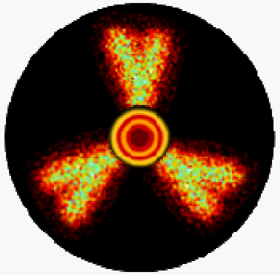
Particle radioactivity

Lecture 1



Marek Pfützner

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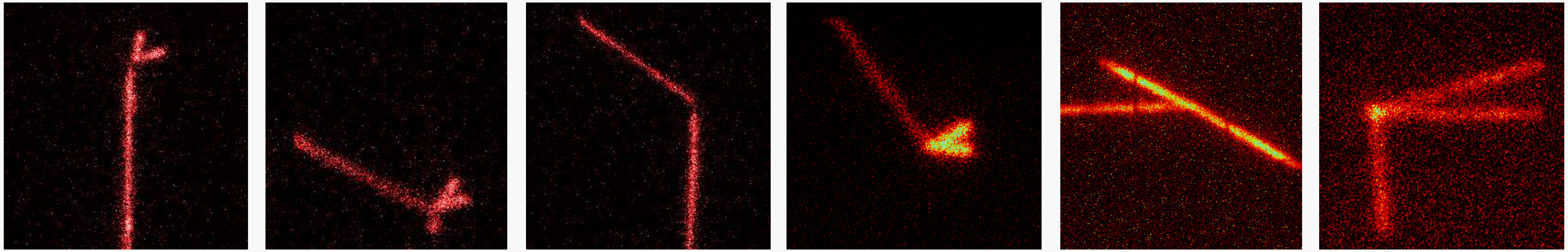
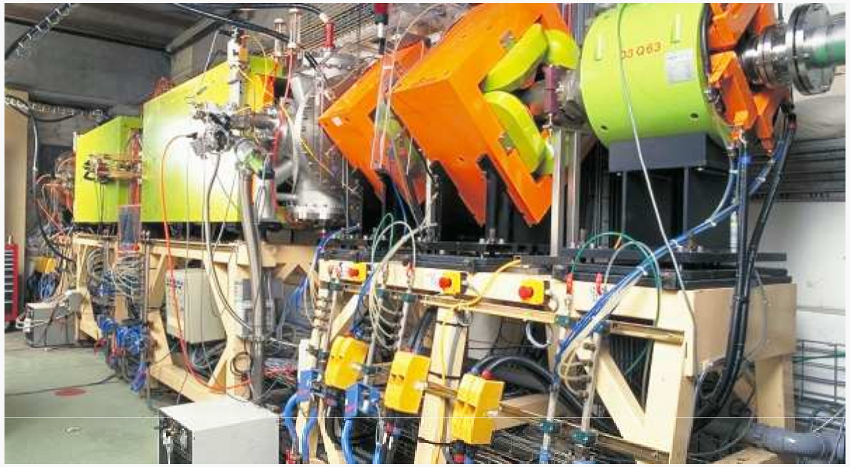
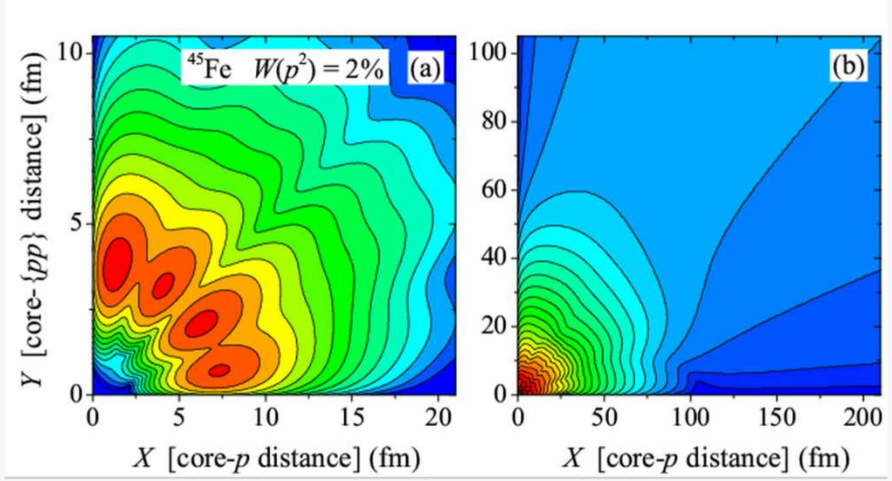


Outline





- Basic introduction
- Experimental techniques
  - reactions
  - separators
  - detection
- Theoretical models
  - Gamow idea
  - p, and 2p emission
  - 3-body model

What is radioactive?

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

Radioactivity

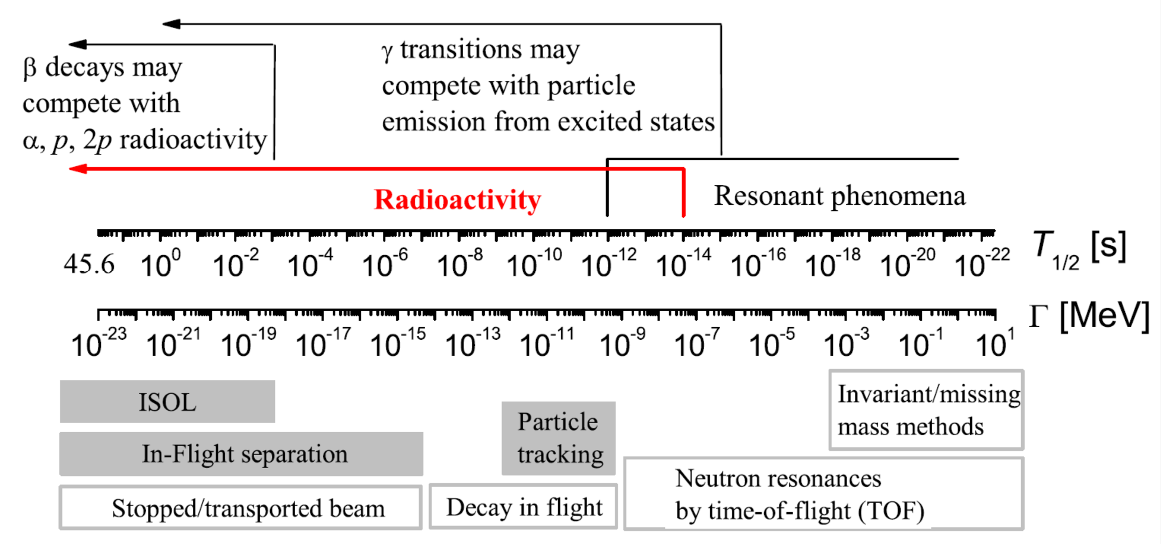
- Slow enough to form neutral atoms
- Characteristic **time** measured directly
- Independent of formation mechanism

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

Reactions/Resonances

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

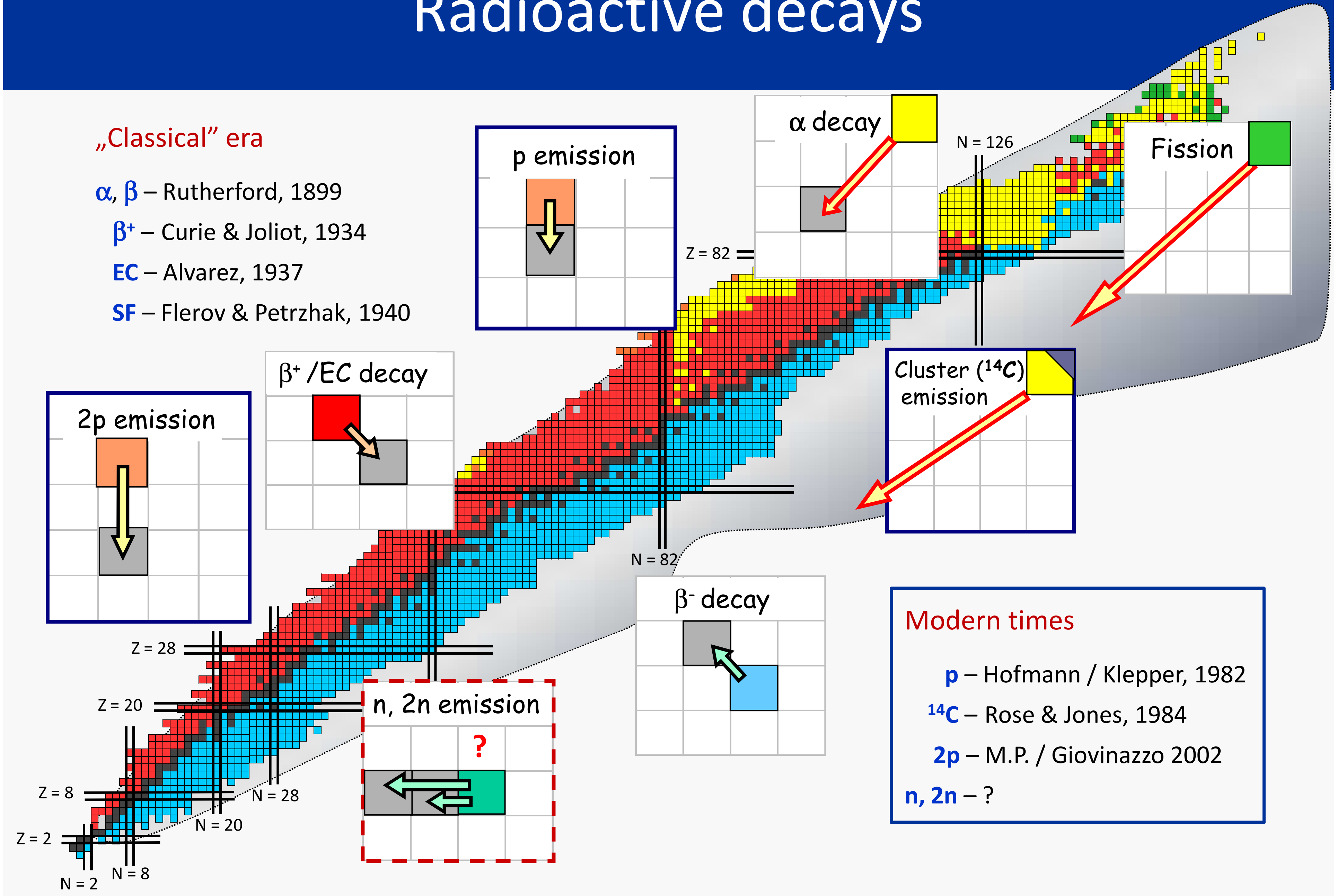
$$\Gamma \geq 1\ \mathrm{meV}$$



Radioactive decays

„Classical" era

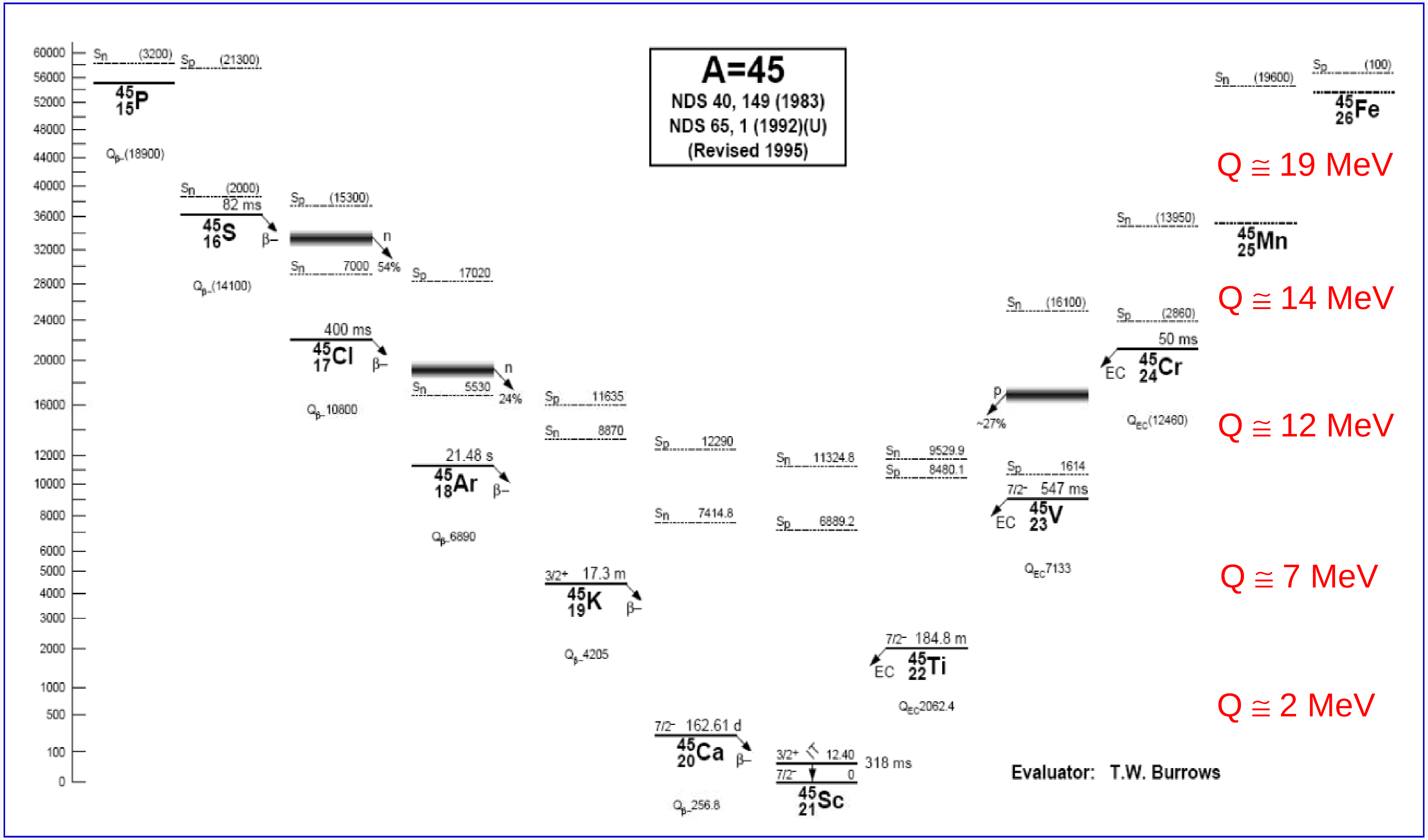
- **α, β** – Rutherford, 1899
- **β^+** – Curie & Joliot, 1934
- **EC** – Alvarez, 1937
- **SF** – Flerov & Petrzhak, 1940



