Radioactivity at the limits of nuclear existence

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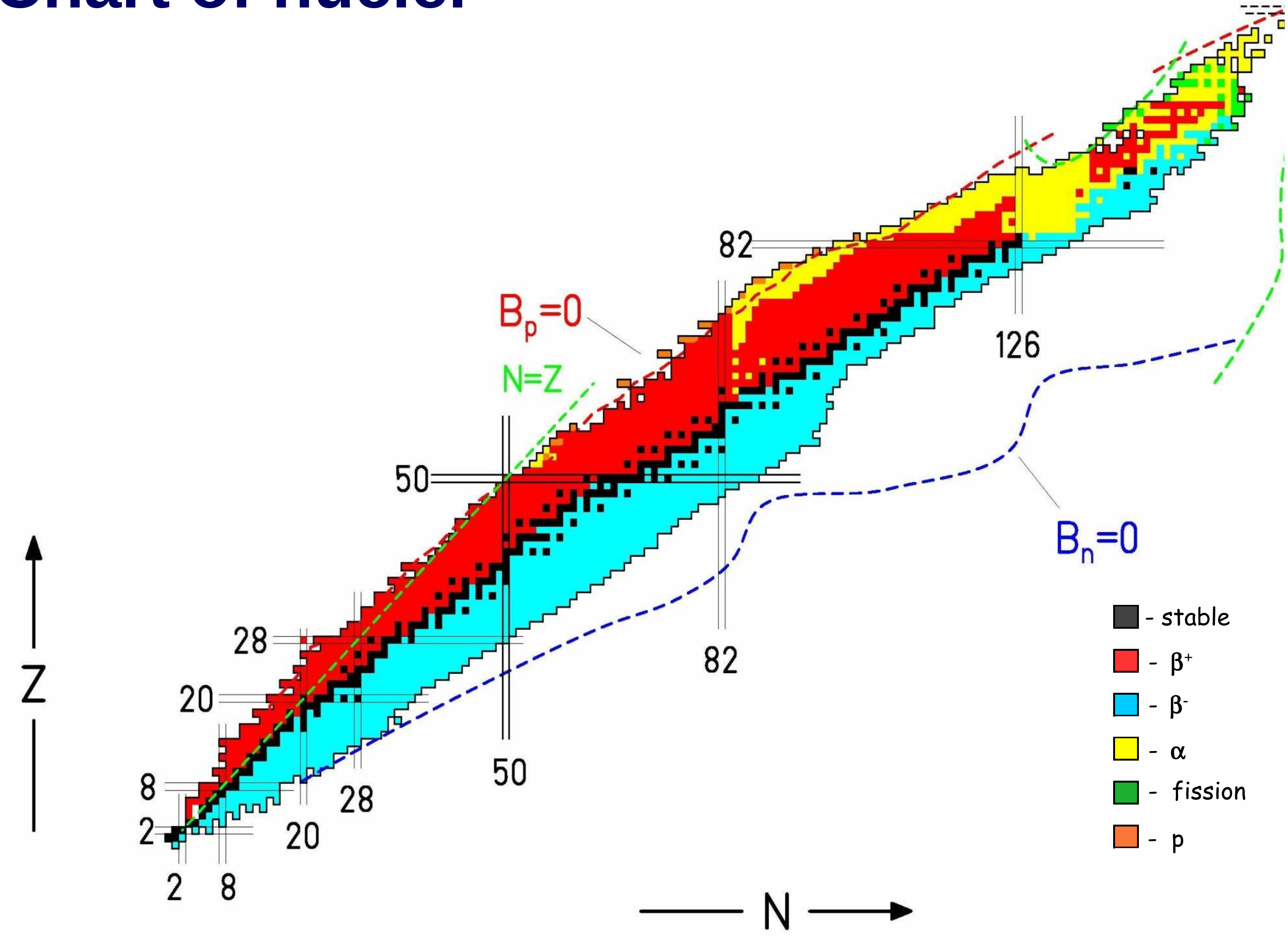
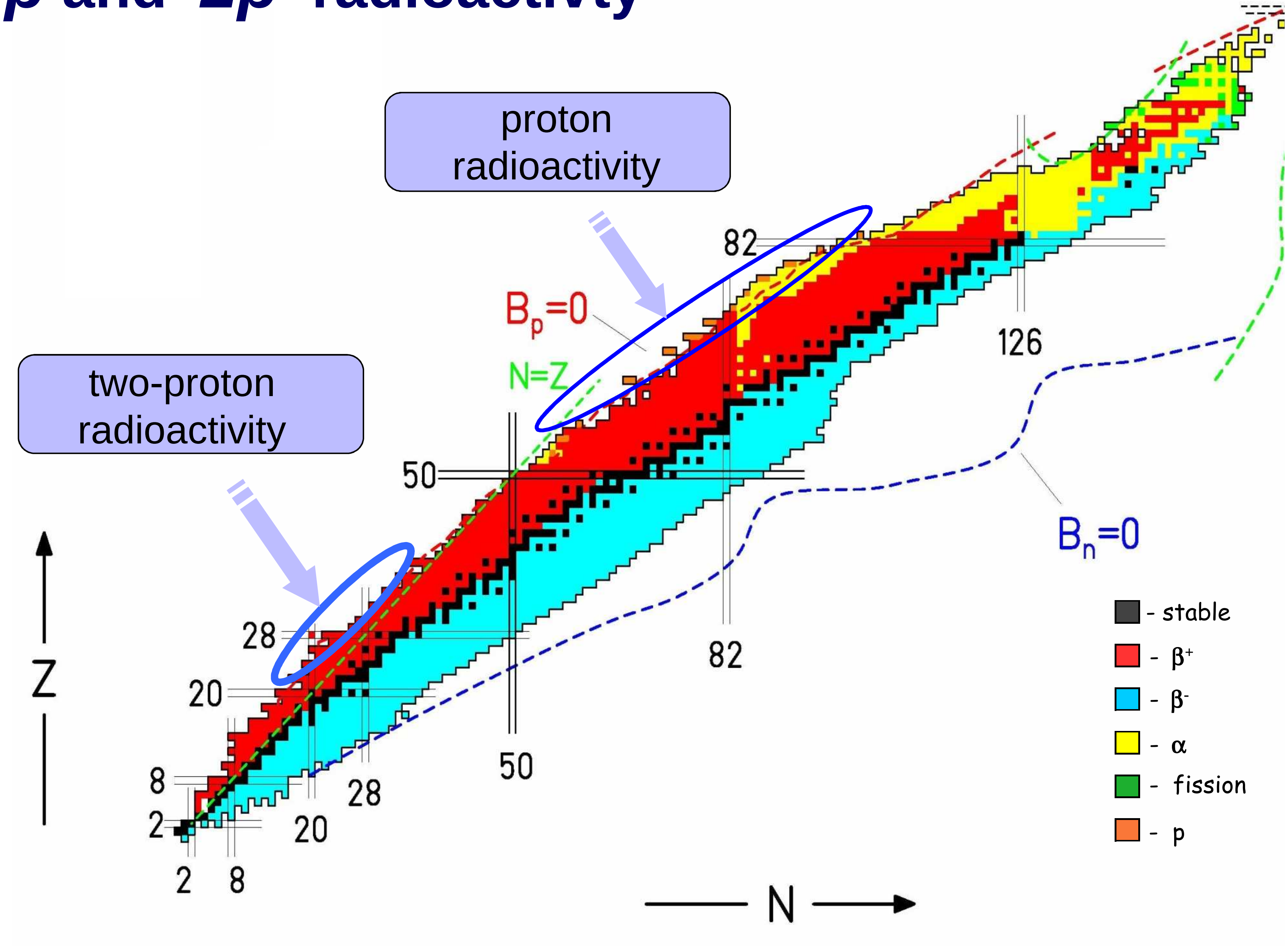
Chart of nuclei

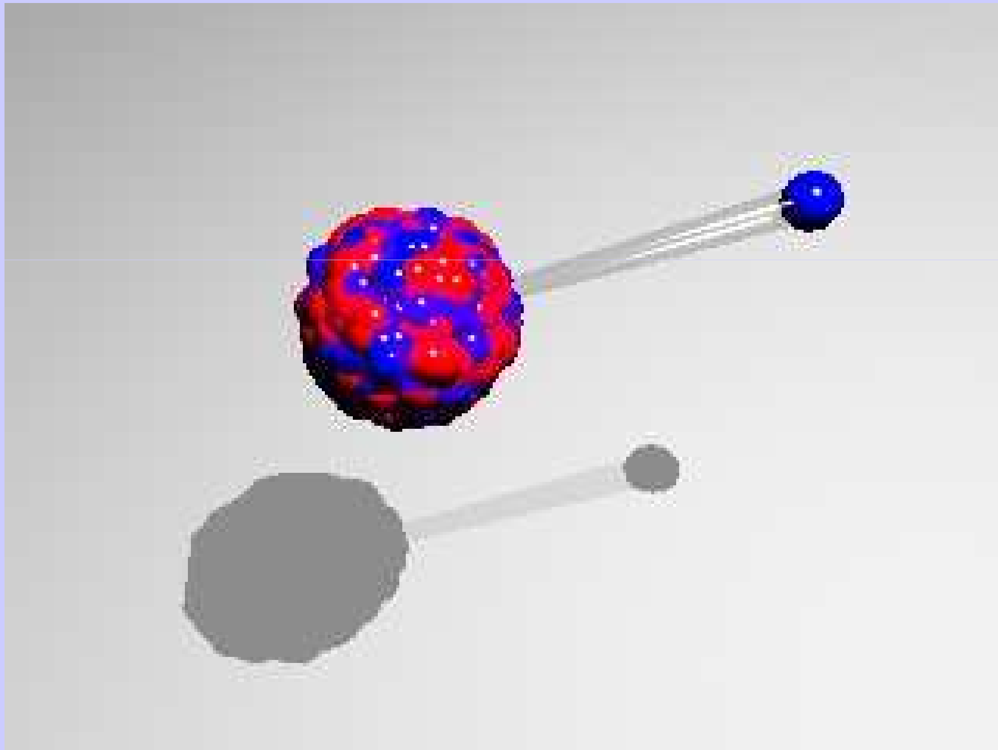


p and *2p* radioactivty



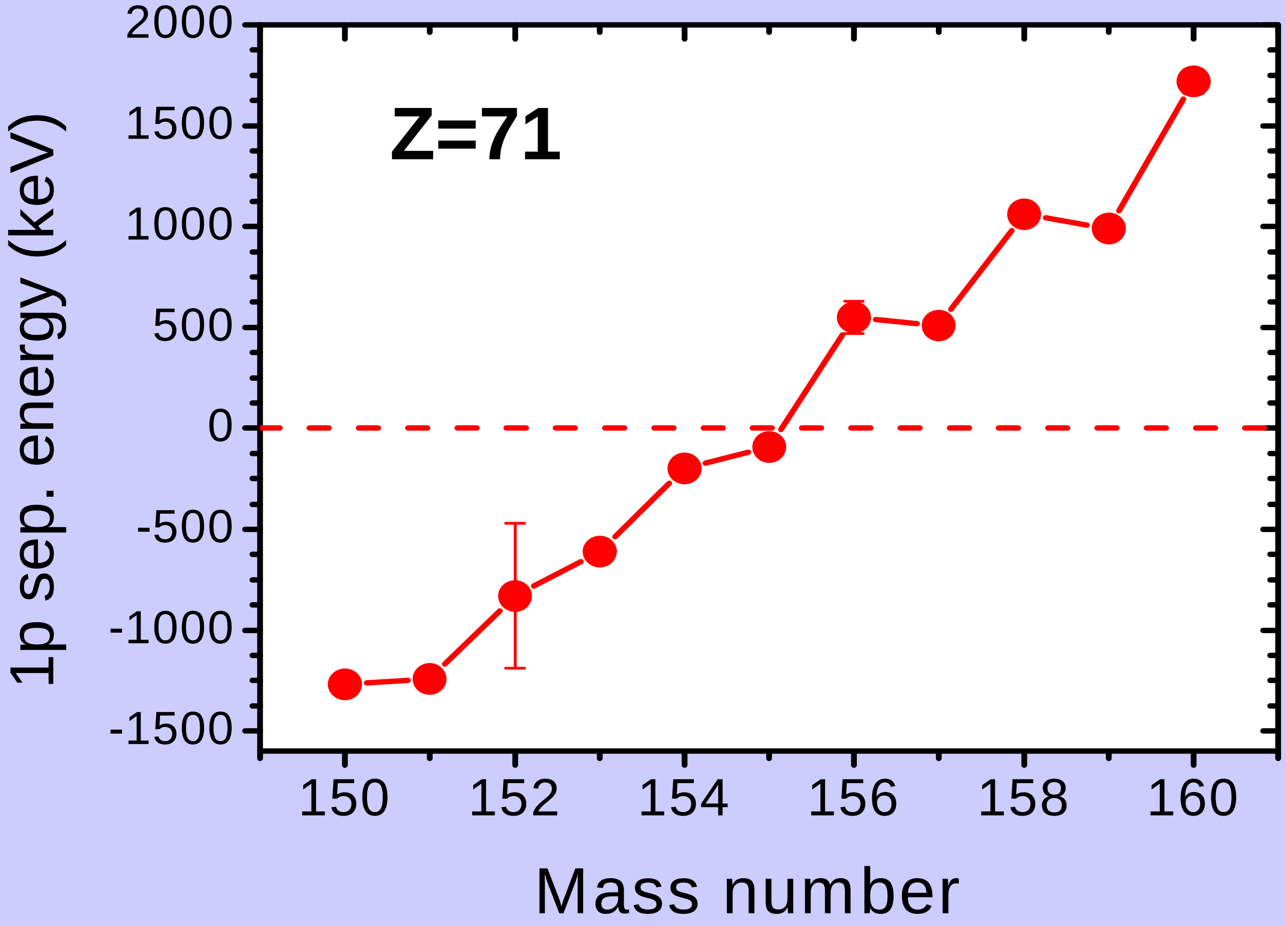
Proton radioactivity

$$(Z, N) \rightarrow (Z-1, N) + p$$



History of studies of proton radioactivity

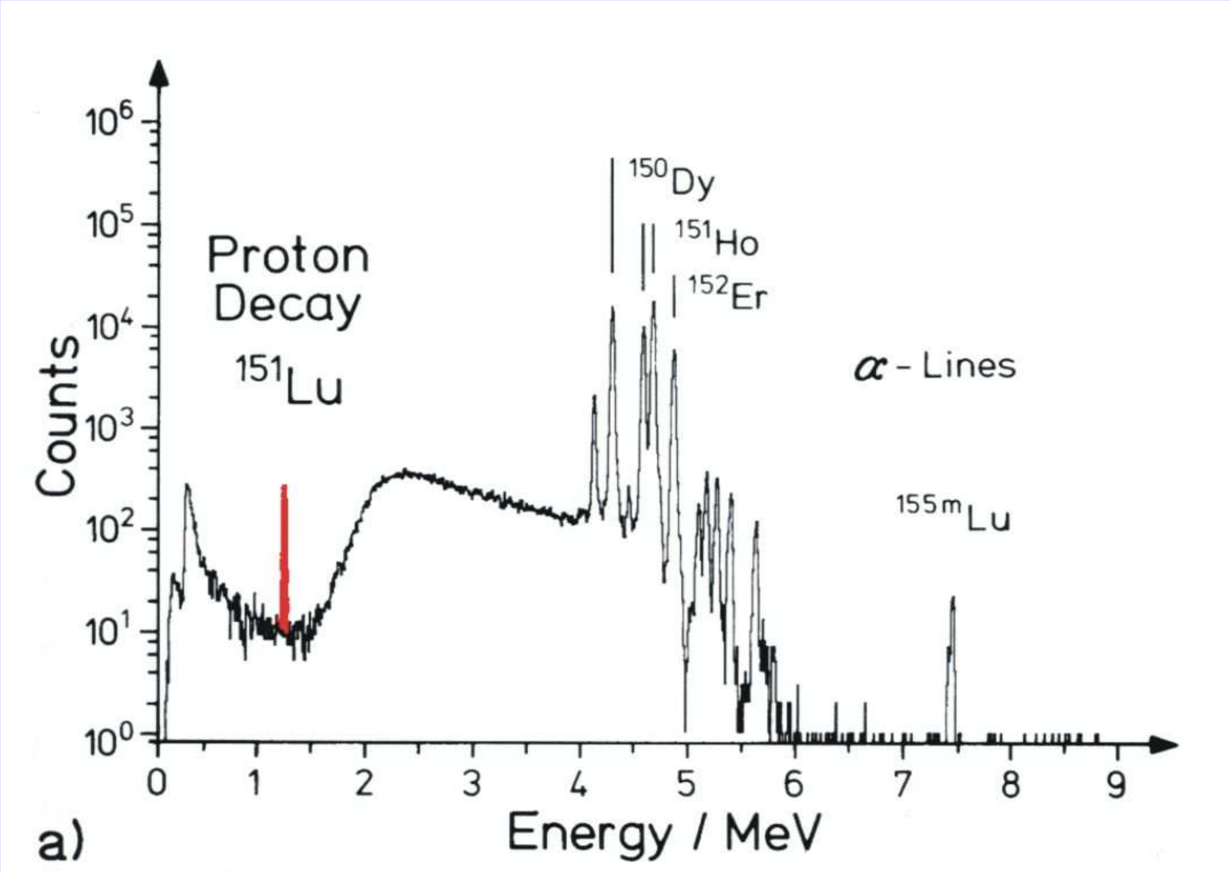
- **1960 – prediction of possibility of *p* emission**



