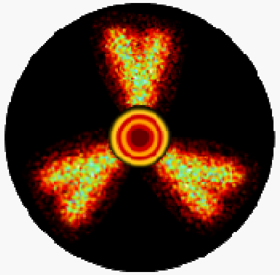
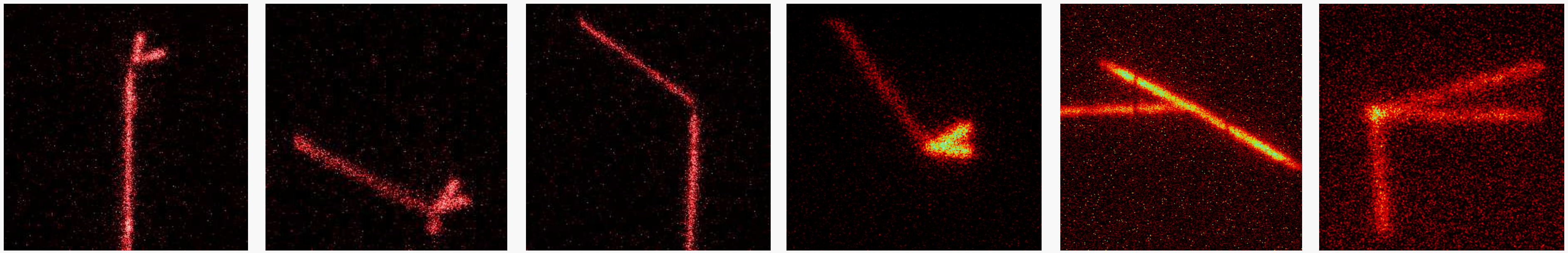
Two-proton radioactivity

Lecture 1



Marek Pfützner

Faculty of Physics, University of Warsaw



Goldansky

ON NEUTRON-DEFICIENT ISOTOPES OF LIGHT NUCLEI AND THE PHENOMENA OF PROTON AND TWO-PROTON RADIOACTIVITY

V I GOLDANSKY

P N Lebedev Physical Institute, USSR Academy of Sciences, Moscow

Received 14 March 1960

Abstract: Application of isobaric invariance principles to light nuclei leads to a very simple relation between the Z-th proton binding energy E_p in nucleus 1 $({}_ZM_N{}^A)$ and the Z-th neutron binding energy E_n in the miror nucleus 2 $({}_NM_Z{}^A)$ With an accuracy of the order of a few per cent their difference $E_{n2} - E_{p1} = \Delta E_{np}$ is independent of N for a given Z and is given by

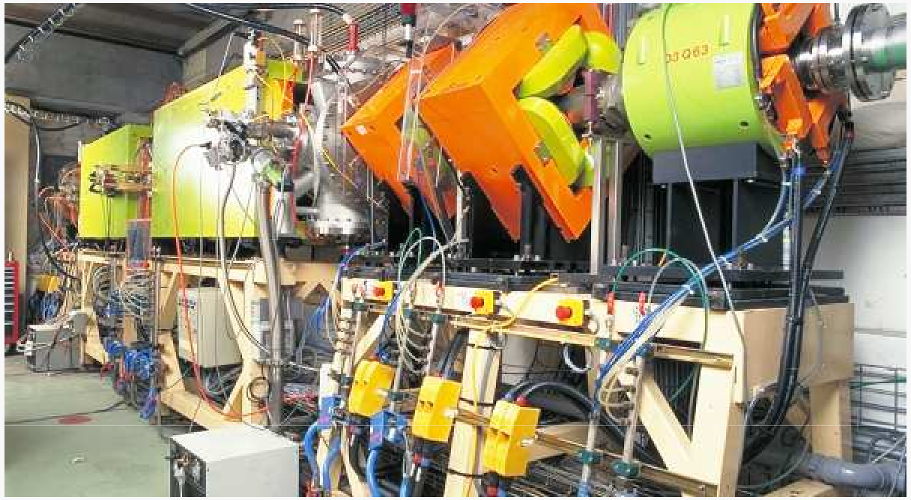
$$\Delta E_{np} \approx E_n({}_ZM_Z^{2Z}) - E_p({}_ZM_Z^{2Z}) \approx 1.2\,\frac{Z-1}{(2Z-1)^{\frac{1}{3}}},$$

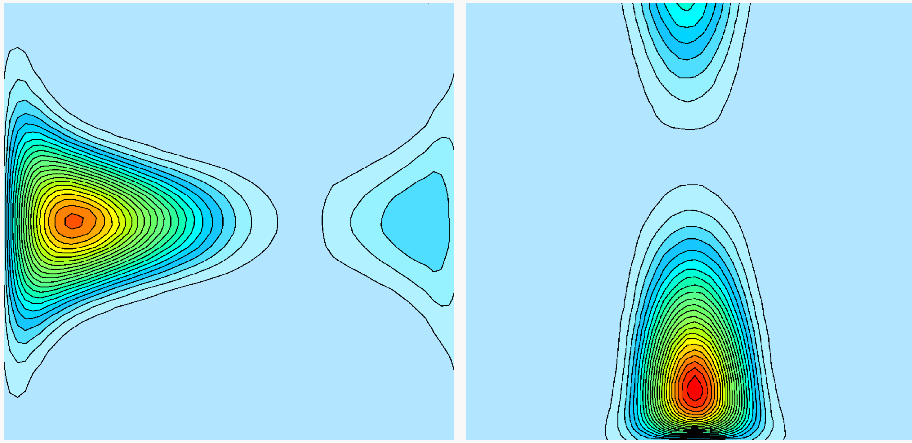
which is more correct than the usual expression $1.2\,(Z-1)/(Z+N-1)^{\frac{1}{3}}$ By exploiting this fact one can predict the existence and properties of almost ninety new neutron-deficient isotopes of light nuclei (up to $Z = 34$) and establish the limits of stability of the isotopes with respect to decay with proton emission Among the specific properties of neutron-deficient isotopes, proton and two-proton radioactivity effects which may occur are of special interest Some nuclei are indicated in which these effects may be observed The main features of a very curious phenomenon of two-proton radioactivity are discussed

Vitaly Iosifovich Goldansky
18.06.1923 (Witebsk) – 14.01.2001 (Moscow)

Nuclear Physics 19 (1960) 482

Outline





- Basic introduction
- The story of ^{45}Fe
  - mass predictions
  - production method
  - discovery of 2p decay
- Quest for p-p correlations
  - OTPC detector
  - images of ^{45}Fe decay
- Introduction to theory
  - Jacobi coordinates
  - Simplified models
- Momentum correlations
- Decays of ^{6}Be, ^{19}Mg, ^{48}Ni and ^{54}Zn
- Predictions of heavier emitters and the full 2p landscape
- Summary

What is radioactive?

- What is plotted on the chart? Present practice: all systems we know something about.
- → Should they plot only those which exist? But what does exist?

Radioactivity

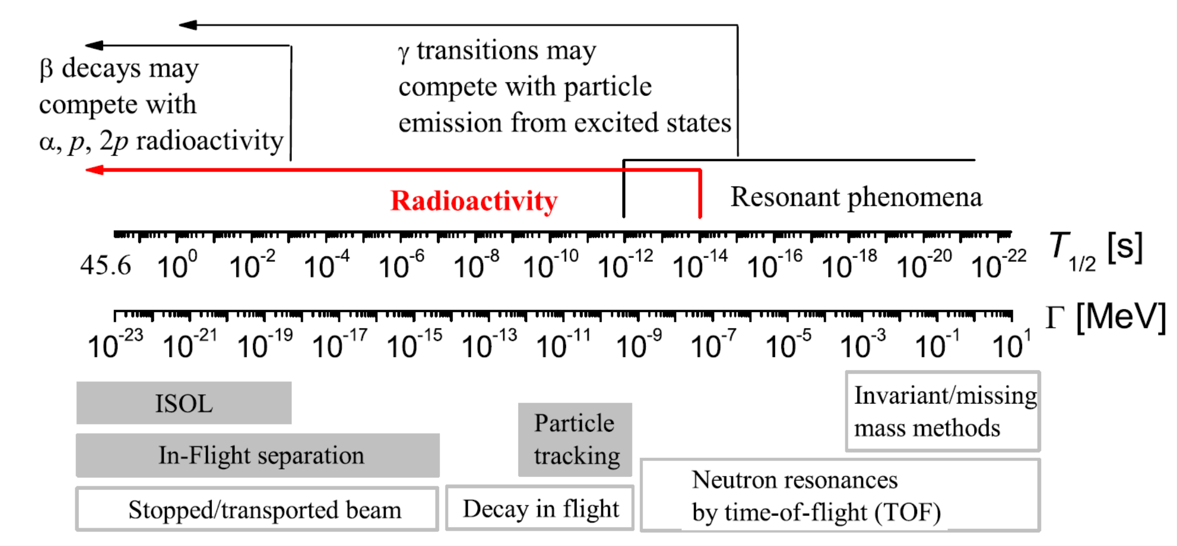
- Slow enough to form neutral atoms
- Characteristic **time** measured directly
- Independent of formation mechanism

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

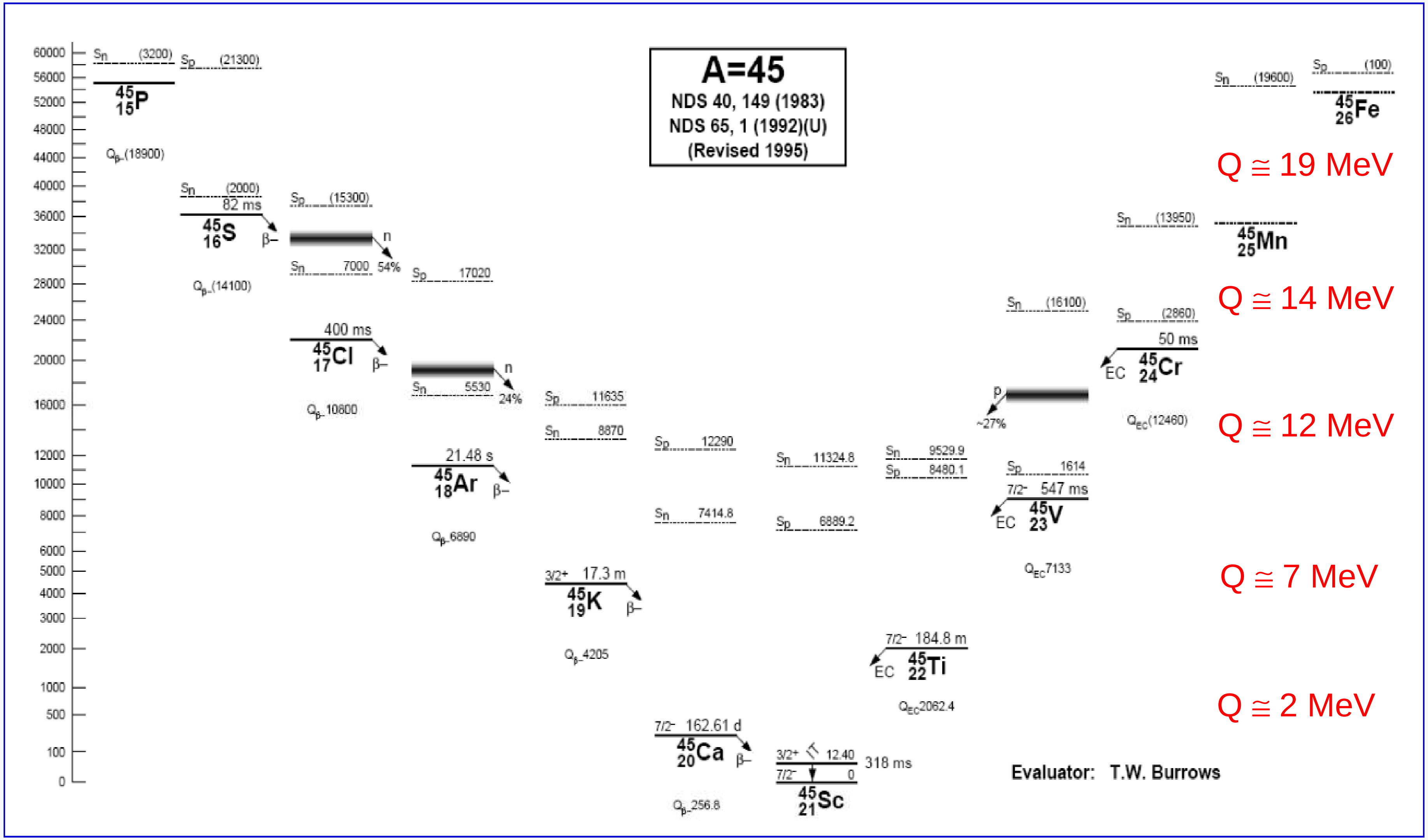
Reactions/Resonances

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

$\Gamma \geq 1$ meV

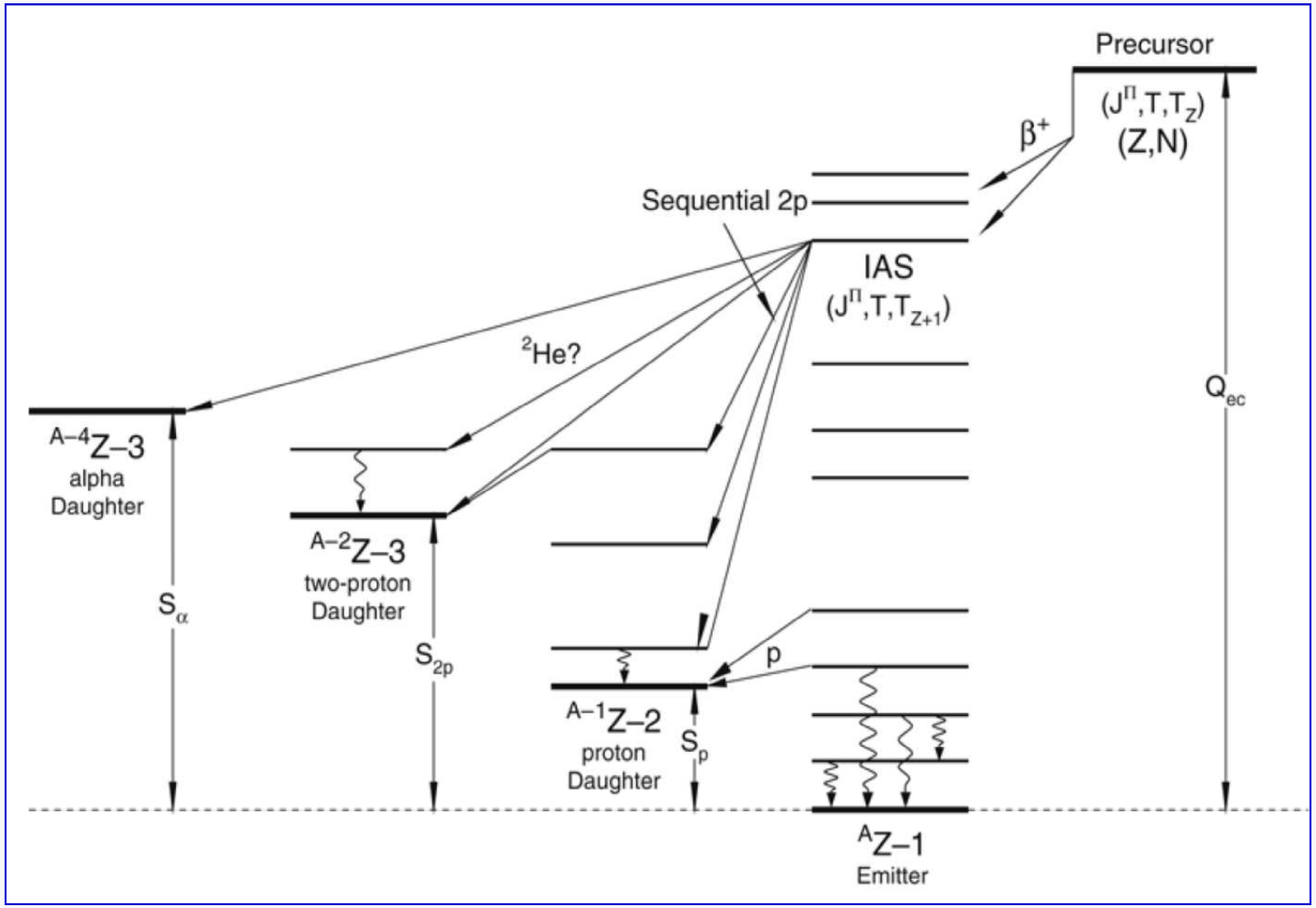


Mass parabola



β-delayed particle emission

- When the decay energy is large, many exotic decay channels open



Blank and Borge, Progress in Part. Nucl. Phys. 60 (2008) 403

Beyond the proton drip-line

Competition between two decay modes

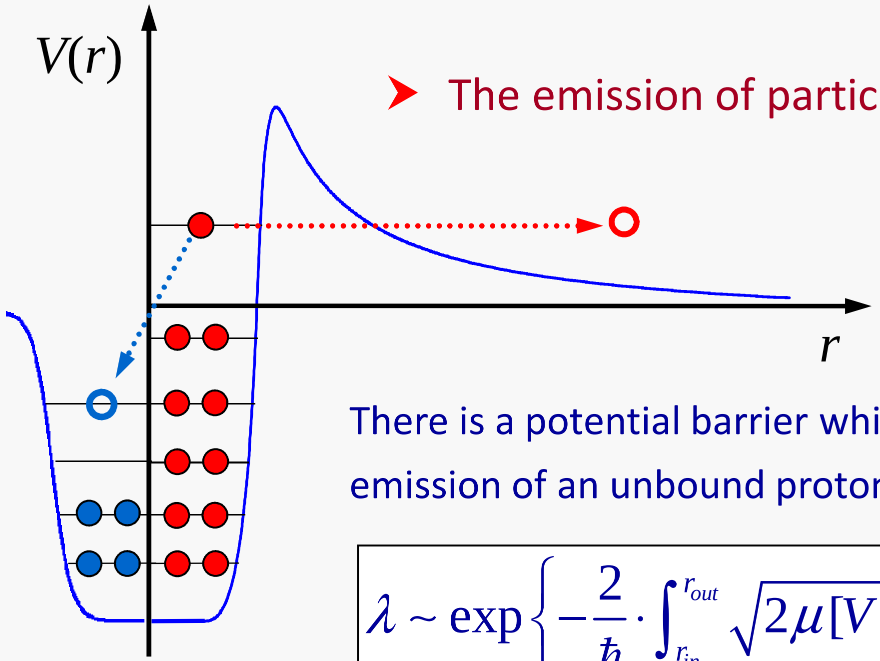
- The β^+ decay

Probability of transition:

$$\lambda \sim Q^5$$

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

→ $T_{1/2} > 1\ \text{ms}$



- The emission of particles

There is a potential barrier which hampers emission of an unbound proton (α, 2p, ^{14}C,..)

