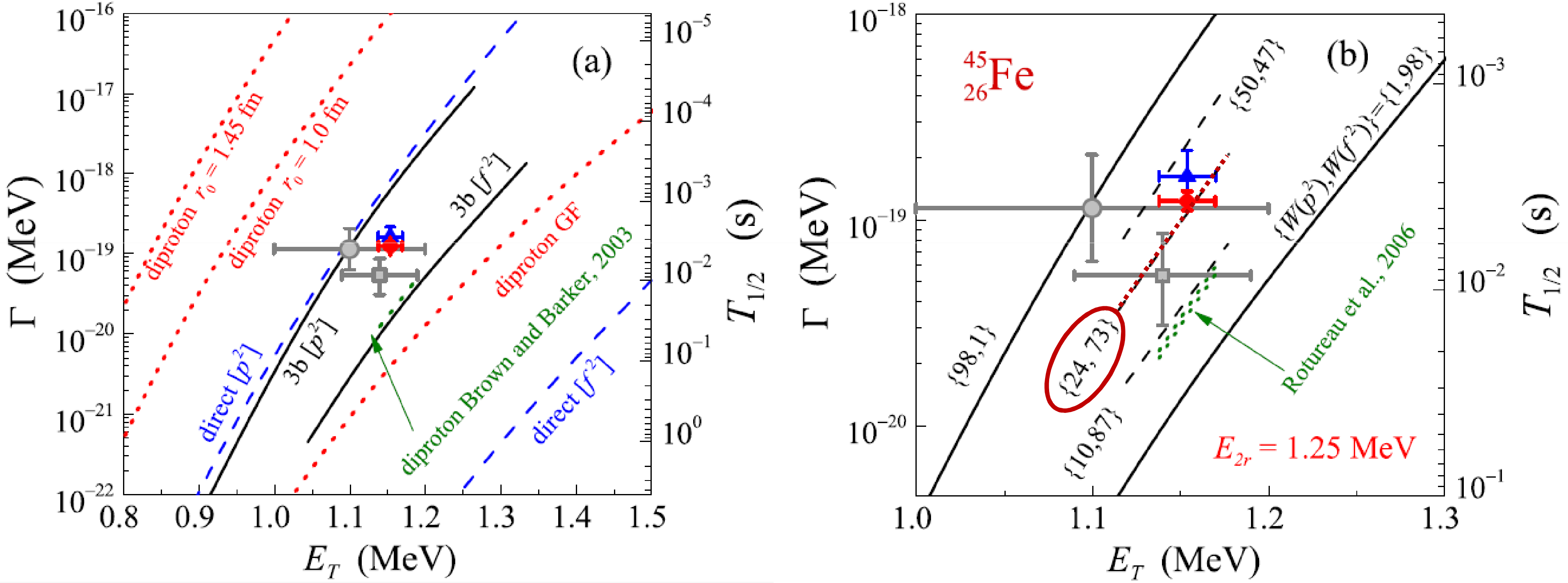

Blank et al., PRL 94 (2005) 232501




Dossat et al., PRC 72 (2005) 054315

# Decay energy and time

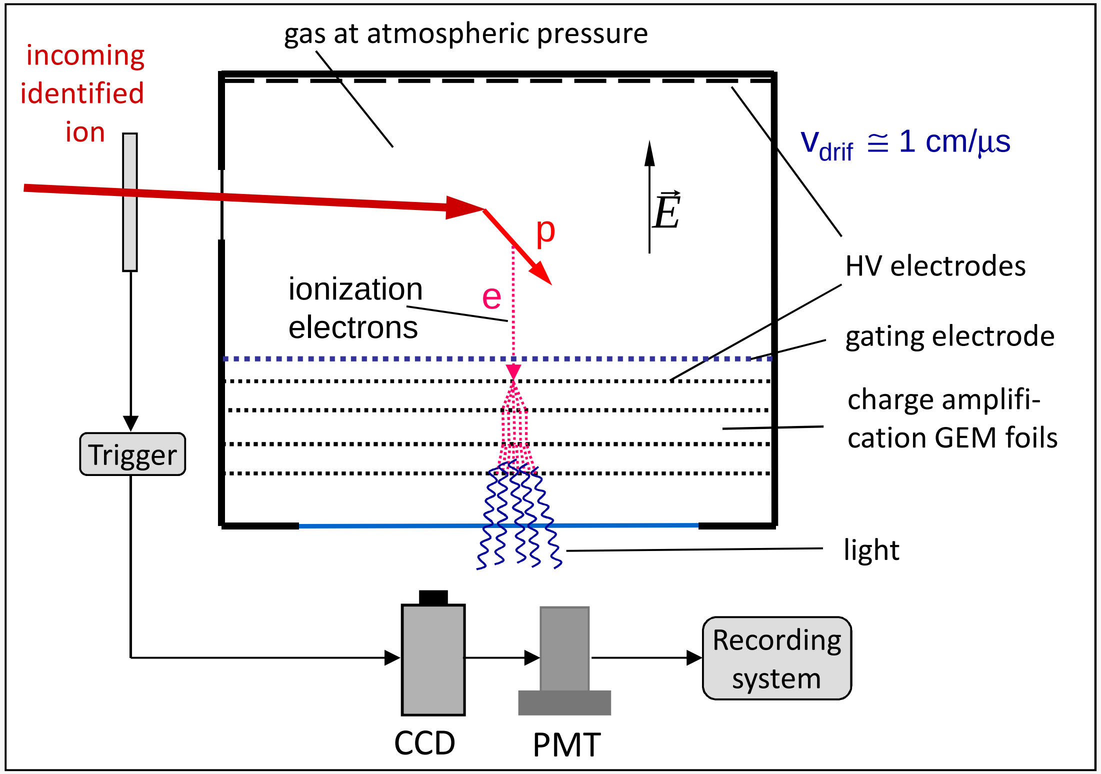
- The decay energy and the lifetime are enough to establish the 2p decay.
  Most models used for comparison, however, are based on two-body approximations.




→ To explore fully the physics of the process, the correlations between proton's momenta must be determined! The three-body model by Grigorenko and Zhukov is the only one which predicts these correlations.