^{175}Lu stable

History of studies of proton radioactivity

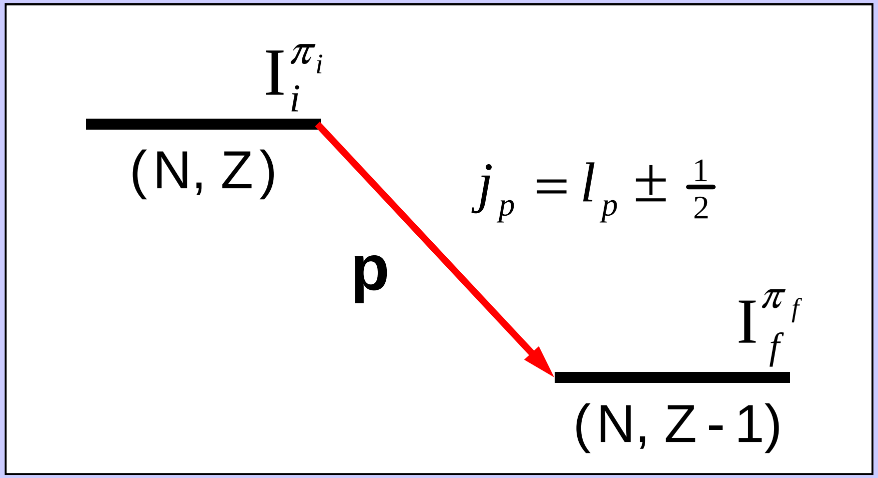
- 1981 – observation of $^{151}Lu \rightarrow ^{150}Yb + p$ decay



$E_p = 1233$ keV
$T_{1/2} = 85$ ms
$b_p = 70\%$

S. Hofmann *et al*., Z. Phys. A305 (1982) 111

Proton radioactivity



Energy conservation

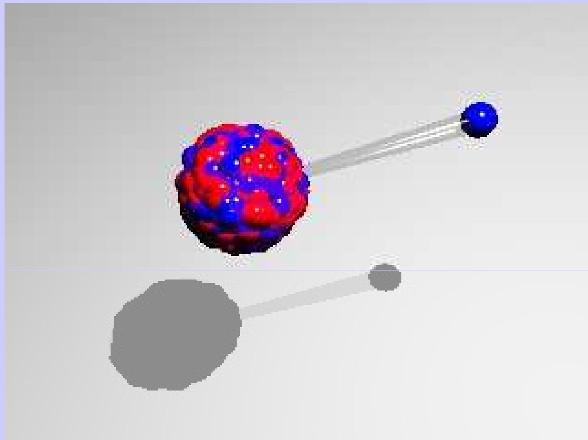
$$Q_p = M_i c^2 - M_f c^2 - m_H c^2 = -S_p > 0$$

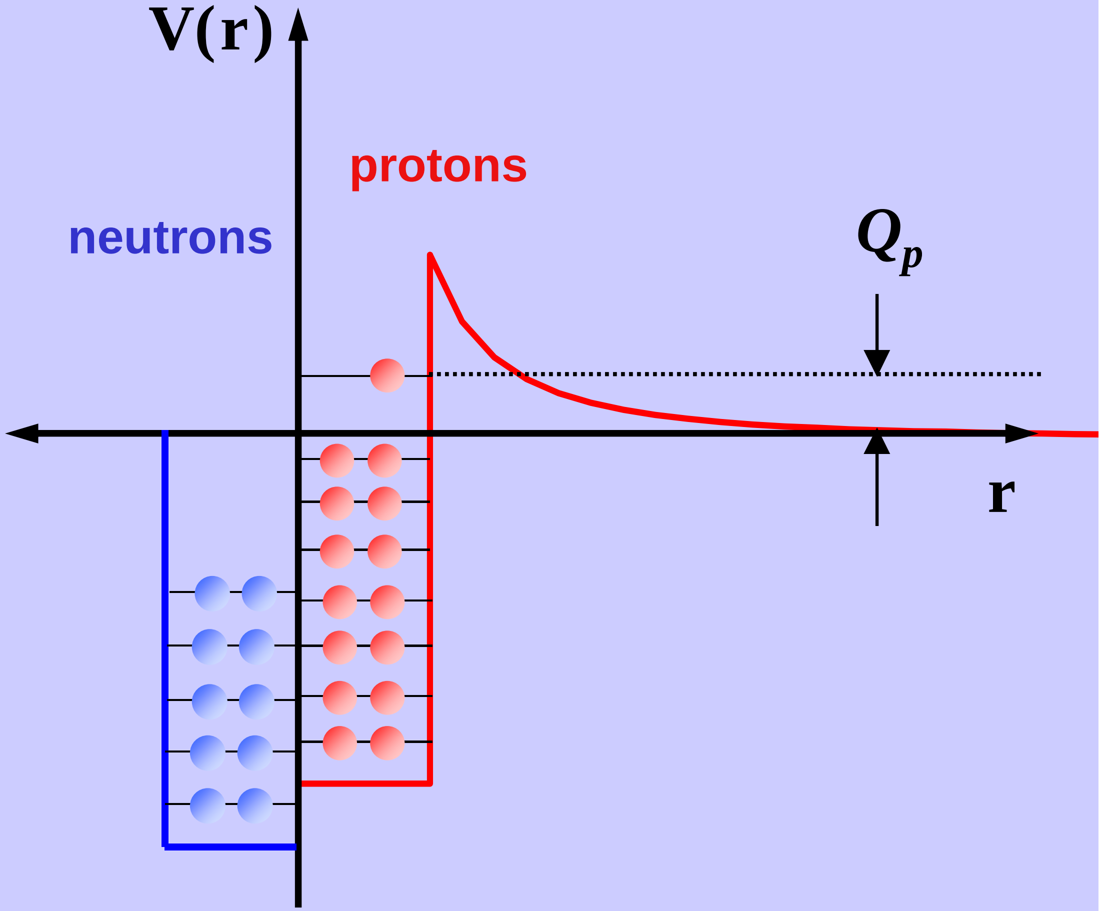
Angular momentum and parity conservation

$$\vec{I}_i = \vec{I}_f + \vec{l}_p + \vec{\tfrac{1}{2}} \qquad \pi_i \cdot \pi_f = (-1)^{l_p}$$

Proton radioactivity

$$(Z, N) \rightarrow (Z-1, N) + p$$





Probability of proton emission

$$\lambda_p = S \cdot \nu \cdot P_{lj}$$

S – spectroscopic factor

ν – frequency of proton movement in nucleus

$$\nu = \frac{\mathrm{v}}{2R} \approx 6 \cdot 10^{21}\ s^{-1}$$

$\mathbf{P}_{lj}$ – probability of barrier penetration

$$\mathrm{P}_{lj} = \mathrm{e}^{-2\mathrm{G}_{lj}}$$

$\mathbf{G}_{lj}$ – Gamow's factor

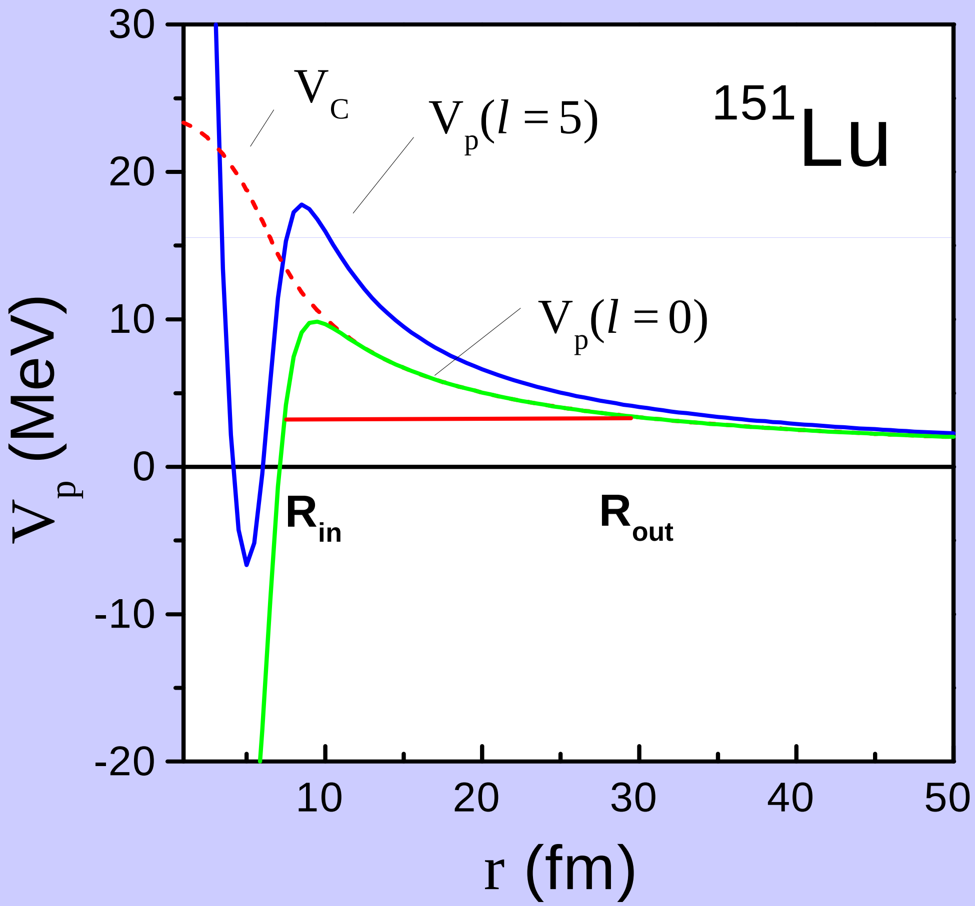
Gamow's factor

$$G_{\ell j} = \int_{R_{in}}^{R_{out}} \sqrt{\frac{2\mu}{\hbar^2}\left(V_p(r) - \tilde{Q}_p\right)}\, dr$$