Modern times

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

Mass parabola



Q ≅ 19 MeV

Q ≅ 14 MeV

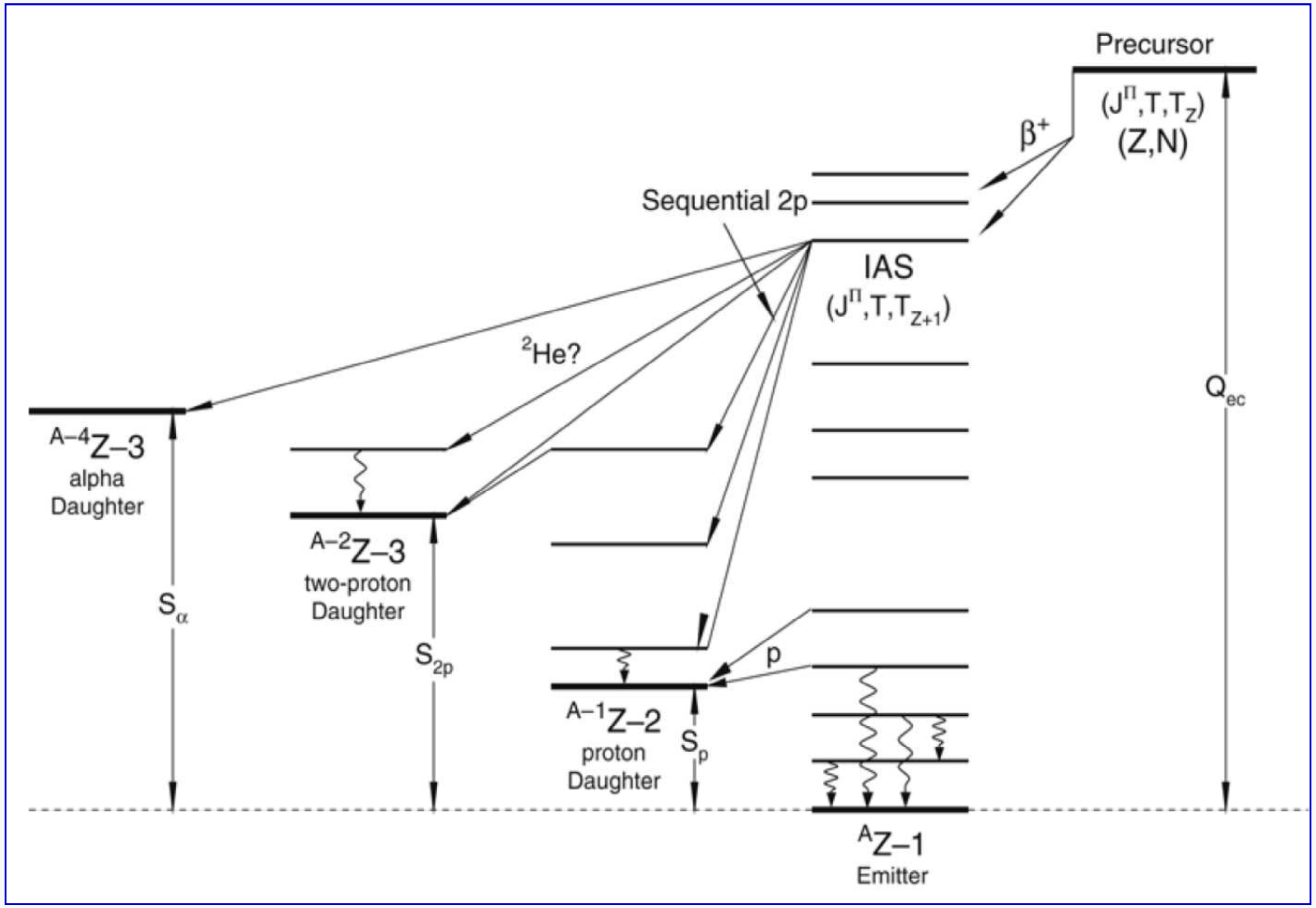
Q ≅ 12 MeV

Q ≅ 7 MeV

Q ≅ 2 MeV

β-delayed particle emission

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



B. Blank, M. 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:

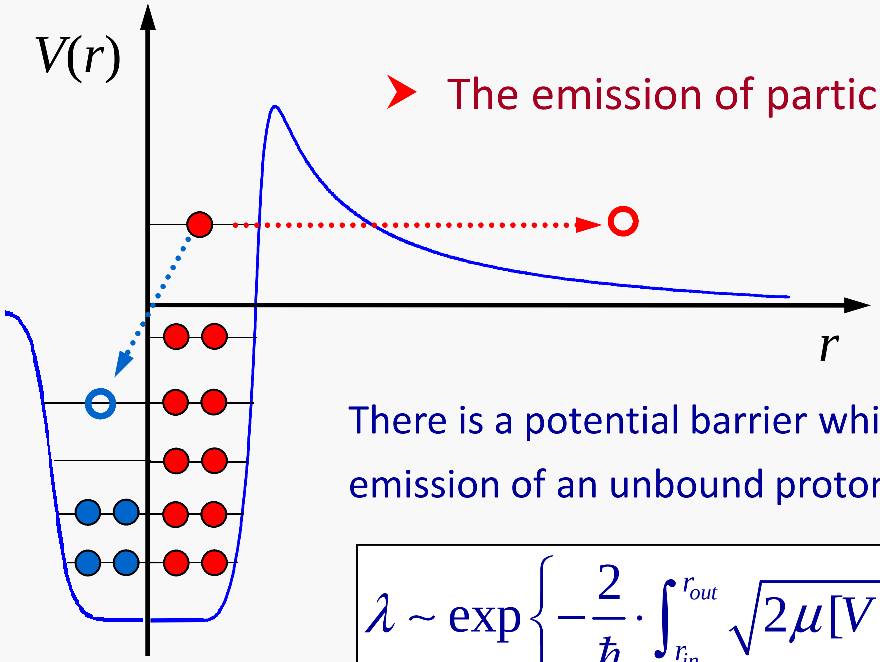
$$\boxed{\lambda \sim Q^5}$$

Decay energy may be large,

but the weak interaction

is really weak

→ $\boxed{T_{1/2} > 1\ \mathrm{ms}}$



- The emission of particles

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

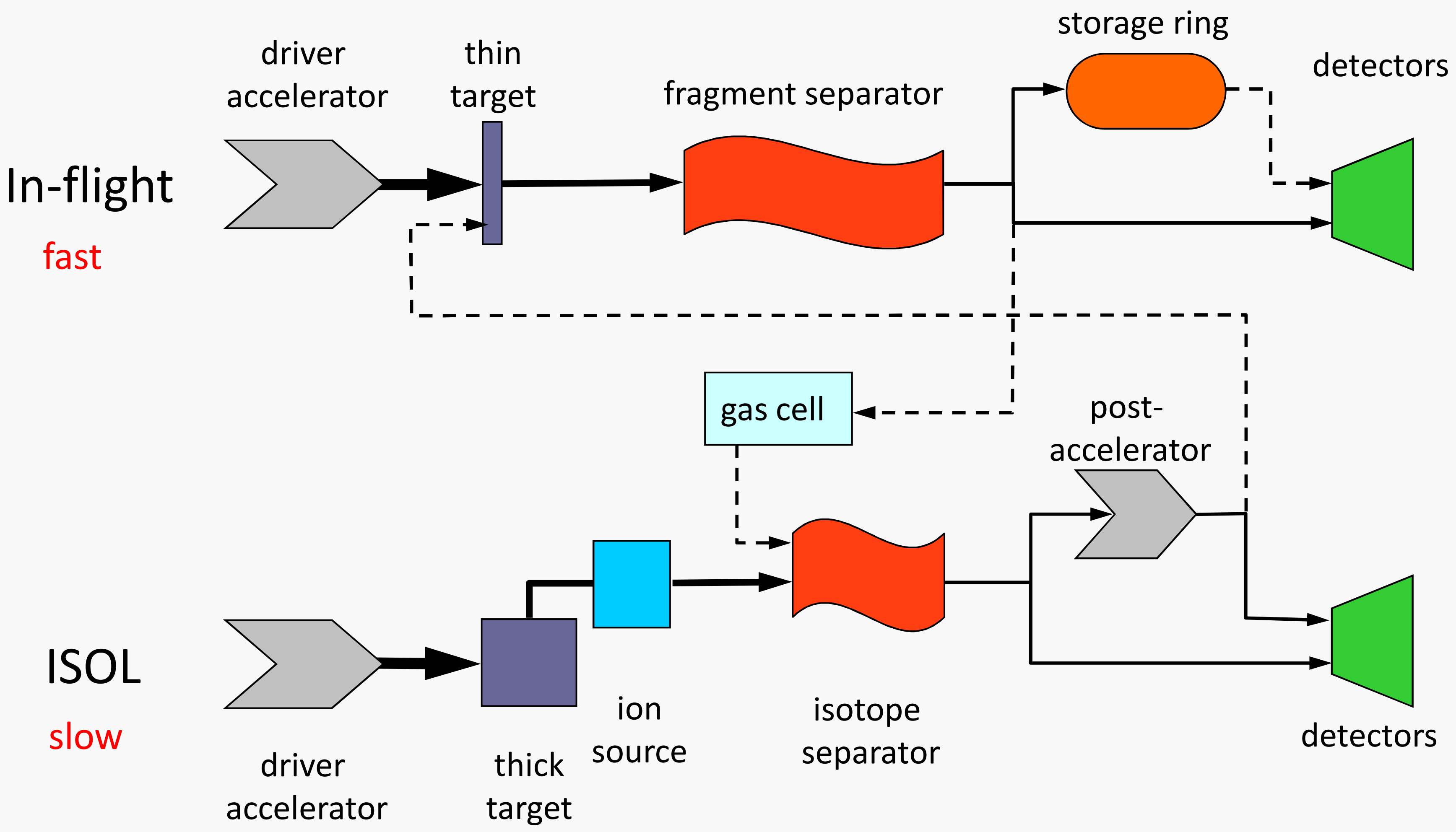
$$\boxed{\lambda \sim \exp\left\{-\frac{2}{\hbar}\cdot\int_{r_{in}}^{r_{out}}\sqrt{2\mu[V(r)-Q_p]}\cdot dr\right\}}$$

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

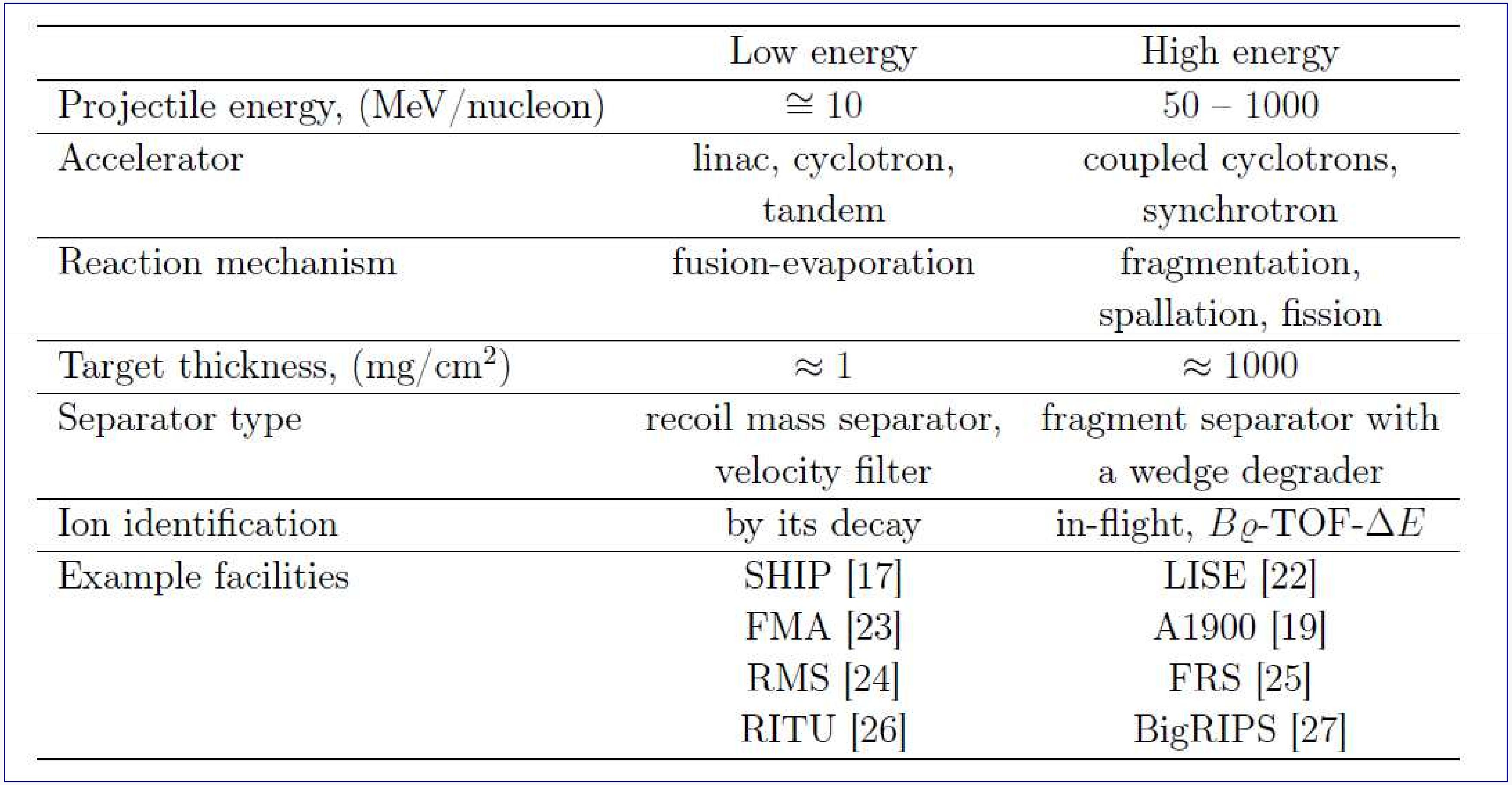
→ To study particle radioactivity fast techniques are needed!

Methods of production

- Two schemes of radioactive beam production



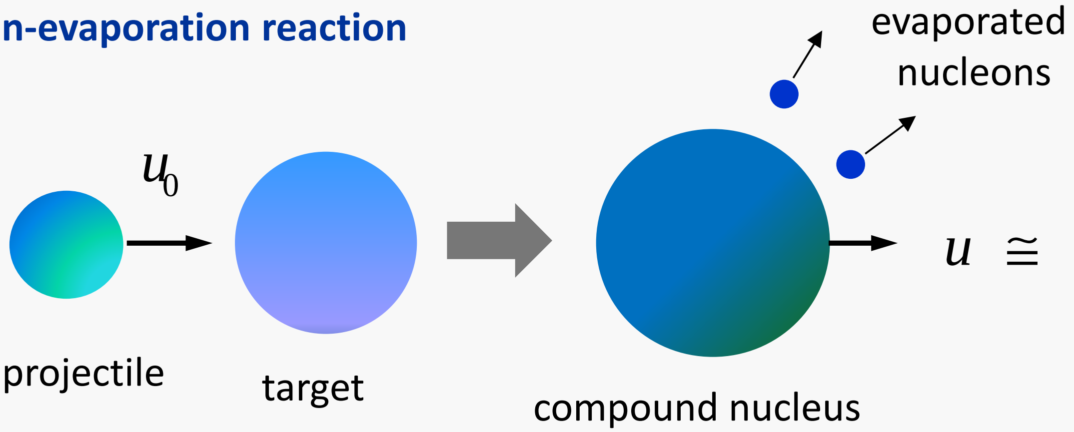
Two classes of in-flight facilities



	Low energy	High energy
Projectile energy, (MeV/nucleon)	$\cong 10$	50 – 1000
Accelerator	linac, cyclotron, tandem	coupled cyclotrons, synchrotron
Reaction mechanism	fusion-evaporation	fragmentation, spallation, fission
Target thickness, (mg/cm^2)	≈ 1	≈ 1000
Separator type	recoil mass separator, velocity filter	fragment separator with a wedge degrader
Ion identification	by its decay	in-flight, $B\varrho$-TOF-ΔE
Example facilities	SHIP [17] FMA [23] RMS [24] RITU [26]	LISE [22] A1900 [19] FRS [25] BigRIPS [27]

Production mechanism: a) fusion

- **Fusion-evaporation reaction**



$$u \cong \frac{m}{m+M} u_0$$

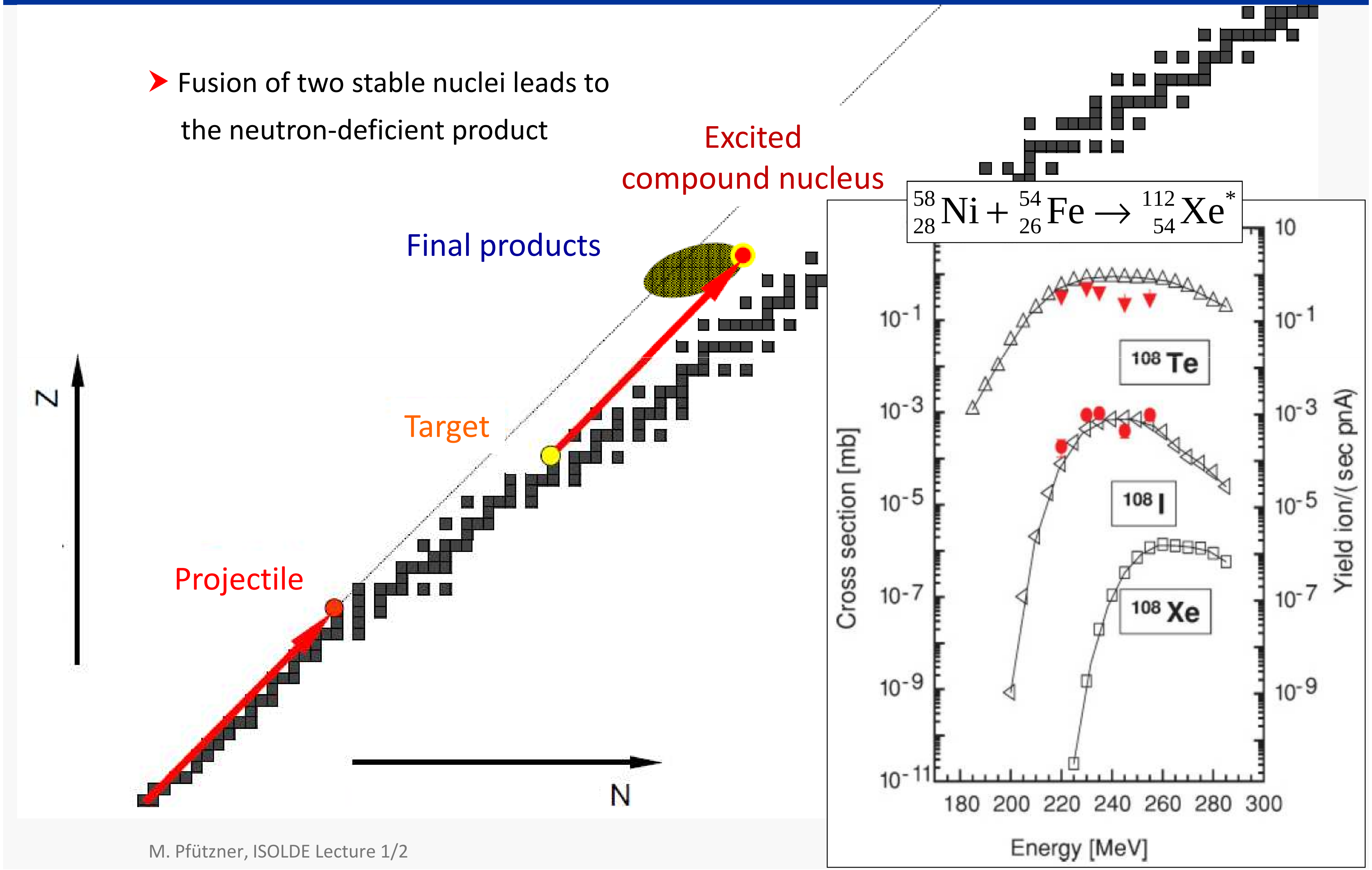
→ Projectile energy has to be precisely tuned: if too small, there will be no contact, if too large, the compound system wil not form. The typical energy is around 8 MeV/u (Coulomb barrier).