# TPC with optical readout

## OTPC – Optical Time Projection Chamber



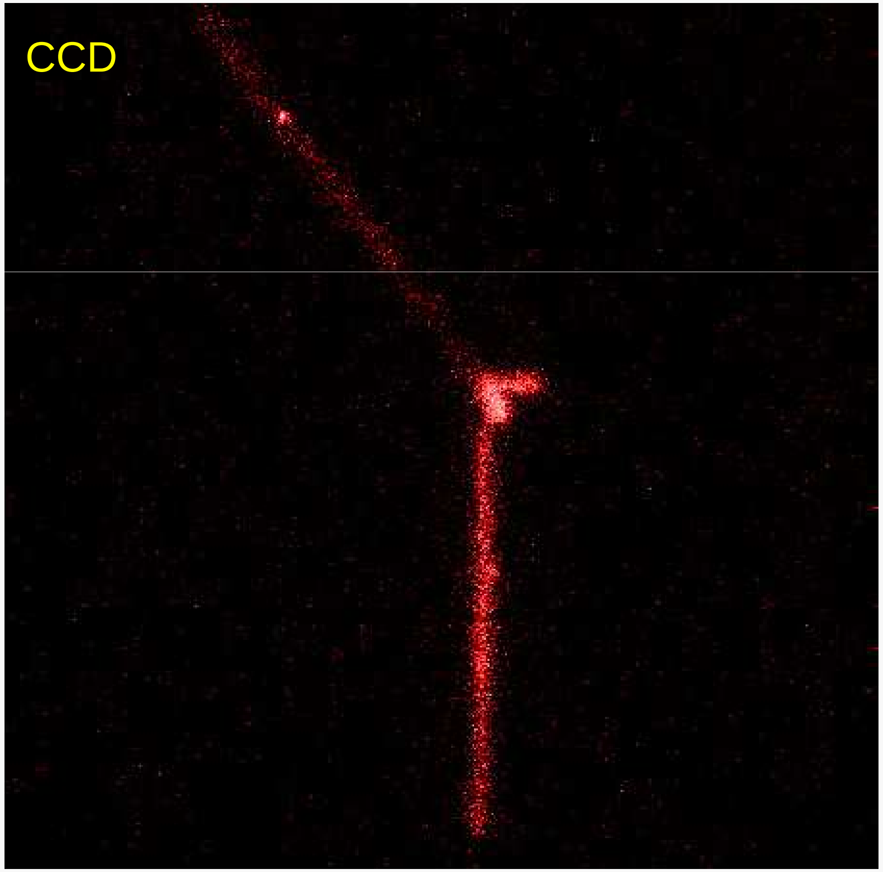

Miernik et al., NIM A581 (2007) 194

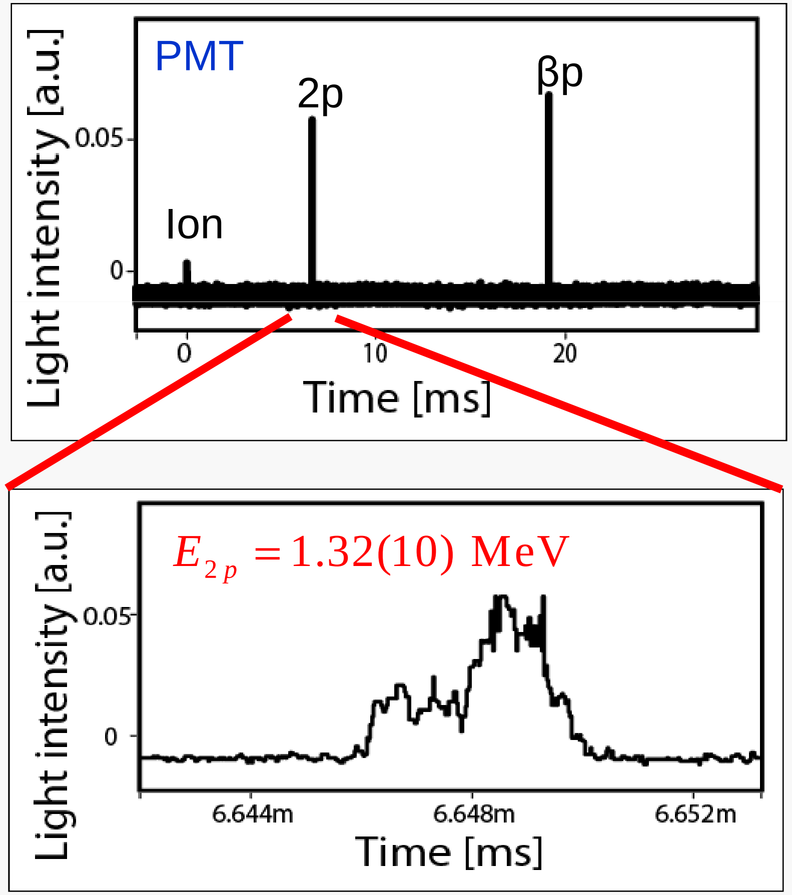
# 2p event

NSCL/MSU, 2011

- The CCD picture yields 2D projection of tracks

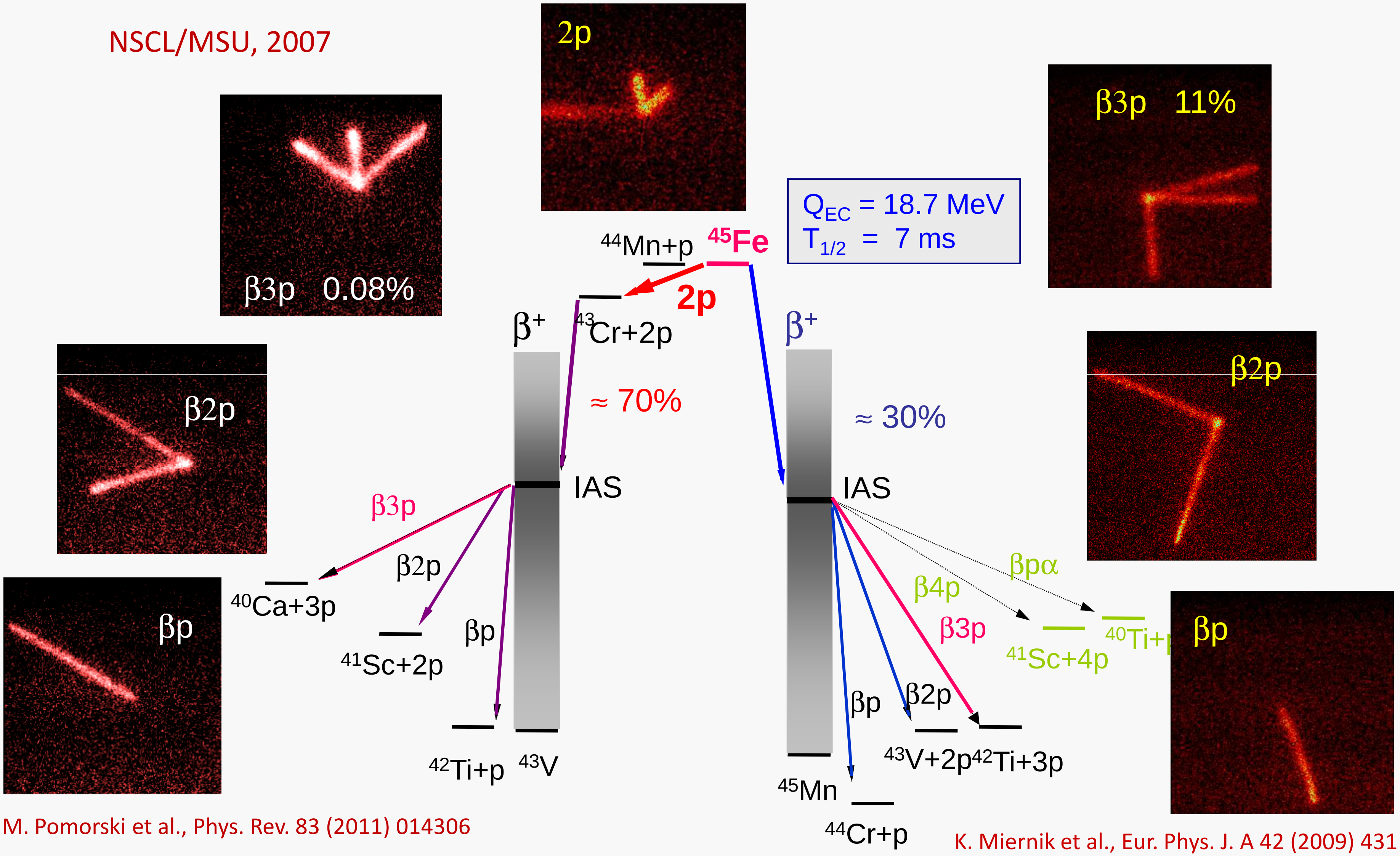