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

→ To find where the drip-line actually is and to predict which decay will happen, precise estimates of atomic masses are required!

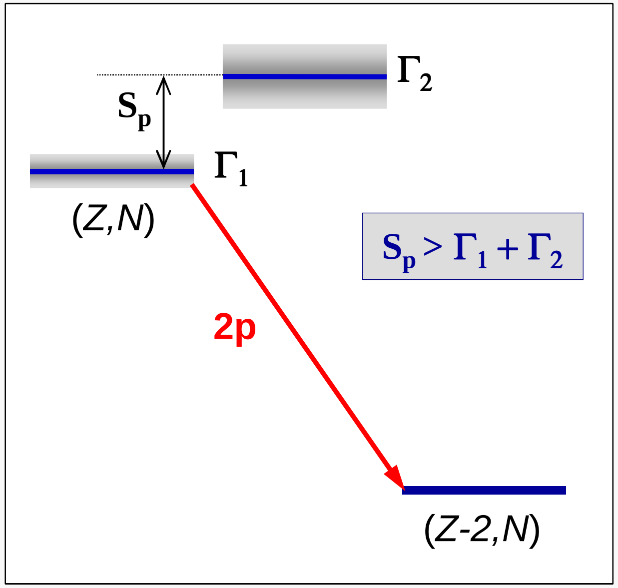
→ To study particle radioactivity fast techniques are needed!

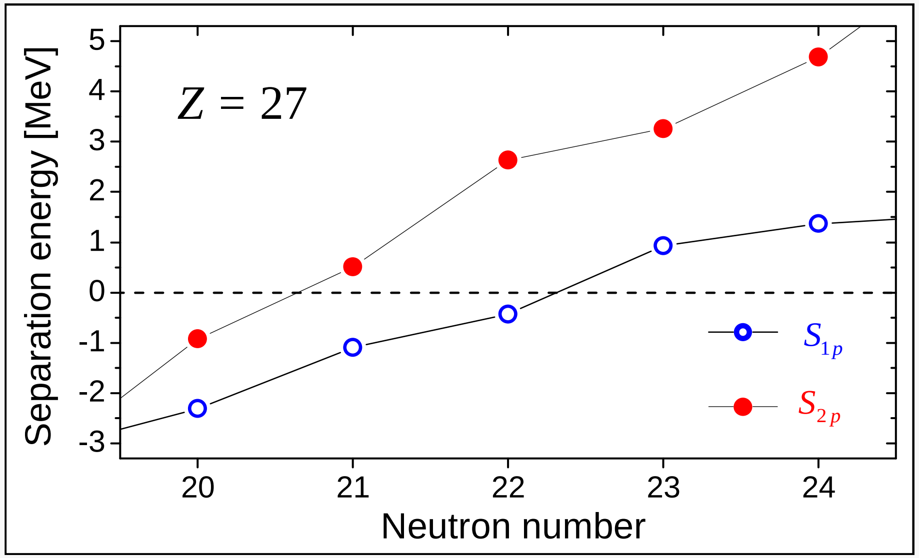
Why particle radioactivity?

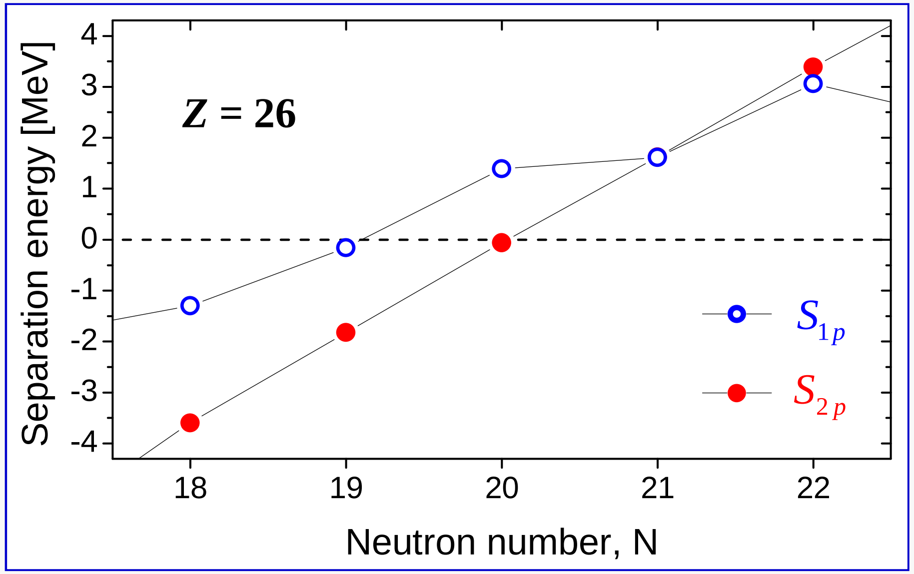
- Charged particles (p, α, 2p,…) are much easier to detect than γ or electrons
- They provide information about very exotic nuclear systems, beyond drip-line
- Allow to determine masses
- Provide a tool to investigate quantum tunneling process
- Test nuclear structure models (single particle levels)
- Probe details of nuclear wave function
- Help to understand decay dynamics
- Yield information about proton pairing
- …

Two protons can be unbound!

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







Goldansky, Nucl. Phys. 19 (1960) 482
Goldansky, Nucl. Phys. 27 (1961) 648
Goldansky, Nuovo Cimento 25, Suppl. 2 (1962) 123

Early considerations

Baz, Goldansky, Goldberg, Zeldovich,
„Light and medium nuclei at the limits of stability, Moscov 1972

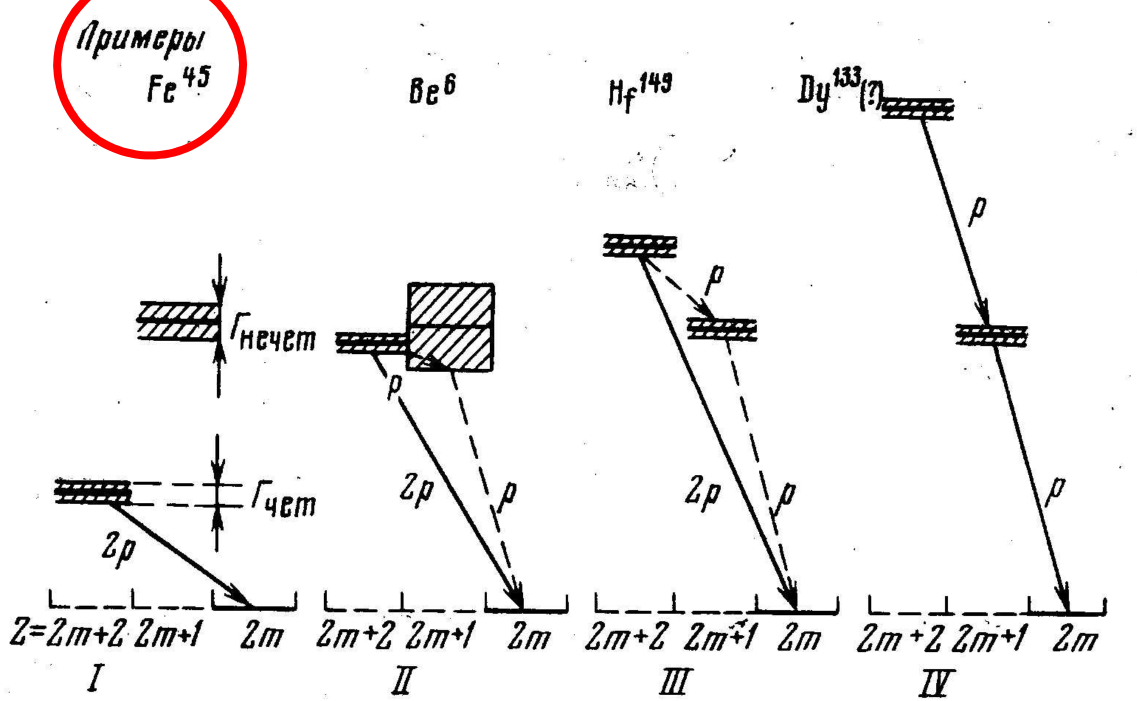
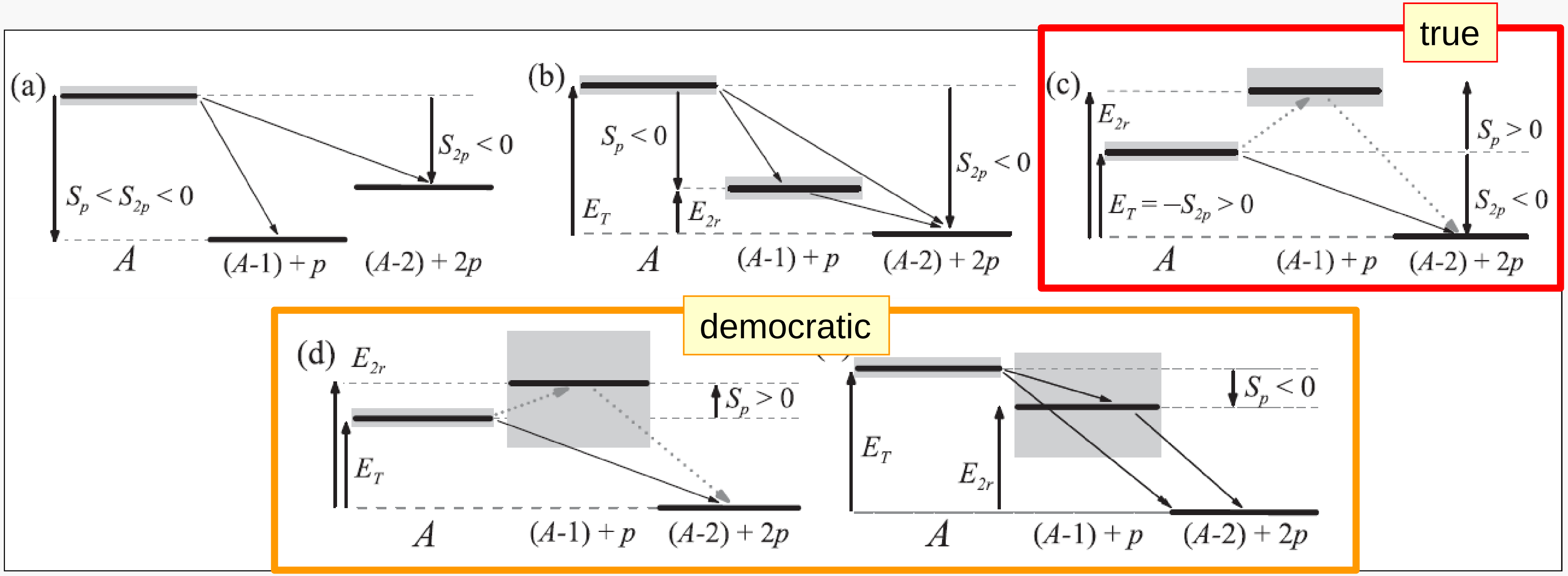


Рис. 48. Различные варианты испускания ядрами пар протонов

Two-proton emission

Energy conditions for different modes of the 2p emission



a) $^{18}Ne^{*}$

b) $^{14}O^{*}$, $^{17}Ne^{*}$

c) ^{19}Mg , ^{45}Fe, ^{48}Ni, ^{54}Zn,...

d,e) ^{6}Be , ^{12}O(?)

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

Pfutzner, Karny, Grigorenko, Riisager, Rev. Mod. Phys. 84 (2012) 567

Predicting masses

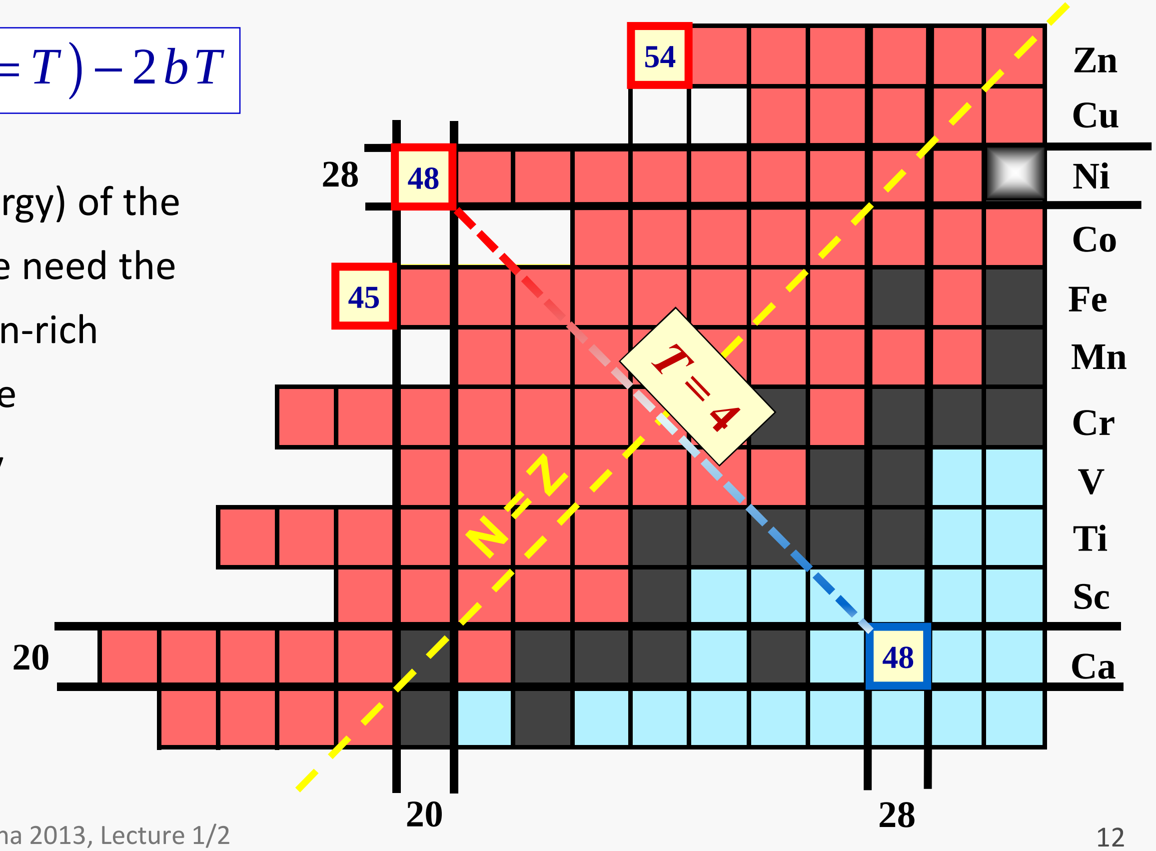
- Global mass models are not precise enough to determine the decay mode.
  However, there is a trick based on the Isobaric Multiplet Mass Equation (IMME):

$$BE(A,T,T_z) = a(A,T) + b(A,T)T_z + c(A,T)T_z^2$$

$$T_z = (N-Z)/2$$

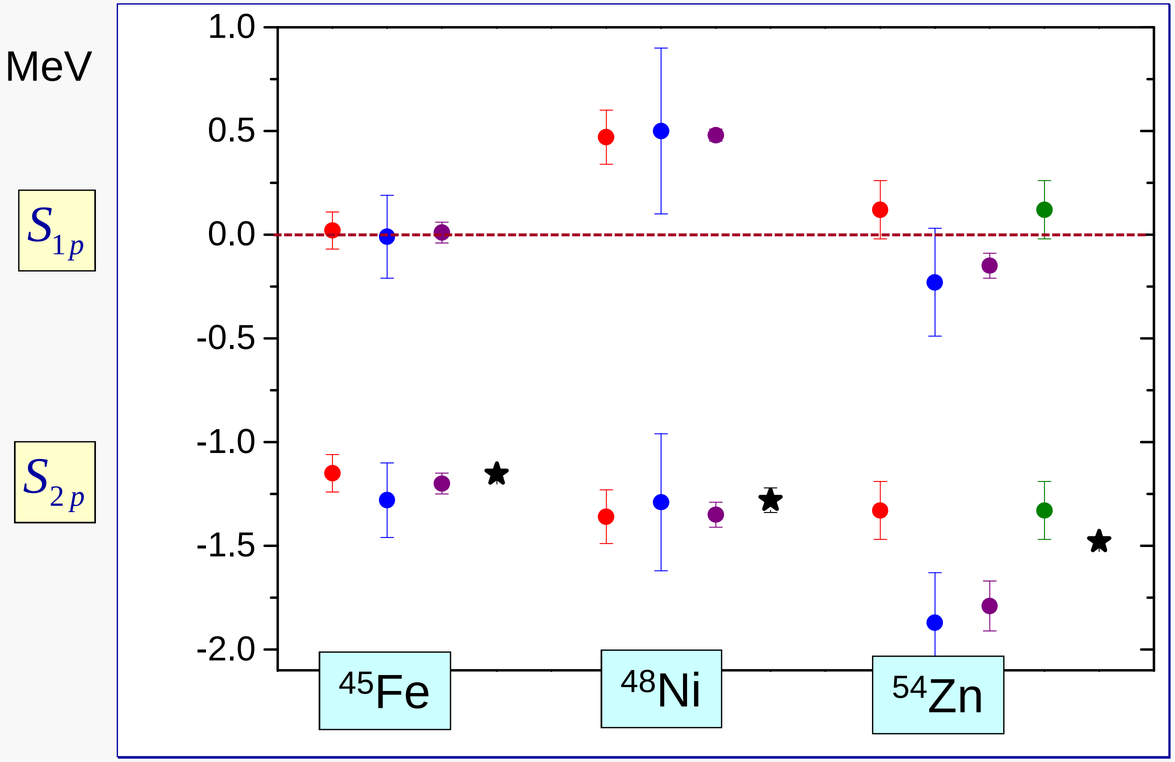
$$BE(T_z=-T) = BE(T_z=T) - 2bT$$

- To get the mass (binding energy) of the neutron-deficient nuclide, we need the **measured mass** of its neutron-rich analogue and the value of the coefficient *b* from the theory (shell-model, systematics…)



First 2p candidates

Predicted 1p and 2p separation energies



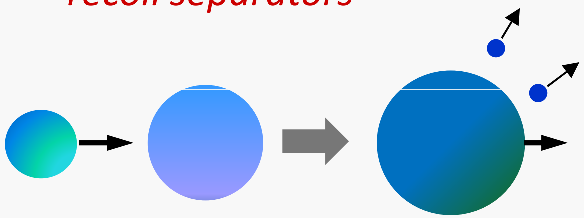
- Brown, PRC 43 (91) R1513
- Ormand, PRC 55 (97) 2407
- Cole, PRC 54 (96) 1240
- Brown *et al.*, PRC 65 (02) 045802