→ The projectile-target combination must be selected to get the right product. This limits the number of possibilities.

→ Reaction very useful for production of neutron deficient nuclei (proton radioactivity). The only reaction leading to synthesis of superheavy elements!

(fusion)

- Fusion of two stable nuclei leads to the neutron-deficient product



Excited compound nucleus

Final products

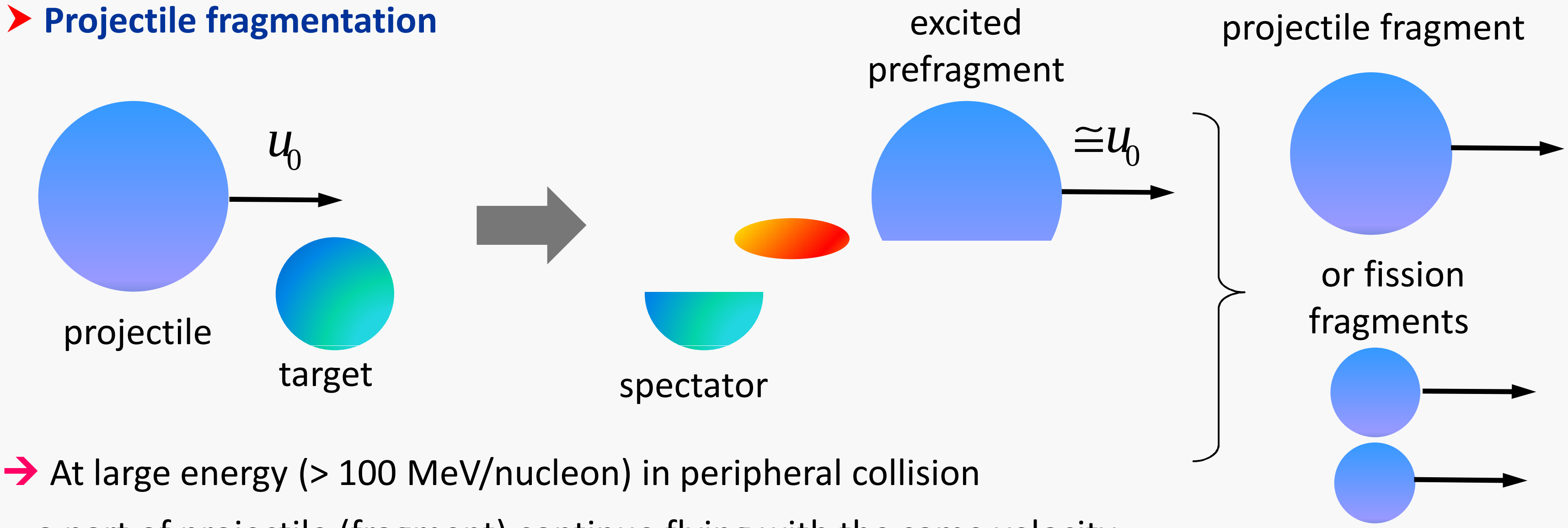
Target

Projectile

$$^{58}_{28}\mathrm{Ni} + ^{54}_{26}\mathrm{Fe} \rightarrow ^{112}_{54}\mathrm{Xe}^{*}$$

b) fragmentation

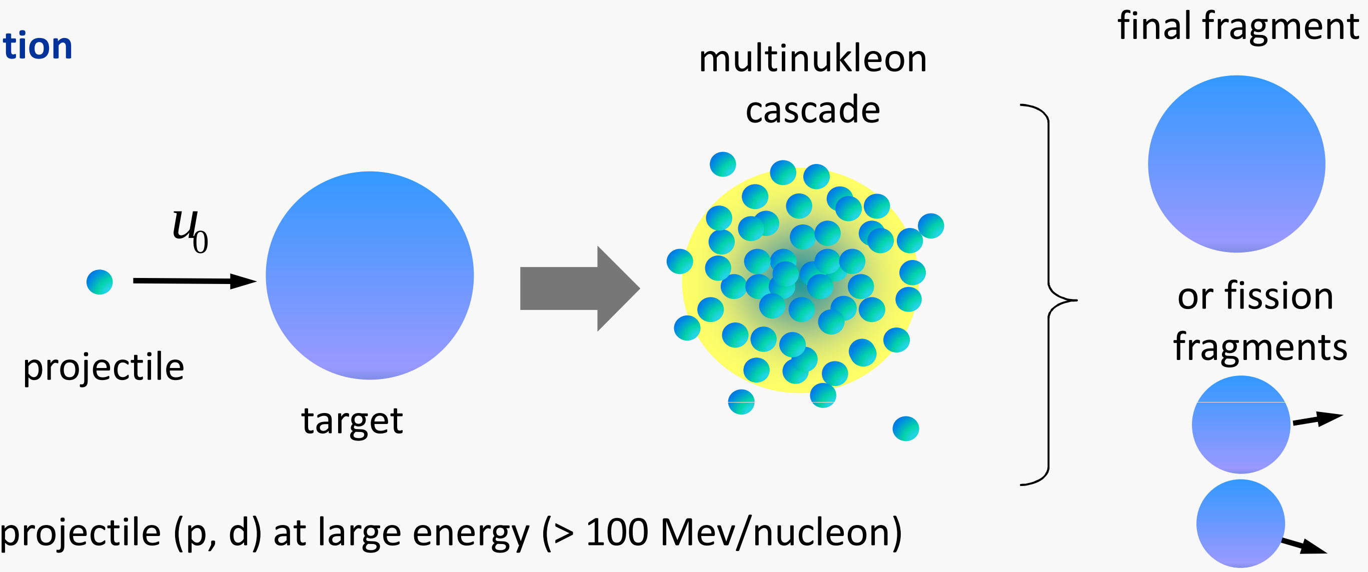
Projectile fragmentation



- At large energy (> 100 MeV/nucleon) in peripheral collision a part of projectile (fragment) continue flying with the same velocity.
- Reaction is universal – any nucleus can be produced which has less nucleons than the projectile. Fragments form a beam, which can be directed to experiments.
- Very useful for studies of most exotic nuclei. Used for example in two-proton radioactivity studies.

c) spallation

- **Spallation**



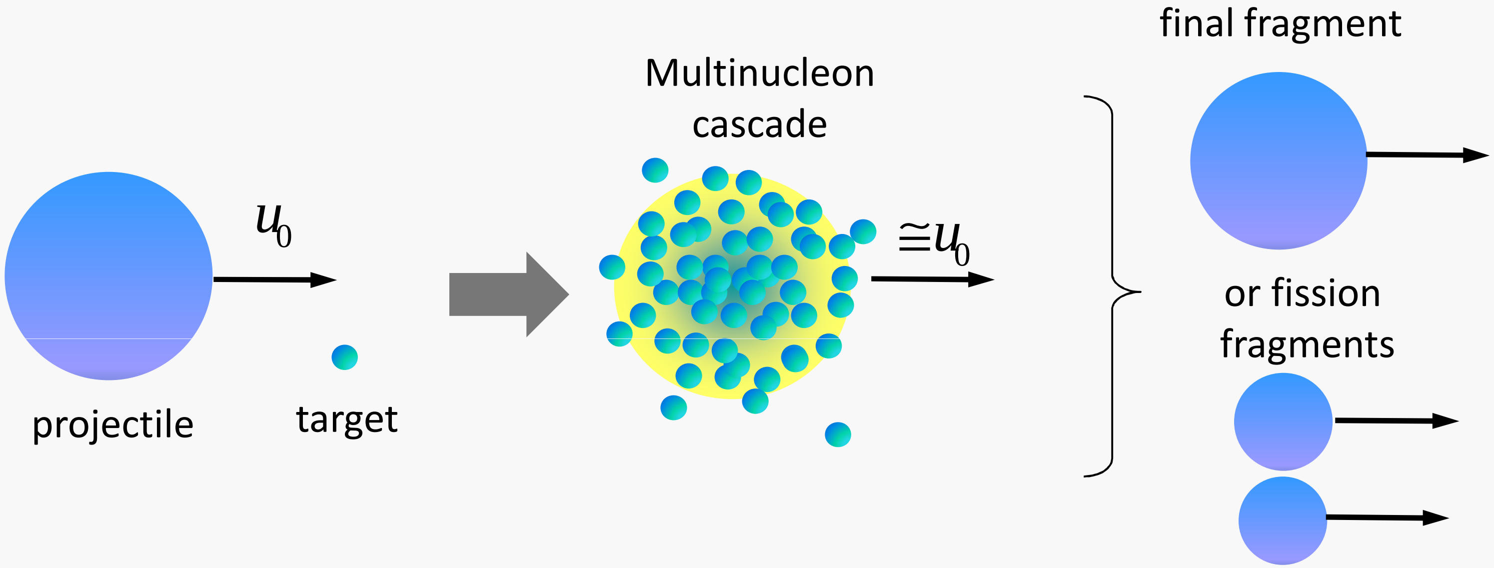
→ Light projectile (p, d) at large energy (> 100 Mev/nucleon) initiates a cascade of collisions between nucleons in the target. Some nucleons evaporate leading to formation of a final fragment or fission.

→ Reaction is universal, any nucleon can be formed which has less nucleons than target. Fragments do not apear as a beam – one has to extract them from target.

→ Main advantage: it is relatively easy to make a proton beam of large energy and large intensity.

Reverse kinematics

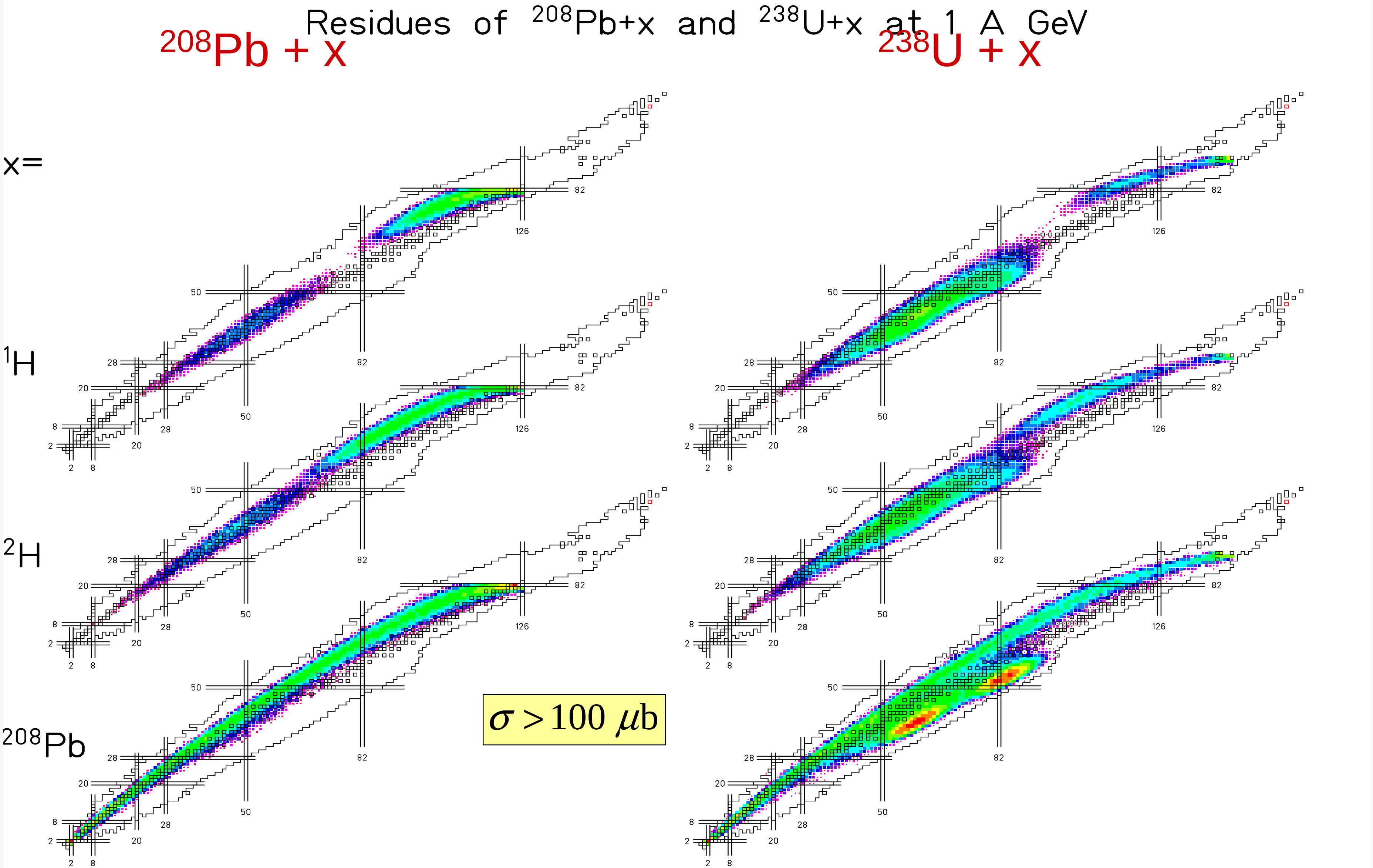
- **Spallation in reverse kinematics**



→ When a massive projectile at large energy hits a light target (p, d) the spallation also occurs.

→ „Reverse" spallation is very similar to fragmentation. The difference is in the excitation mechanism of the intermediate system.