- The PMT provides information on sequence, timing, and z-coordinate




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

# Decays of $^{45}$Fe and $^{43}$Cr



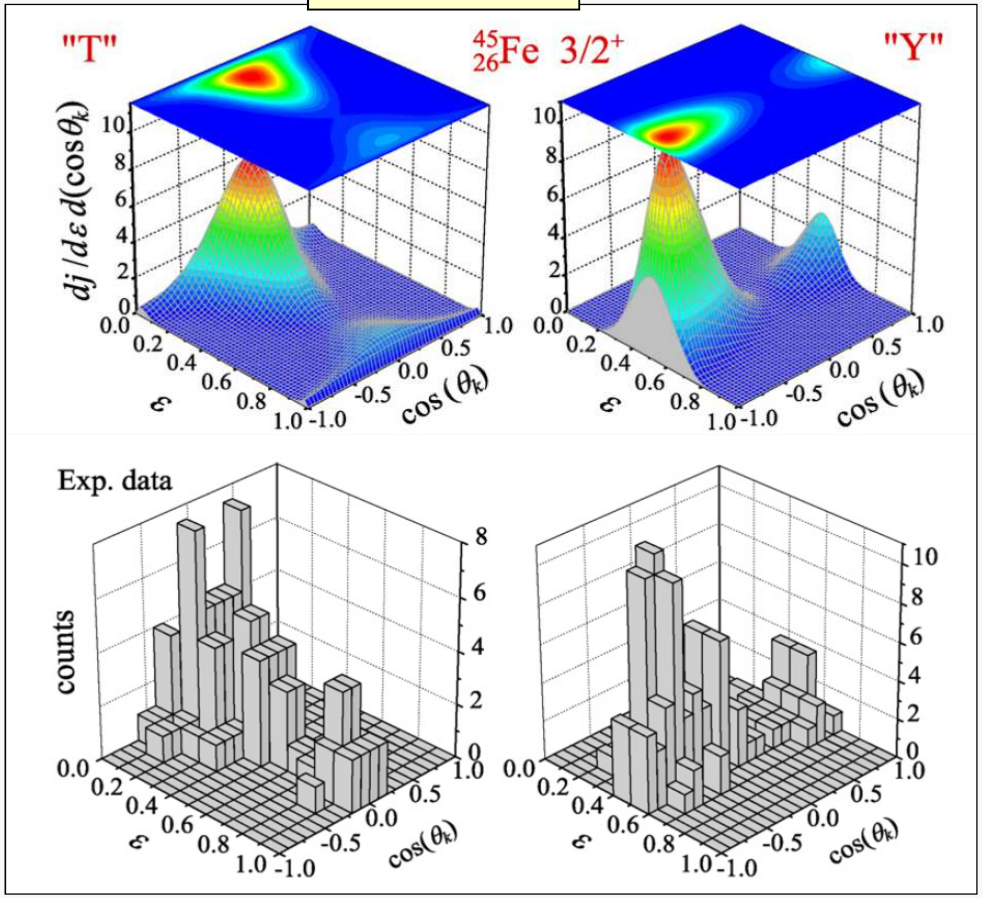

M. Pomorski et al., Phys. Rev. 83 (2011) 014306

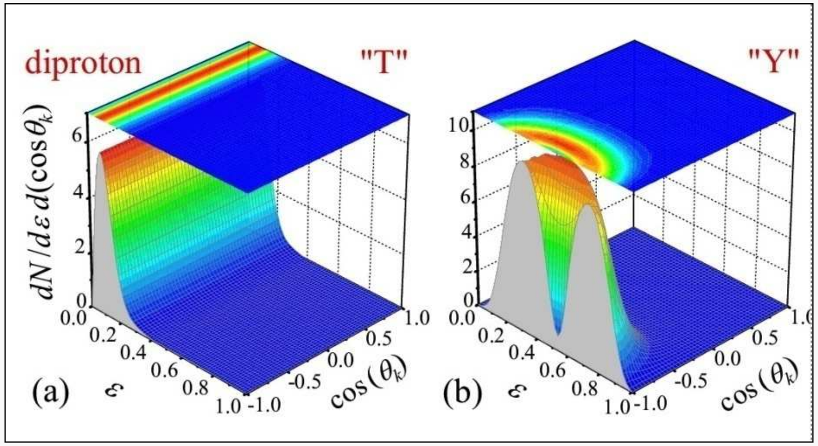
K. Miernik et al., Eur. Phys. J. A 42 (2009) 431