★ Exp

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



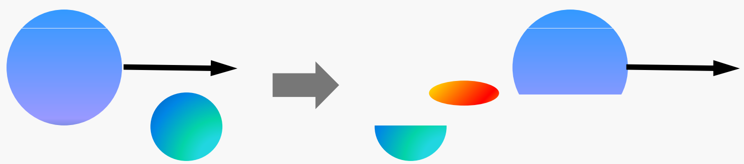
Low energy: ≈ Coulomb barrier

- large beam intensity
- thin target

identification by decays

p and α radioactivity,
(also superheavy elements)

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



High energy: ≈ above Fermi energy

- lower beam intensity
- thick target

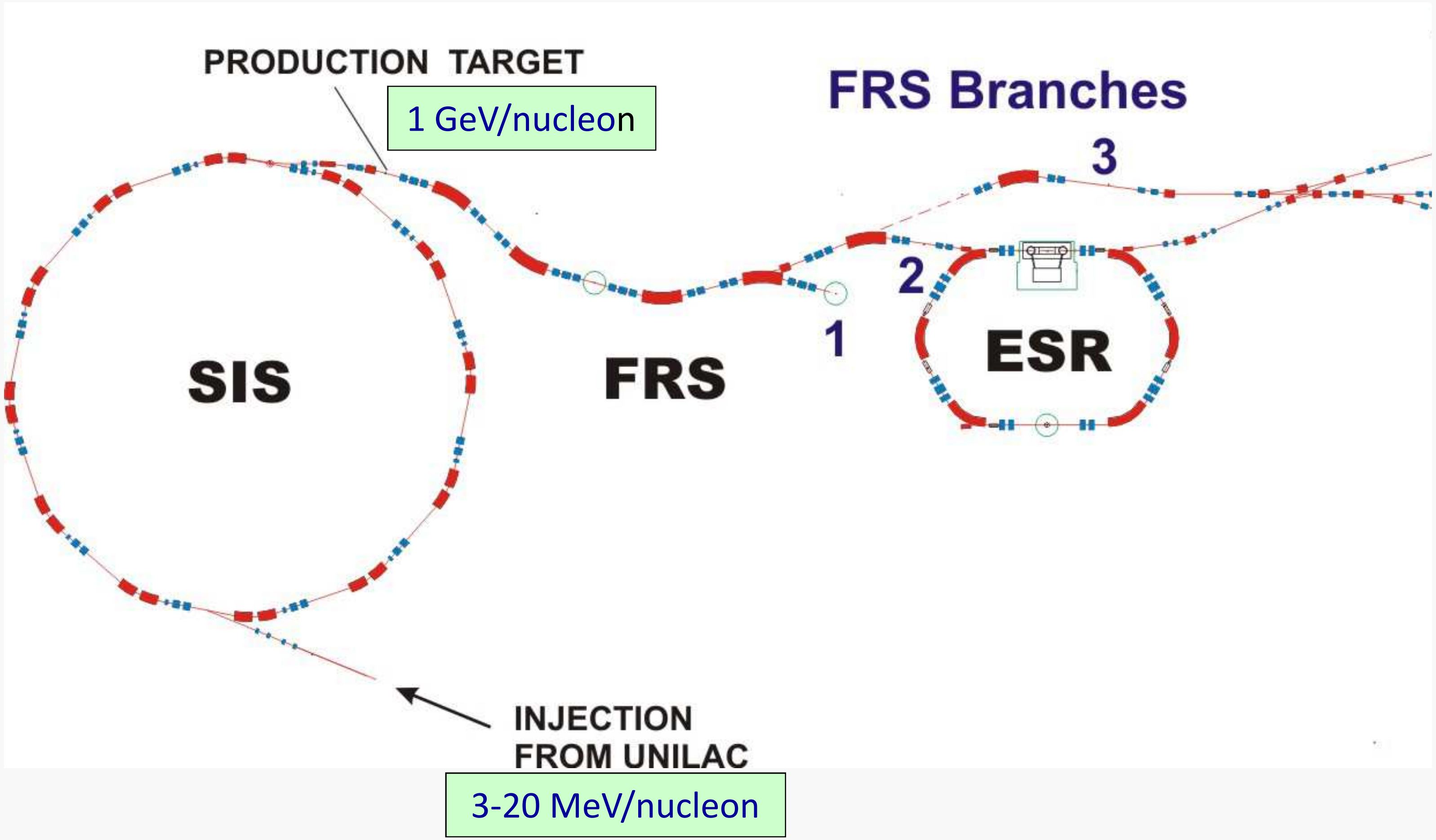
identification in-flight

single ion sensitivity

2p radioactivity

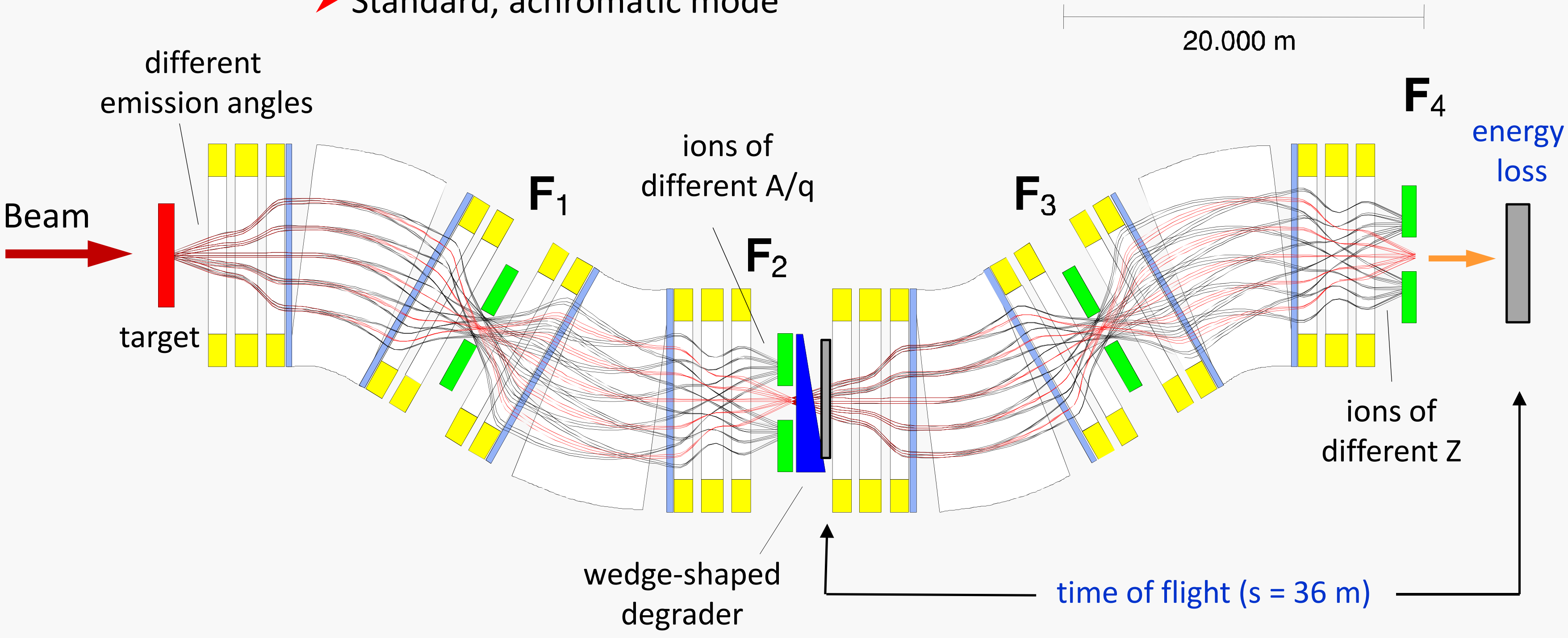
Fragment separator

Example: FRS at GSI Darmstadt



FRS – ion optics and particle ID

➤ Standard, achromatic mode



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

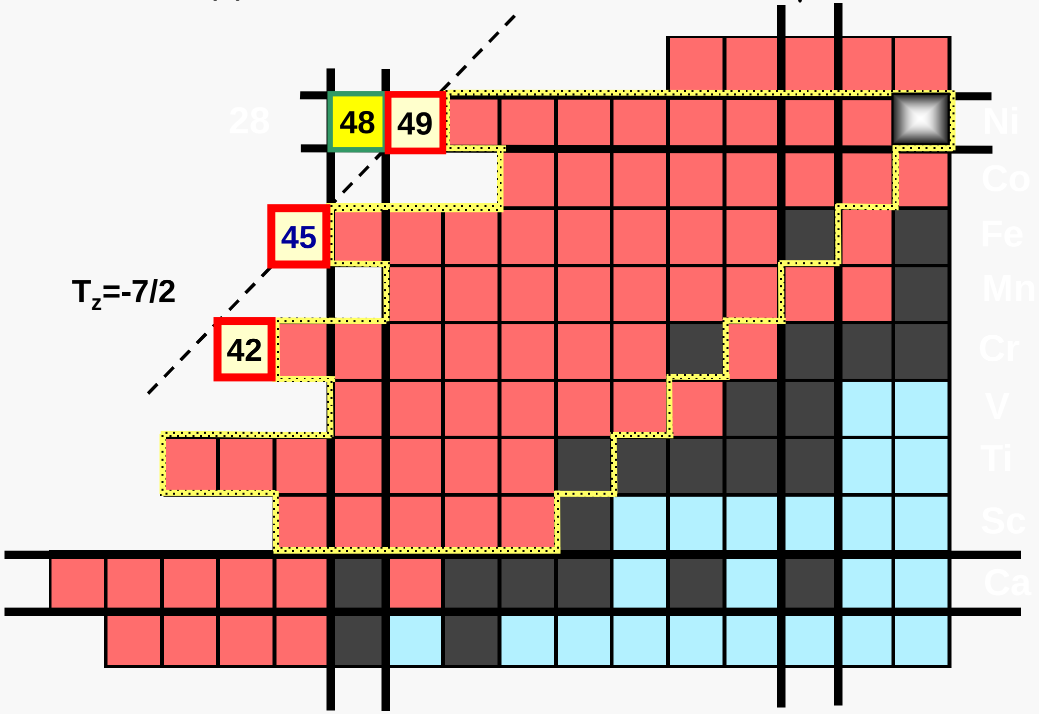
➤ Full in-flight identification of each ion

Geissel et al., NIM B70 (1992) 286

A long way to discovery

by Bordeaux-GANIL-GSI-Warsaw collaboration

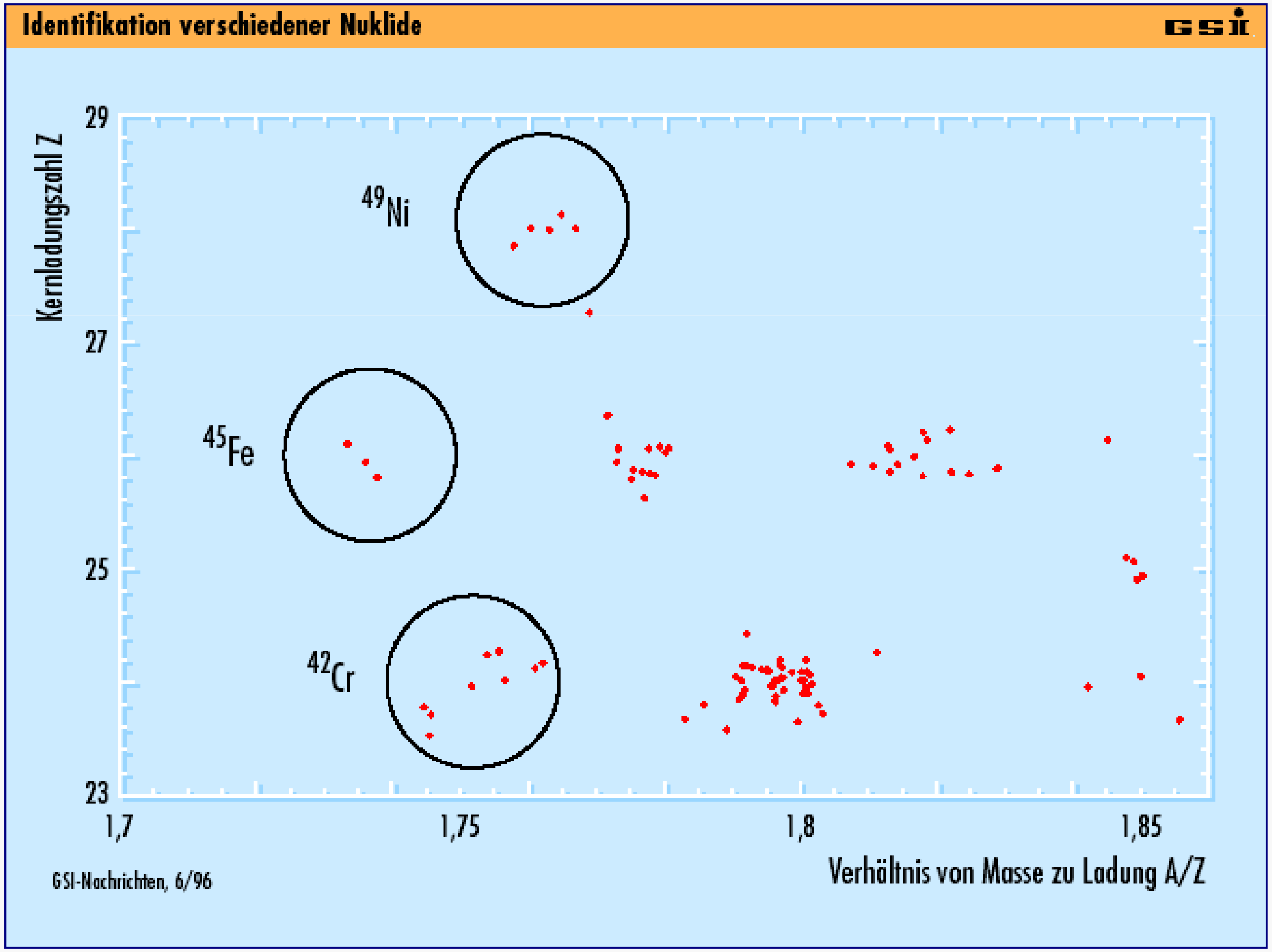
- **GSI 1992 :** first experiment, determination of x-sections, ^{50}Ni
- **GSI 1996 :** first observation of ^{45}Fe (3 ions!), ^{49}Ni and ^{42}Cr
- **GANIL 1999 :** discovery of ^{48}Ni, 53 ions of ^{45}Fe
- **GANIL VII 2000 :** next attempt of ^{45}Fe spectroscopy : 22 ions of ^{45}Fe
- **GSI VII 2001 :** new approach to ^{45}Fe studies : focus on μs lifetimes



Example of identification

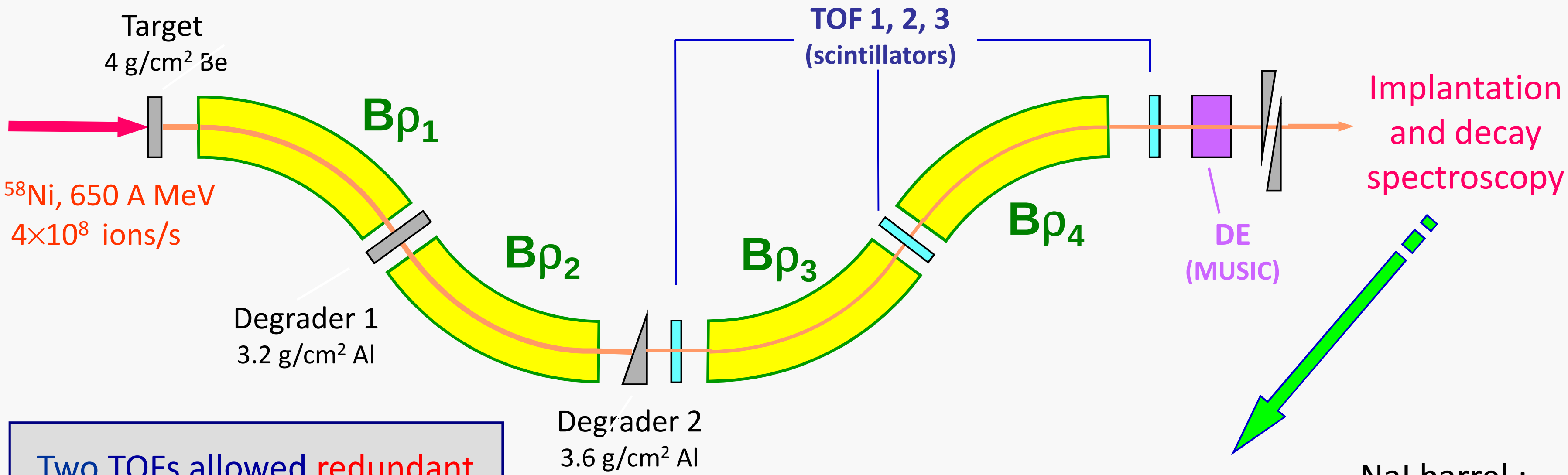
➤ First observation of three new nuclides : ^{42}Cr, ^{45}Fe i ^{49}Ni