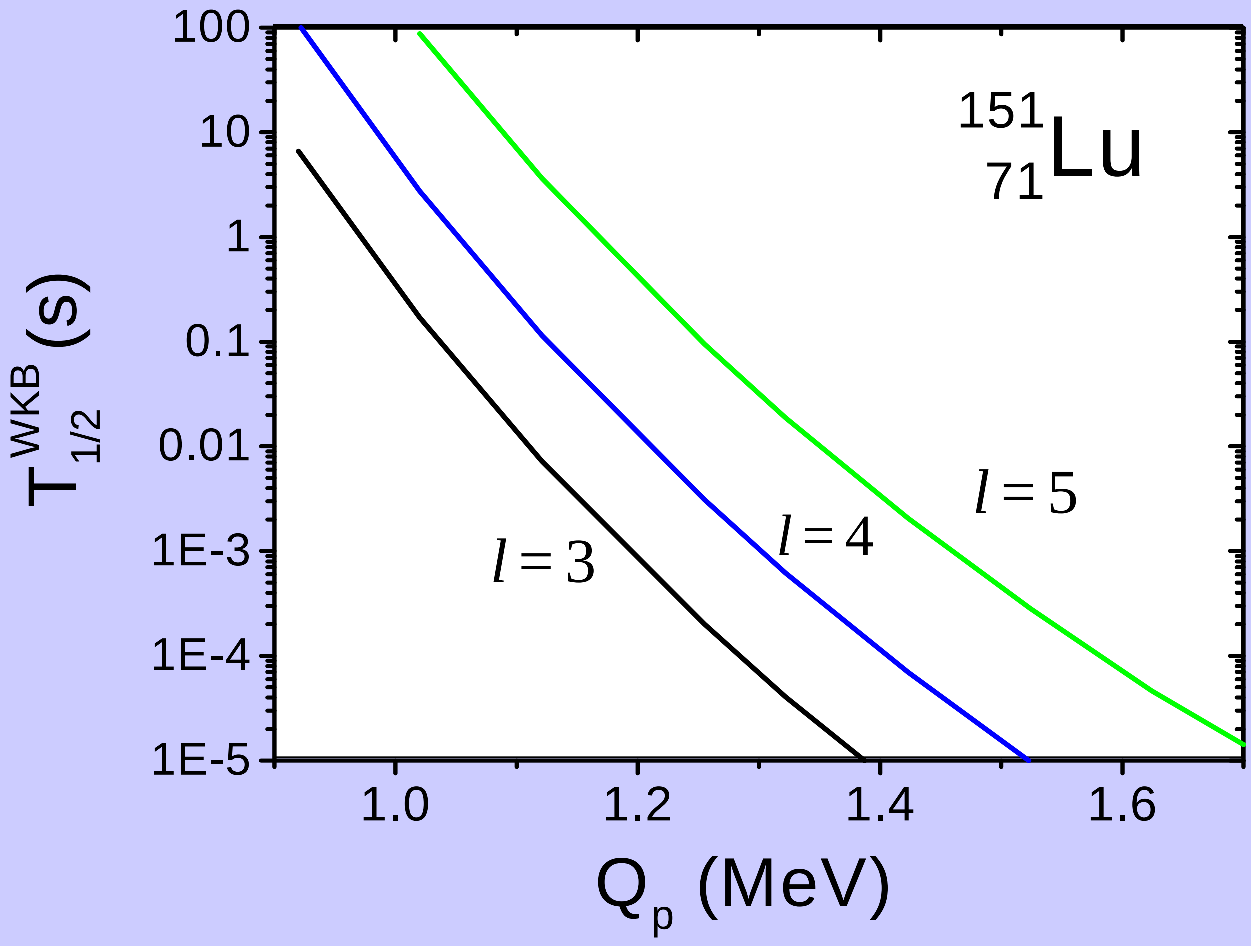
$V_p(r)$ – interaction potential

$$V_p(r) = V_N(r) + V_C(r) + V_l(r)$$

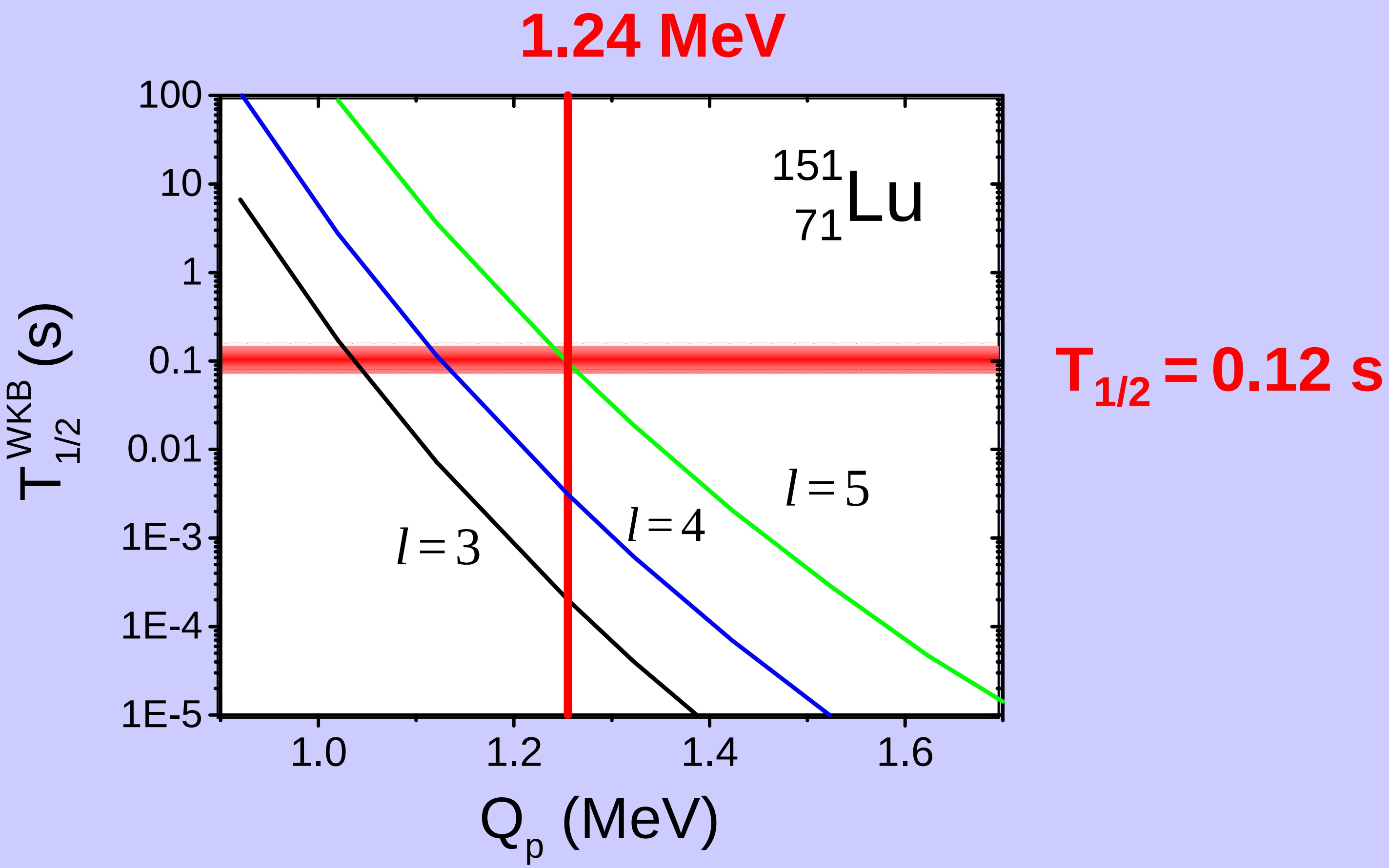
R_{in}, R_{out} – turning points



WKB calculations for ^{151}Lu



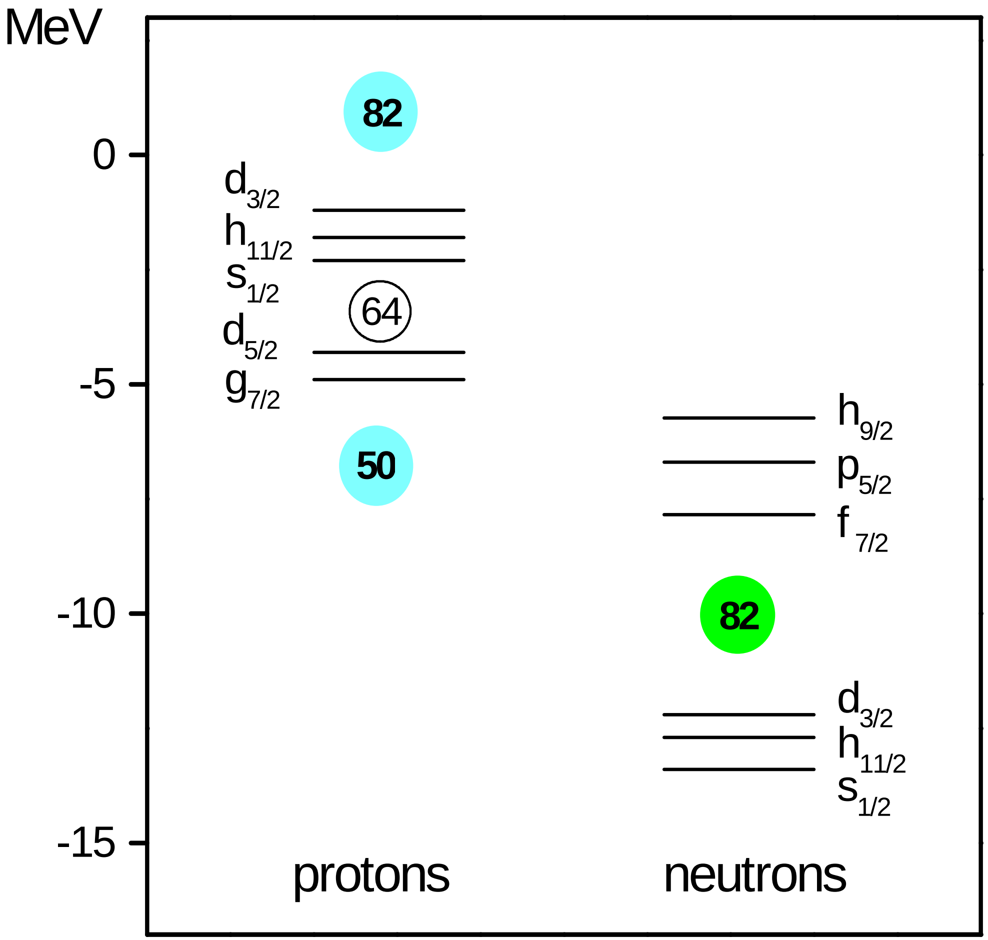
WKB calculations for ^{151}Lu



for $l_p = 5$

$$\frac{T_{1/2}^{WKB}}{T_{1/2}^{exp}} = 0.6$$

Single-particle states



$^{151}_{71}Lu_{80}$

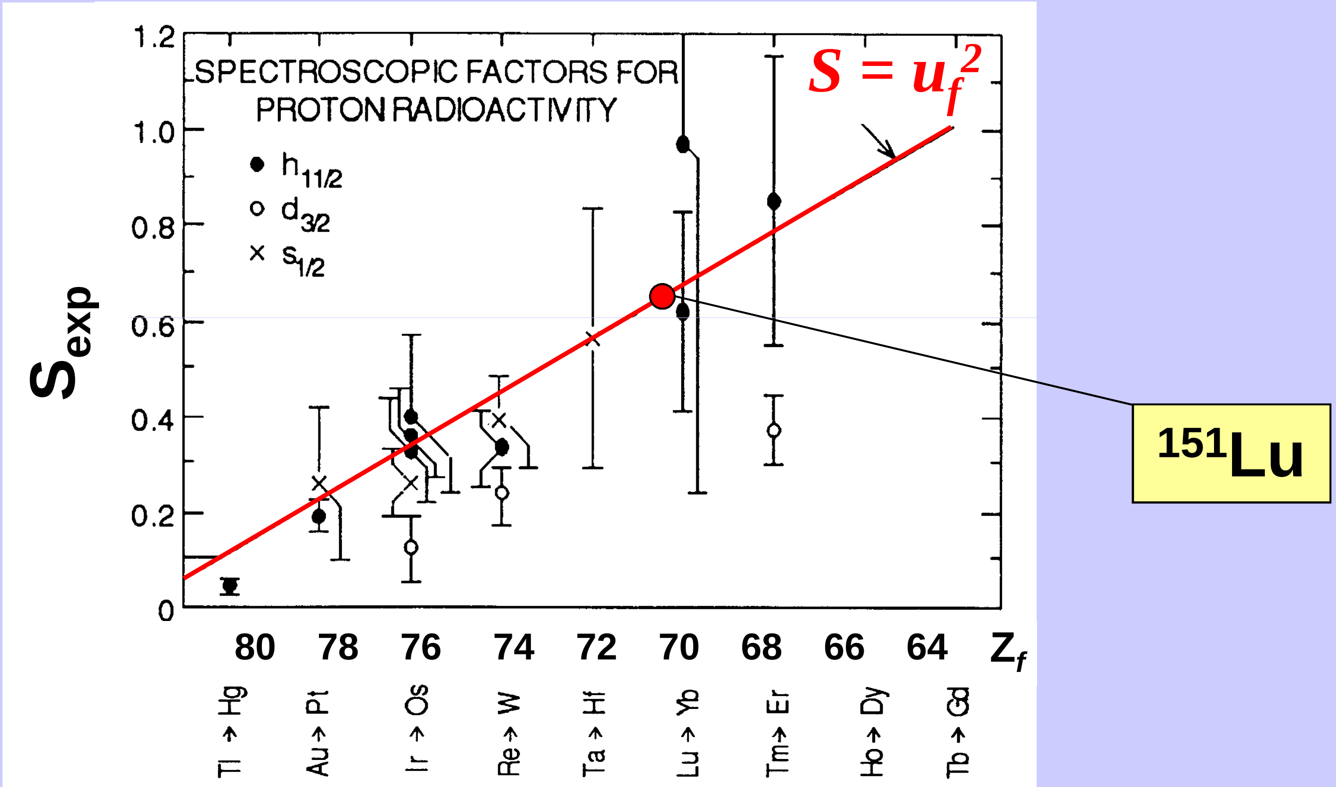
Valent particles:

5 protons on $h_{11/2}$

2 neutrons on $d_{3/2}$

S factors for p emitters with 64 < Z < 82

- filled proton orbitals : $s_{1/2}$, $d_{3/2}$ i $h_{11/2}$



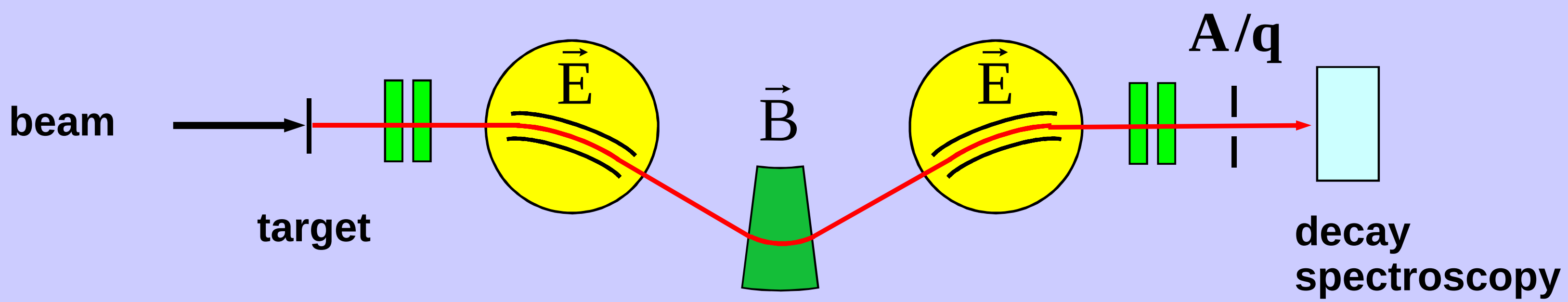
P.J. Woods *et al*., Anu. Rev. Nucl. Part. Sci. 47 (1997) 541

Proton decay of $^{131}_{63}Eu$

- production in fusion-evaporation reaction

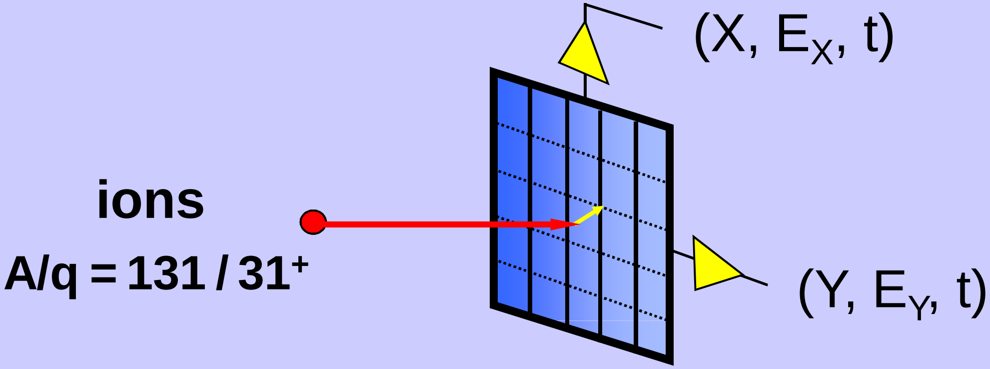
$^{78}Kr + {}^{58}Ni \rightarrow {}^{136}Gd^{*} \rightarrow {}^{131}Eu + p4n$	$\sigma = 90$ nb

- recoil mass separation (FMA – Argonne)



- **decay spectroscopy**

detector **D**ouble-sided **S**ilicon **S**trip **D**etector



Typical parameters:

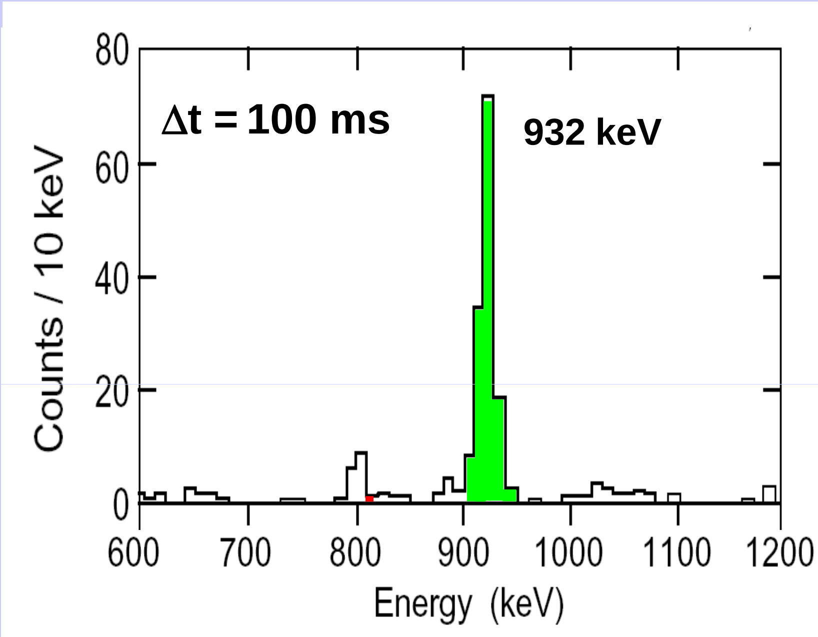
40 × 40 × 0.1 mm

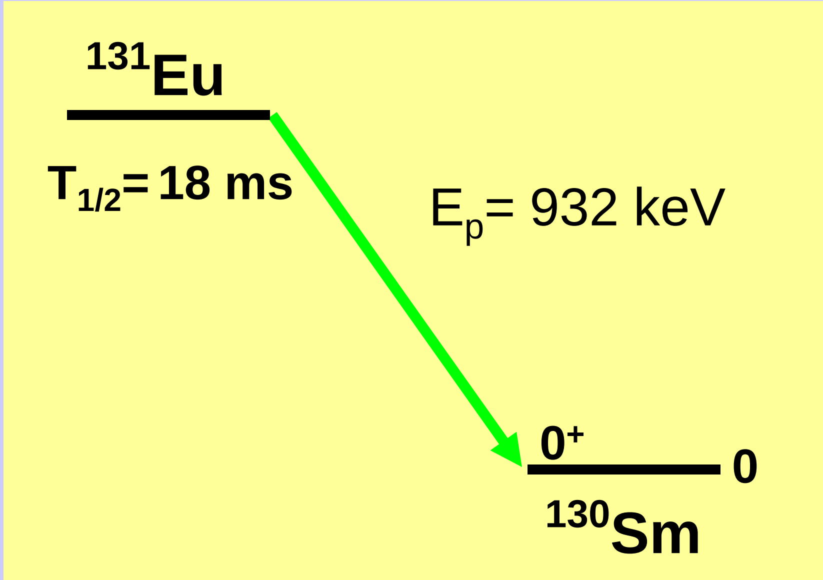
40 × 40 strips

Rgistration of (X, E_X, t) and (Y, E_Y, t) enables:

- **determination of X and Y position**
- **energy measurement**
- **determination of implantation – decay time**