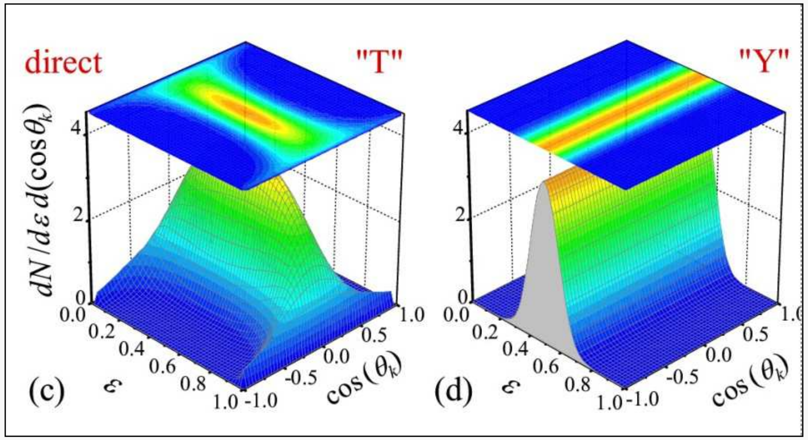
K. Miernik et al., PRL 99 (07) 192501

# $p$-$p$ correlations in $^{45}$Fe

$W(p^2) = 24\%$




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

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

# *p-p* correlations in $^6$Be

- Radioactive beam experiment at Texas A&M University

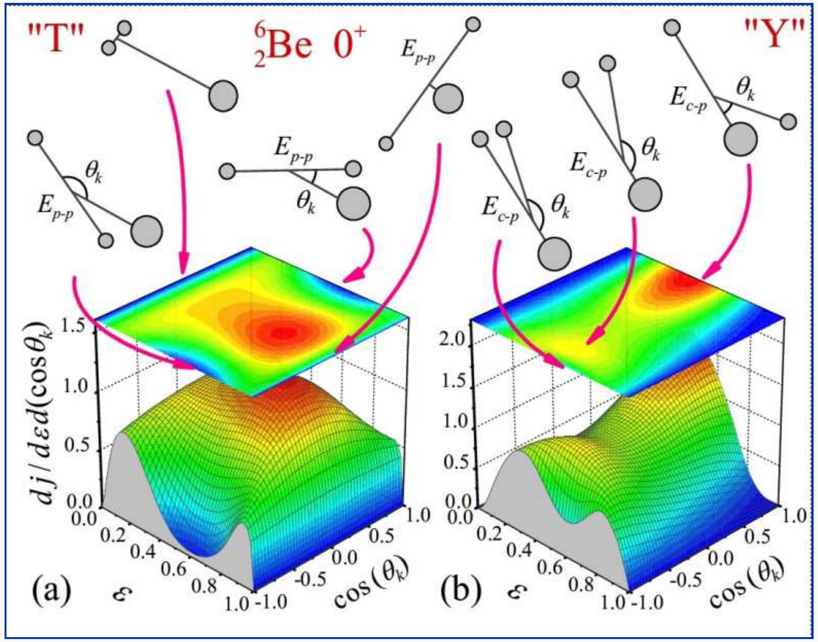
$^{10}$C inelastic scattering

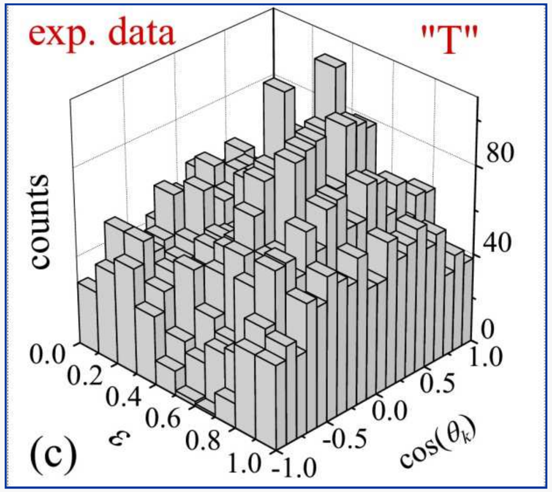
❶ p ($^{10}$B, $^{10}$C) n @15 MeV/u

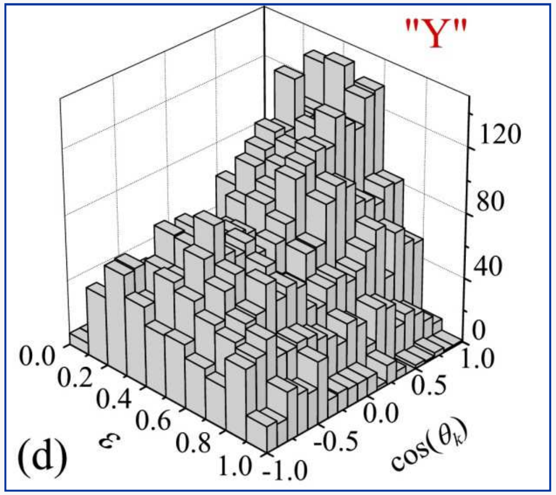
❷ 11 MeV/u $^{10}$C + C/Be → $^{10}$C*

❸ $^{10}$C* → $^6$Be + α

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



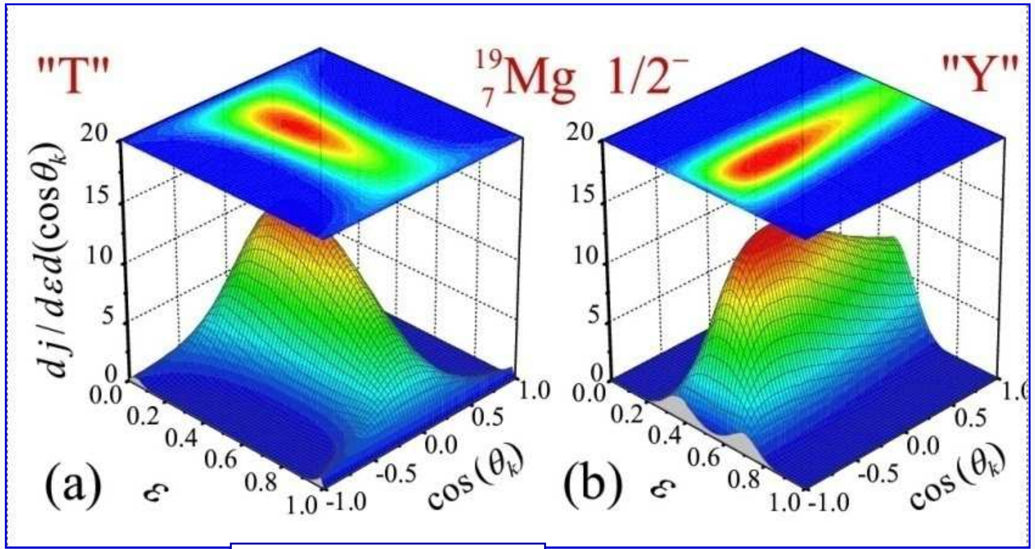
# Case of $^{19}$Mg

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

  Radioactive beam experiment

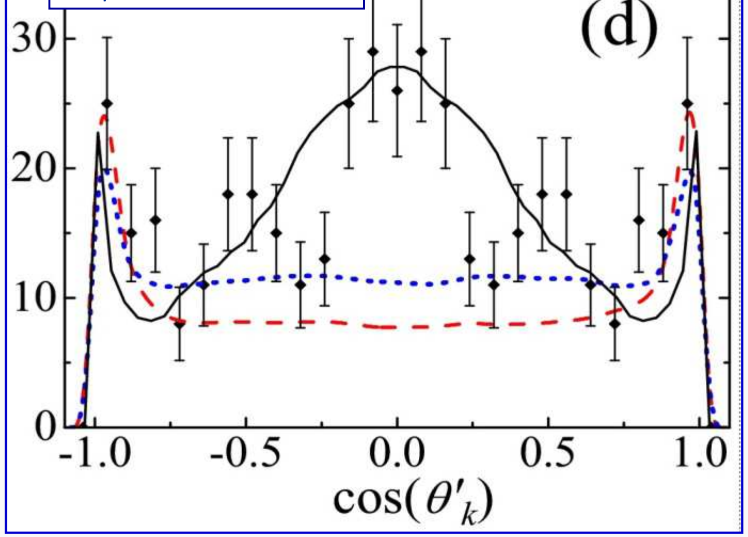
  ❶ $^{24}$Mg @ 600 MeV/u + Be → $^{20}$Mg

  ❷ $^{20}$Mg + Be → $^{19}$Mg



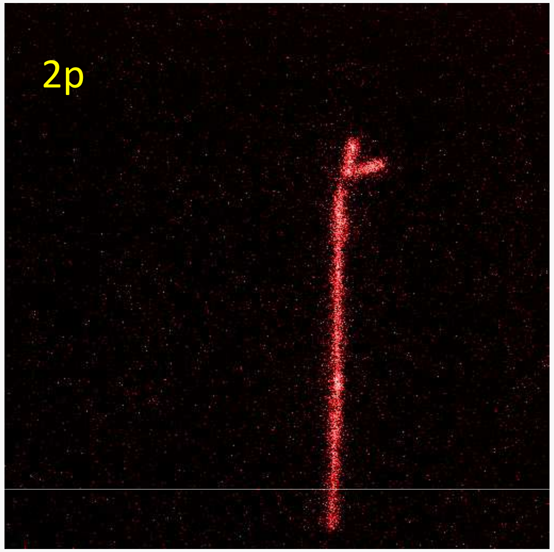

- Only projection of proton's momenta on the plane could be determined.