FRS, GSI, 1996

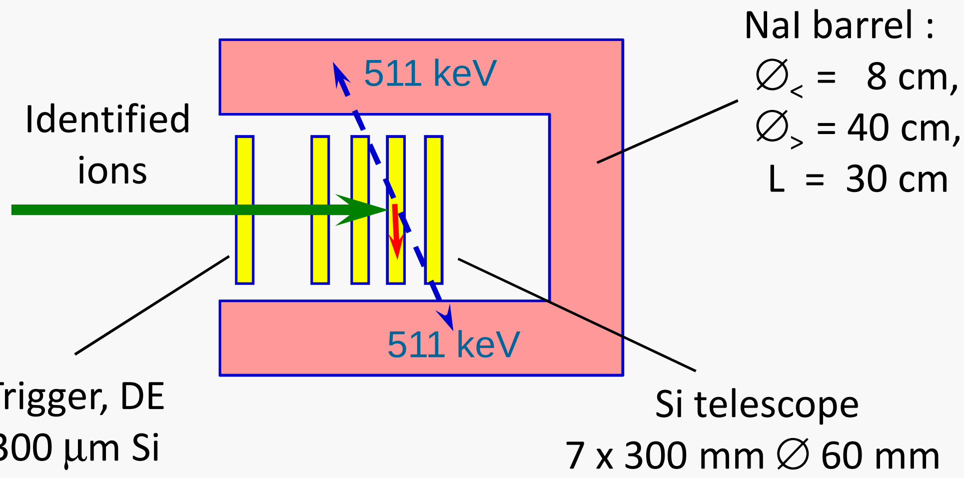


Decay of ^{45}Fe studied at GSI

- FRS @ GSI July 2001



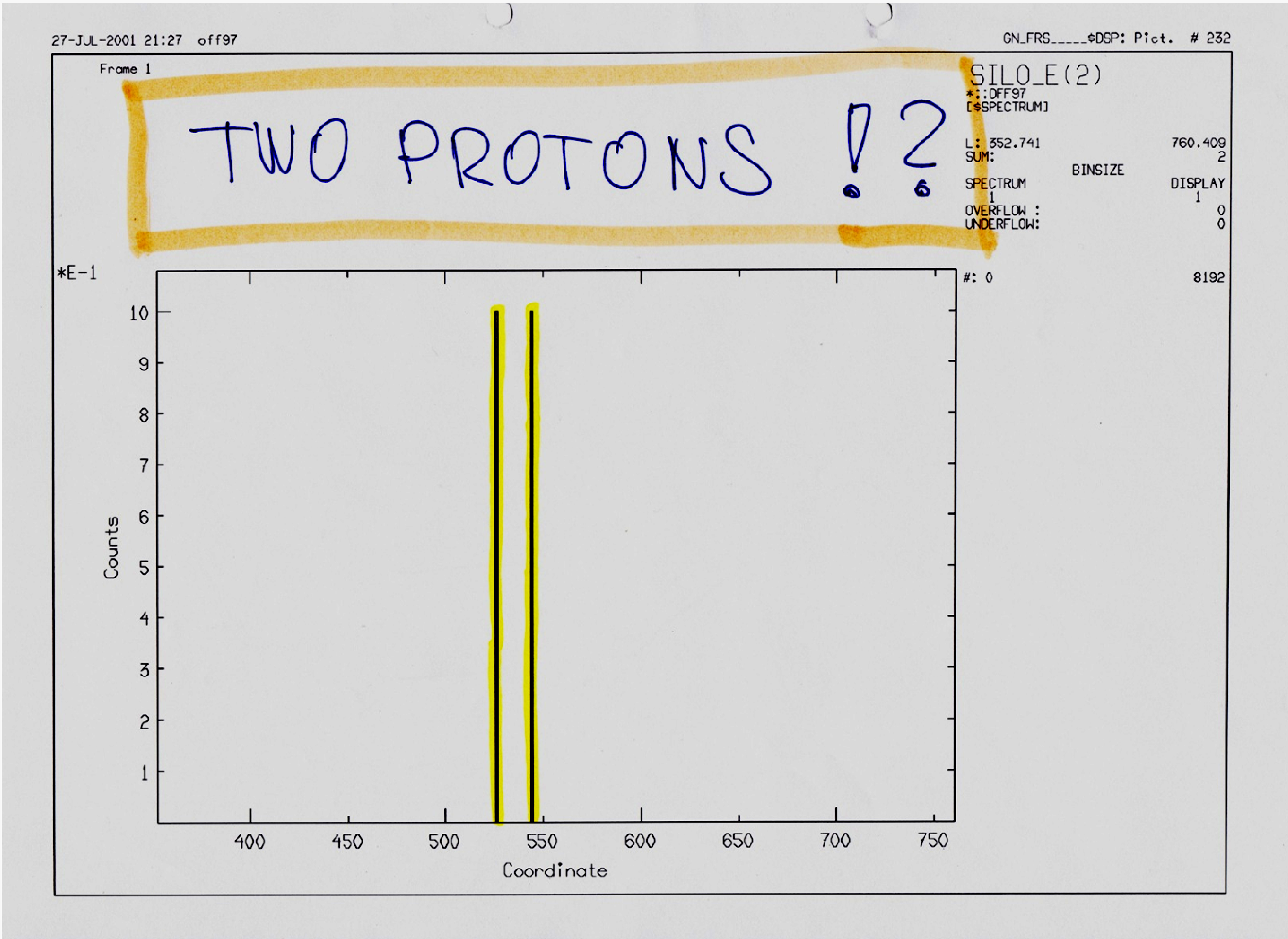
Two TOFs allowed redundant in-flight identification by the Bρ – TOF – ΔE method



Dead-time free recording of all events following the implantation due to digital electronics (XIA)
→ great sensitivity!

On-line joke ?

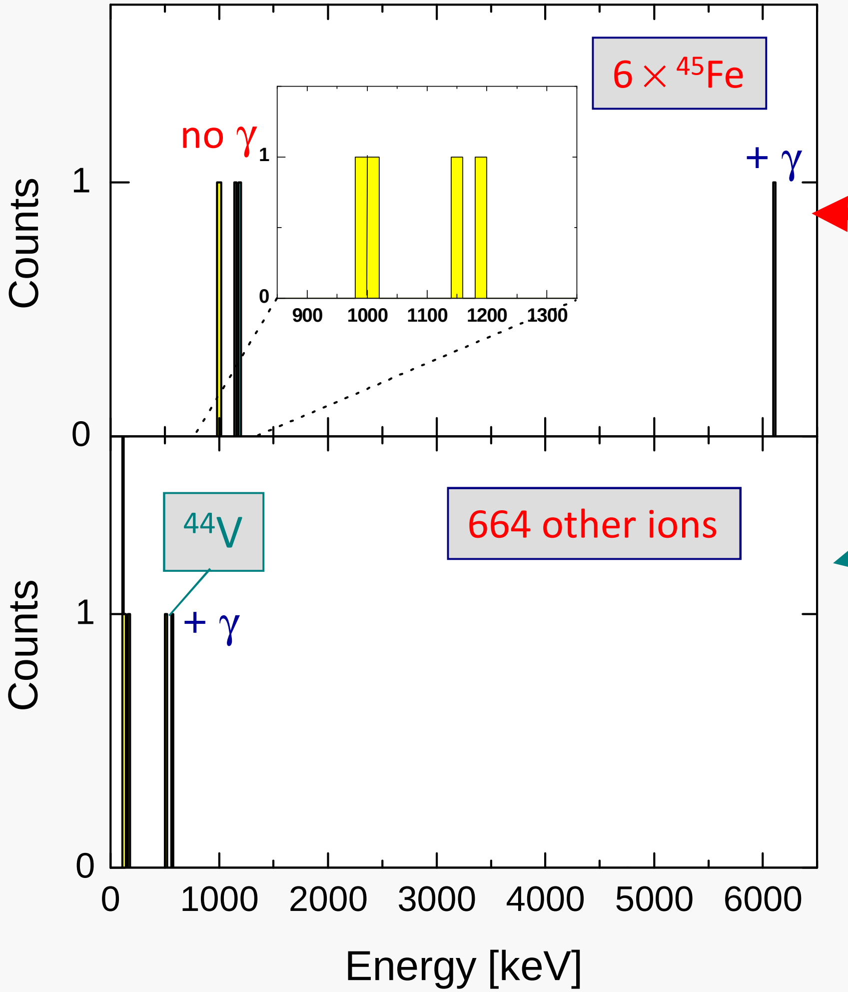
FRS Messhütte, 27 July, 2001

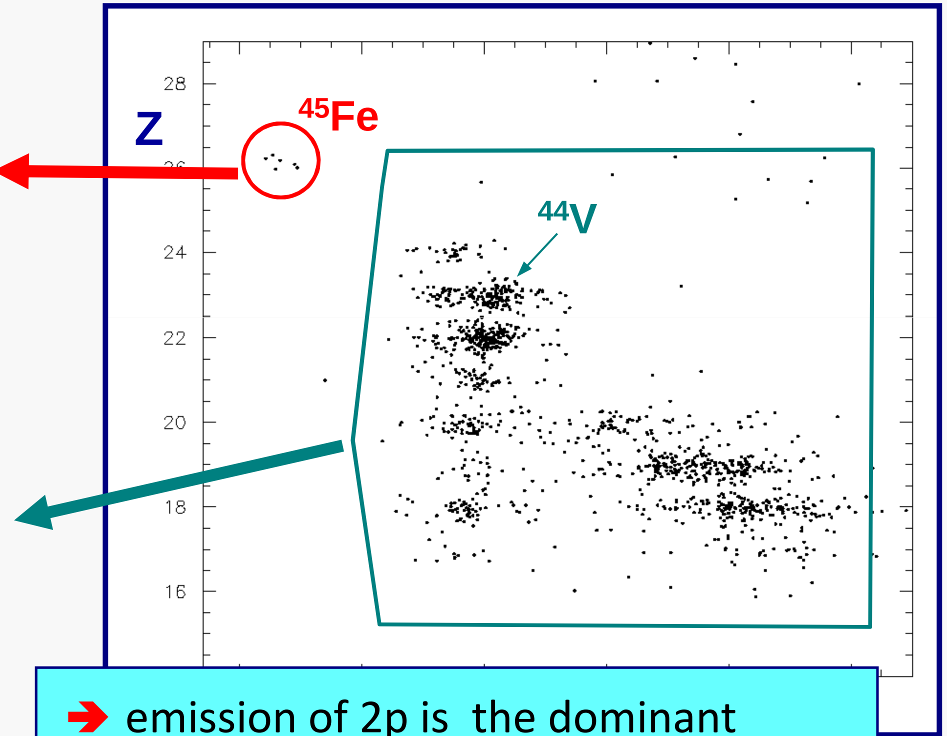


Results from the GSI experiment

Events correlated with the stopped ions : implantation and decay in the same detector

M. P. et al., EPJ A 14 (2002) 279
M. P. et al., NIM A 493 (2002) 155





➔ emission of 2p is the dominant (80%) decay mode of ^{45}Fe :

E_{2p} = 1.1(1) MeV

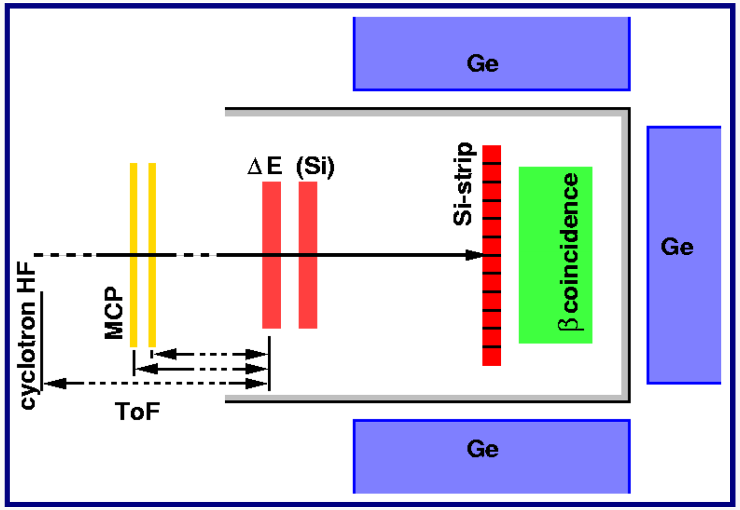
$T_{1/2} = 3.2^{+2.6}_{-1.0}$ ms

Results from the GANIL experiment

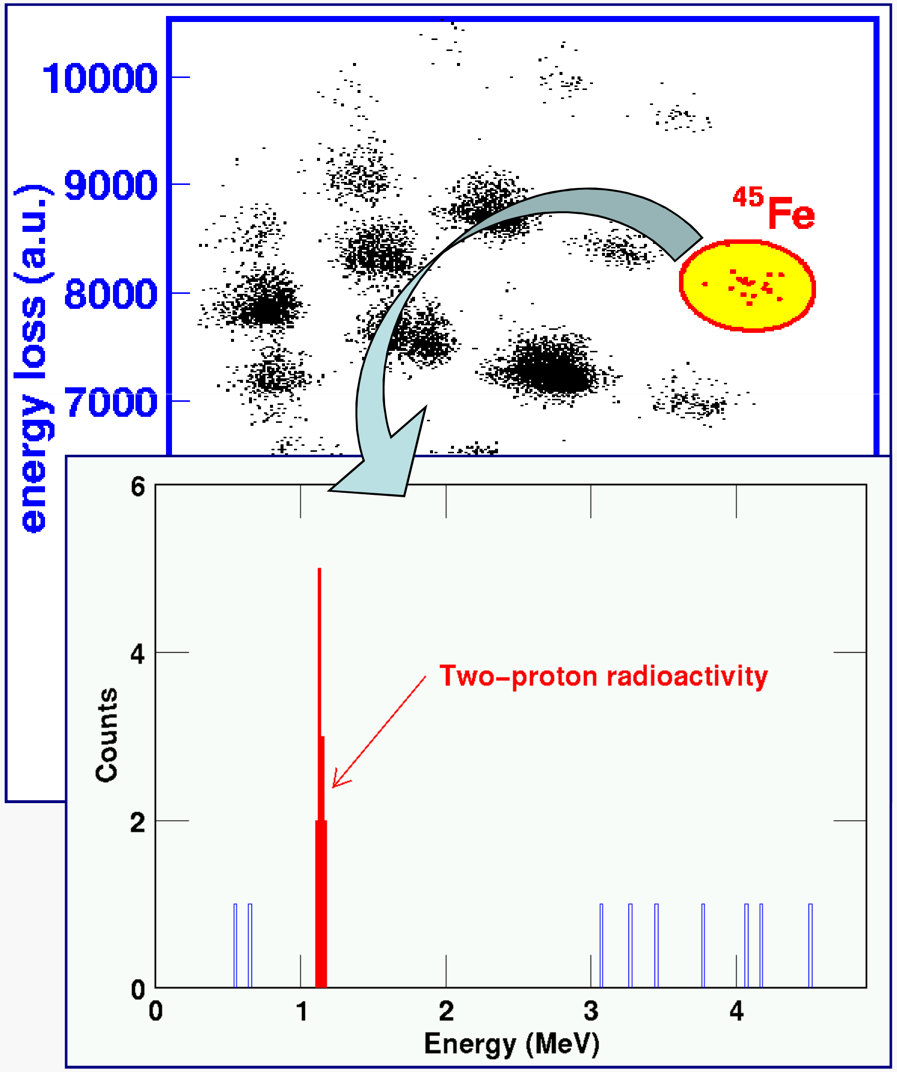
- LISE @ GANIL July 2000

J. Giovinazzo et al., PRL 89 (2002) 102501

^{58}Ni @ 75 MeV/A on nickel target
High primary beam intensity: 3-5μA



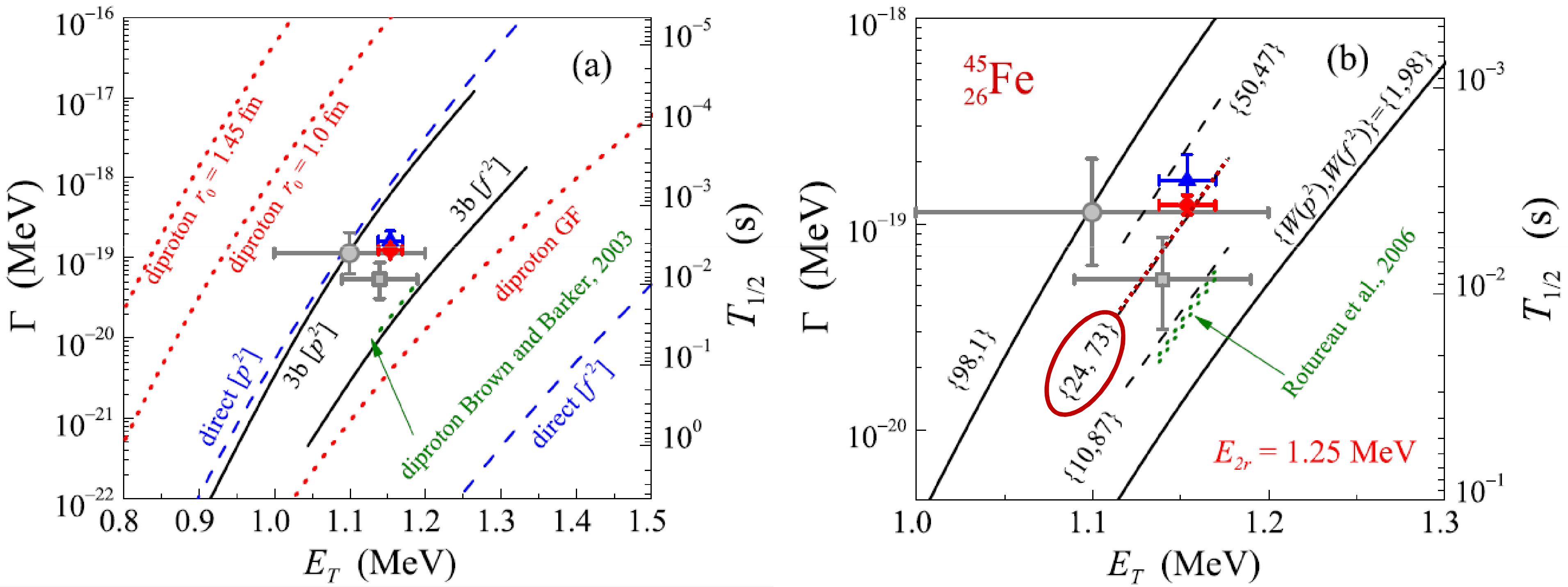
- 22 ions of ^{45}Fe implanted
  - 12 counts in a narrow peak
  - no β and no γ in coincidence
  - no βp pile-up



$E_{2p} = 1.14(5)$ MeV
$T_{1/2} = 4.7^{+3.4}_{-1.4}$ ms

^{45}Fe: decay energy and time

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

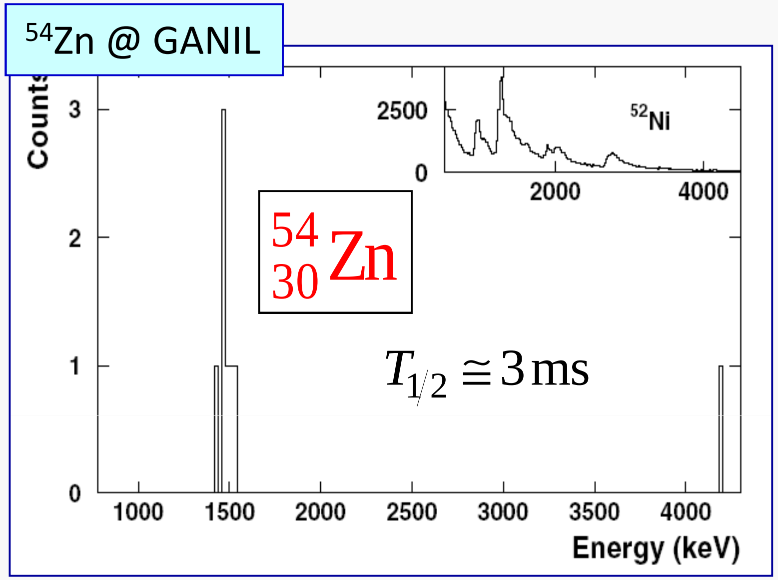


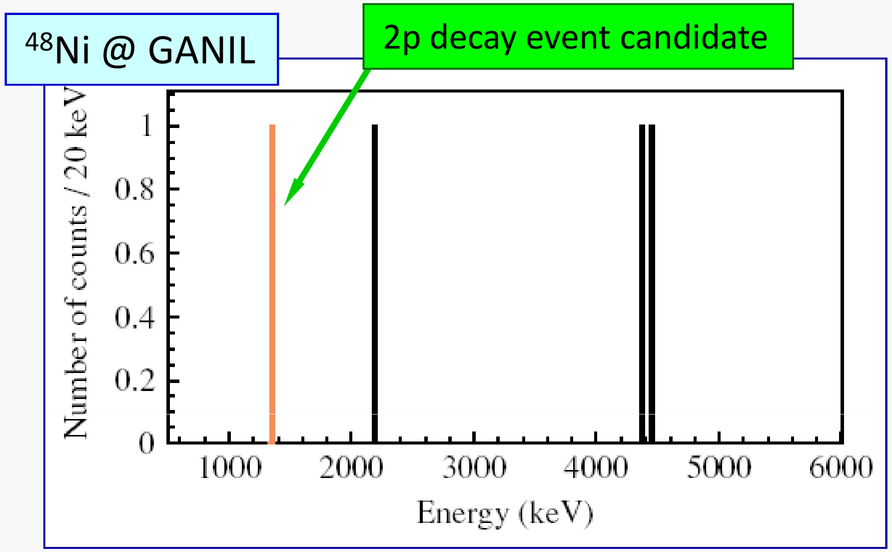
Grigorenko and Zhukov, Phys. Rev. C 68 (2003) 054005

Brown and Barker, PRC 67 (2003) 041304(R)

Rotureau, Okołowicz, and Płoszajczak, Nucl. Phys. A767 (2006) 13

Other *2p* candidates





GANIL: fragmentation of ^{58}Ni beam @ 75 MeV/u

8 ^{54}Zn ions implanted in a Si strip detector

B. Blank et al., PRL 94 (05) 232501

GANIL: fragmentation of ^{58}Ni beam @ 75 MeV/u

4 ^{48}Ni ions implanted in a Si strip detector

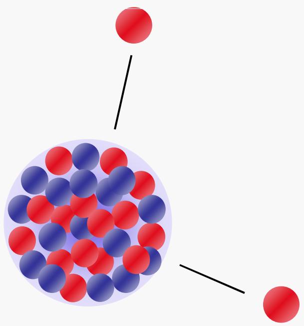
C. Dossat et al., PRC 72 (05) 054315

- Total decay energy and half-life can be precisely measured after implantation into a thick Si detector. Then, however, information on individual proton's momenta is lost!