Proton decay of $^{131}_{63}$Eu

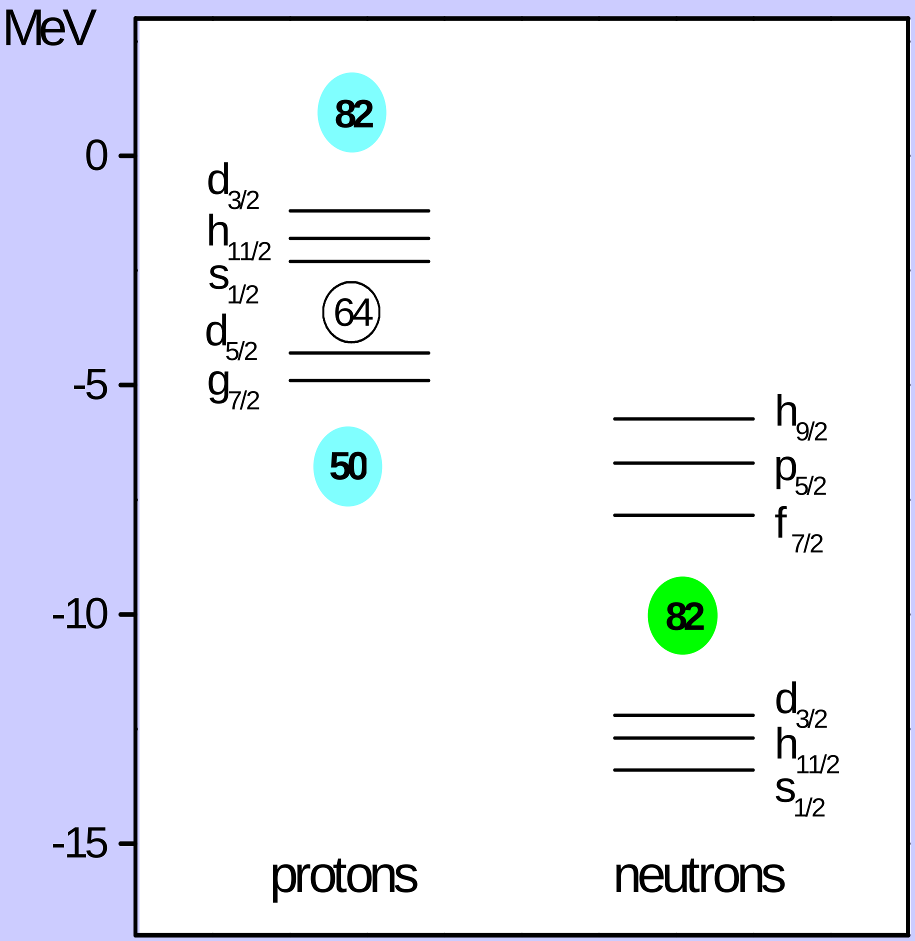




120 hours of measurement

A. Sonzogni *et al*., Phys. Rev. Lett. 83 (1999) 1116

Single-particle states for $^{131}_{63}$Eu



for transition

^{131}**Eu(d$_{5/2}$)** $\rightarrow$ ^{130}**Sm(0$^+$) + p**

$$l_p = 2 \qquad T_{1/2}^{WKB} = 0.5 \text{ ms}$$

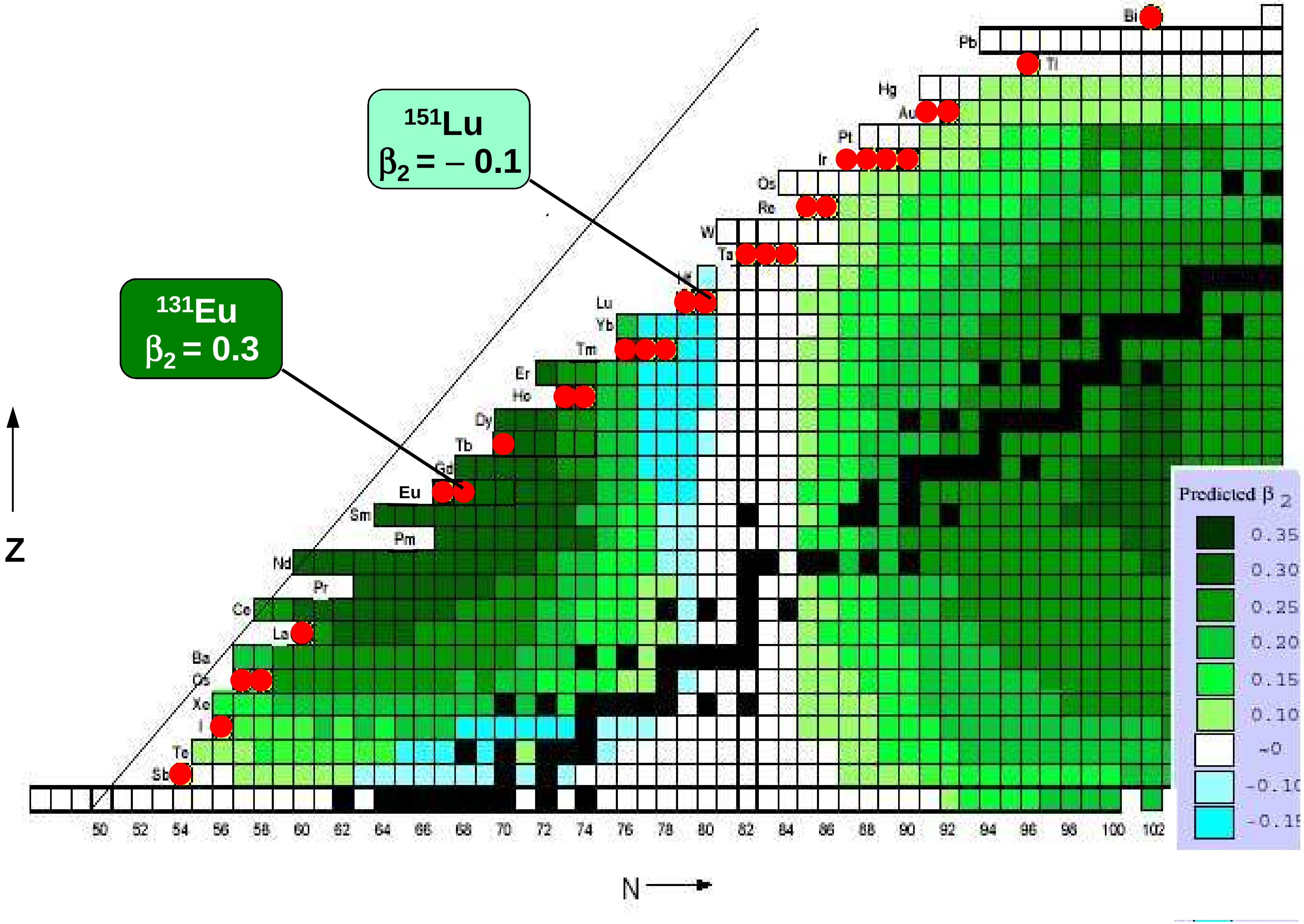
$$S_{exp} = 0.02$$

$$S_{th} = u_j^2 = 0.52$$

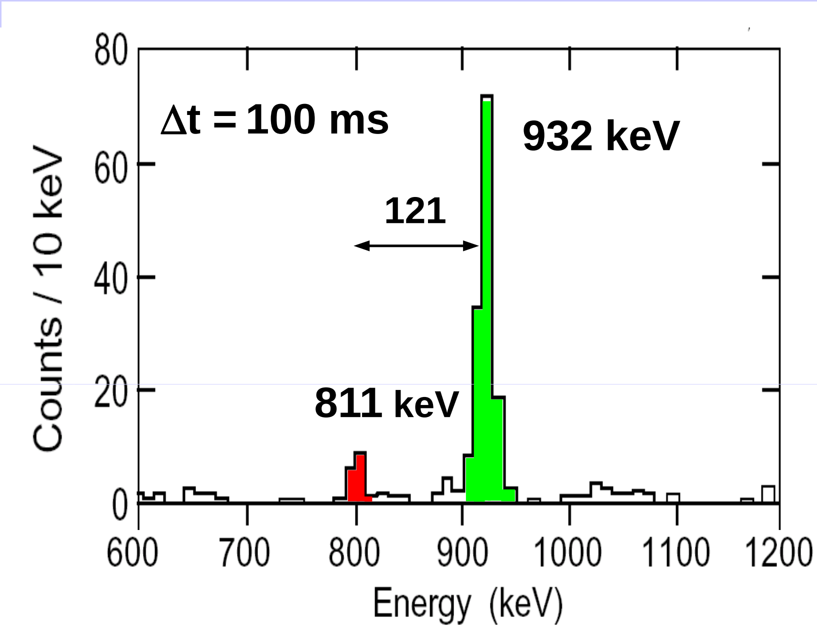
!!!

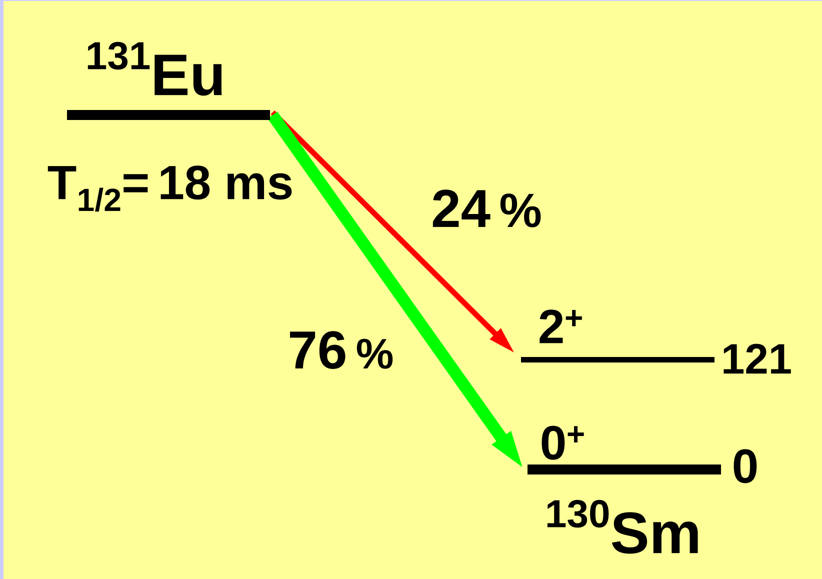
B.Barmore *et al*., Phys. Rev. C62 (2000) 054315

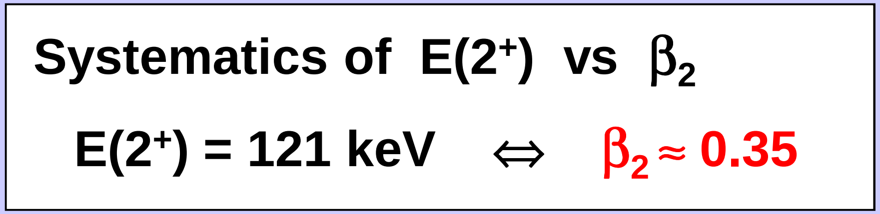
Map of nuclear deformation



Fine structure in the *p*-decay of $^{131}_{63}$Eu



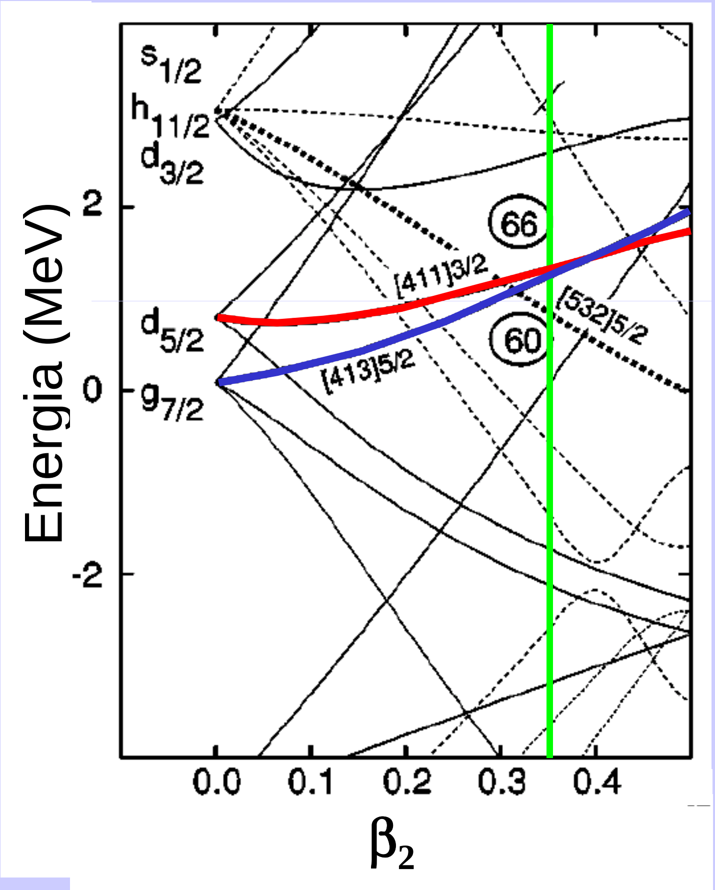


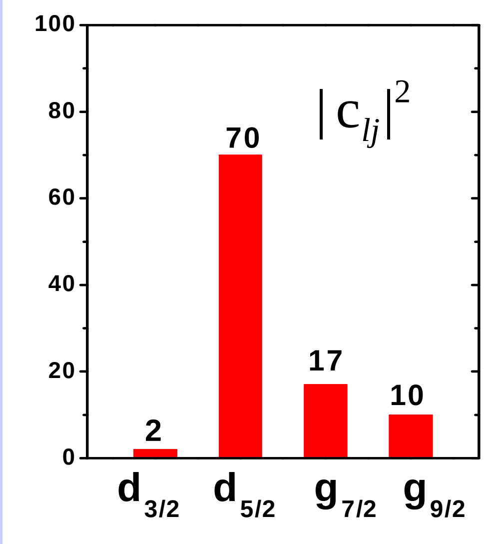


A. Sonzogni *et al*., Phys. Rev. Lett. 83 (1999) 1116

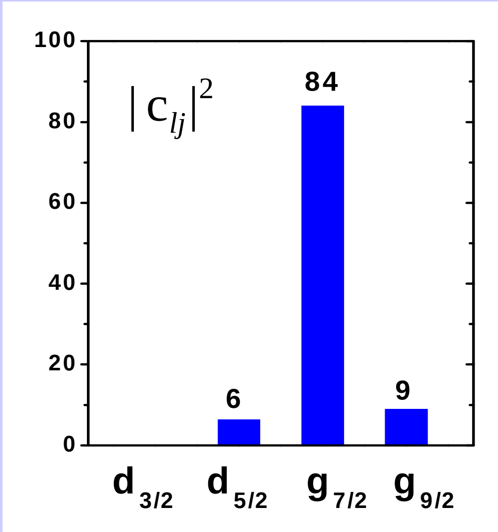
WF structure of odd proton in $^{131}_{63}$Eu

$$\Omega^{\pi}[N, n_z, \Lambda] = \sum_{l,j} c_{lj} |N, \ell, j\rangle$$





3/2$^+$[411]

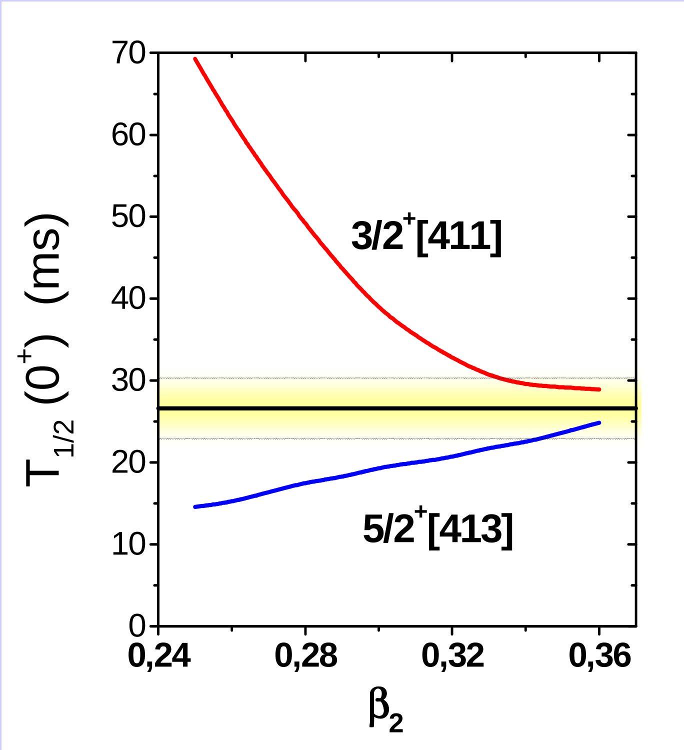


5/2$^+$[413]

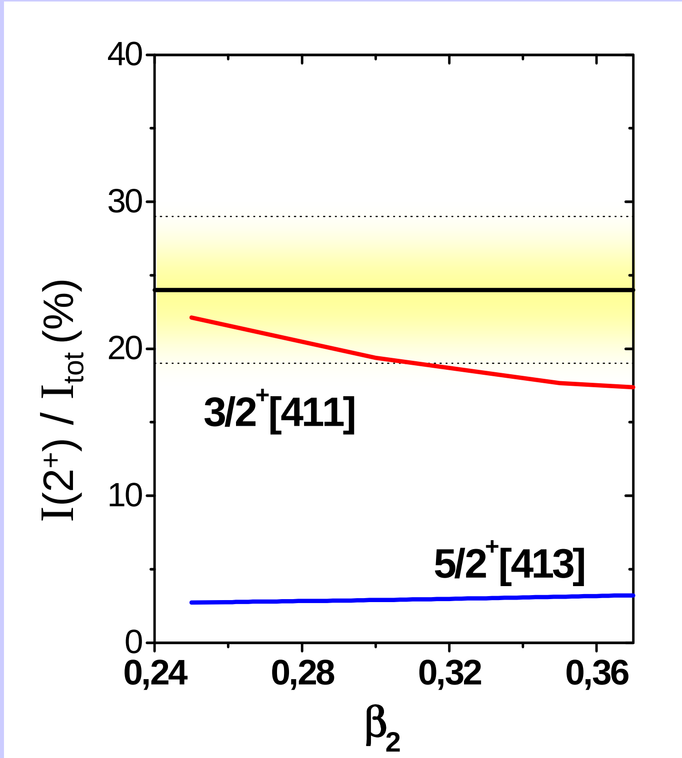
B.Barmore *et al*., Phys. Rev. C62 (2000) 054315

Calculations including deformation

Lifetime



feeding of 2^+



Conclusion:

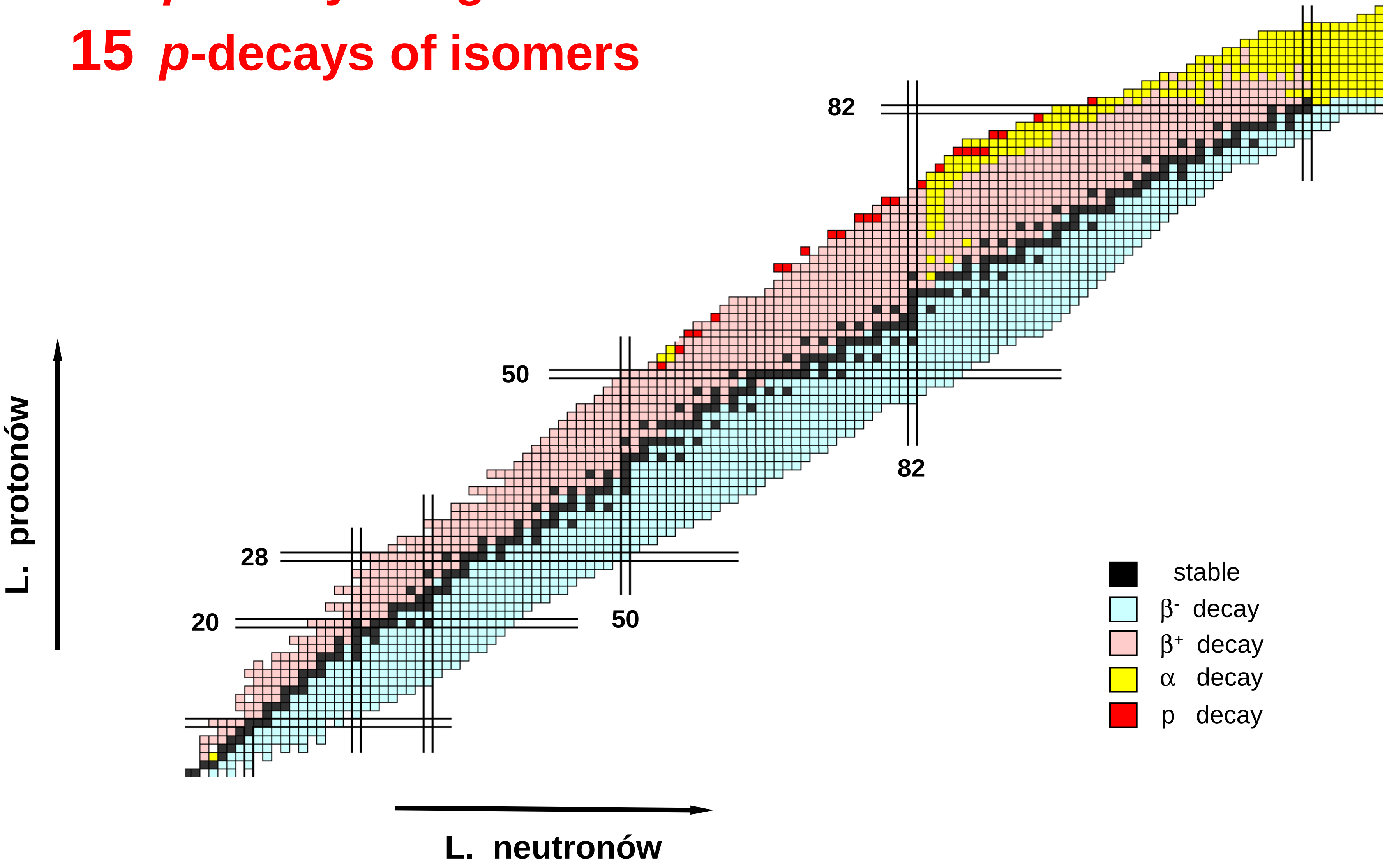
proton emission from deformed $3/2^+$[411] state observed