Examples of fragmentation/spallation



^{208}Pb + x

^{238}U + x

x=

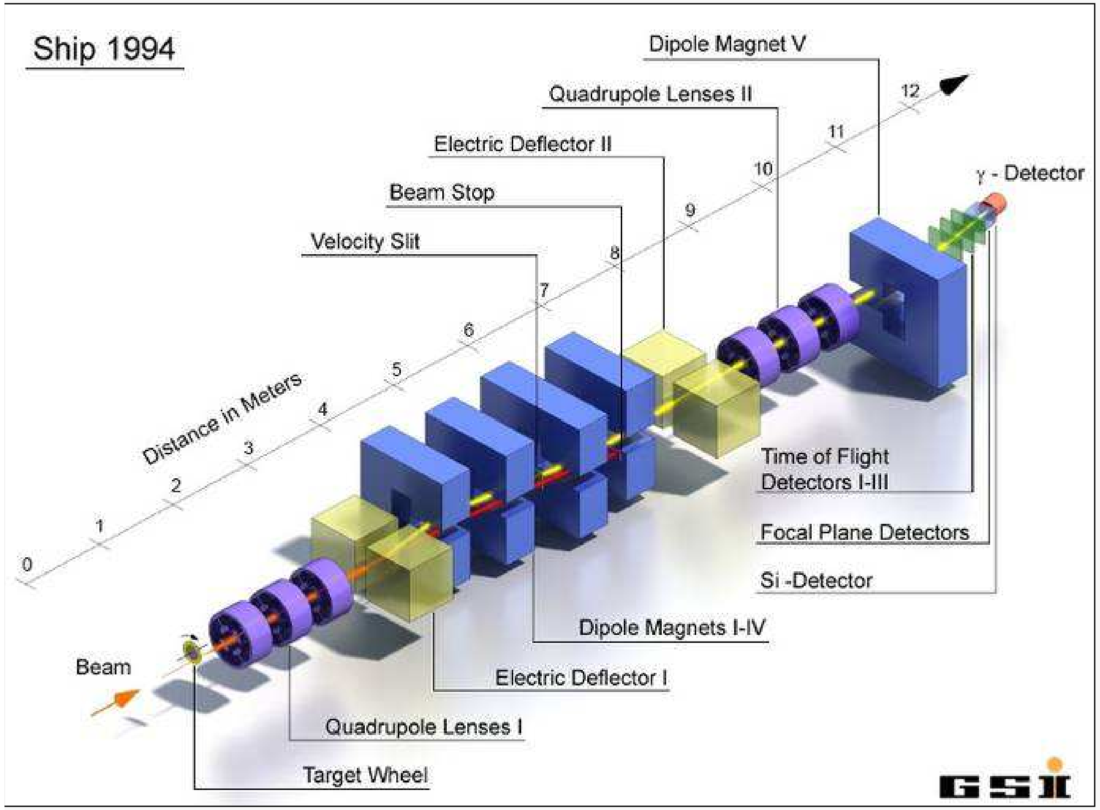
^{1}H

^{2}H

^{208}Pb

$\sigma > 100\ \mu b$

Recoil separator

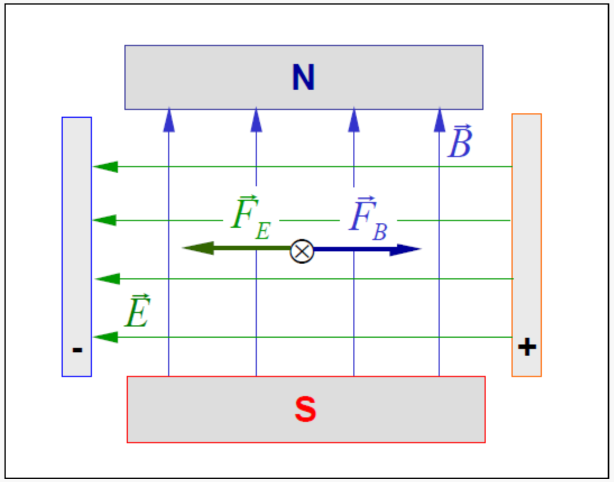


Münzenberg et al., NIM 161 (1979) 65

Uniform magnetic field
(dipole magnet)

$$B\rho\ [\mathrm{Tm}] = \frac{p}{q} = 3.107\,\gamma\beta\,\frac{A}{Q}$$

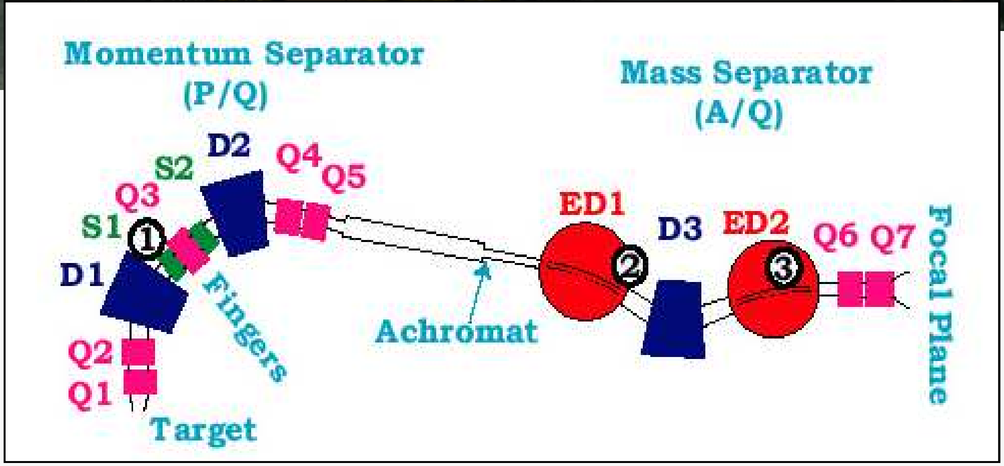
Crossed magnetic and electric fields
(velocity filter)



$$F_B = q\,v\,B, \qquad F_E = q\,E$$

Recoil separator 2

Recoil Mass Separator @ ORNL



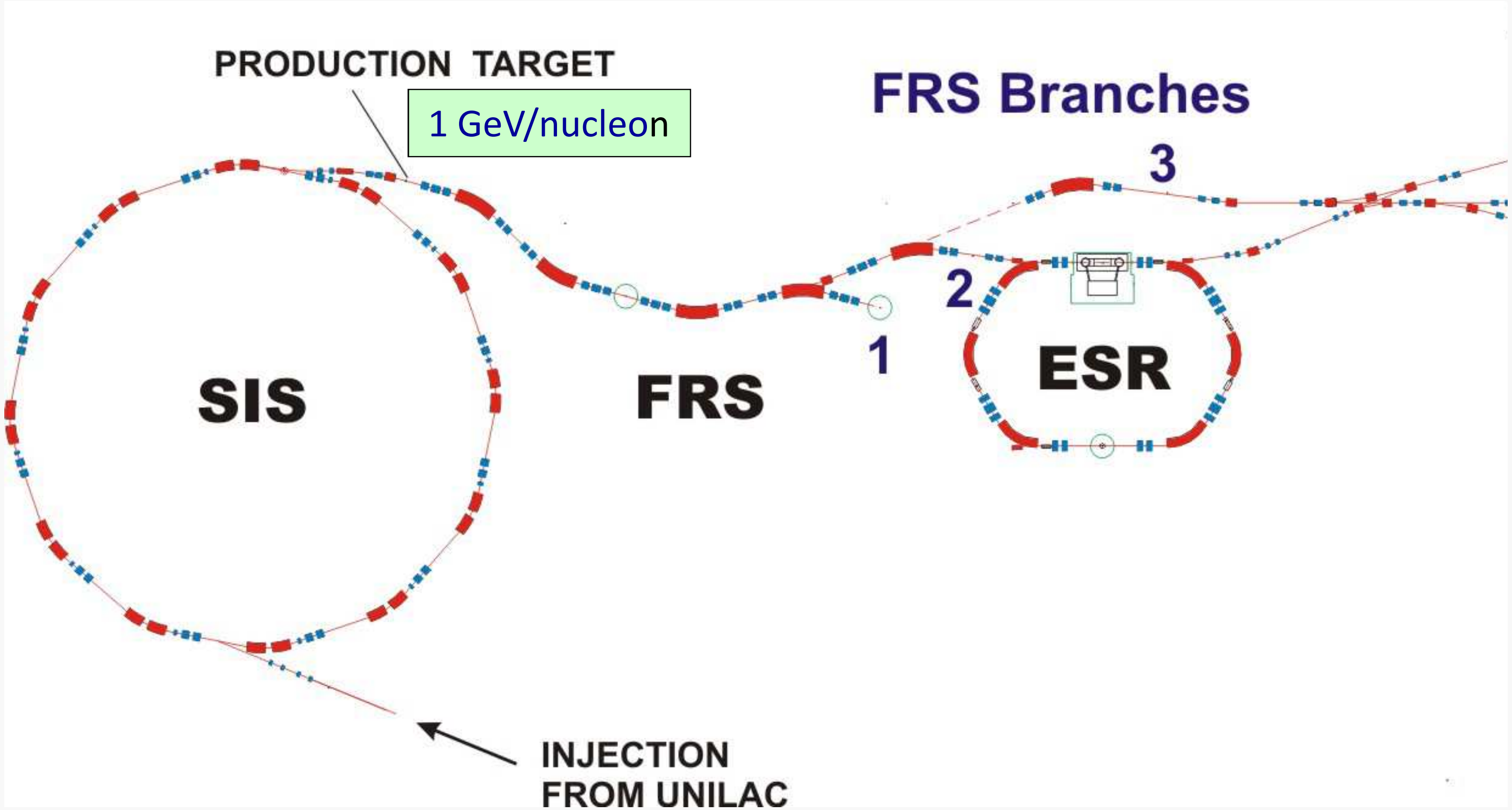
Fragment Mass Analyser @ ANL

Gross et al., NIM A 450 (2000) 12

Davids et al., NIM B 70 (1992) 358

Fragment separator

Example: FRS at GSI Darmstadt

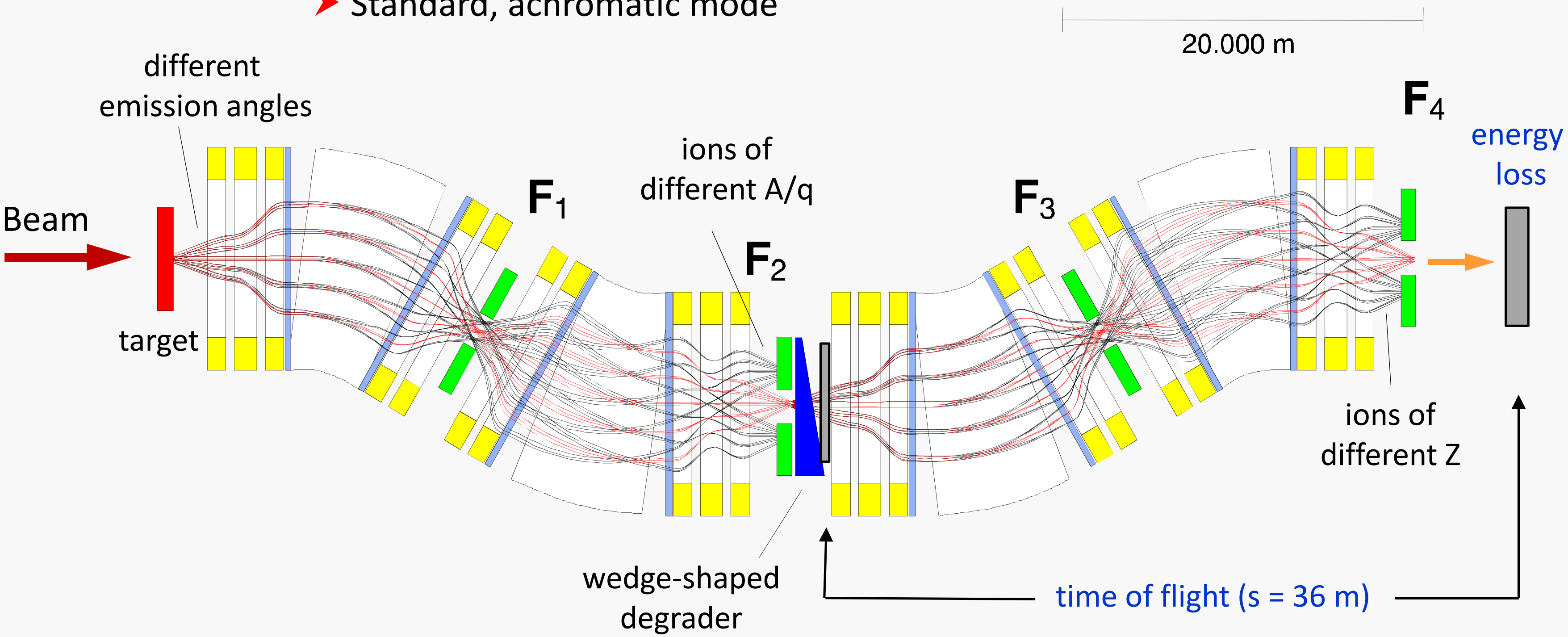


1 GeV/nucleon

3-20 MeV/nucleon

FRS – ion optics and particle ID

- Standard, achromatic mode



$\left.\begin{array}{l}\text{Time-of-flight} \rightarrow v \\ \text{Positions + B field} \rightarrow B\rho\end{array}\right\} \rightarrow A/q \approx \mathbf{A/Z}$

Energy loss ΔE → **Z**

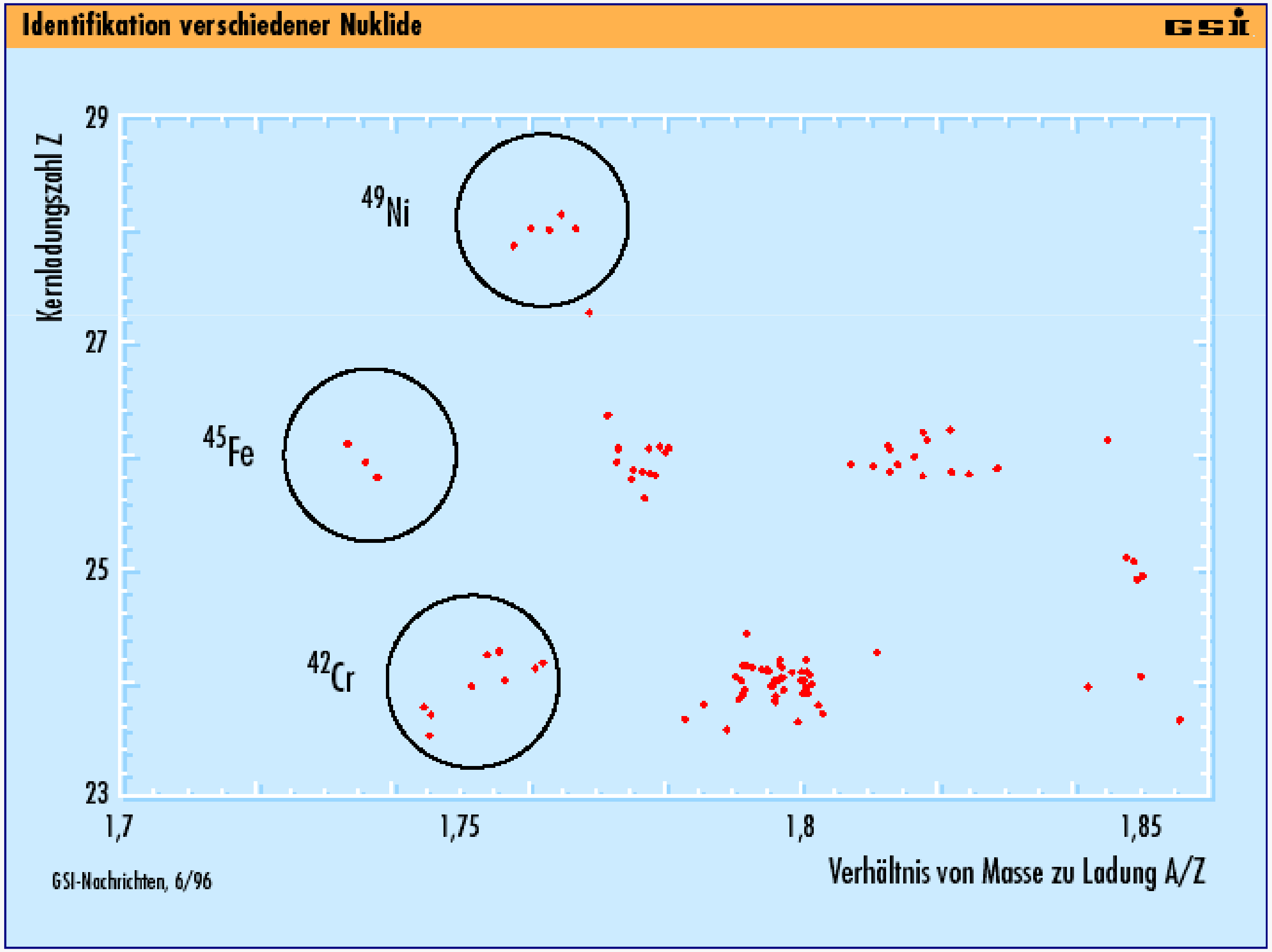
- Full in-flight identification of each ion