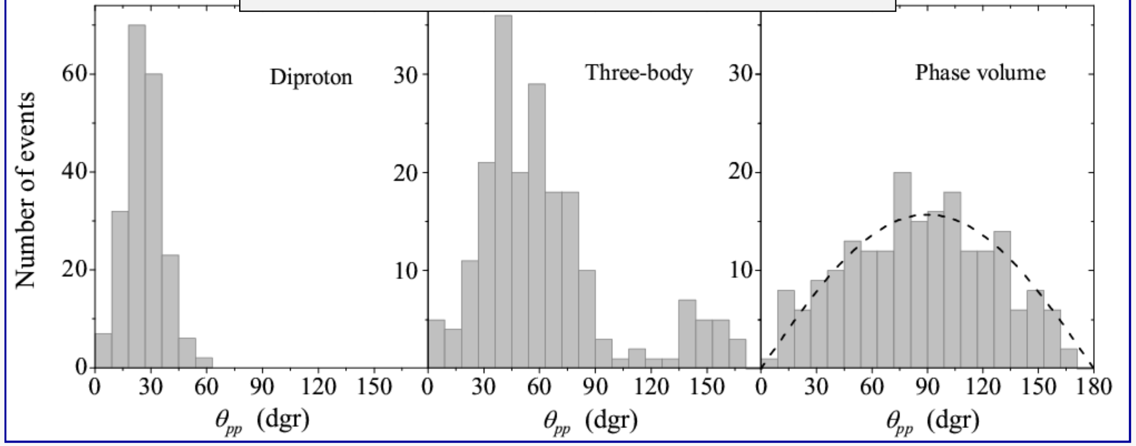
The experimental challenge of 2p decay

- 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.

- The goal: detect both protons separately, measure their energies, and determine their angular distribution



Predicted 2p opening angle for ^{45}Fe

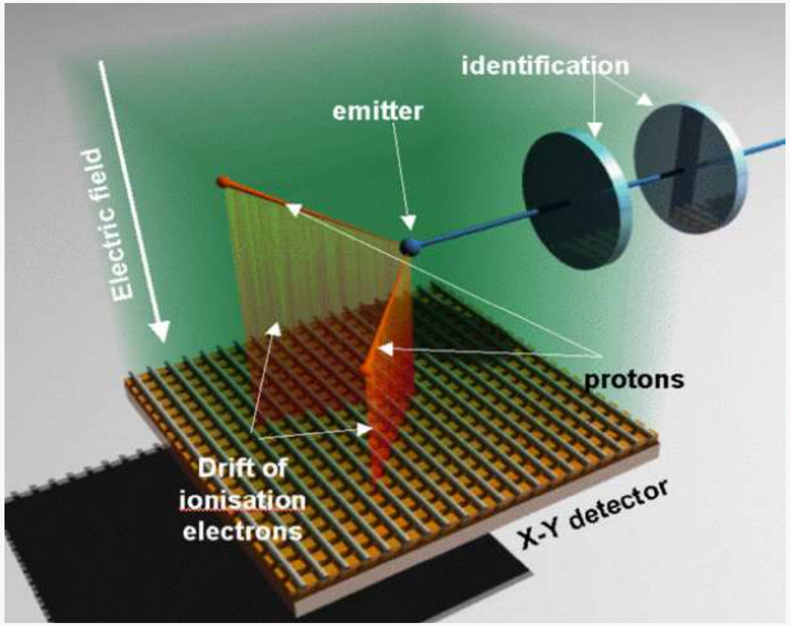


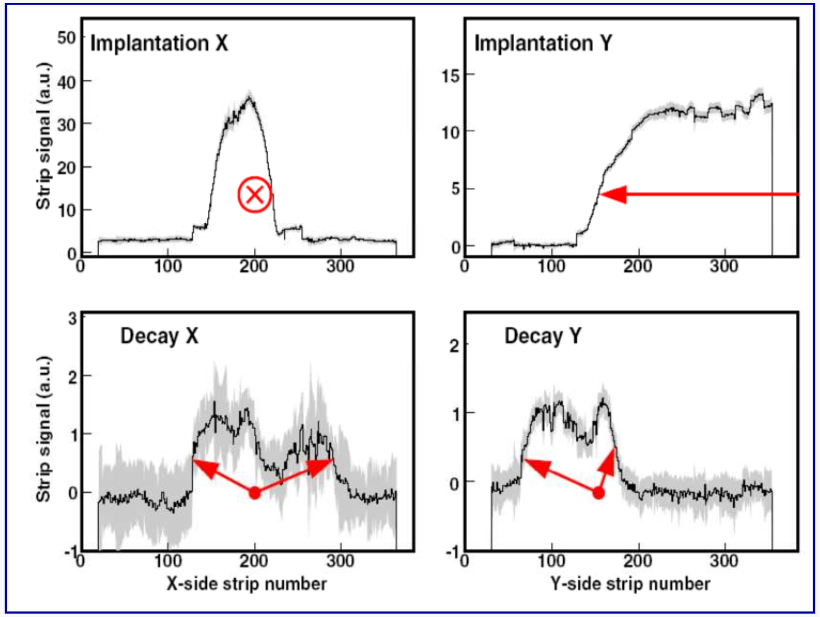
L. Grigorenko : simulation for 200 events

Solution: a TPC detector

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.





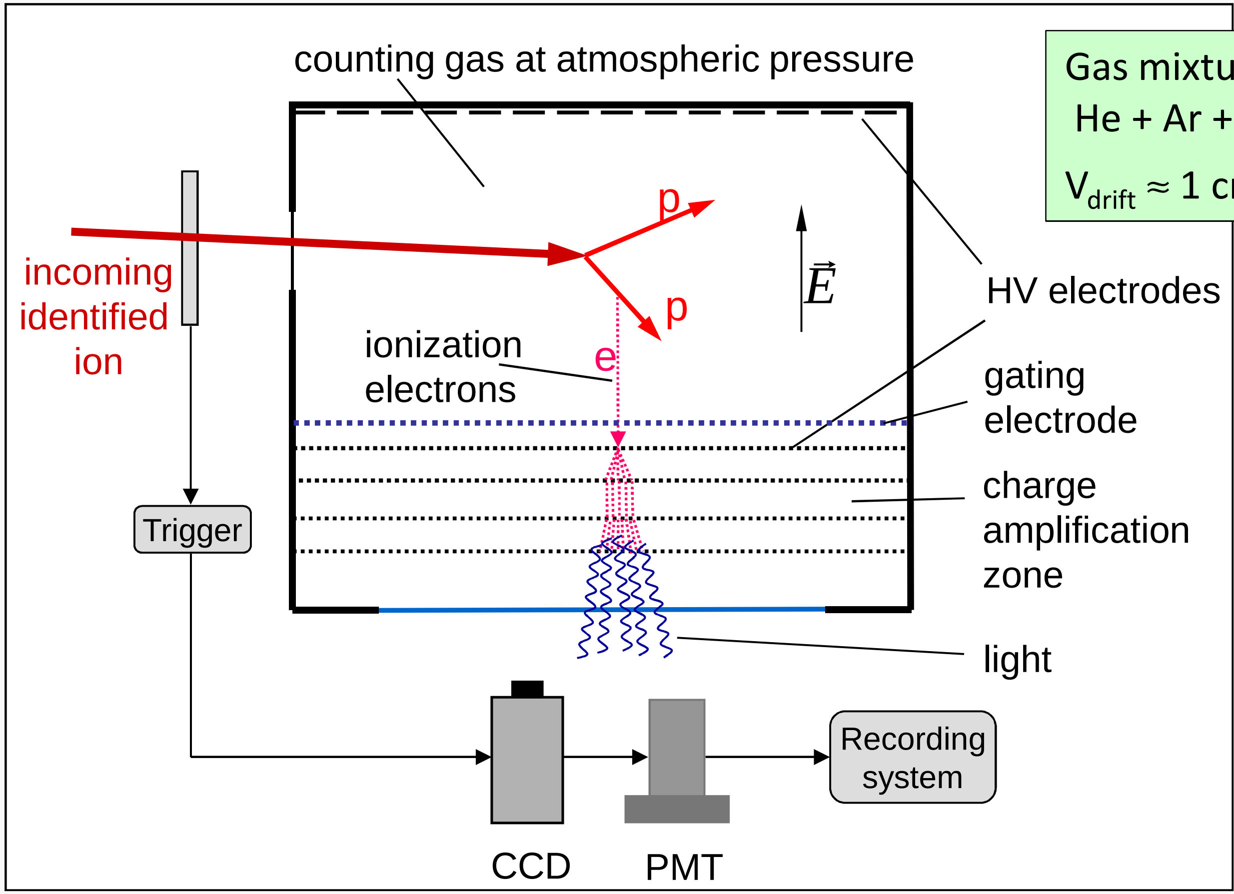
A decay event of ^{45}Fe

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

J. Giovinazzo et al., PRL 99 (2007) 102501

Novel idea: optical readout

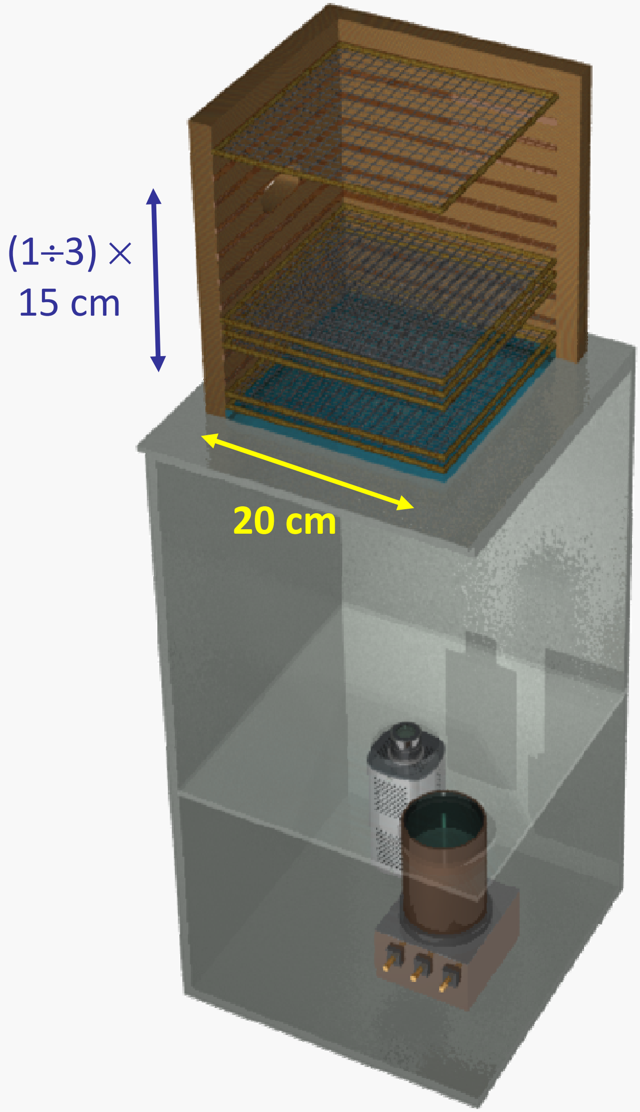
- OTPC: Optical Time Projection Chamber



Gas mixture:
He + Ar + N_2 (≈1%)
$V_{drift} \approx 1$ cm/μs

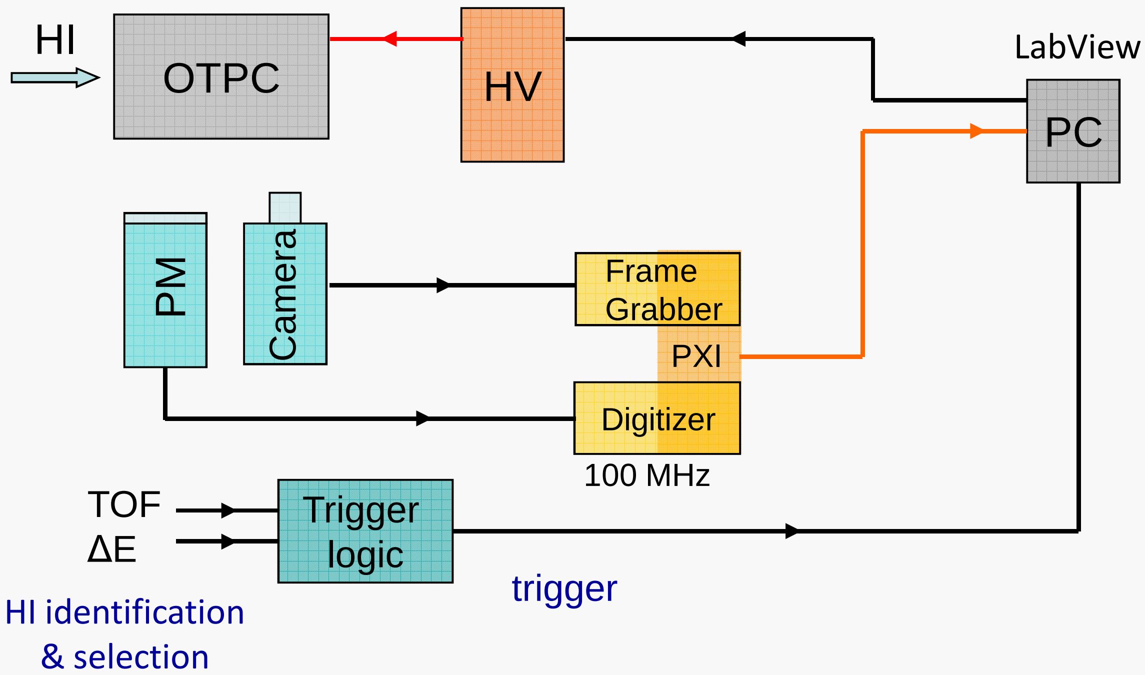
M. Ćwiok et al., IEEE TNS, 52 (2005) 2895 K. Miernik et al., NIM A581 (2007) 194

OTPC data acquisition

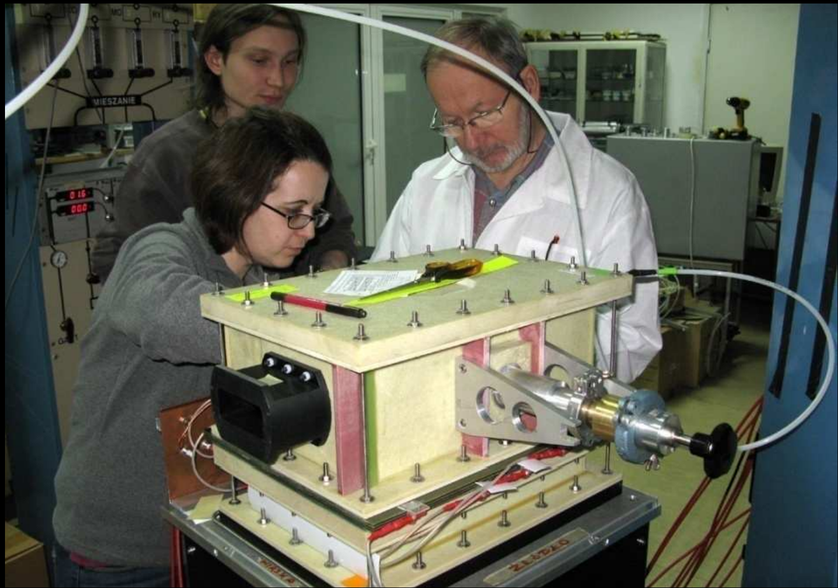


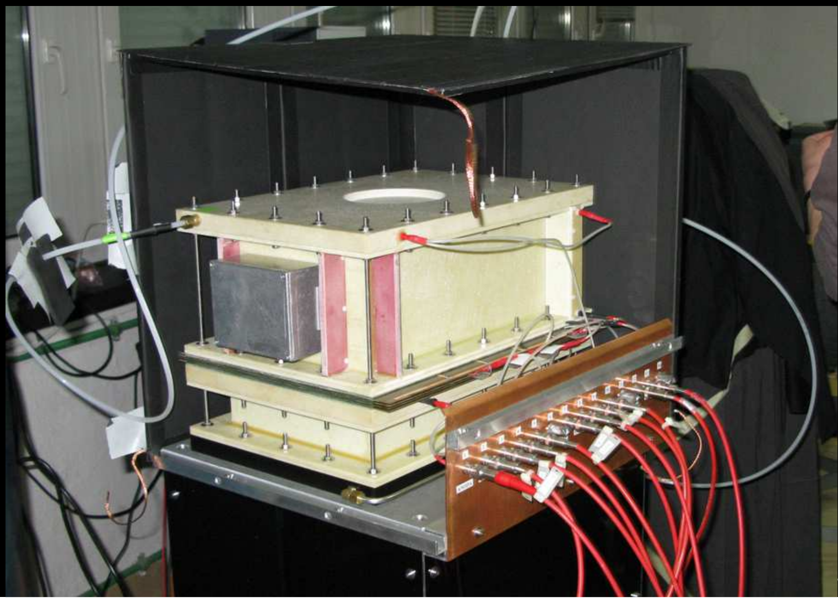
CCD 2/3''