C. Davids et al., Phys. Rev. Lett. 80 (1998) 1849

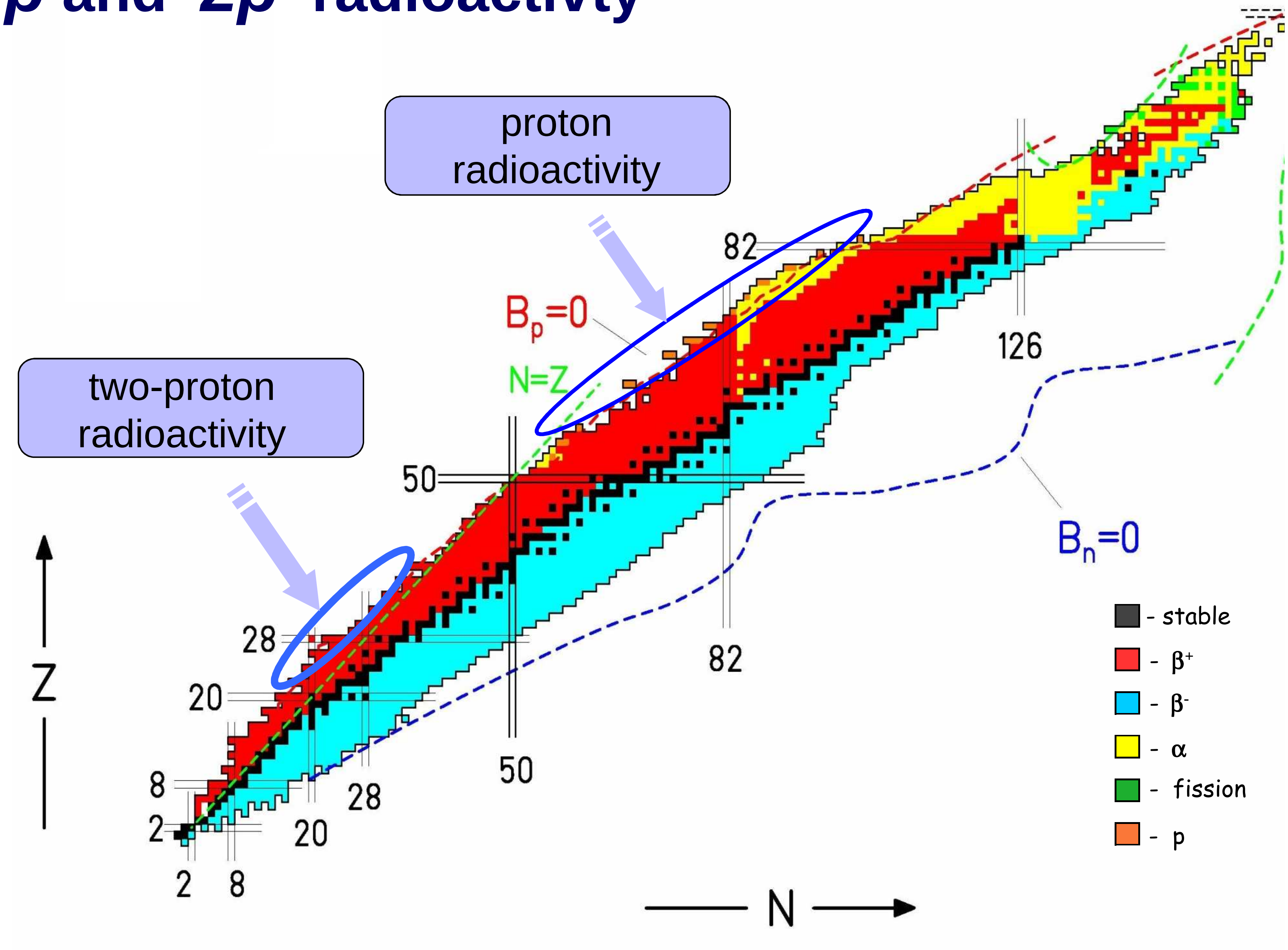
Known proton emitters

30 *p*-decays of ground states

15 *p*-decays of isomers

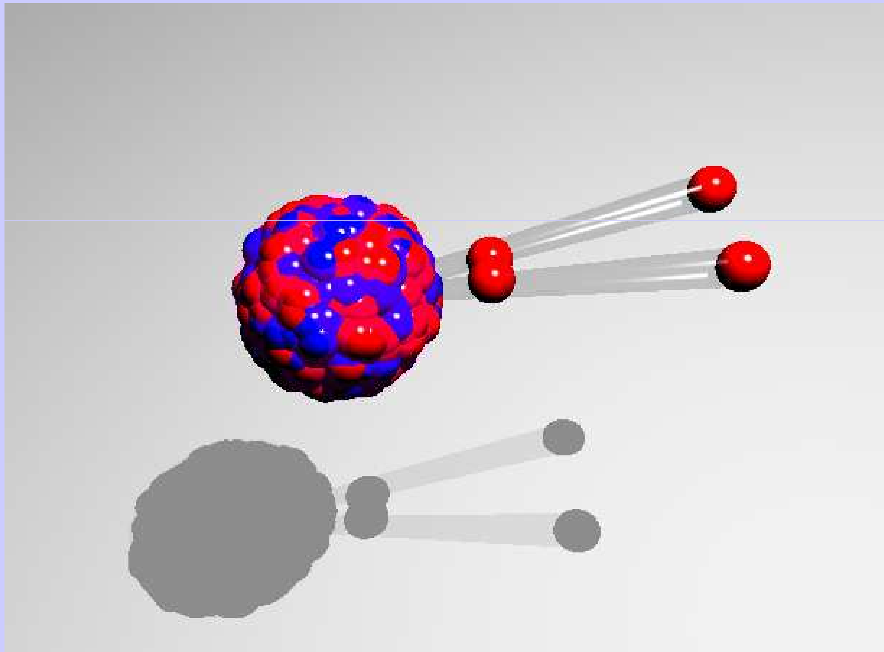


p and *2p* radioactivty

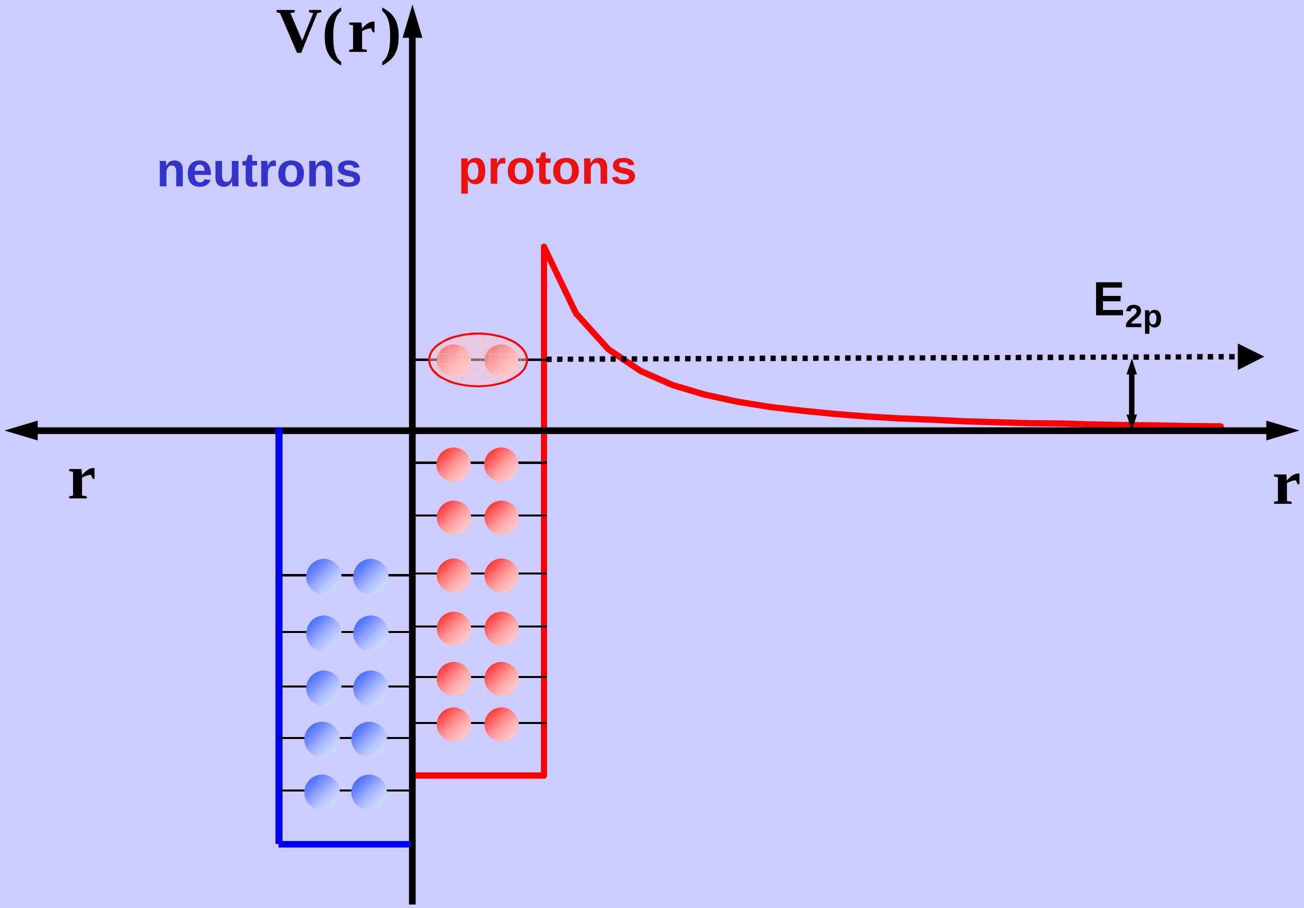


Two-proton radioactivity (*3 isotopes*)

$$(Z, N) \rightarrow (Z-2, N) + p + p$$

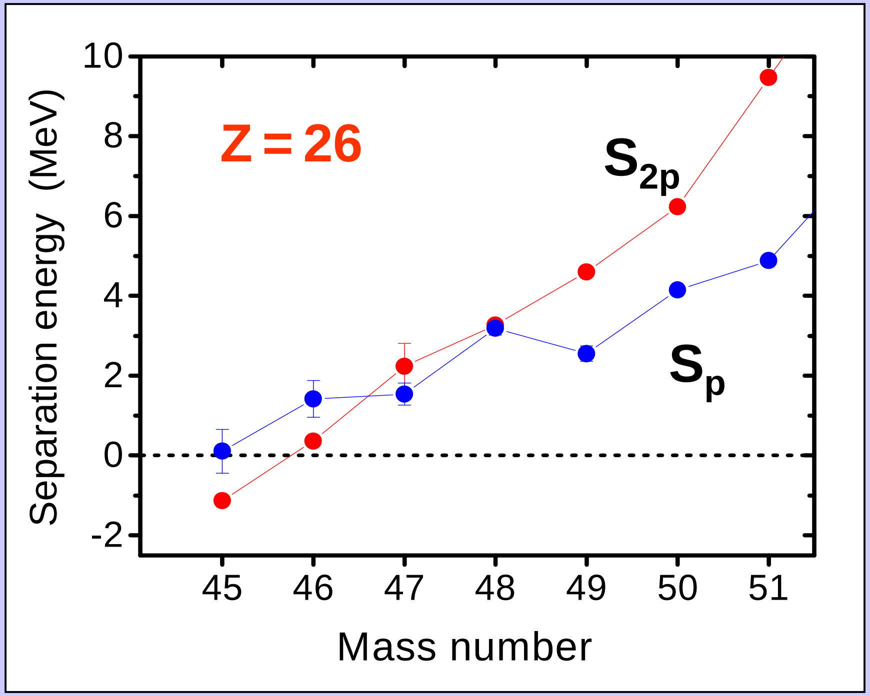


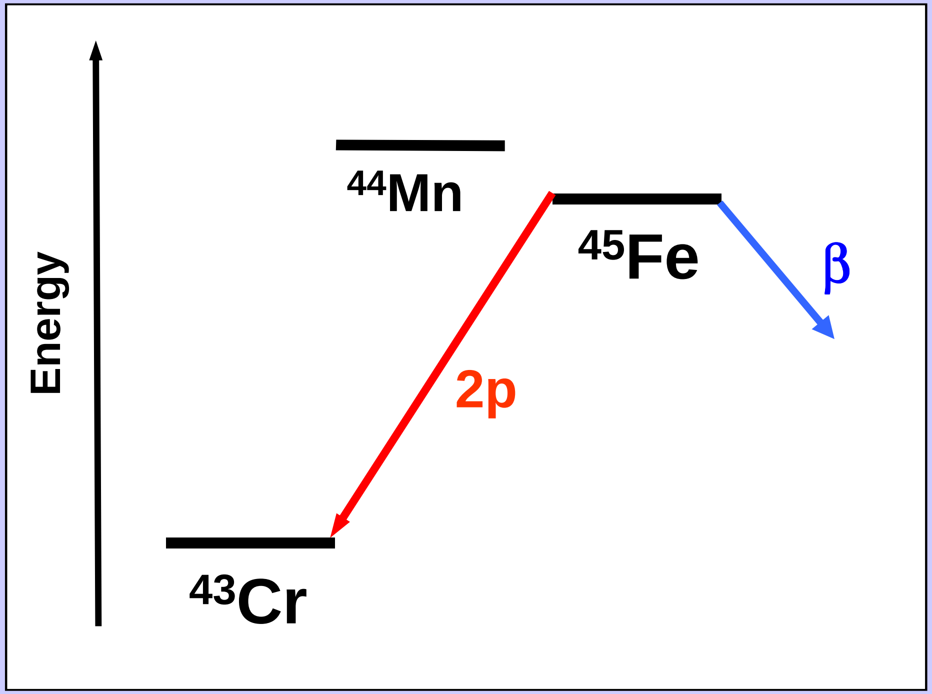
2p emission process



Two-proton radioactivity

- **prediction - V. Goldansky in 1960**



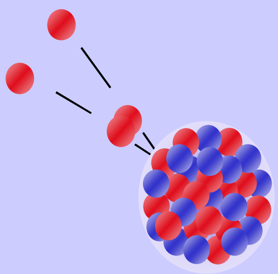


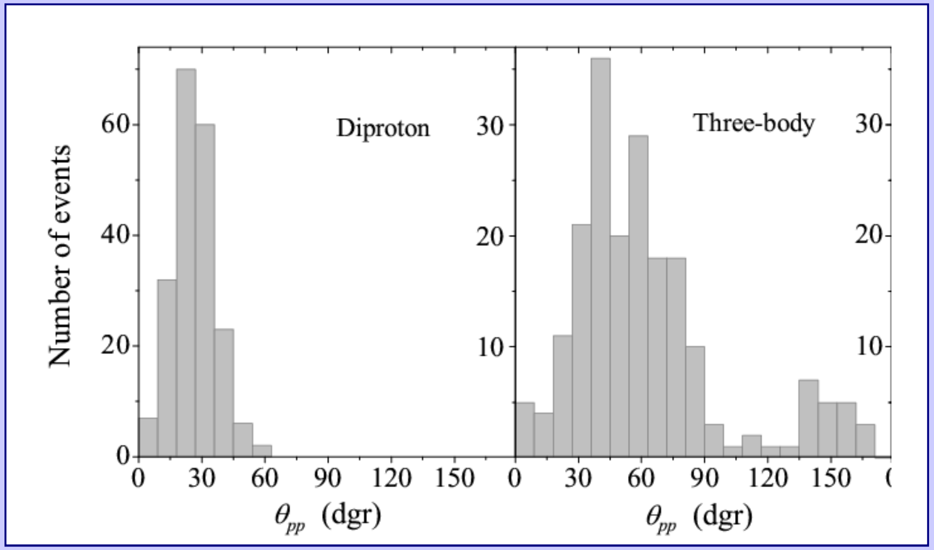
- single proton branch closed
- large Q_β value

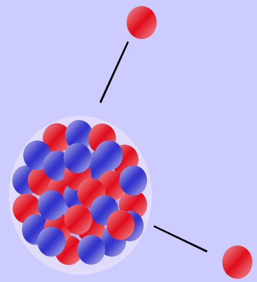
Experimental challenges

- **detection of individual protons**
- **energy measurement**
- **determination of angular correlation**