Geissel et al., NIM B70 (1992) 286

Example of identification

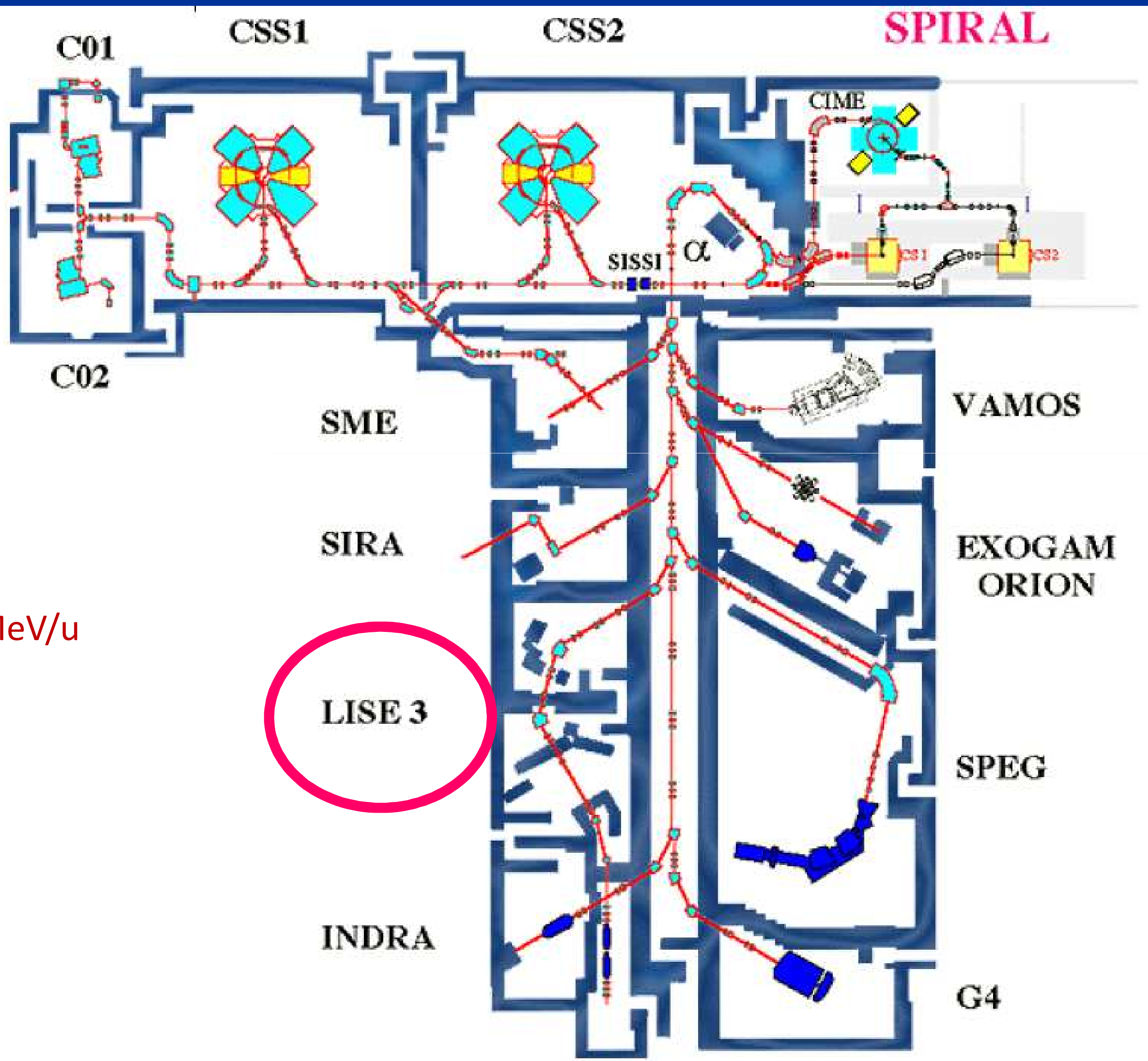
- First observation of three new nuclides : ^{42}Cr, ^{45}Fe i ^{49}Ni

FRS, GSI, 1996



Example 2: GANIL

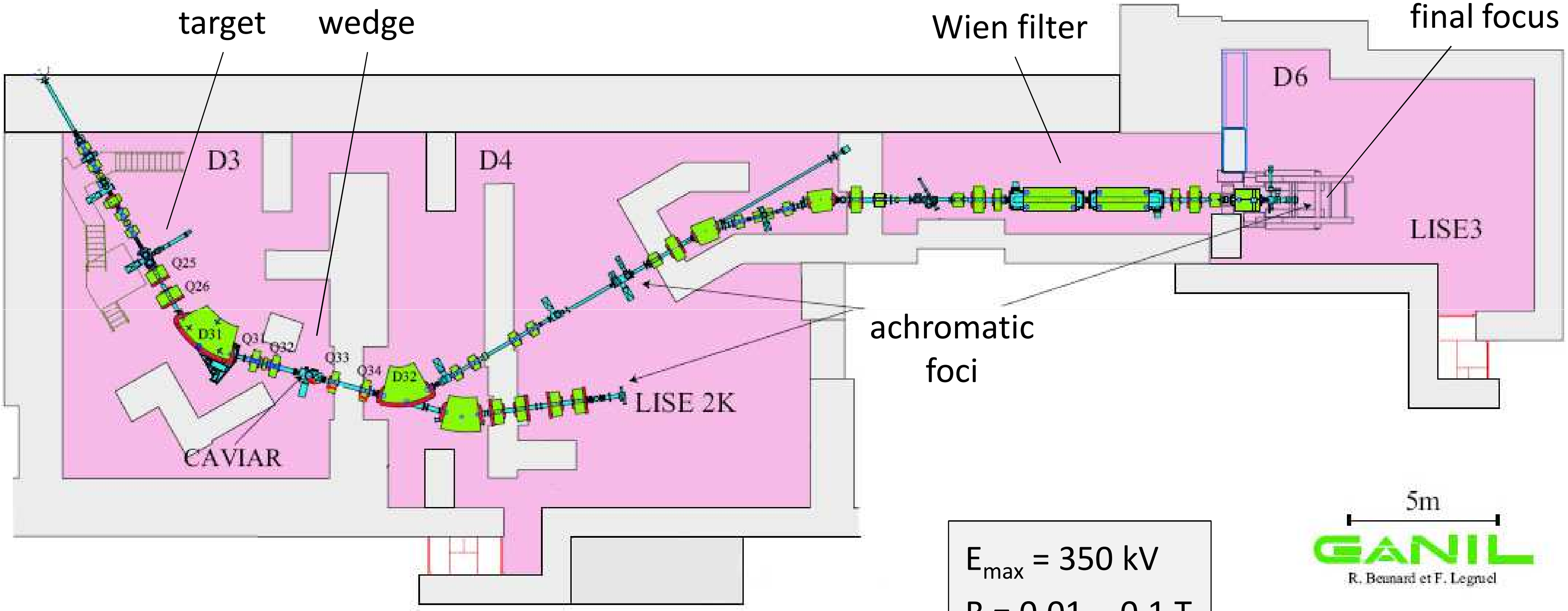
Grand Accelerateur
National d'Ions Lourds
Caen, Francja



Two cyclotrons

Beams:
C – U up to 95 MeV/u

LISE @ GANIL



target

wedge

Wien filter

final focus

achromatic foci

E_{max} = 350 kV

B = 0.01 – 0.1 T

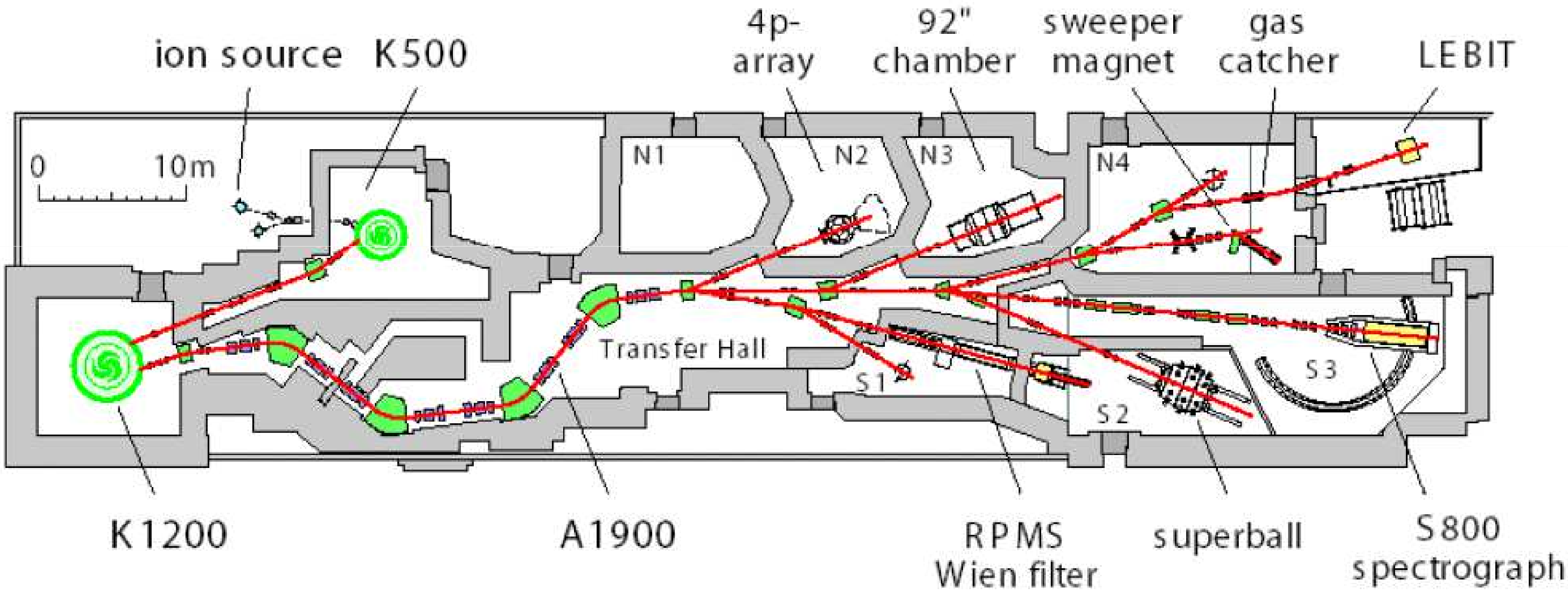
D_V = 3 cm/%

Target – D6 focus: 42 m

Mueller and Anne, NIM B56 (1991) 559

Example 3: A1900 @ NSCL/MSU

National Superconducting Cyclotron Laboratory at Michigan State University, East Lansing, USA

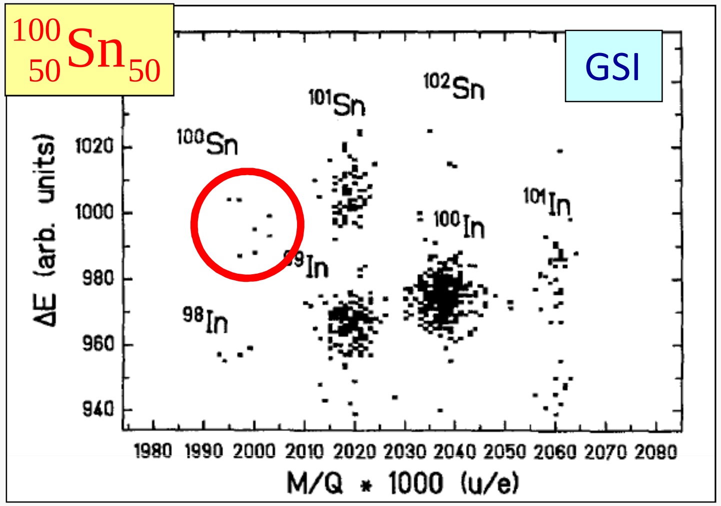


Two cyclotrons

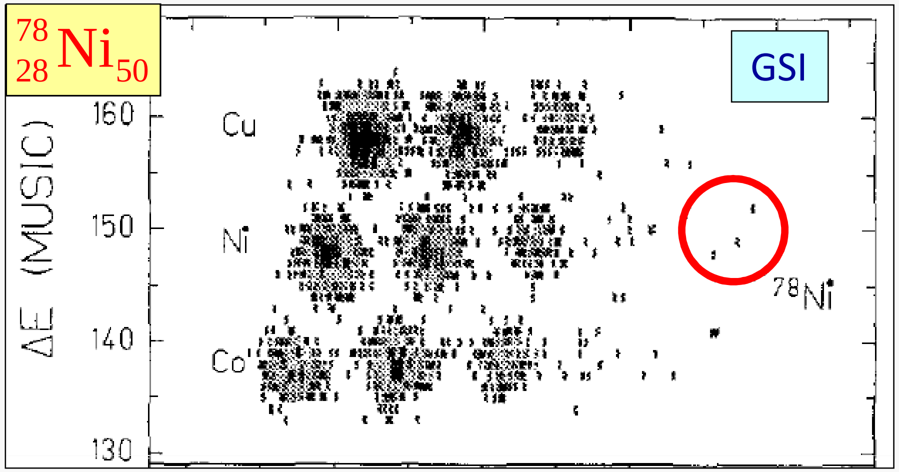
Beams:
O – U up to 170 MeV/u

Morrissey et al., NIM B204 (2003) 90

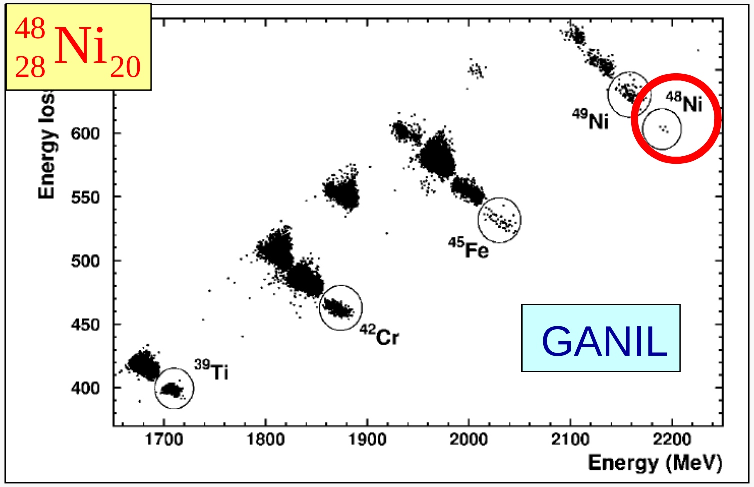
Fragmentation milestones



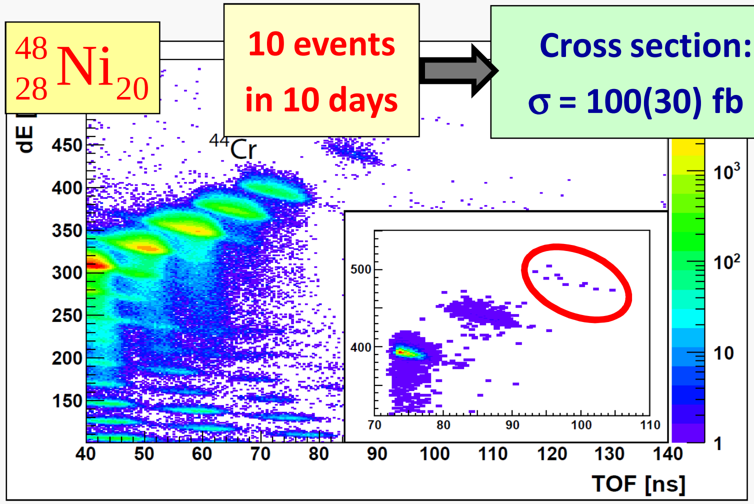
Schneider et al., Z. Phys. A 348 (1994) 241



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



B. Blank et al., PRL 84 (00) 1116

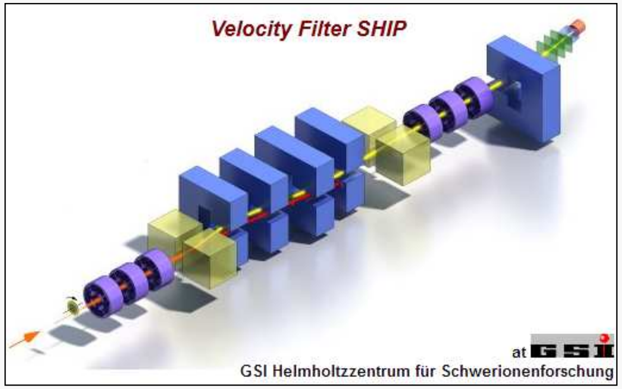


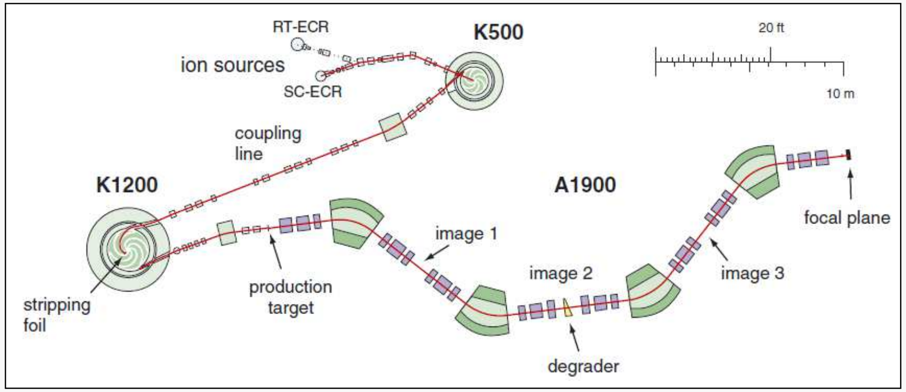
10 events in 10 days

Cross section: σ = 100(30) fb !