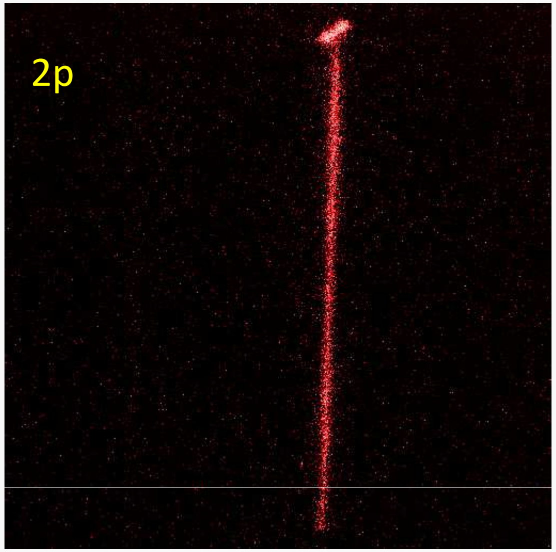
$T_{1/2}$ = 4.0(15) ps

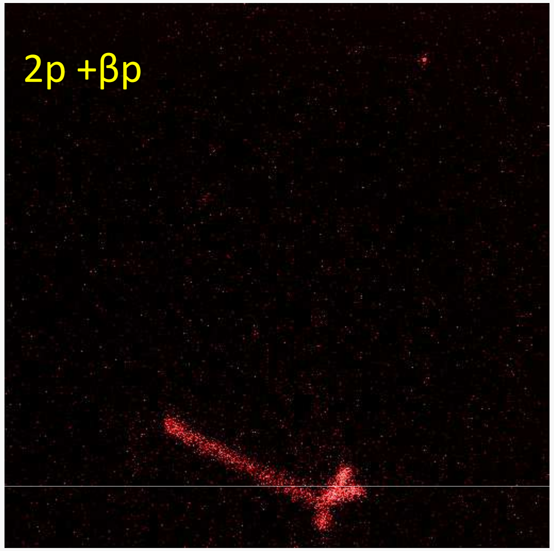


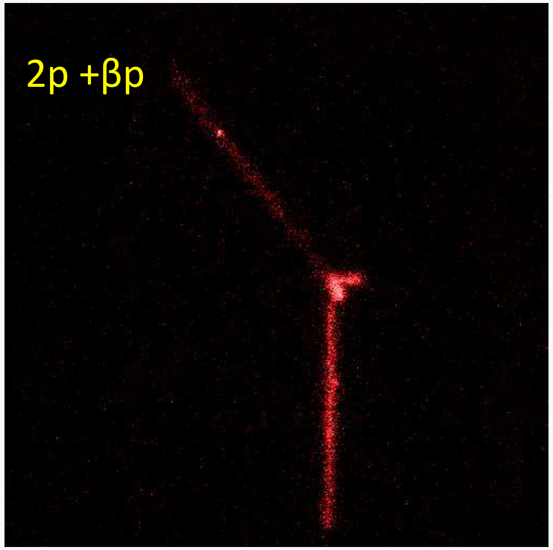

Mukha et al., PRL. 99 (2007) 182501
Mukha et al., PR C 77 (2008) 061303(R)