Predicted *p-p* opening angle for ^{45}Fe

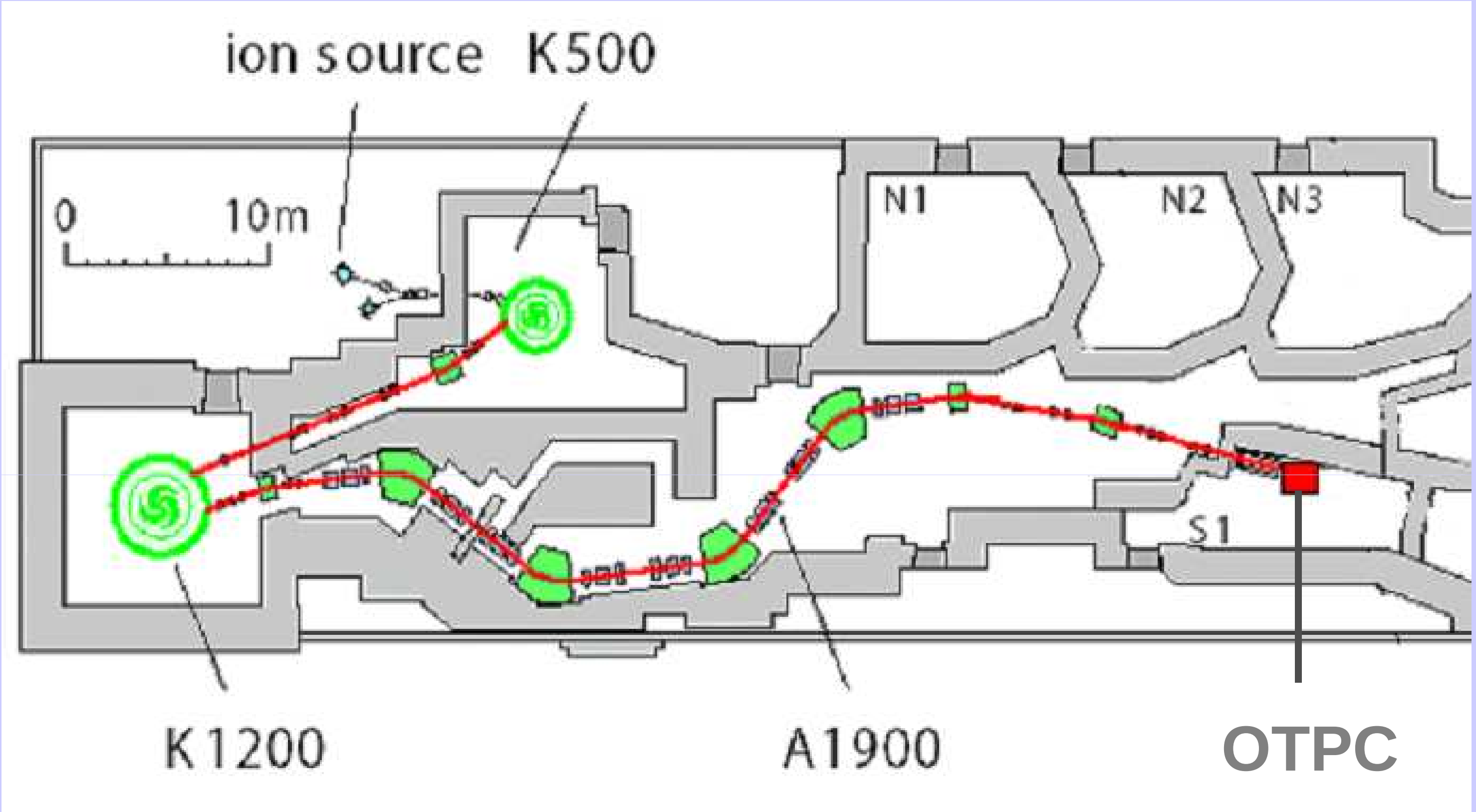






L. Grigorenko : simulation for 200 events

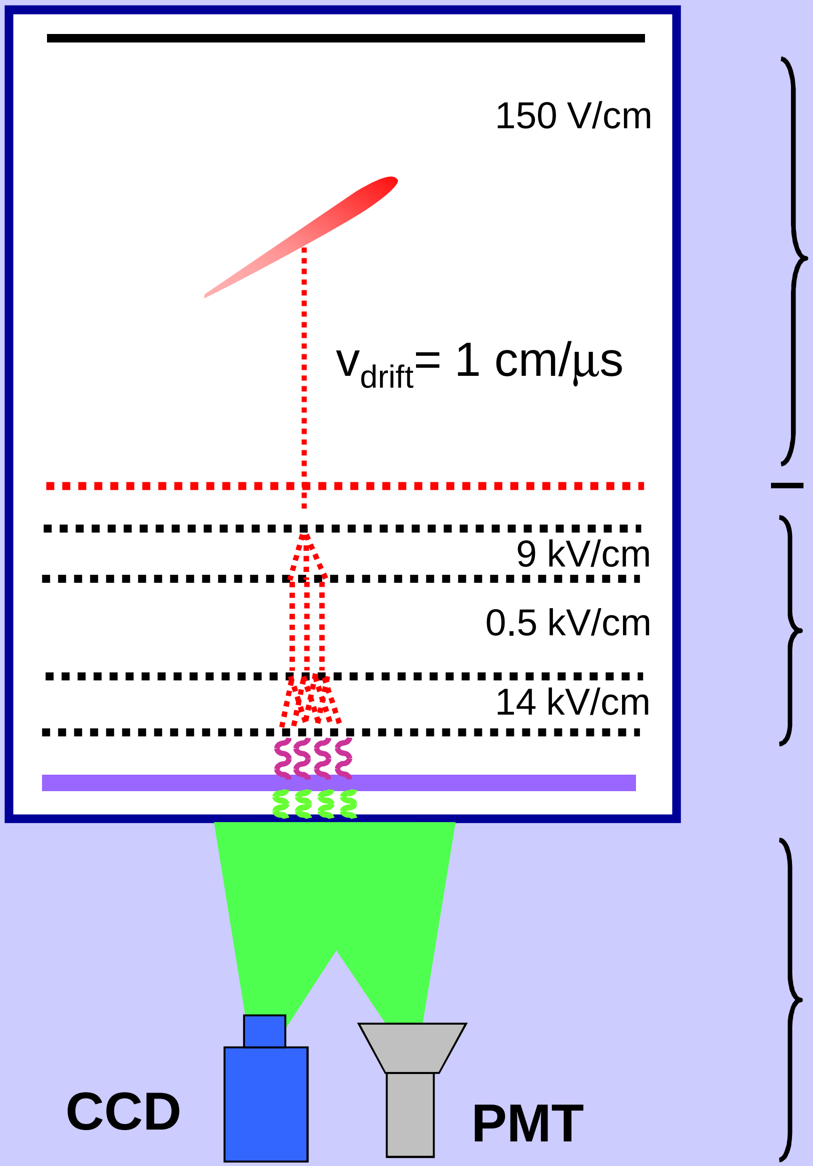
Experiment at NSCL / MSU



Production: ^{58}Ni (161 MeV/u) + ^{nat}Ni $\rightarrow$ ^{45}Fe

Identification in-flight: ΔE + TOF

Optical Time Projection Chamber



active volume

66%He + 32%Ar

gating electrode

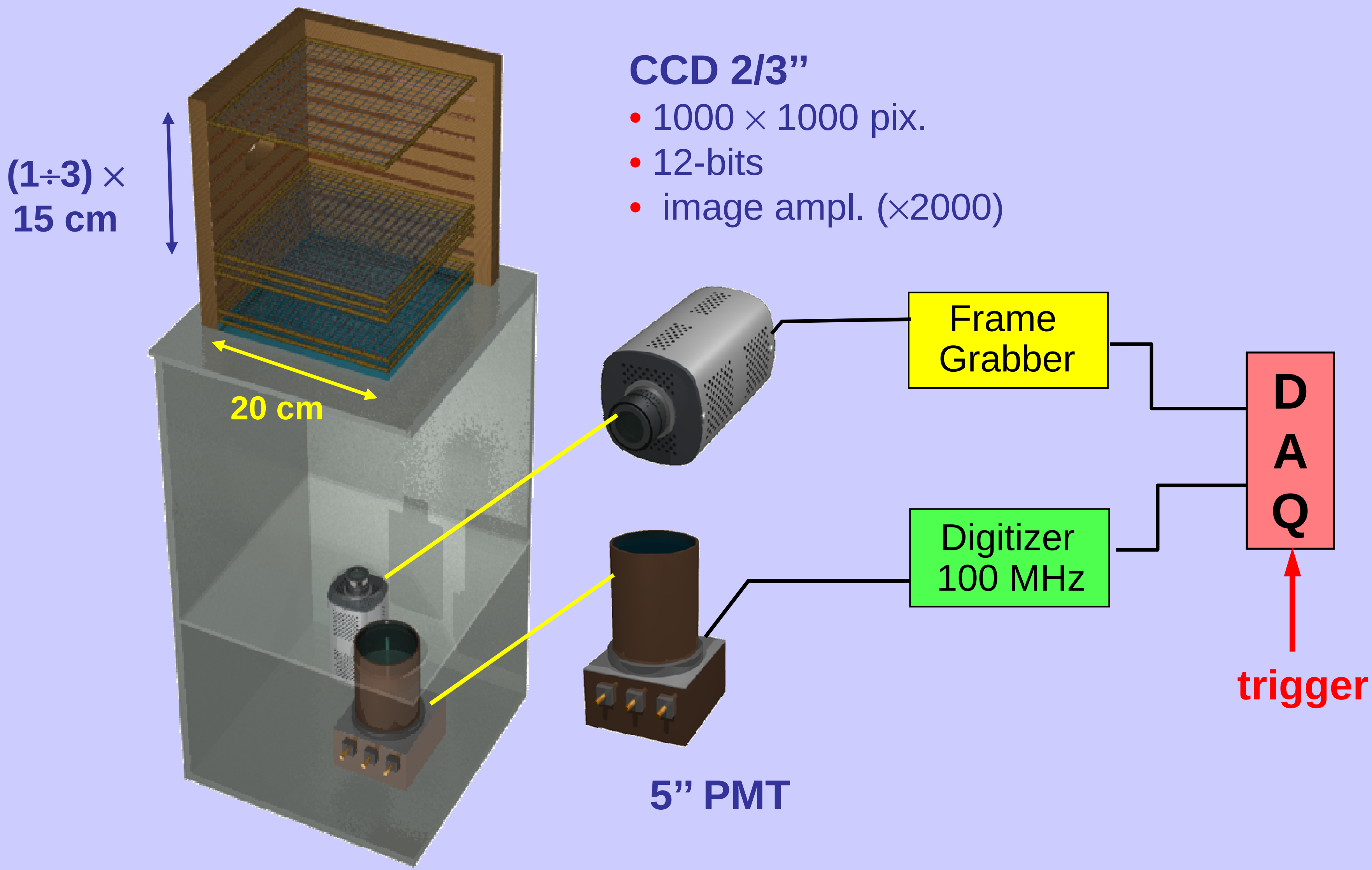
amplification

light detection

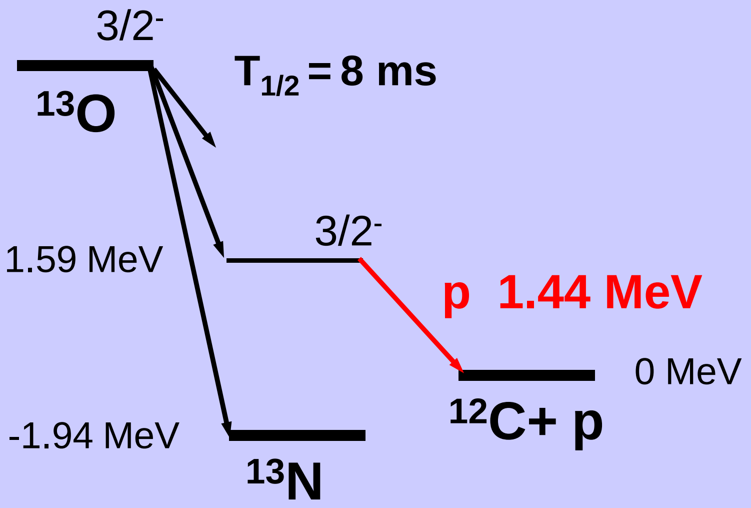
M. Ćwiok et al., IEEE TNS, 52 (2005) 2895