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

Production efficiency





- Hunt for element 120 at SHIP

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

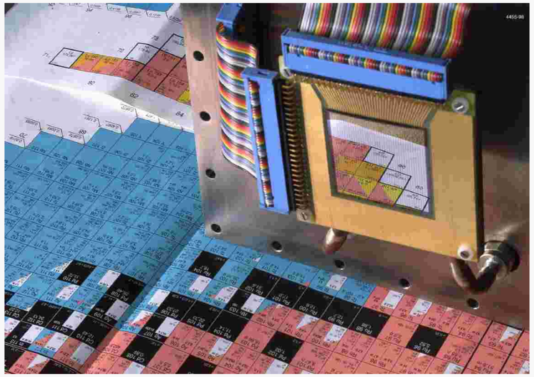
- Production of $^{48}\mathrm{Ni}$ at NSCL

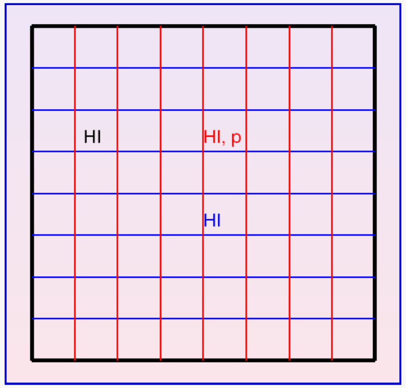
fragmentation $^{58}\mathrm{Ni} + {}^{\mathrm{nat}}\mathrm{Ni} \rightarrow {}^{48}\mathrm{Ni}$

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	

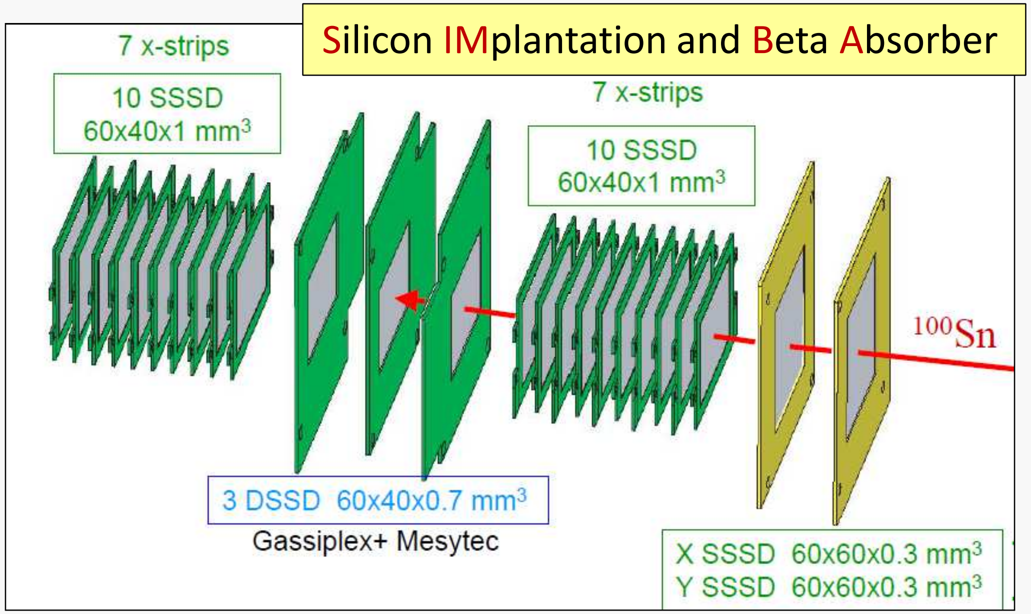
DSSSD

DSSSD – Double Sided Silicon Strip Detector

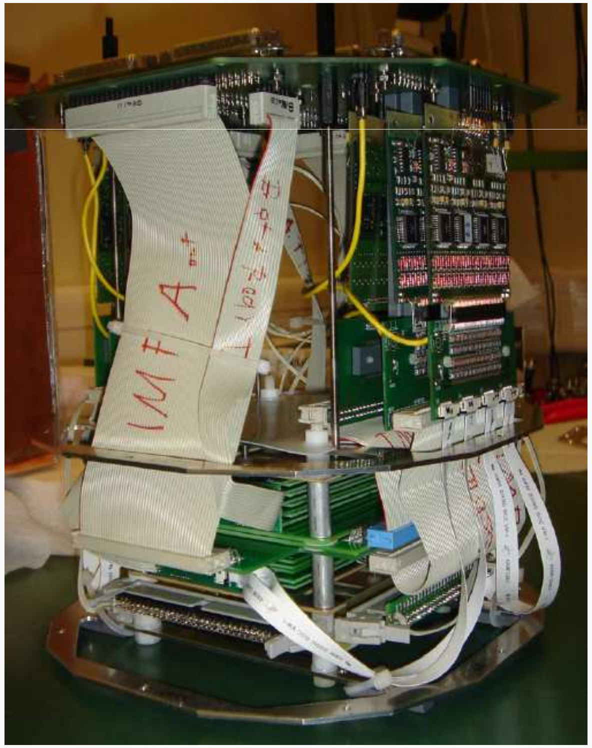




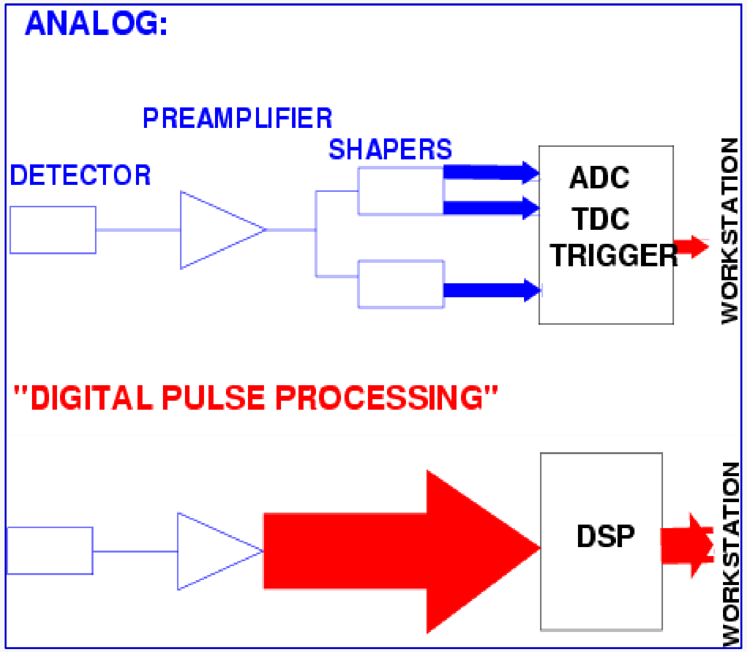
- Correlations between ion-implantation and its decay in space and in time



Silicon IMplantation and Beta Absorber



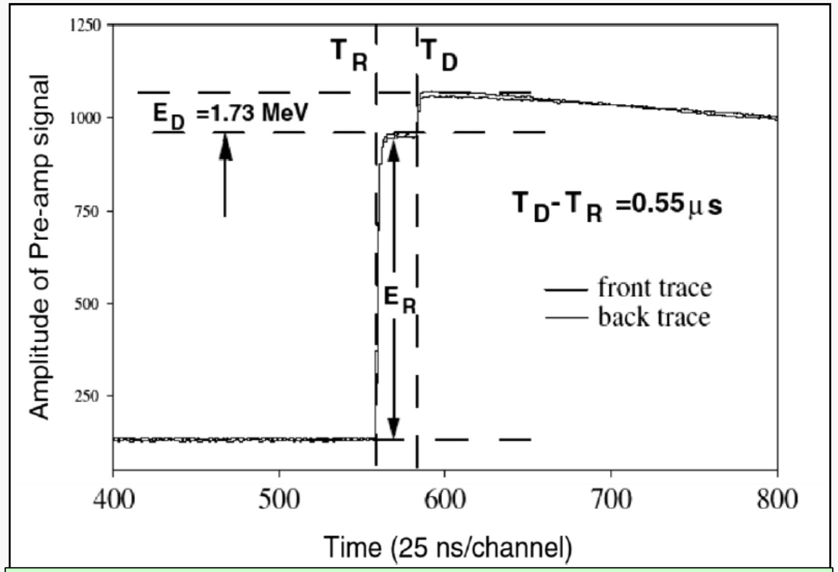
Digital tricks



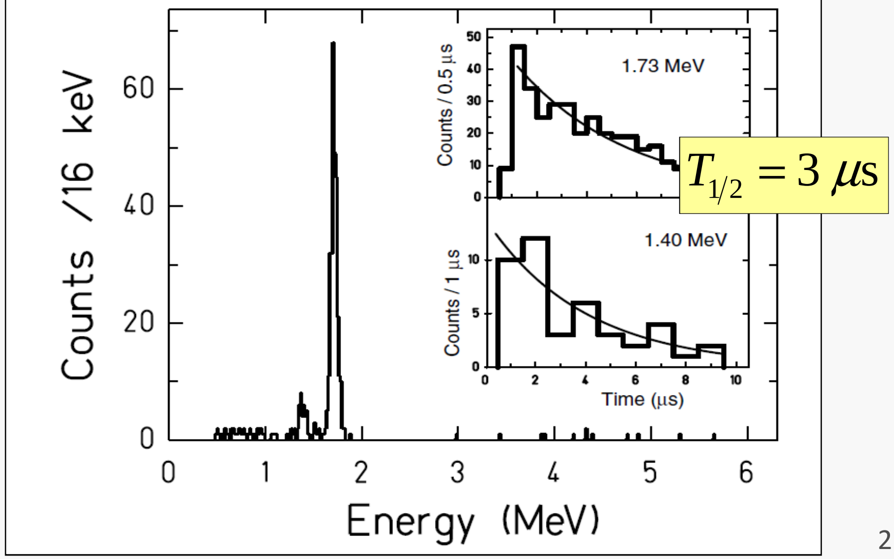
Grzywacz, NIM B 234(2007)

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

- In the „proton-catcher” mode only pile-up events are stored



Fine structure in proton emission from ^{145}Tm



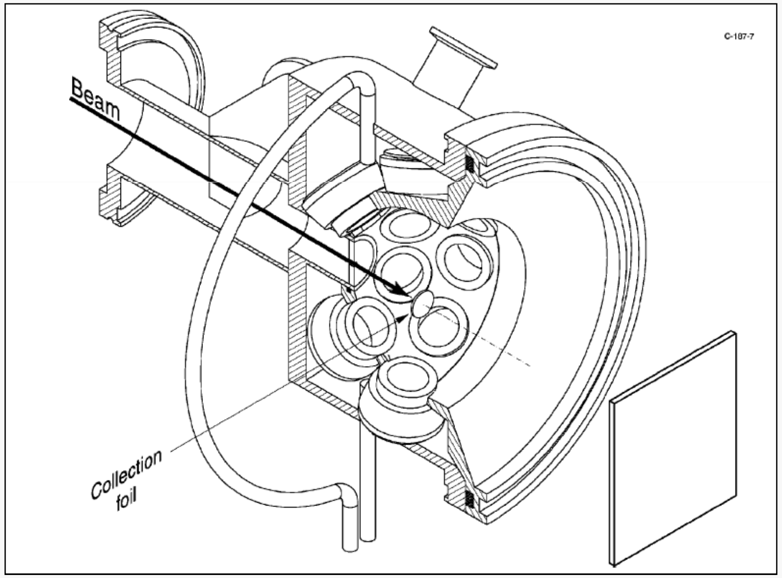
$T_{1/2} = 3\ \mu s$

Multiparticle decays

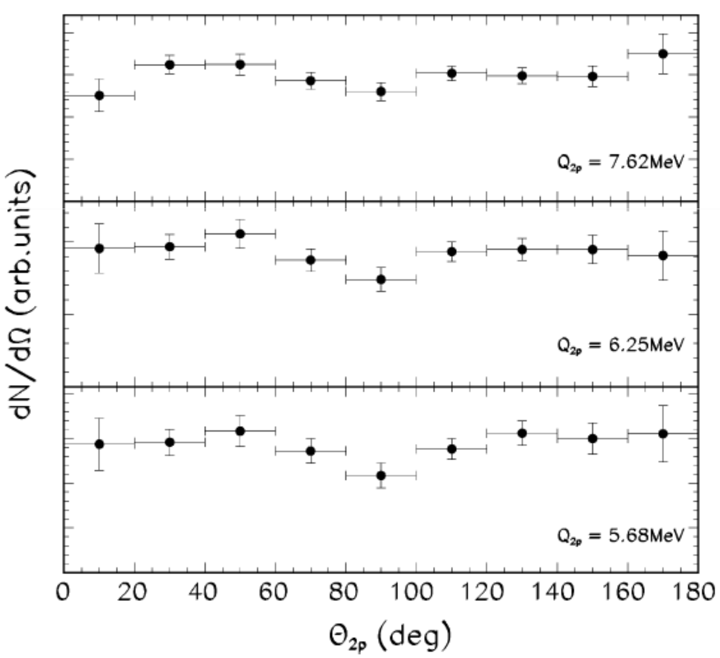
- Correlations between emitted particles contain important information

- Sometimes p-p correlations can be measured by arrays of Si detectors

  Example: β2p decay of ^{31}Ar @ISOLDE

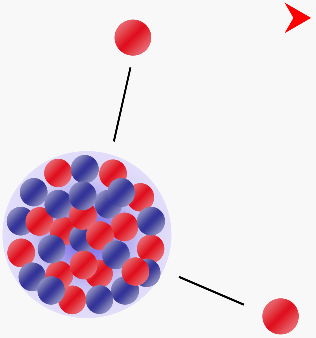


H.O.U. Fynbo et al. / Nuclear Physics A 677 (2000) 38–60



- However, after the fragment separator ions have large energy spread and a **thick detector** must be used to stop them