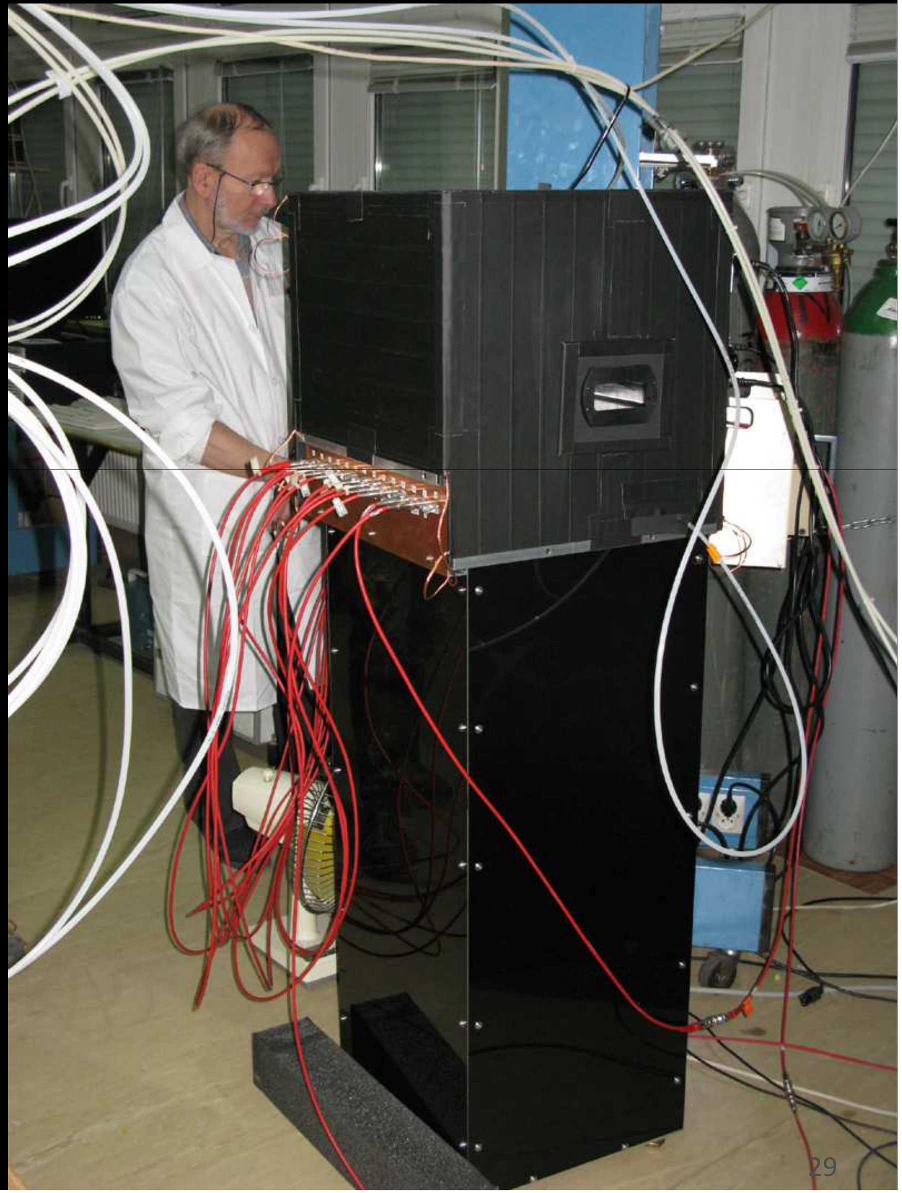
- 1000 × 1000 pix.
- 12-bits
- image ampl. (×2000)



OTPC



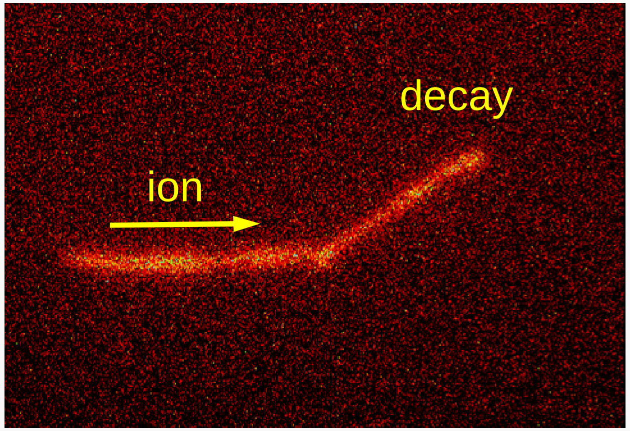




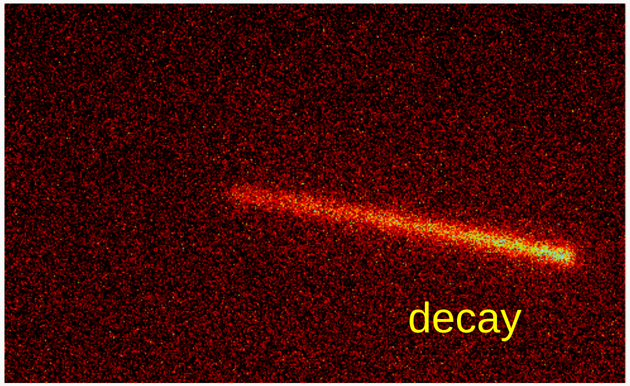
Principle of operation

CCD image

tracks of the ion and emitted particle(s)

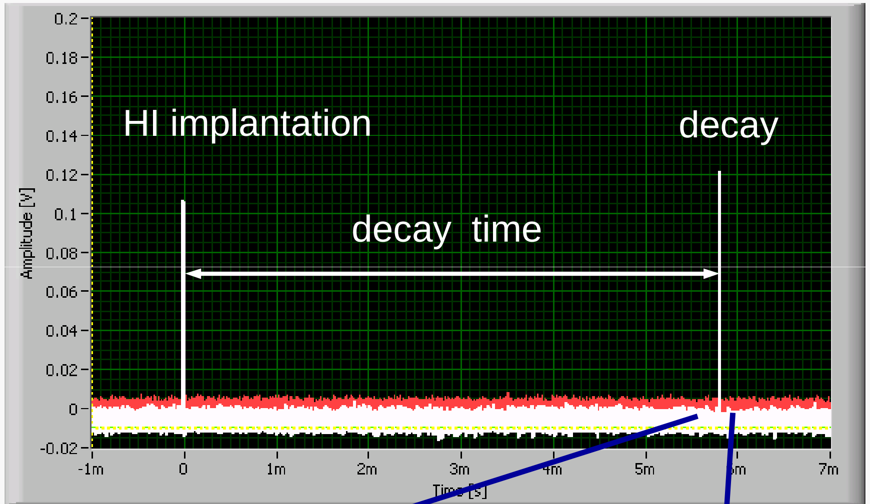


or only emitted particle(s)

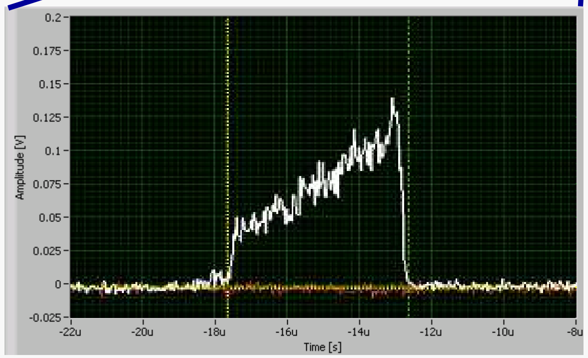


PMT signal sampled

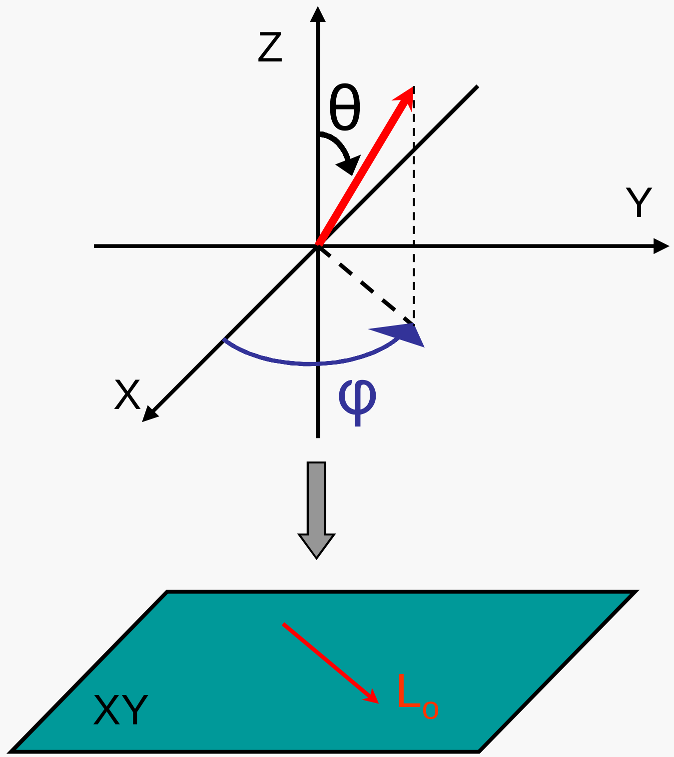
time sequence of events



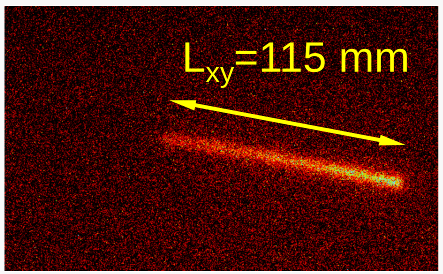
decay details

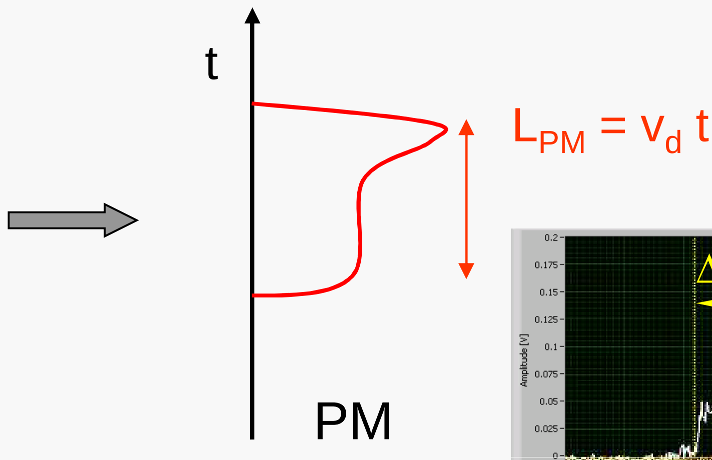


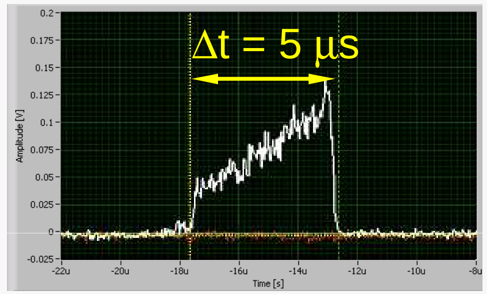
Event reconstruction



Camera

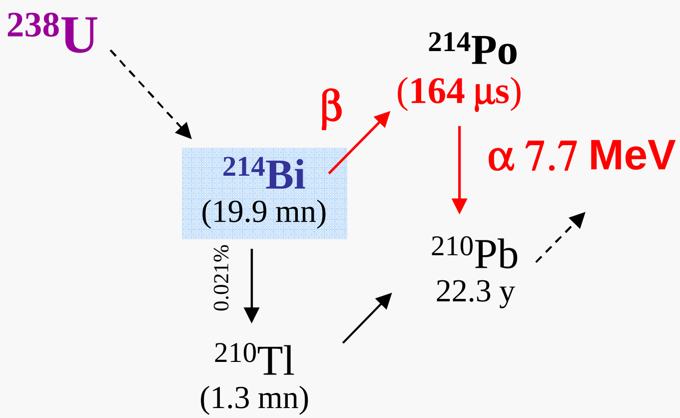




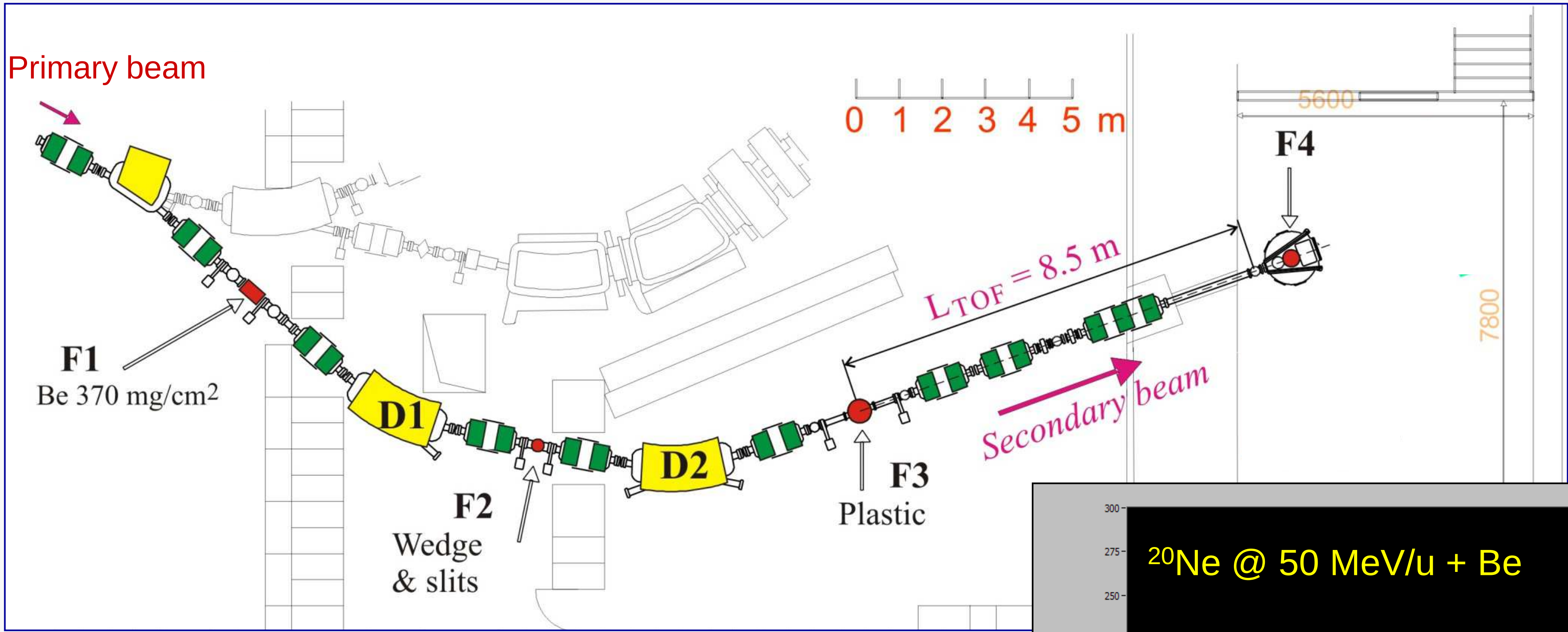


$$L = \sqrt{115^2 + (5\cdot 10)^2} = 125\,\mathrm{mm} \quad \Leftrightarrow \quad E_\alpha = 7.8\ \mathrm{MeV}$$

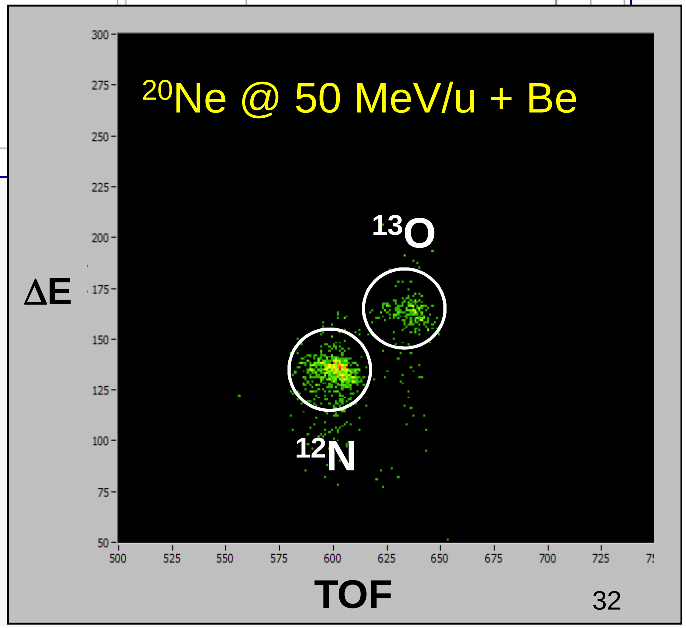
→ ^{214}Po α decay



ACCULINNA @ FLNR, Dubna



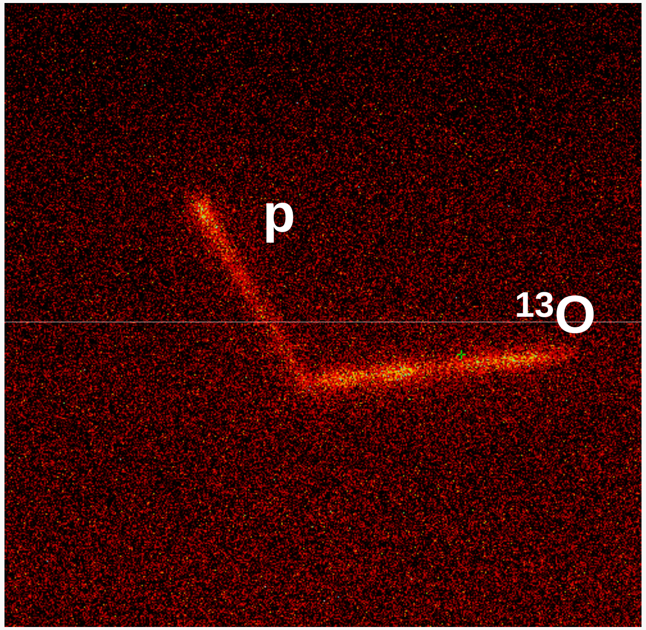
- Low-energy fragment separator, full identification of selected ions by TOF-ΔE method



Testing with decays of implanted ions

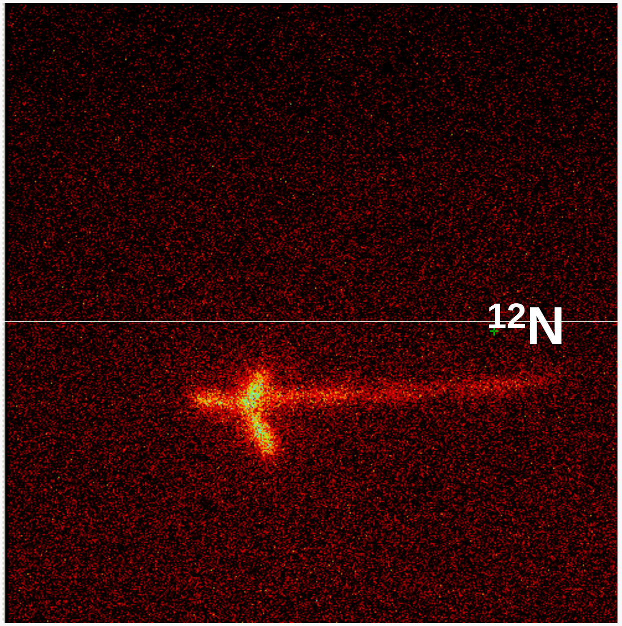
Acculinna separator, JINR, Dubna, 2006

^{20}Ne (50 MeV/u) + Be →...