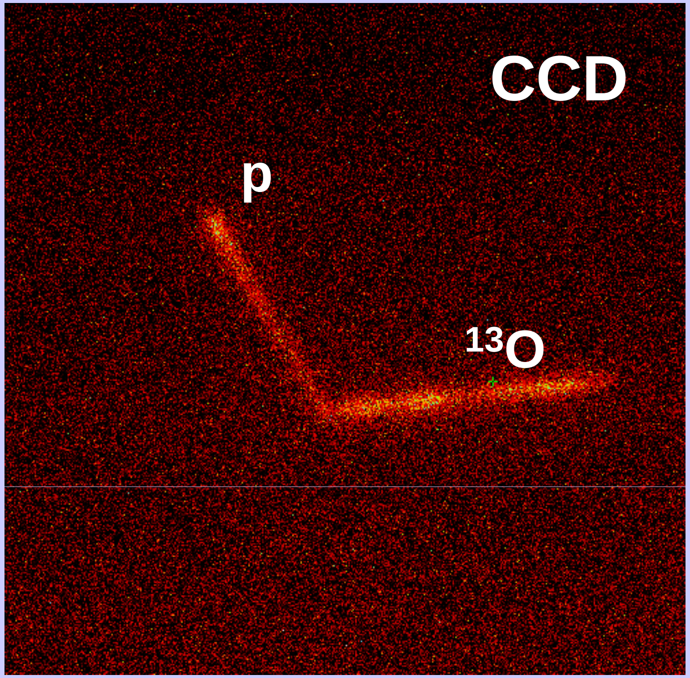
K. Miernik et al., NIM A581 (2007) 194

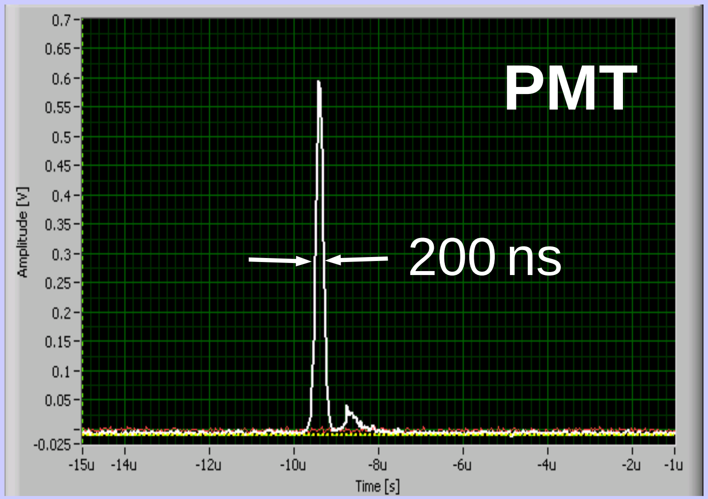
Optical Time Projection Chamber



Protons after beta decay of ^{13}O

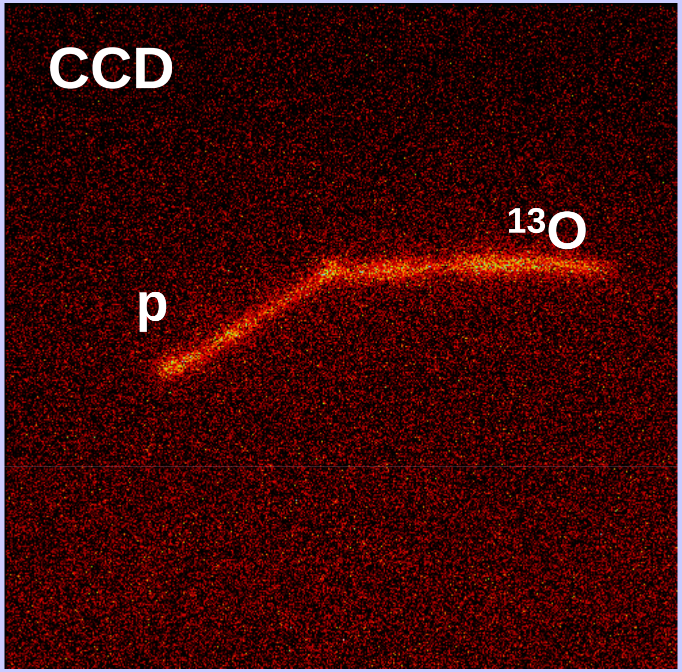


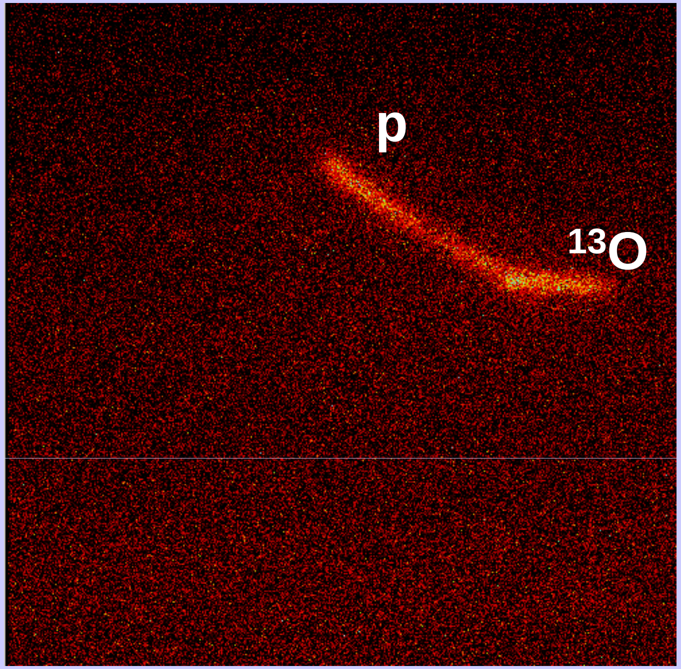


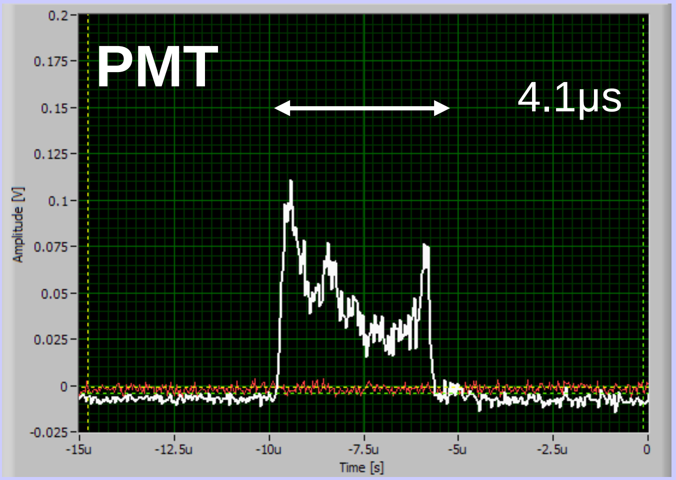


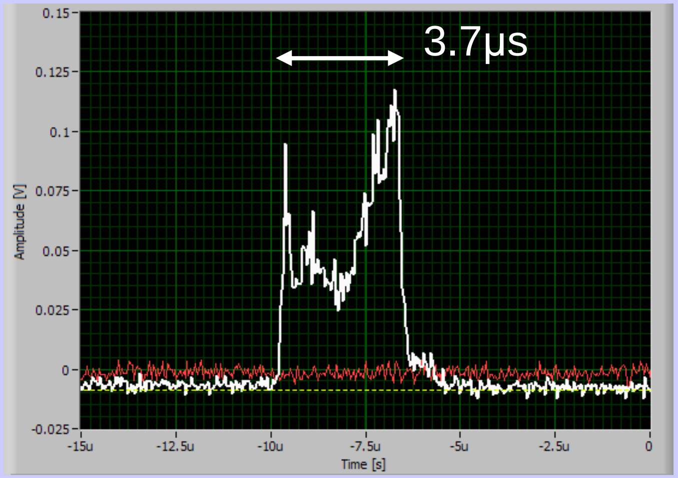
K. Miernik. et al., NIM A 581(2007)194

Protons after beta decay of ^{13}O

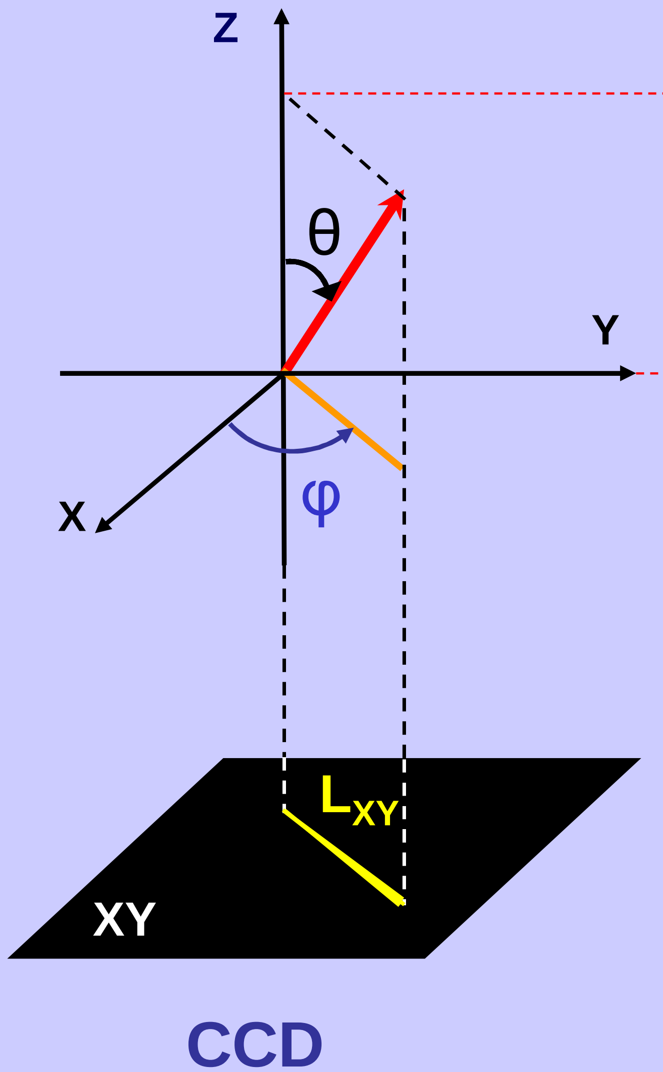


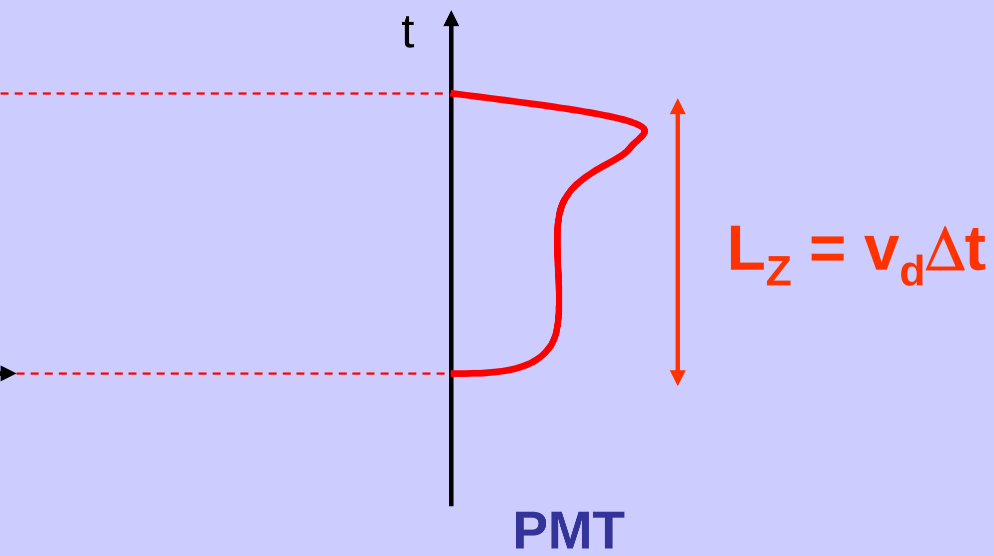






Events reconstruction





Track coordinates (r, Θ, φ)