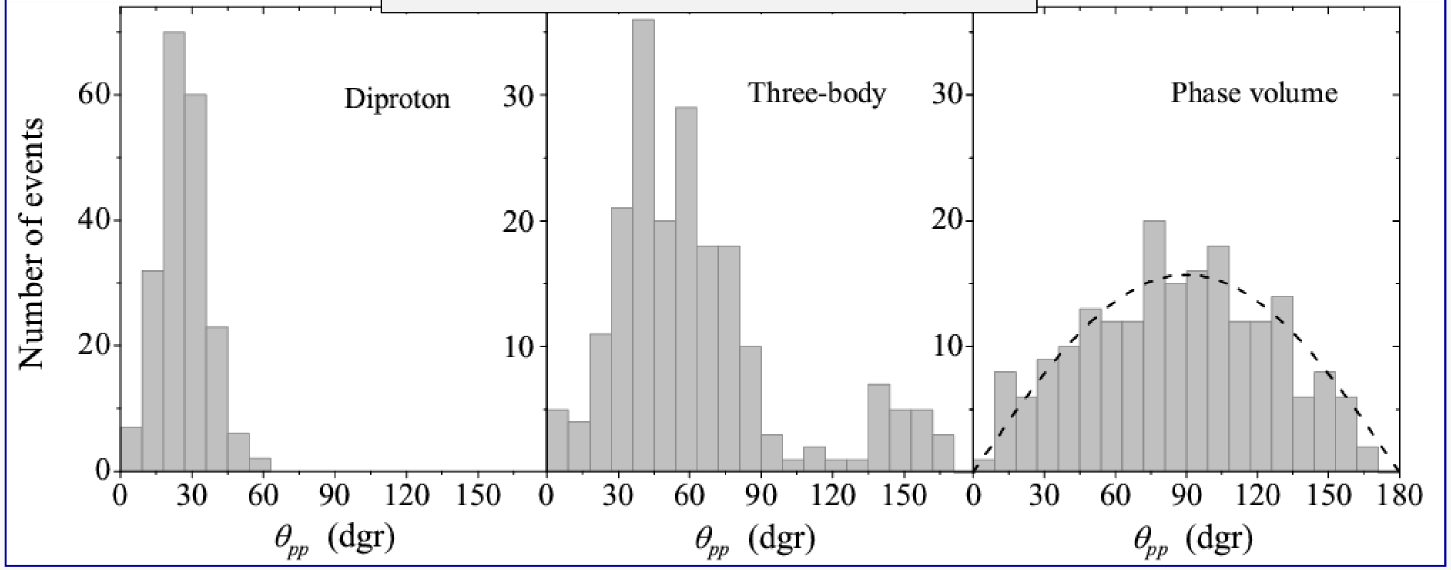
The experimental challenge of 2p decay



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

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

Predicted 2p opening angle for ^{45}Fe

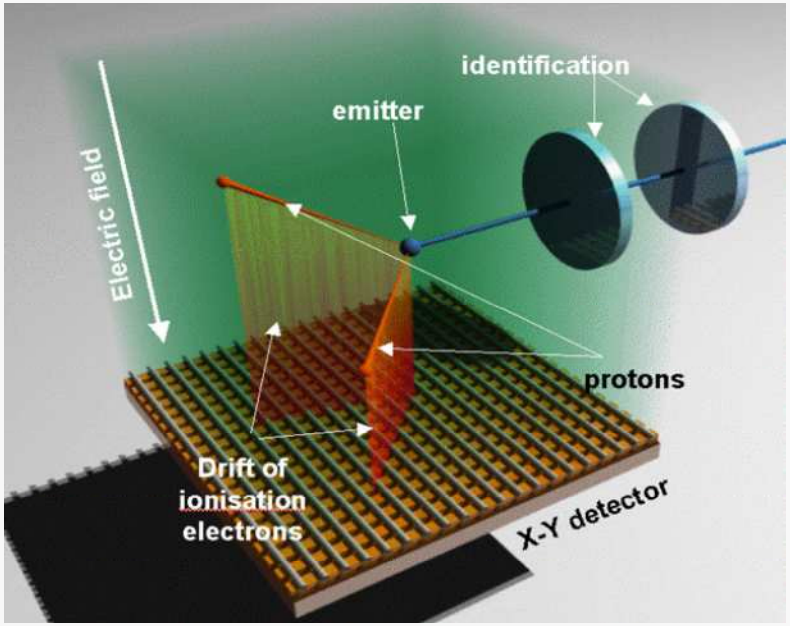


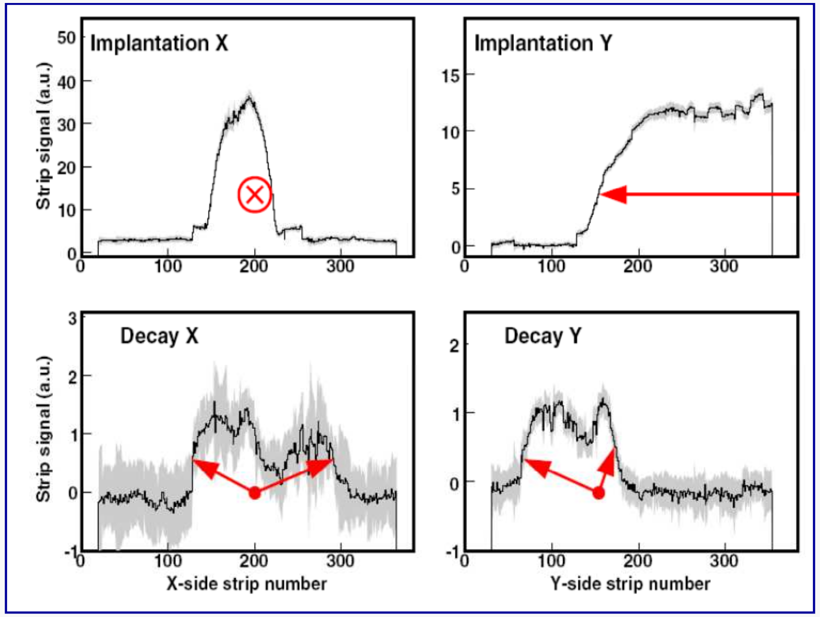
L. Grigorenko : simulation for 200 events

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

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

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

Novel idea

G. Charpak, W. Dominik, J. P. Farbe, J. Gaudaen, F. Sauli, and M. Suzuki,

"Studies of light emission by continuously sensitive avalanche chambers,"

NIM A269 (1988) 142

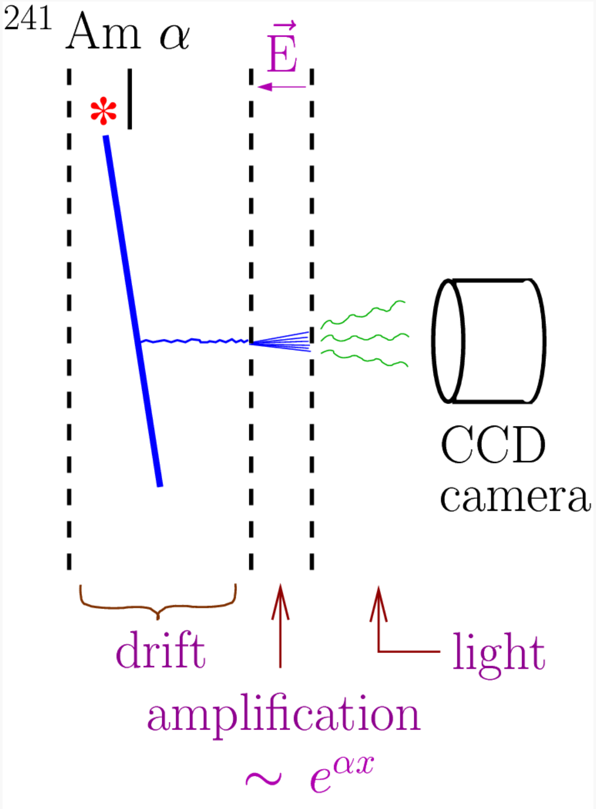
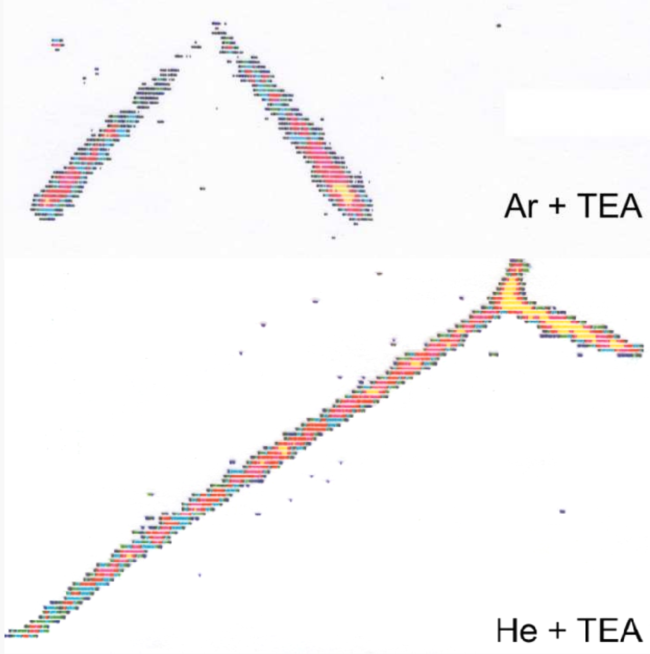


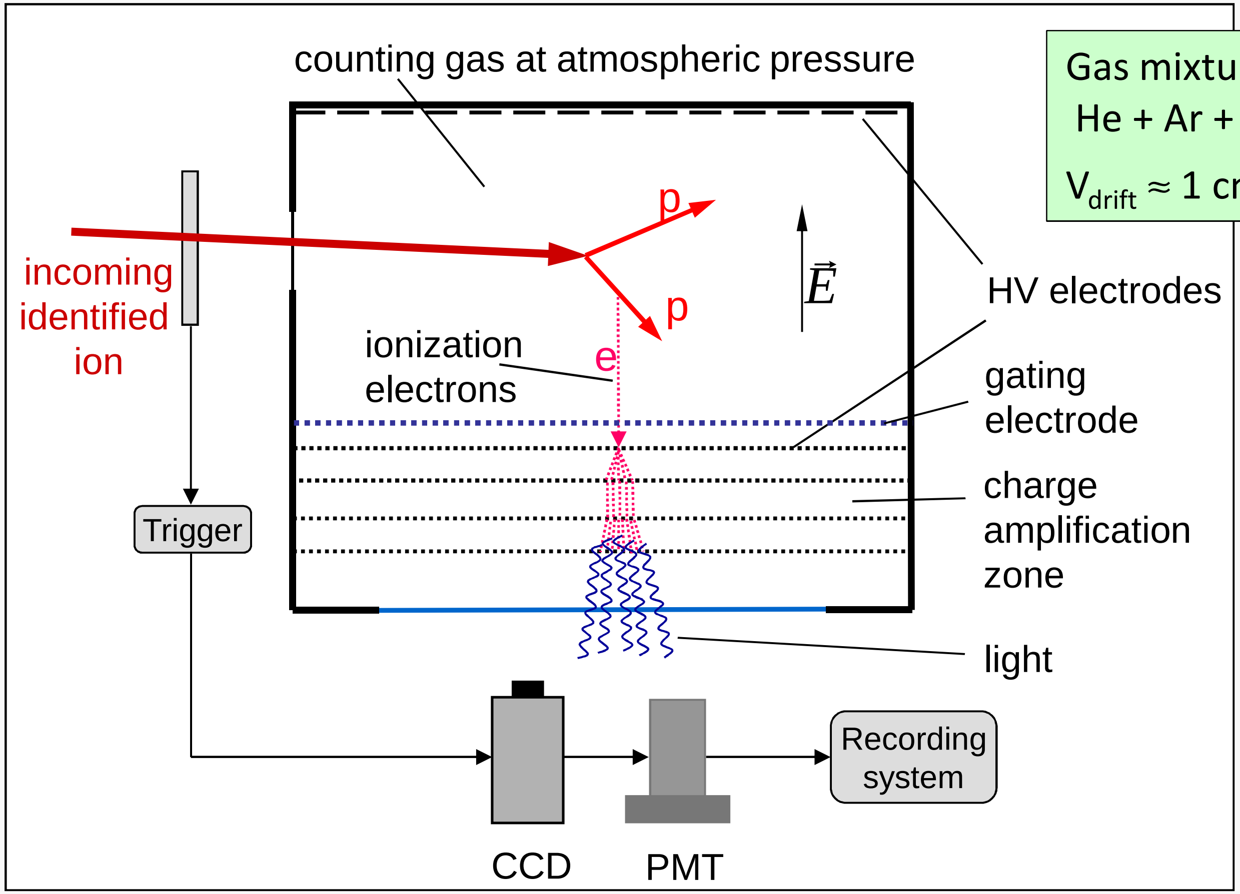
Image examples of α-particle tracks



TEA = Triethylamine $N(C_2H_5)_3$

Optical TPC

- OTPC: Optical Time Projection Chamber

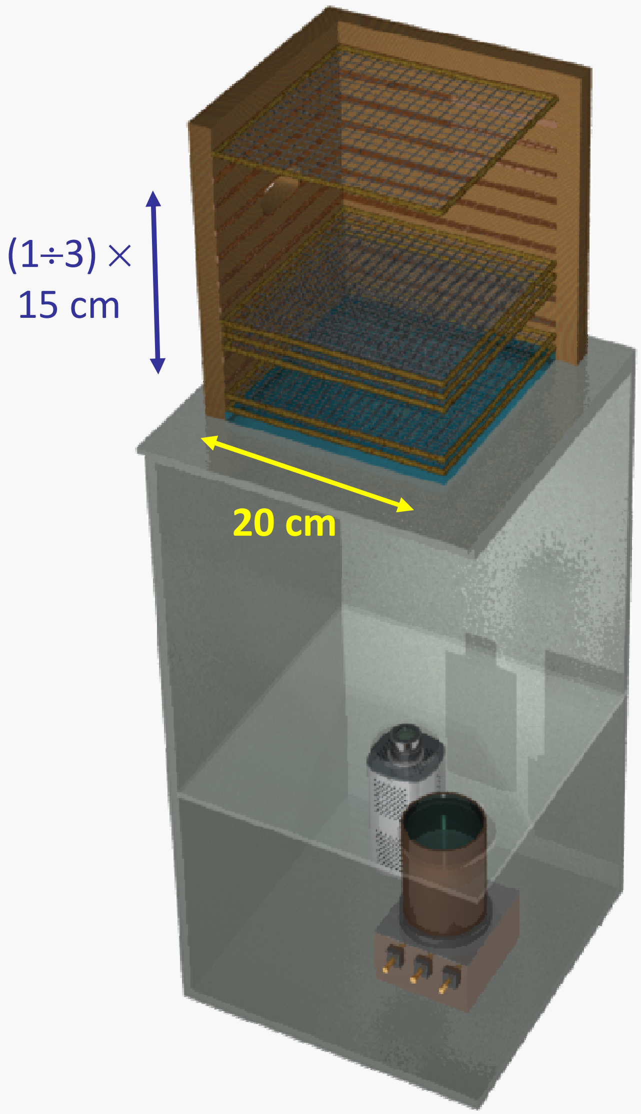


Gas mixture:
He + Ar + N_2 (≈1%)
$V_{drift} \approx 1$ cm/μs

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

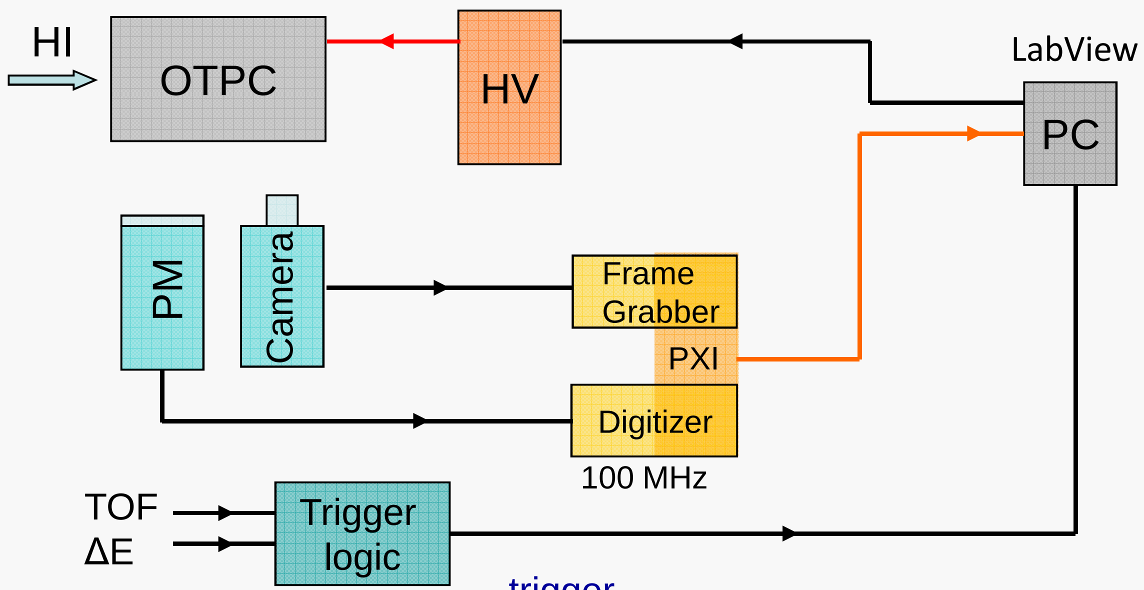
K. Miernik et al., NIM A581 (2007) 194

OTPC data acquisition



CCD 2/3''