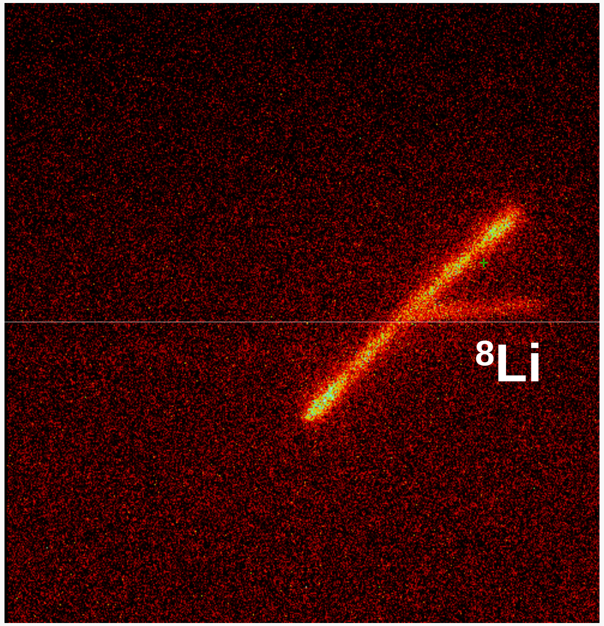
β*p* emission from ^{13}O

$$^{13}O \xrightarrow[8\,\mathrm{ms}]{\beta} {}^{13}N^{*} \rightarrow {}^{12}C + p$$



β3α decay of ^{12}N

$$^{12}O \xrightarrow[11\,\mathrm{ms}]{\beta} {}^{12}C^{*} \rightarrow 3\alpha$$



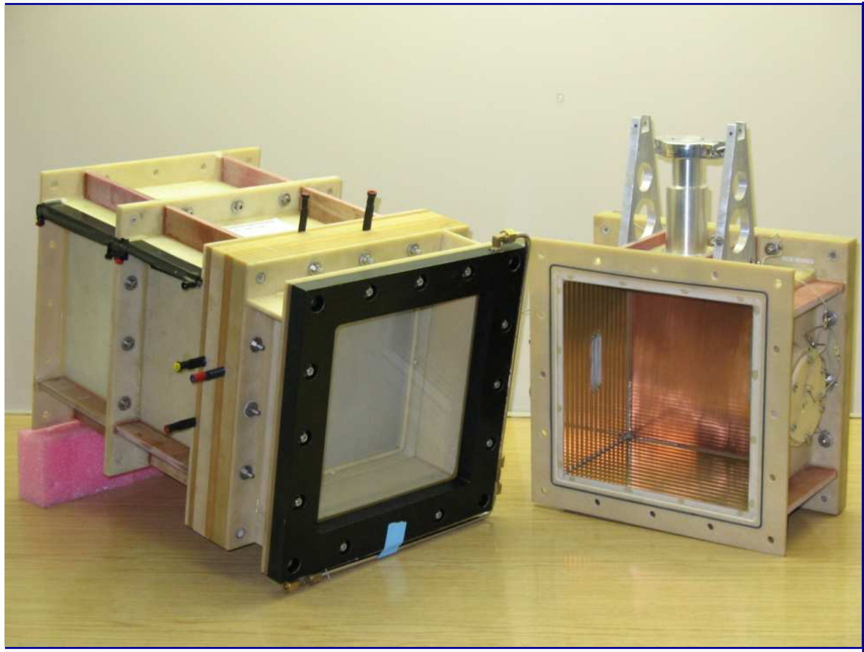
β2α decay of ^{8}Li

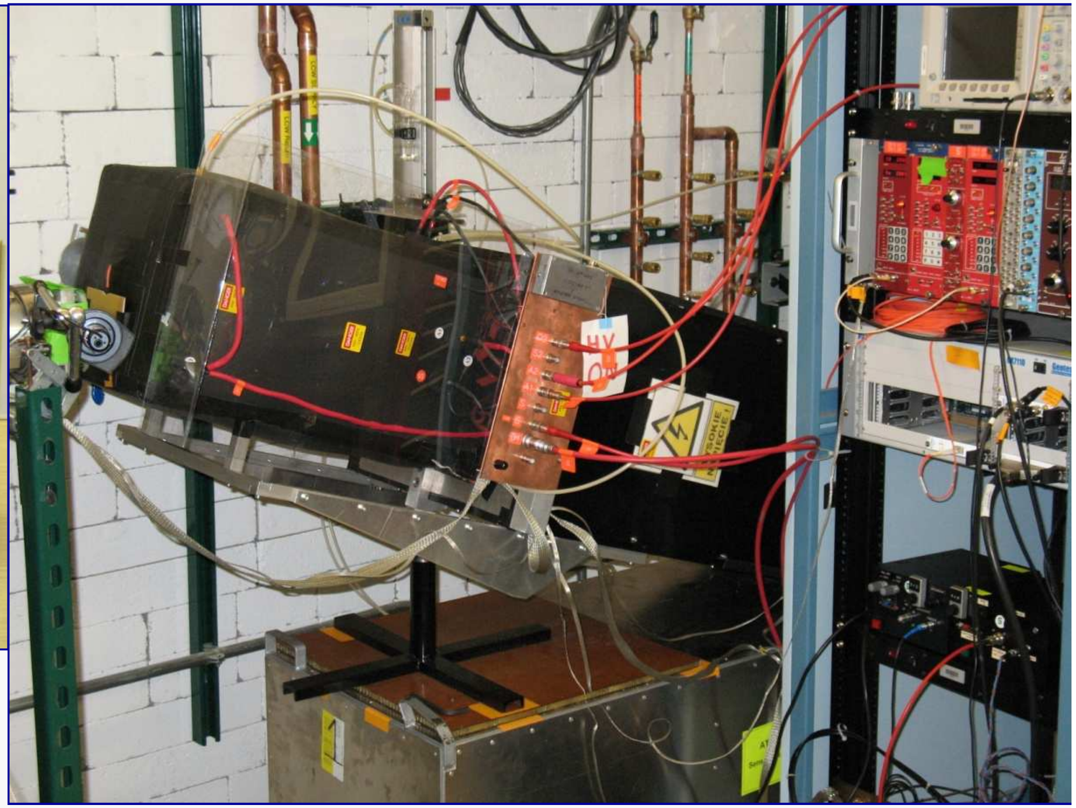
$$^{8}Li \xrightarrow[840\,\mathrm{ms}]{\beta} {}^{8}Be^{*} \rightarrow 2\alpha$$

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

Experiment at NSCL/MSU

February 2007





Gas mixture:

66% He + 32% Ar + 1% N_2 + 1% CH_4

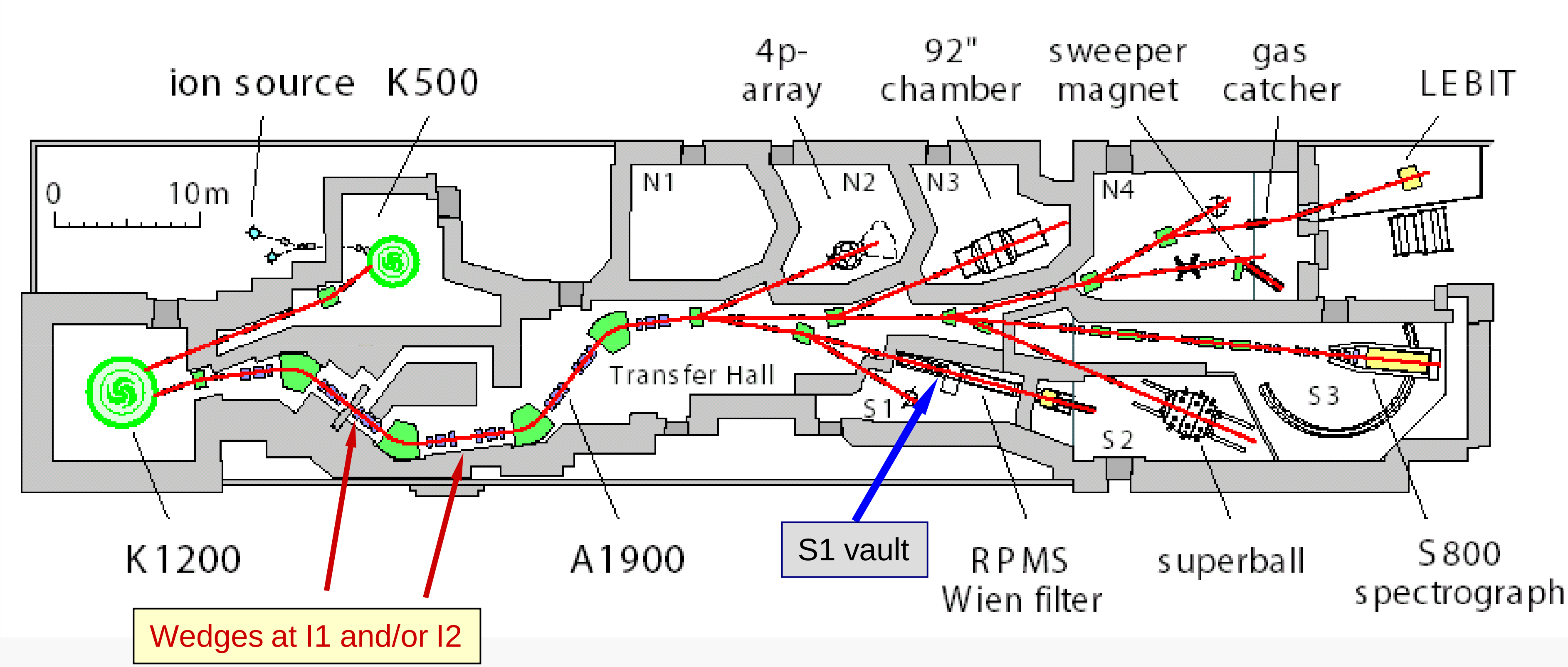
- range of 550 keV proton ≈ 2.3 cm
- range spread of ^{45}Fe ion ≈ 50 cm

Active volume: 20×20×42 cm^3

Reaction: ^{58}Ni at 161 MeV/u + ^{nat}Ni → ^{45}Fe

Separation and in-flight identification (ΔE + TOF) in A1900 with two-wedge system