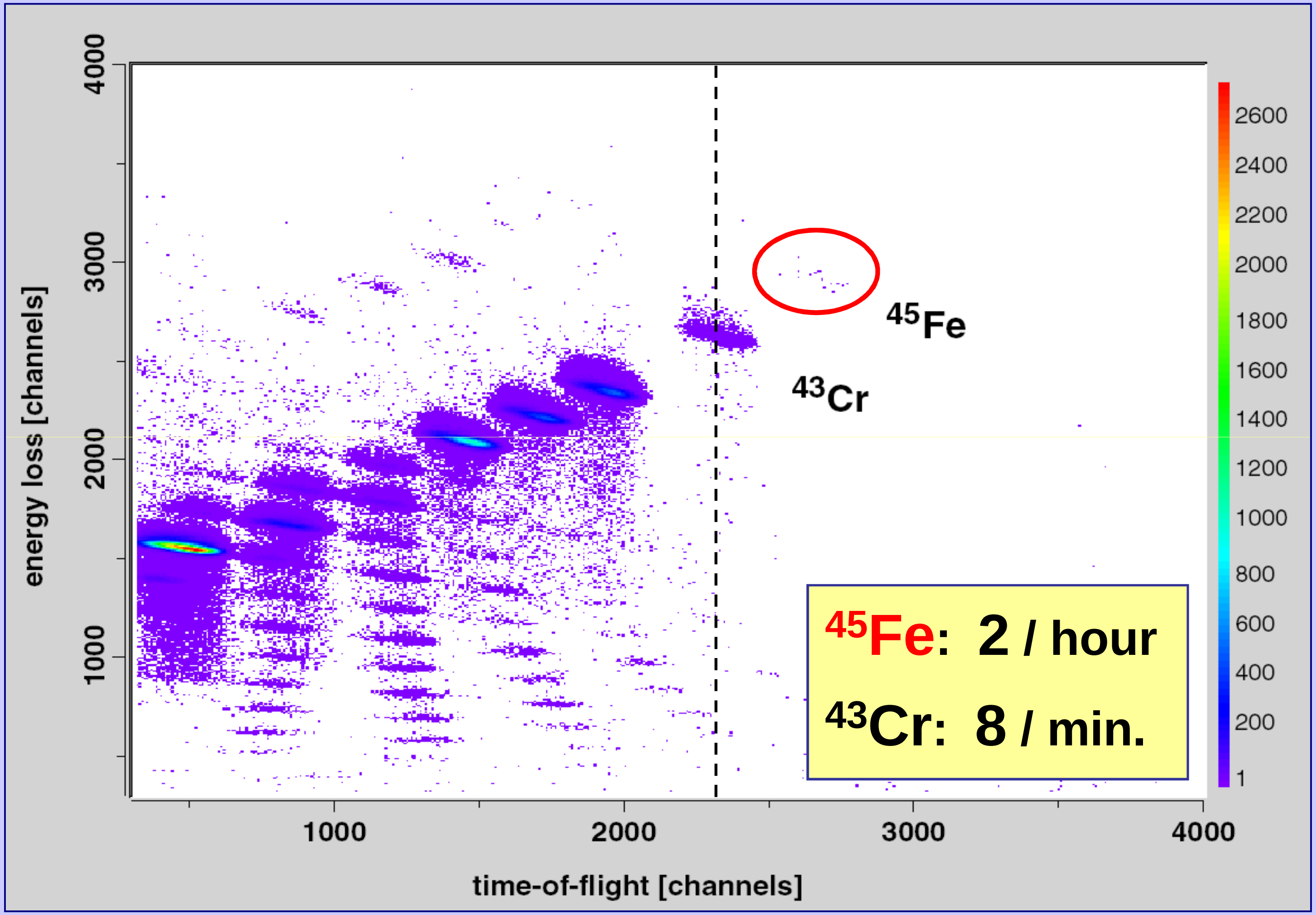
$L_{XY} = r \sin\Theta$

$L_Z = r \cos\Theta$

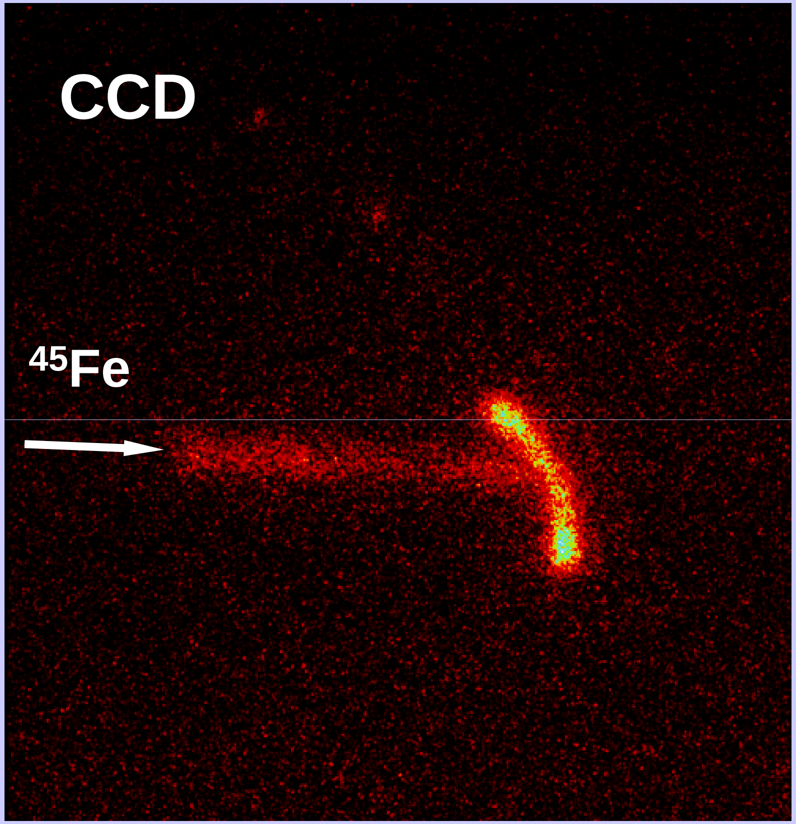
$r^2 = L_{XY}^2 + L_Z^2$

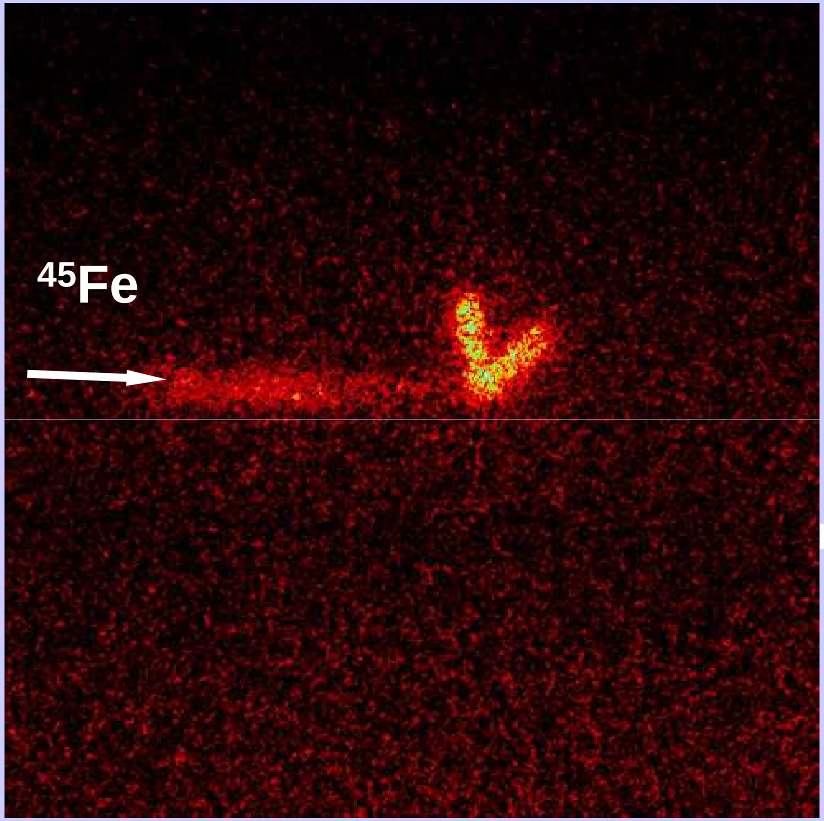
$\Theta = \arctan(L_{XY}/L_Z)$

Ion identification



2p decay of ^{45}Fe





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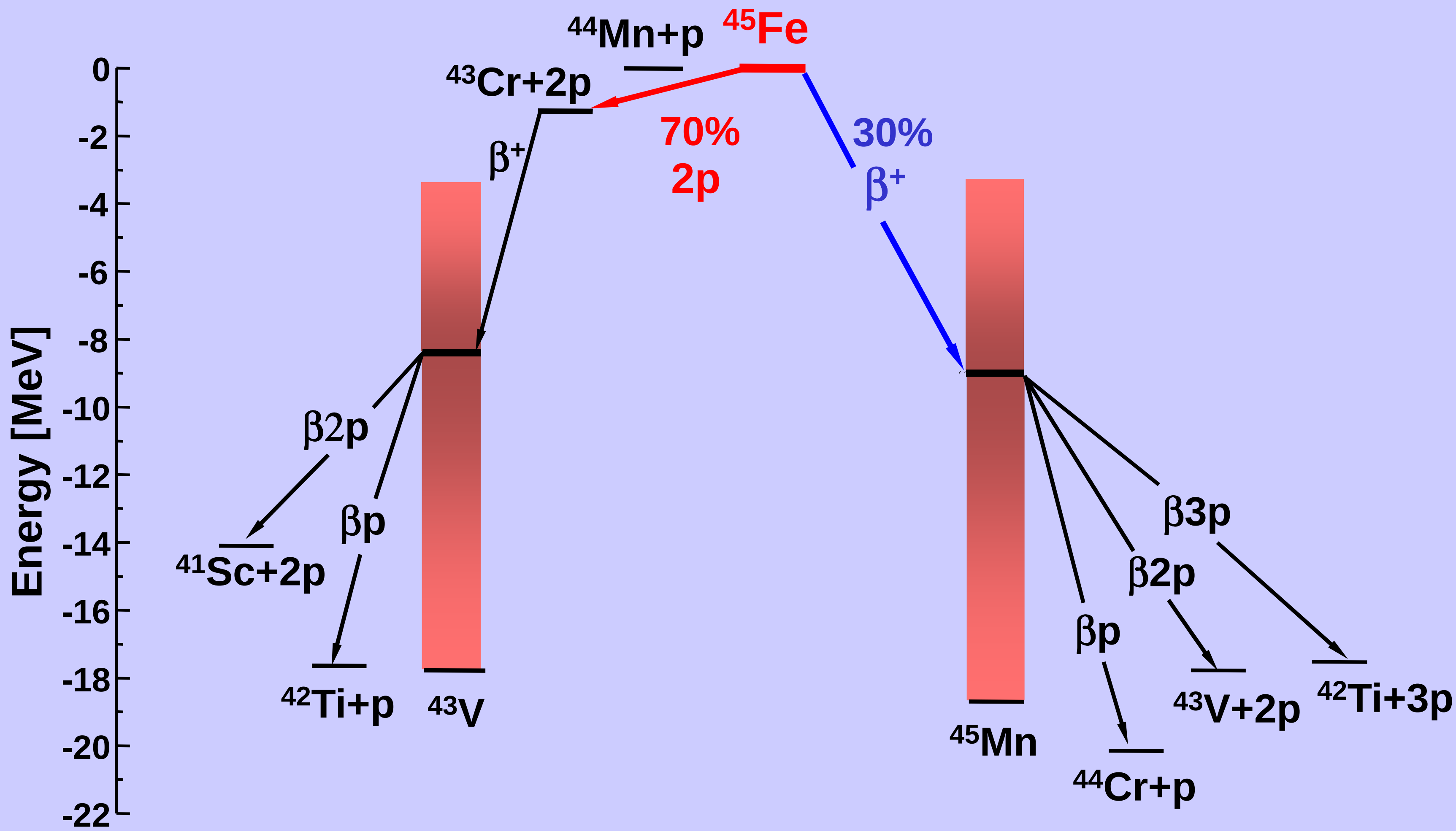
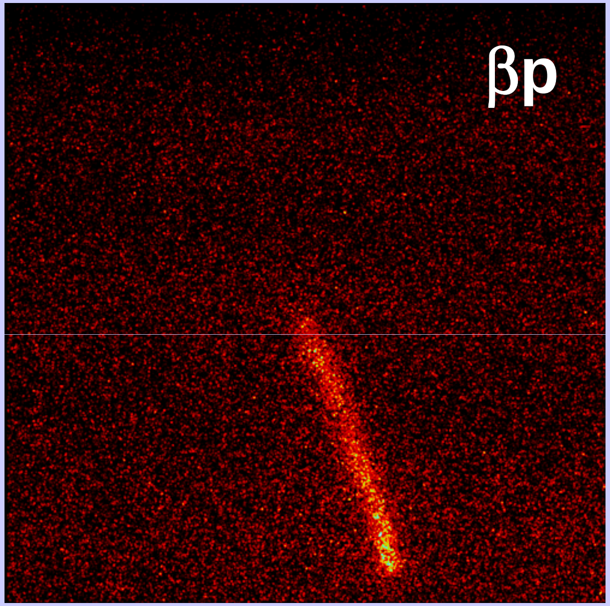
K. Miernik *et al*., PRL 99, 192501 (2007)

Decay scheme of ^{45}Fe

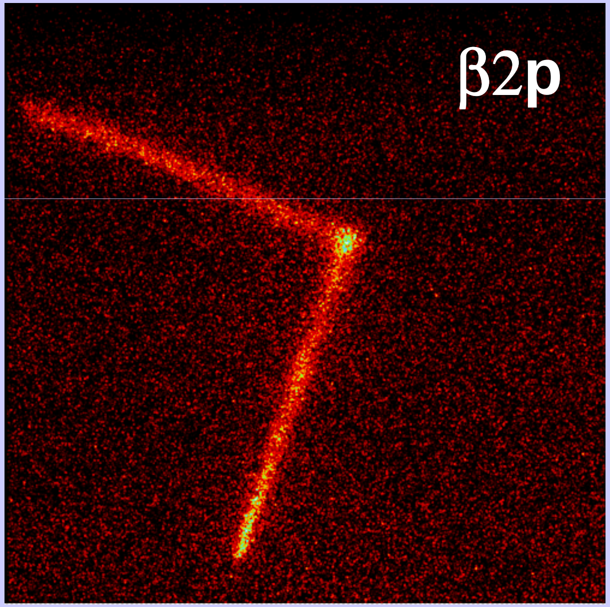


β^+ decay of ^{45}Fe

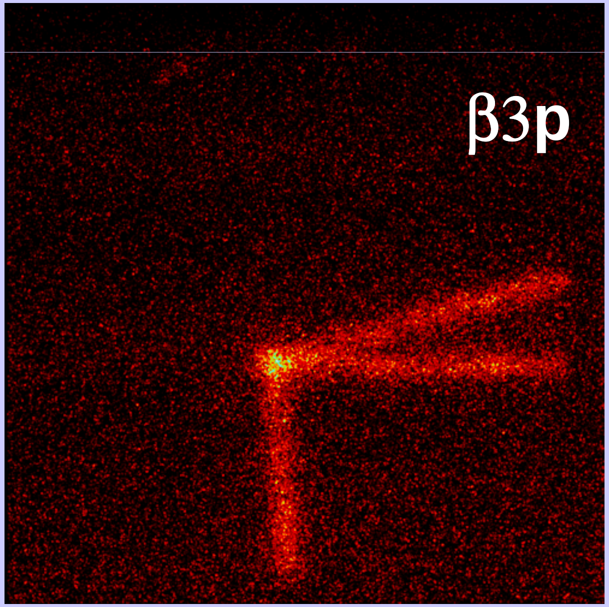
24 events



10 events

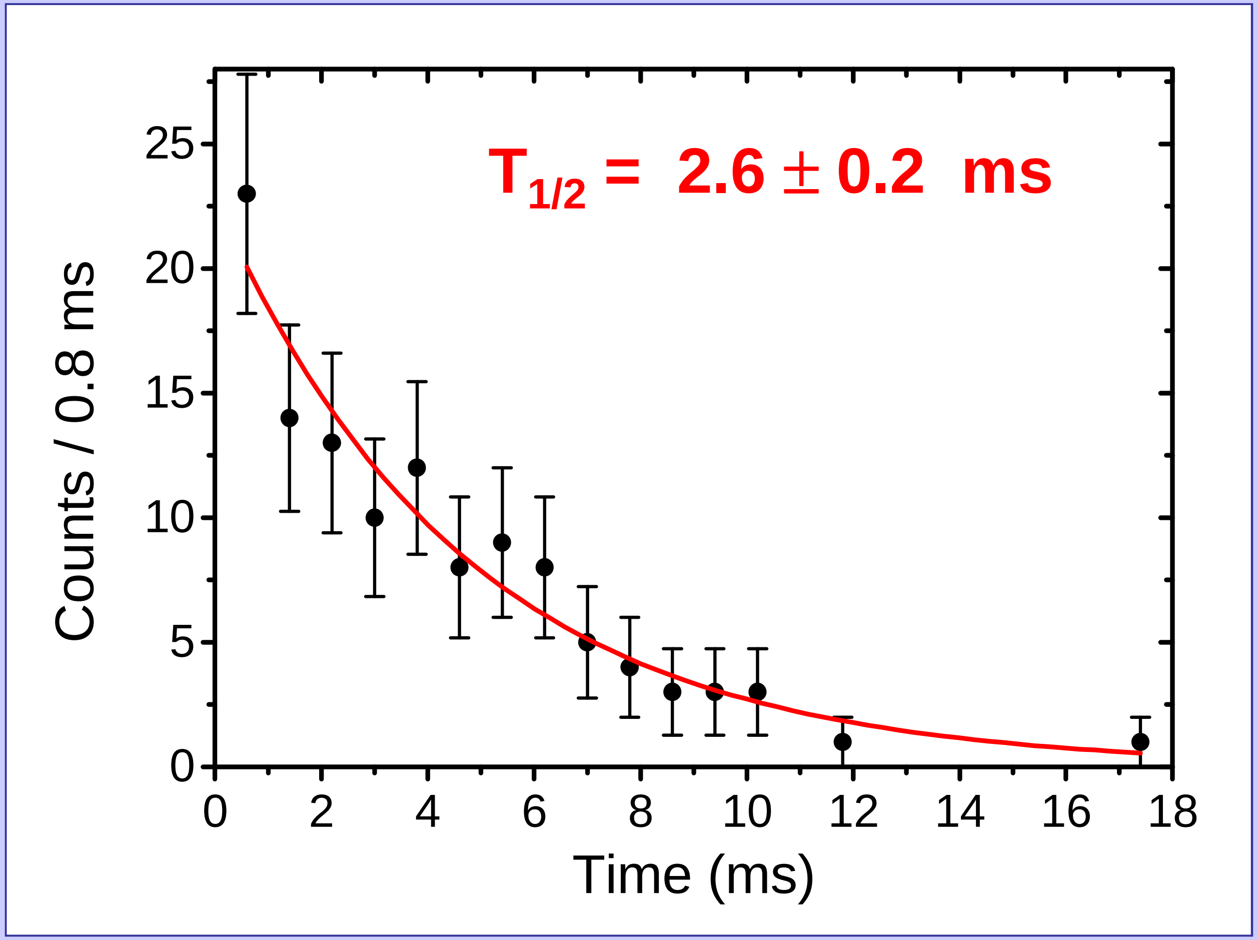


4 events

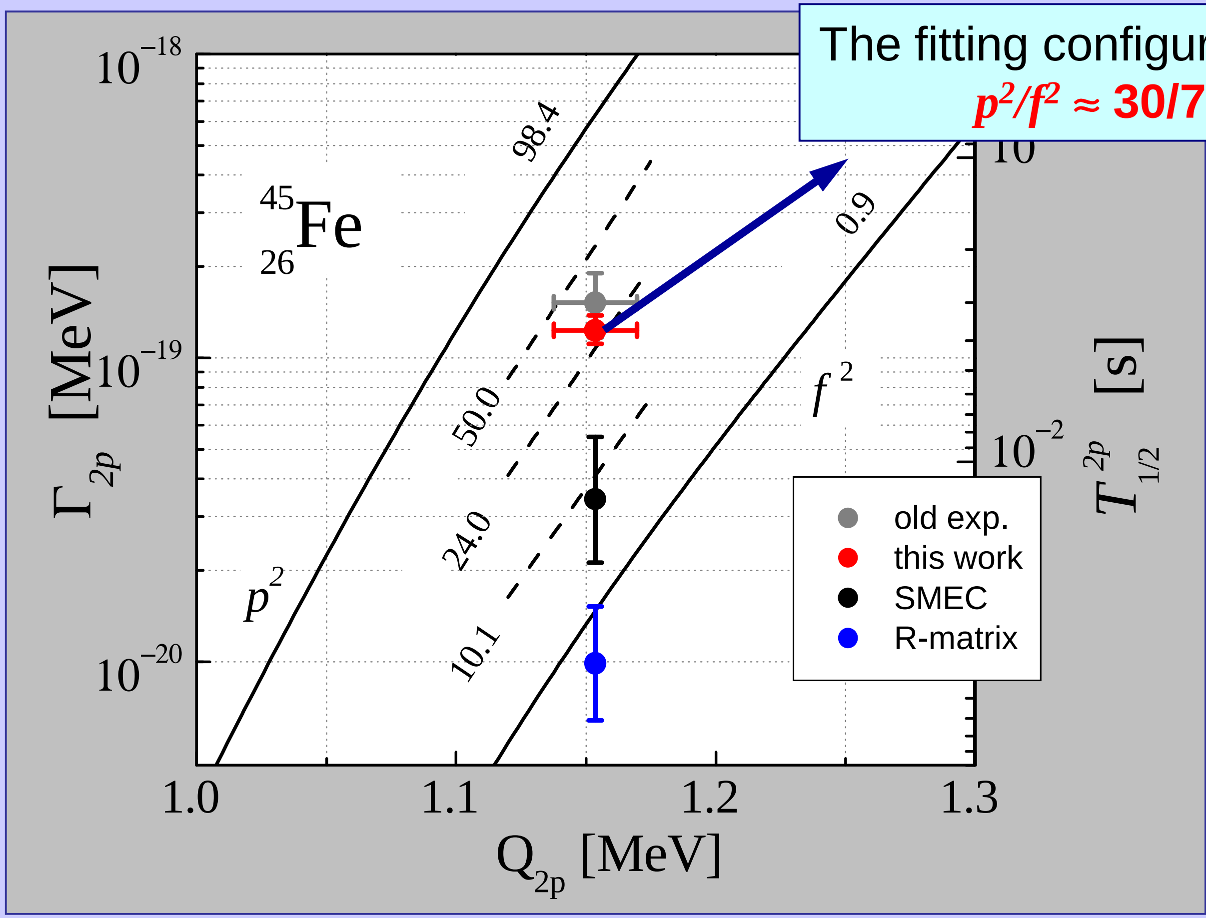


K. Miernik *et al*., PRC 76 (2007) 041304(R)

Lifetime of ^{45}Fe



Partial 2*p* half-life of ^{45}Fe



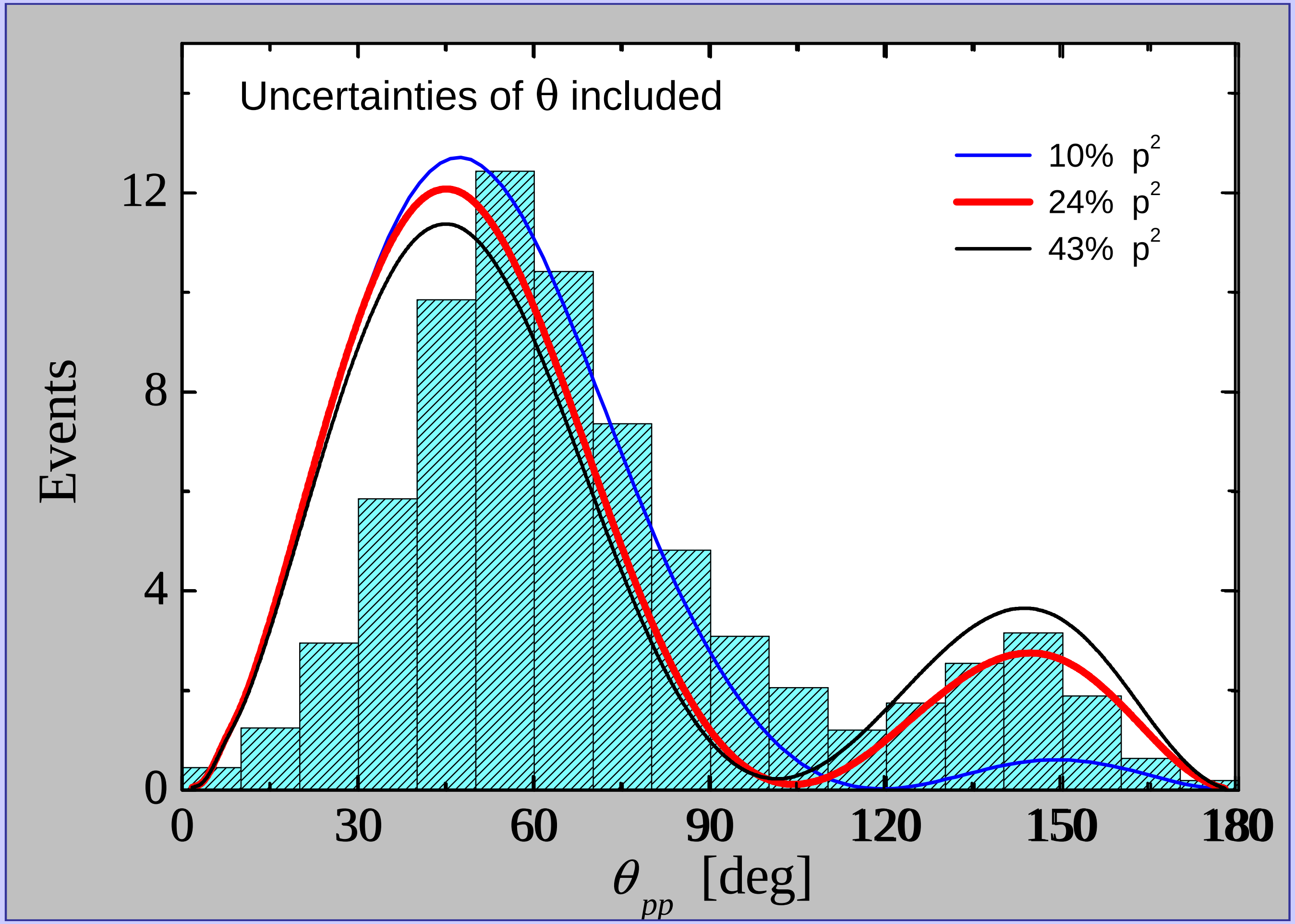
The fitting configuration
$p^2/f^2 \approx$ 30/70

3-body model: L.V. Grigorenko and M.V. Zhukov, PRC 68 (2003) 054005

SMEC: J. Rotureau, J. Okołowicz, M. Płoszajczak, NPA 767 (2006) 13

R-matrix: B.A. Brown, F.C. Barker, PRC 67 (2003) 041304

p-*p* angular correlation



K. Miernik *et al*., PRL 99, 192501 (2007)
L.V. Grigorenko and M.V. Zhukov, PRC 68 (2003) 054005

Summary

- studies of p and $2p$ decays provide information on:
  - limits of nuclear existence
  - masses of exotic nuclei
  - sequence of single-particle states
  - structure of WF of nuclear states