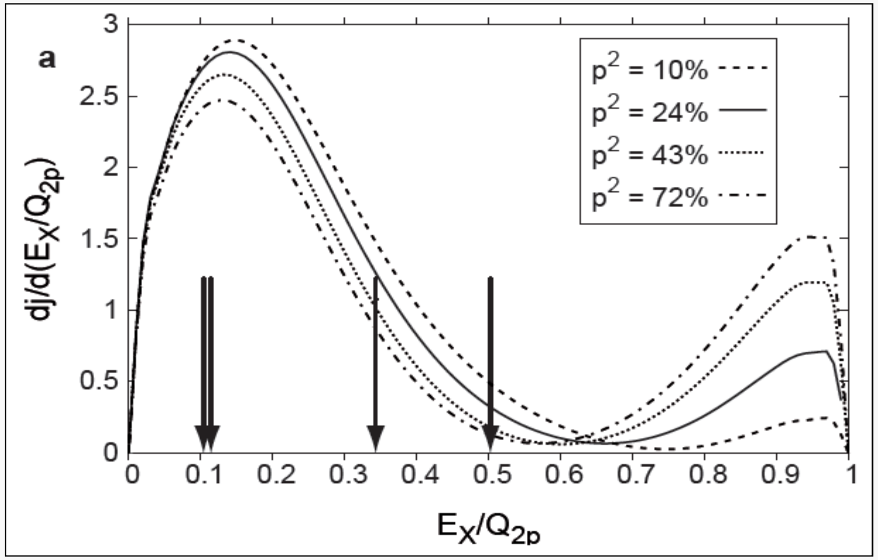
# $2p$ decays of $^{48}$Ni



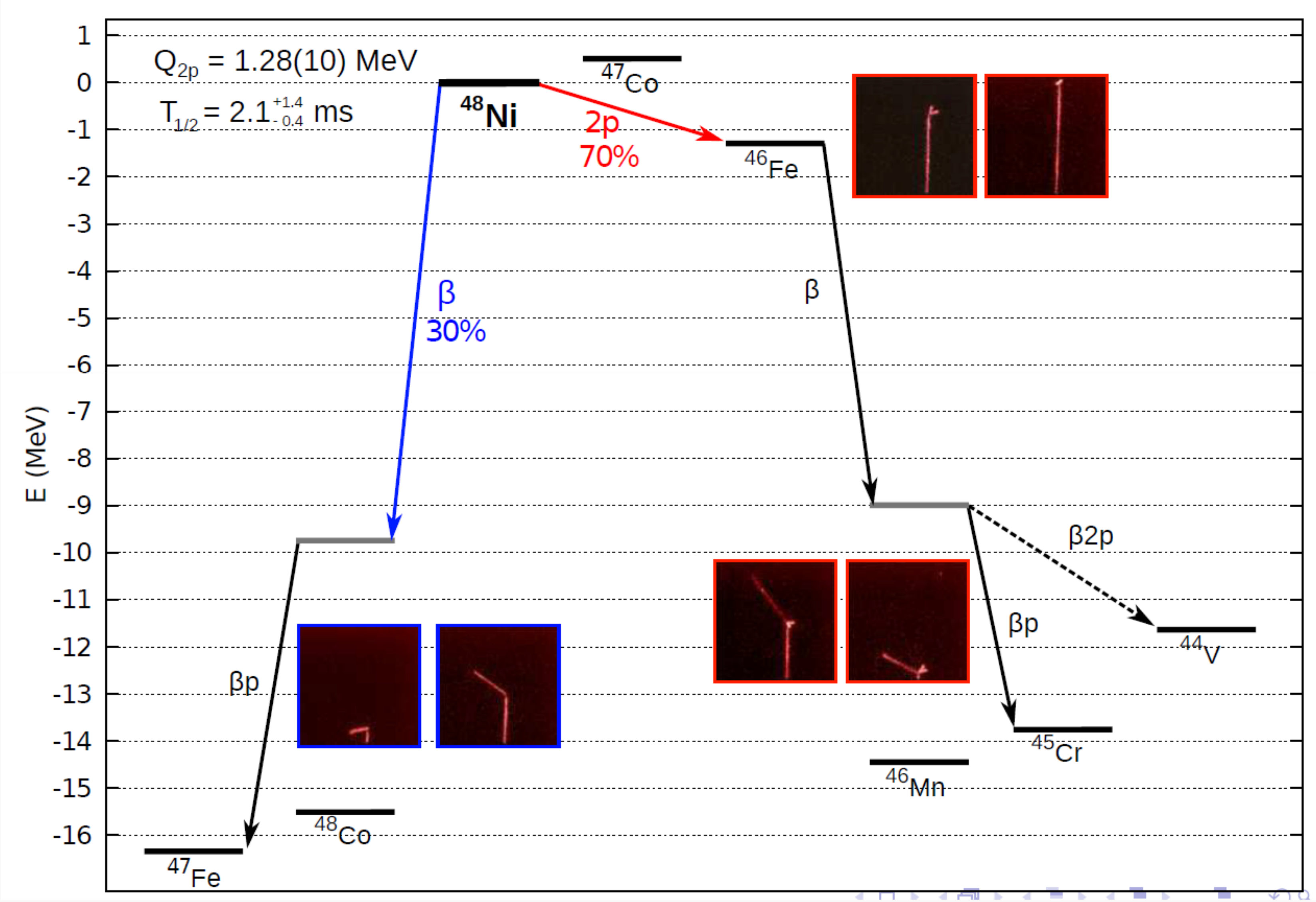



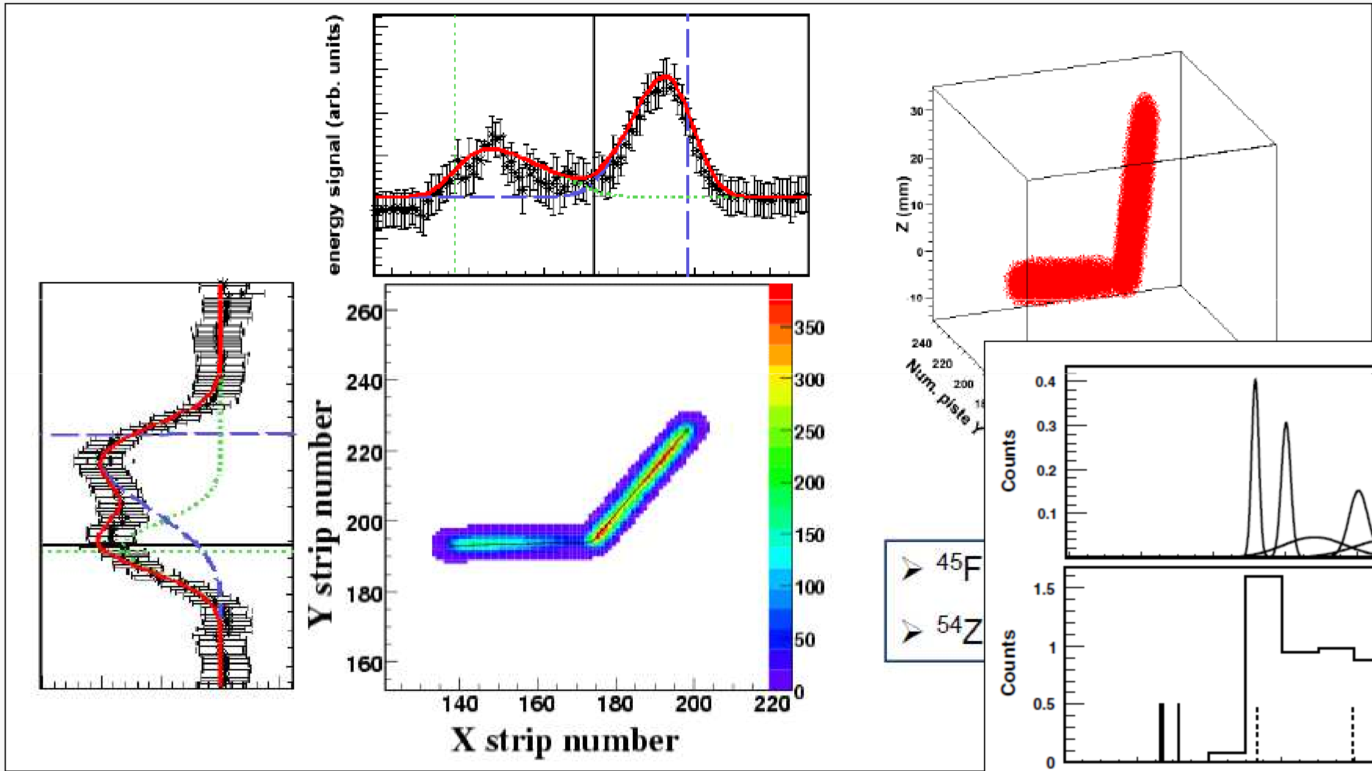

Pomorski et al., Acta Phys. Pol. B 43 (2012) 267

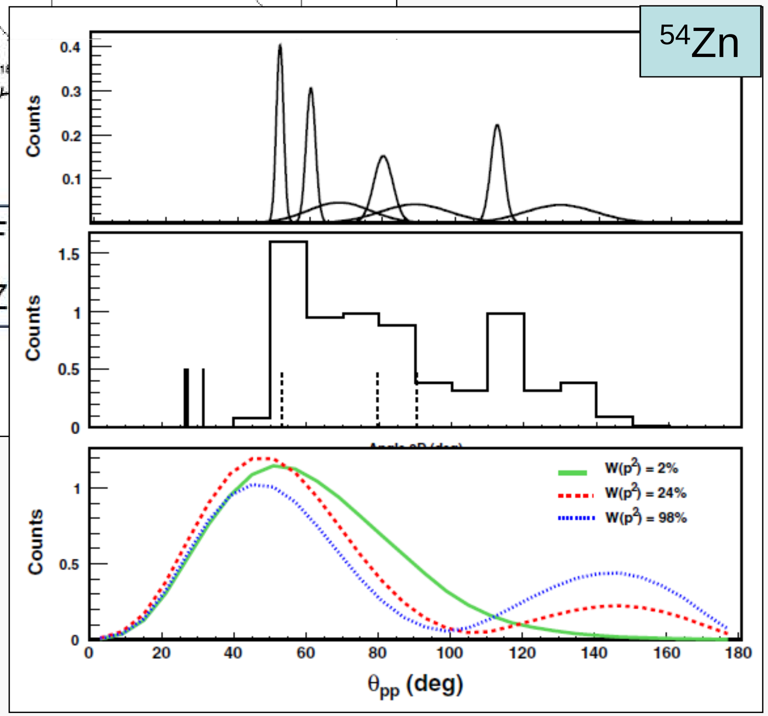
# Decay scheme of $^{48}$Ni



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

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