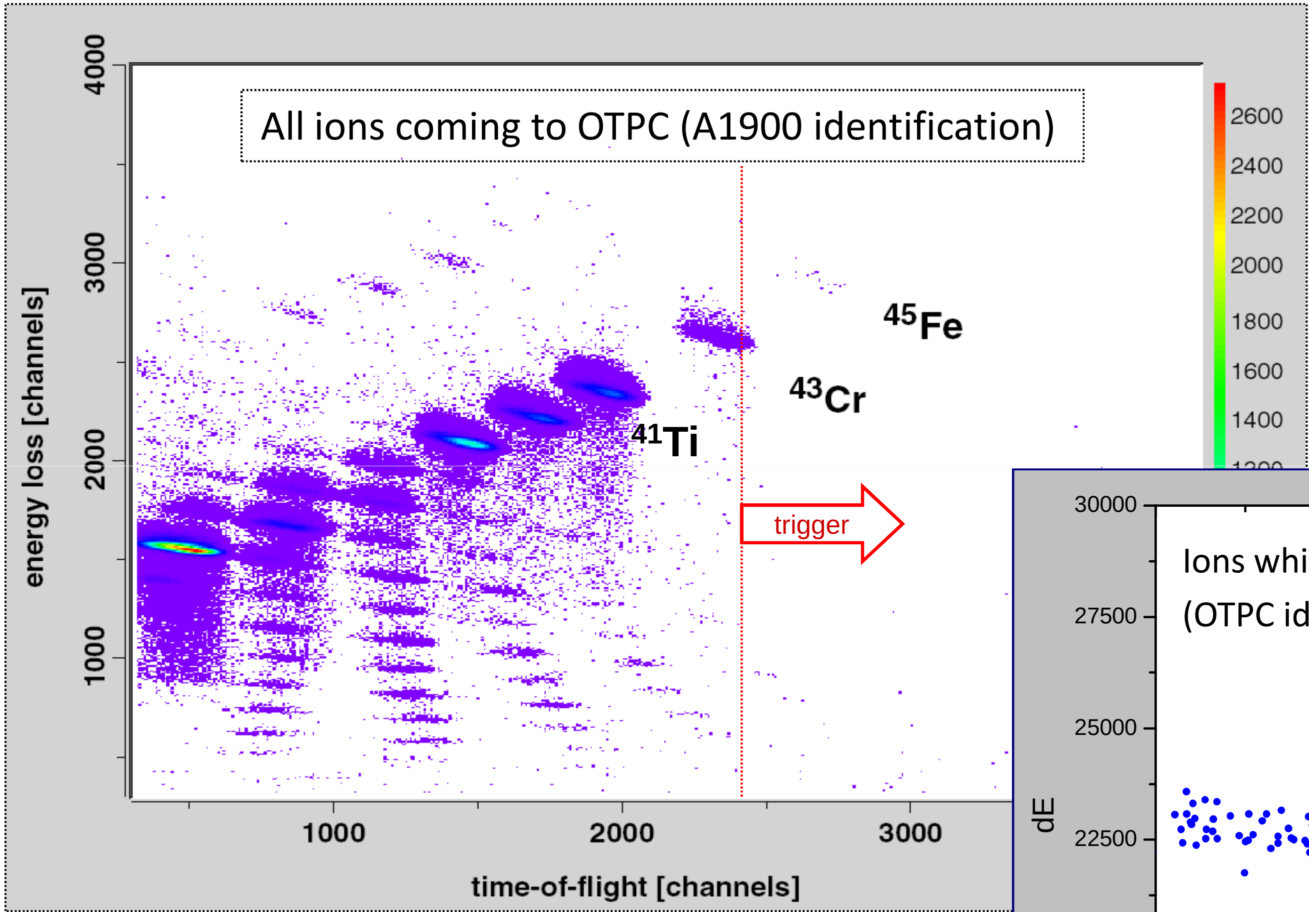
A1900 separator



Reaction: ^{58}Ni at 161 MeV/u + ^{nat}Ni → ^{45}Fe

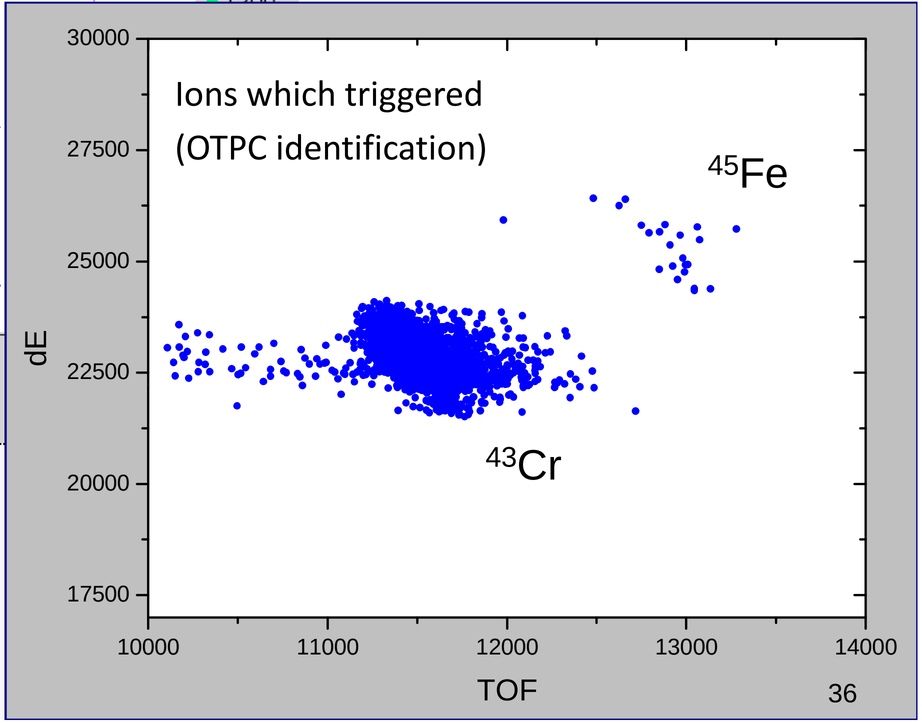
Ion identification in-flight : ΔE + TOF

Ion identification



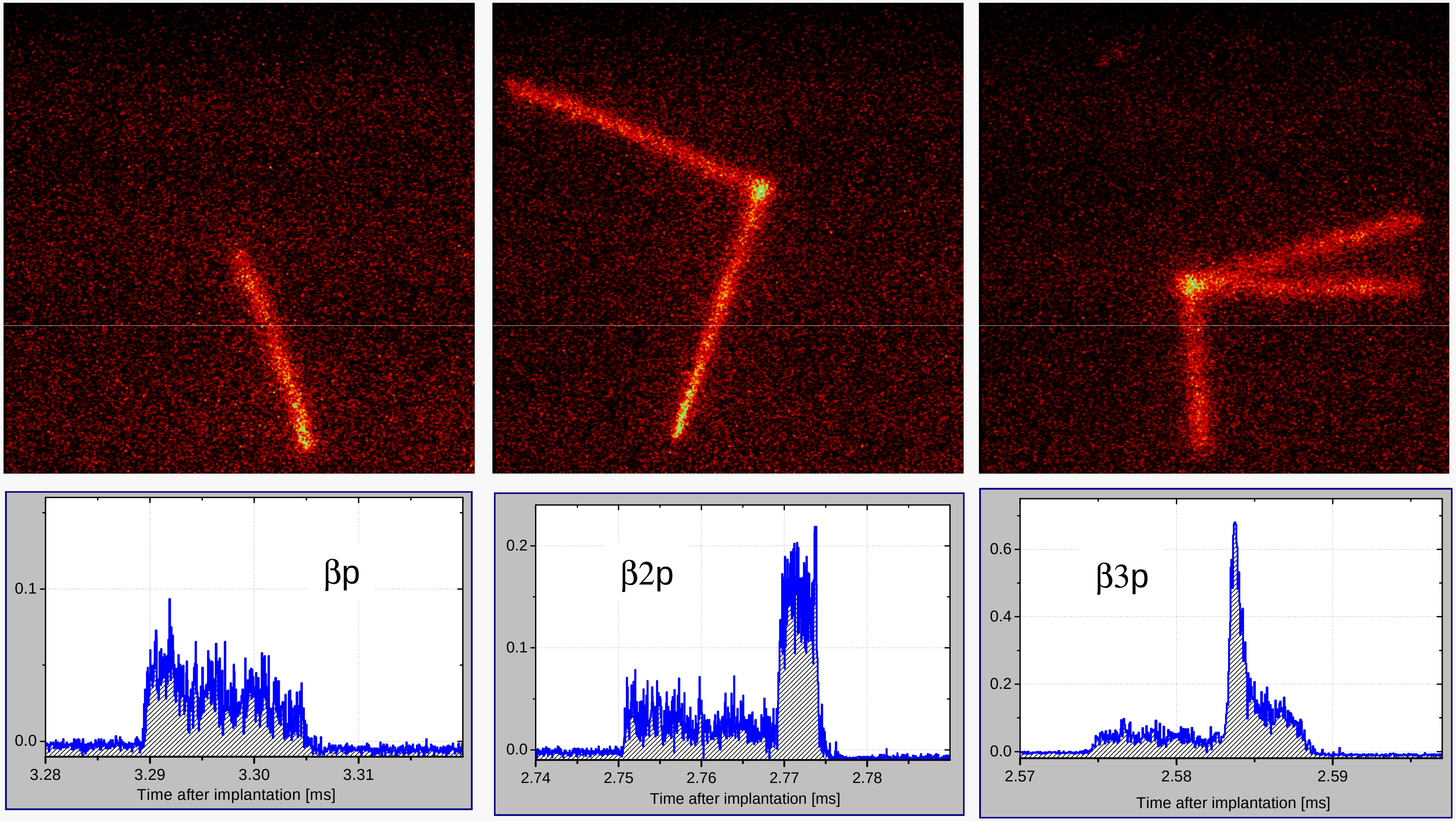
^{45}Fe: 2 /h

^{43}Cr: 8 /min.

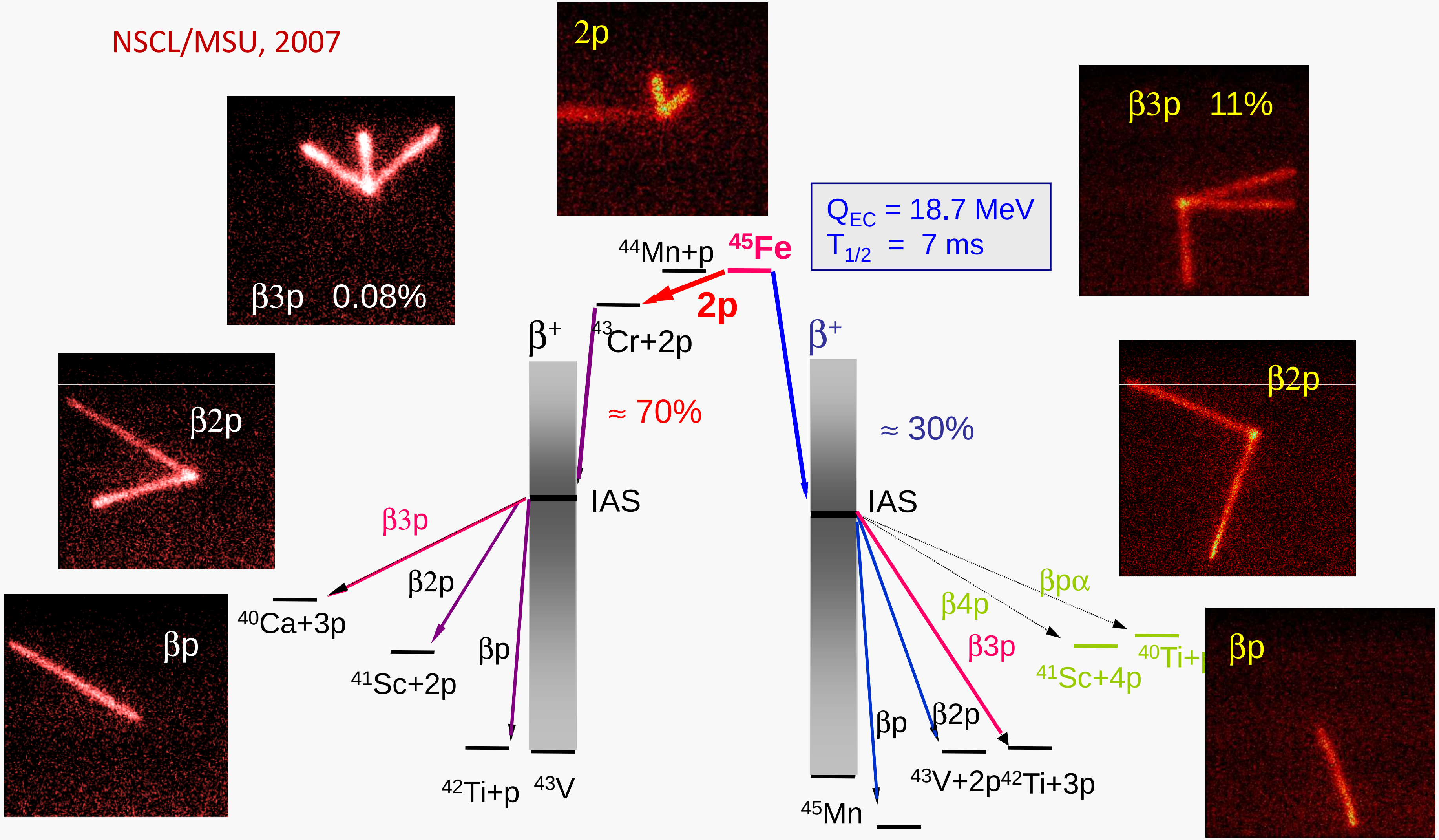


2p events from ^{45}Fe

β delayed protons from ^{45}Fe



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

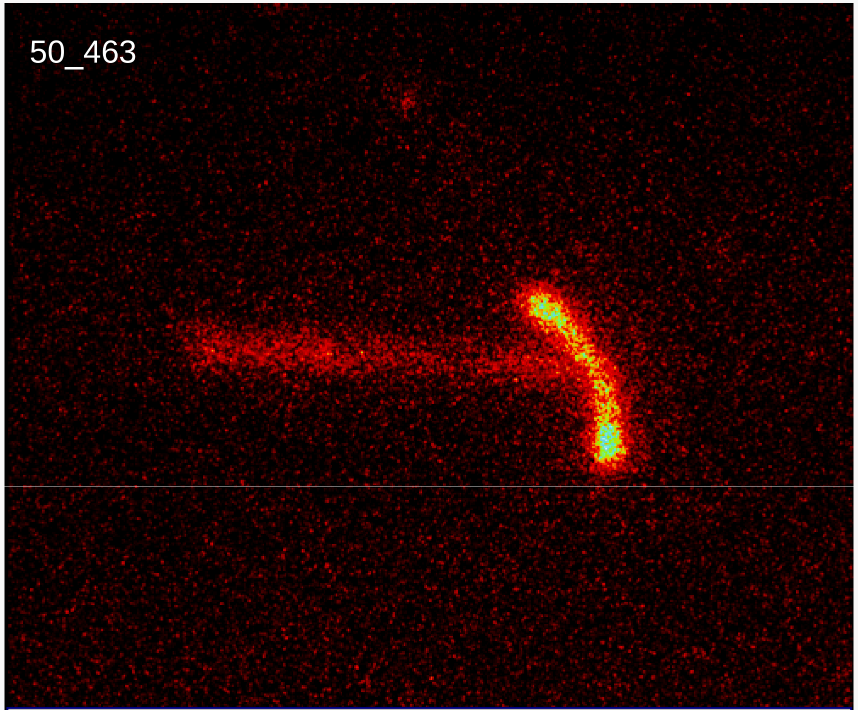


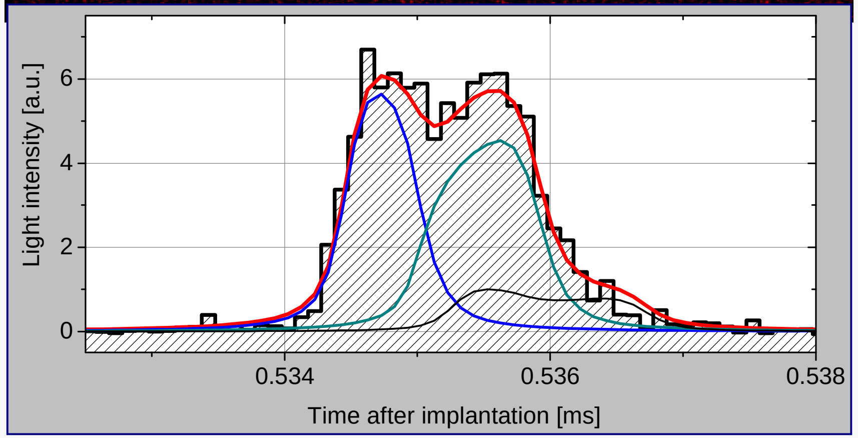
M. Pomorski et al., Phys. Rev. 83 (2011) 014306

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

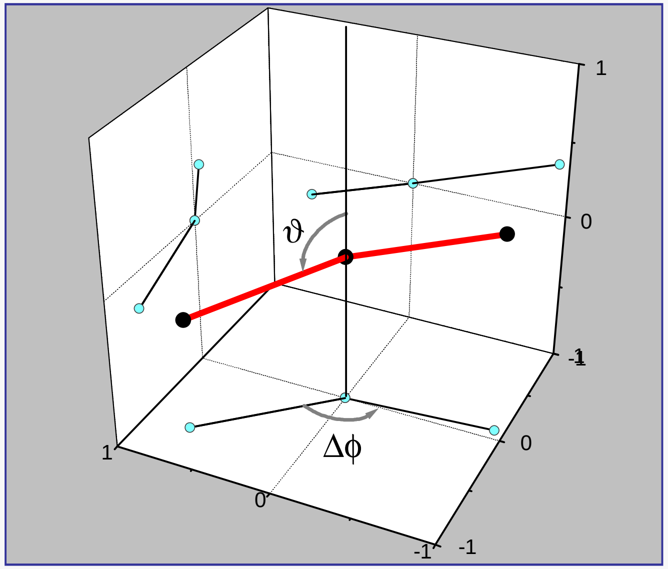
K. Miernik et al., PRL 99 (07) 192501

3D reconstruction





- Full *p-p* corellation pattern could be established



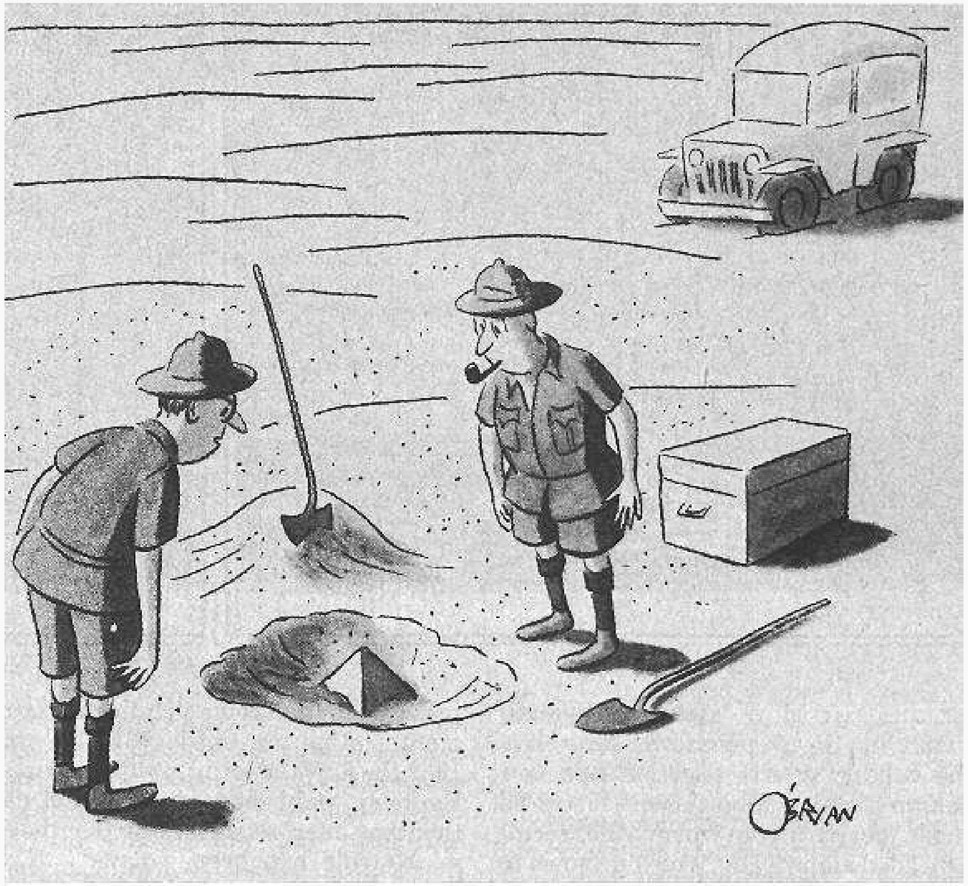
$\vartheta_1 = (104 \pm 2)°$, $\vartheta_1 = (70 \pm 3)°$

$\Delta\phi = (142 \pm 3)^o$ → $\theta_{pp} = (143 \pm 5)^o$

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

☺

- More information on the OTPC and more decay images can be found at
  http://www.fuw.edu.pl/~pfutzner/Research/OTPC/OTPC.html



"This could be the discovery of the century. Depending, of course, on how far down it goes."

Radioactive decays

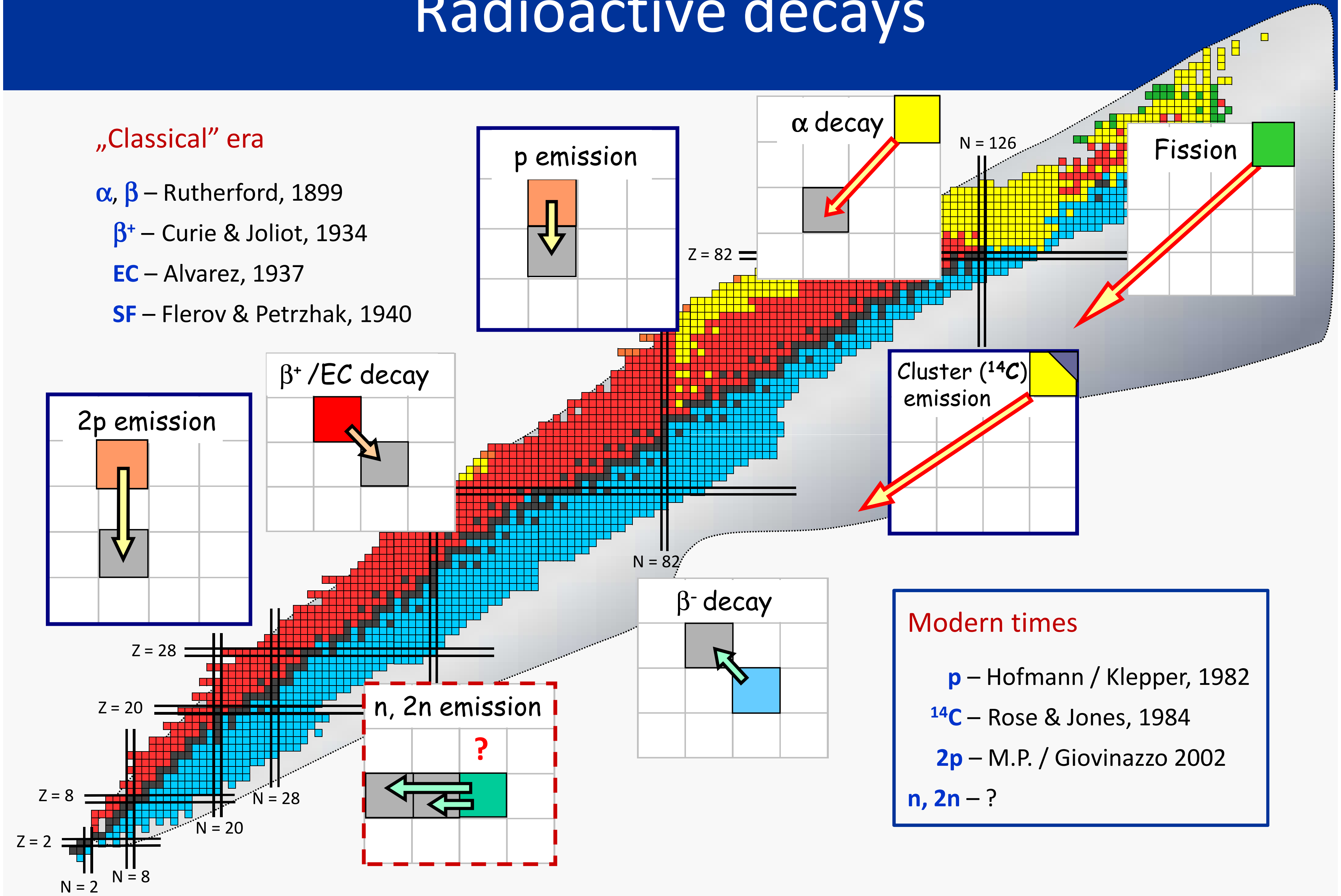
„Classical” era

α, β – Rutherford, 1899

β⁺ – Curie & Joliot, 1934

EC – Alvarez, 1937

SF – Flerov & Petrzhak, 1940



Modern times

p – Hofmann / Klepper, 1982

¹⁴C – Rose & Jones, 1984

2p – M.P. / Giovinazzo 2002

n, 2n – ?