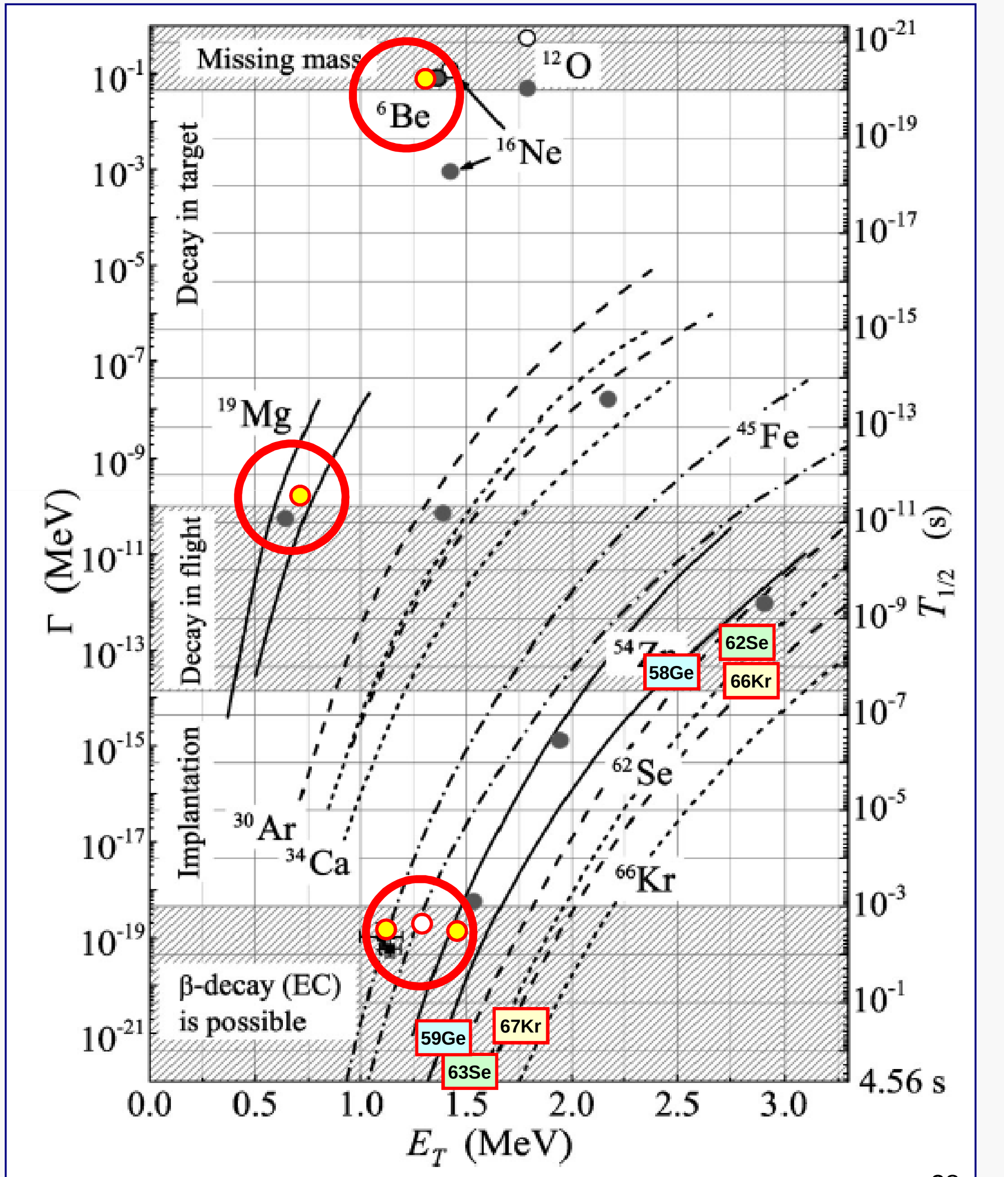




Ascher et al., PRL 107 (2011) 102502

# Range of lifetimes

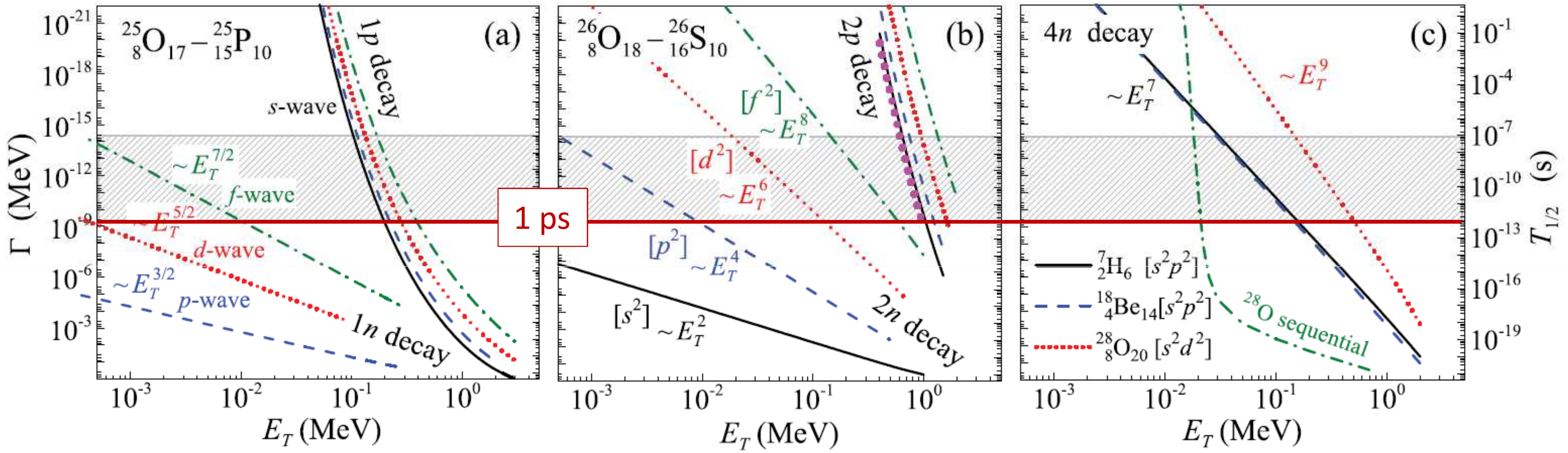
➤ The three-body model seems to work in the range of half-lives covering 18 orders of magnitude!

- 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



# 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 ($p$, $\alpha$) at the proton drip-line is very **efficient tool** in nuclear spectroscopy. Yields 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**" $\alpha$-decay $^{104}$Te $\rightarrow$ $^{100}$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. 2p radioactivity appears to be a **genuine 3-body phenomenon**.

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

# Thank you!