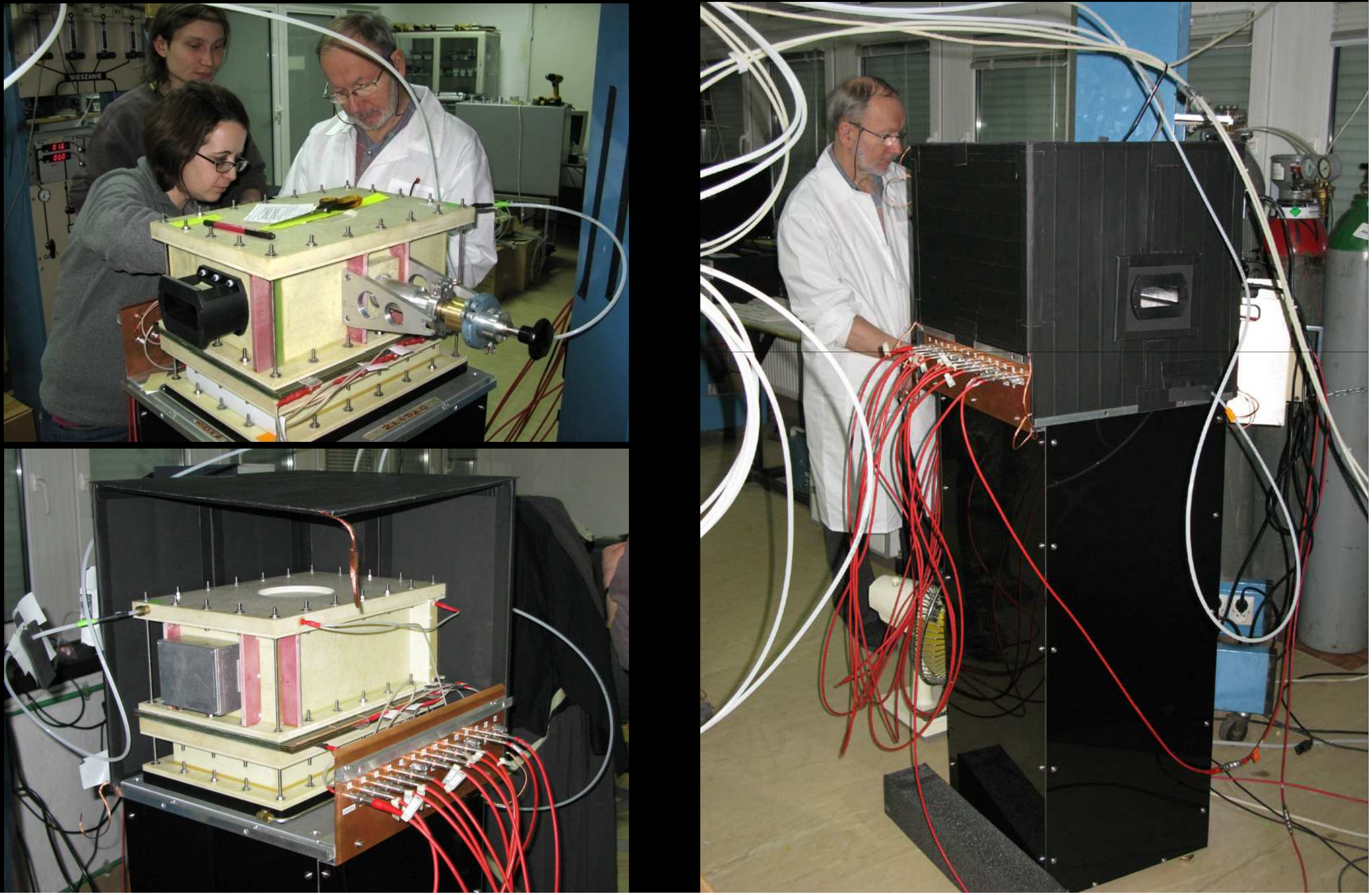
- 1000 × 1000 pix.
- 12-bits
- image ampl. (×2000)



trigger

HI identification
& selection

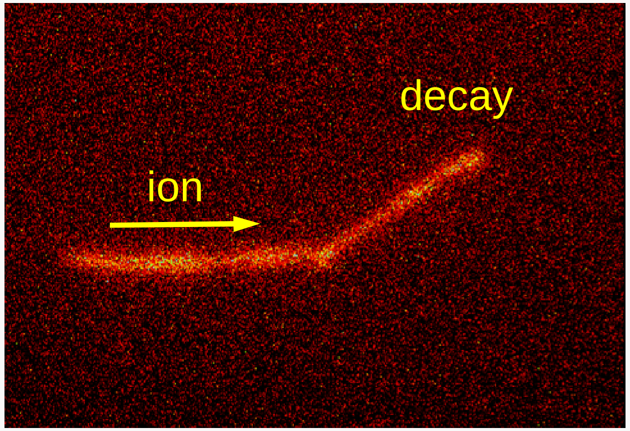
OTPC



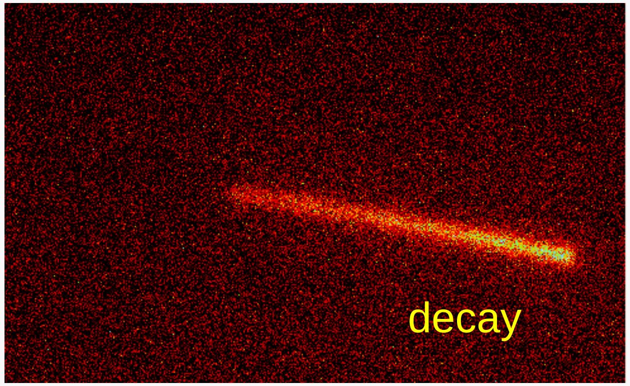
Principle of operation

CCD image

tracks of the ion and emitted particle(s)

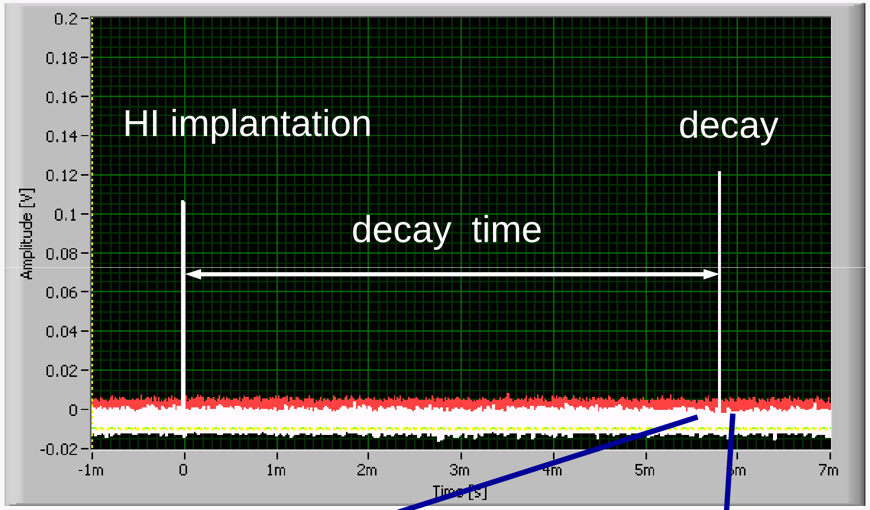


or only emitted particle(s)

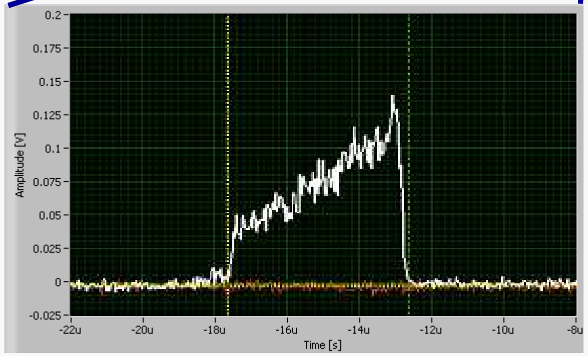


PMT signal sampled

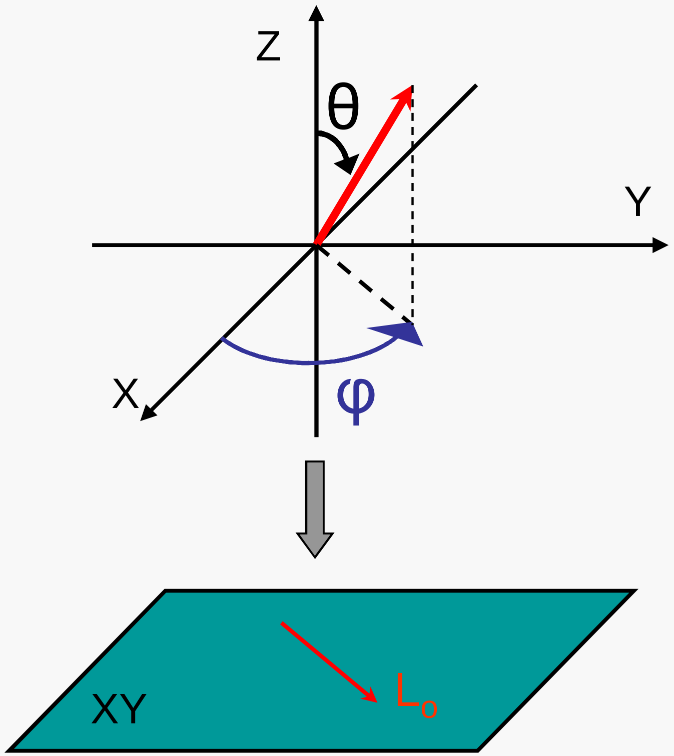
time sequence of events



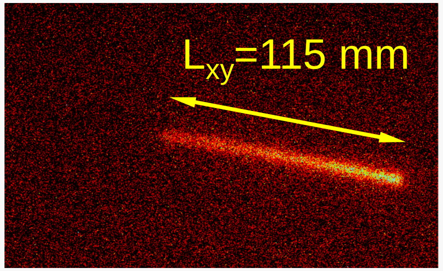
decay details

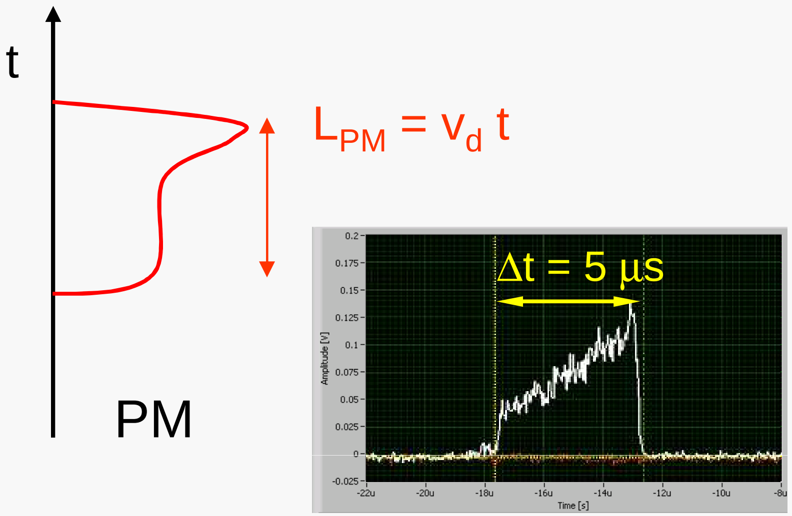


Event reconstruction



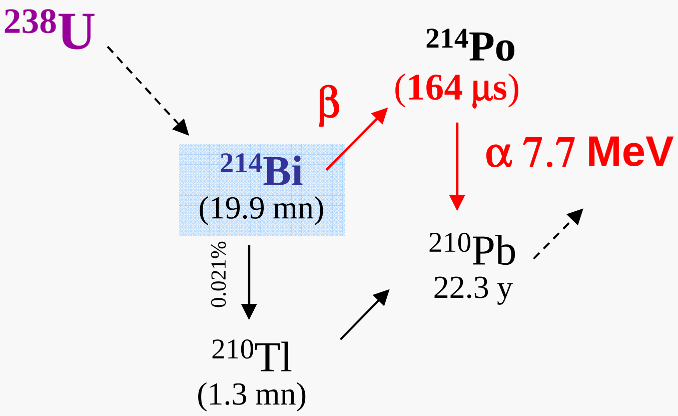
Camera





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

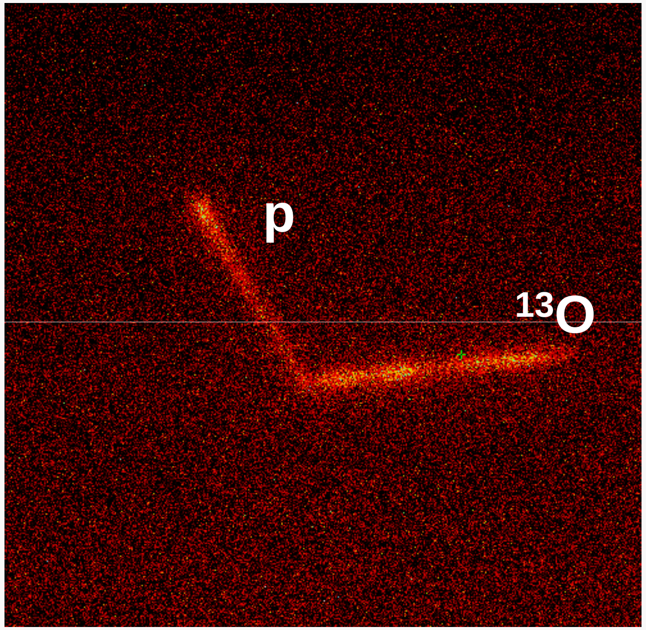
→ ^{214}Po α decay



Testing with decays of implanted ions

Acculinna separator, JINR, Dubna, 2006

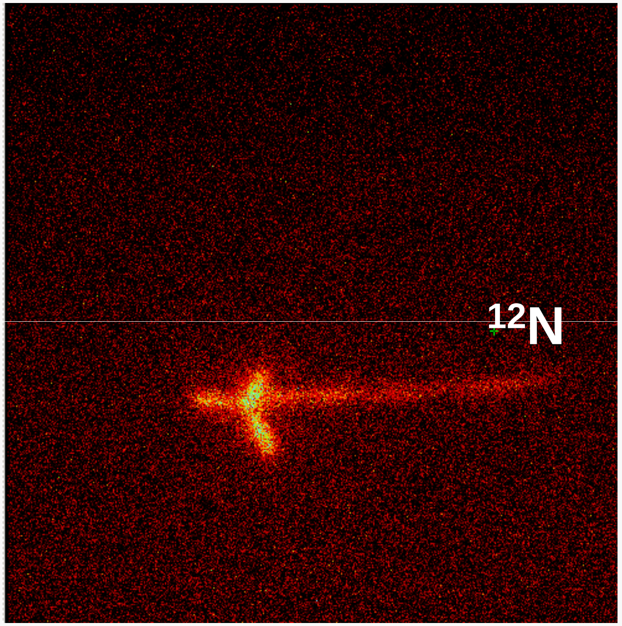
^{20}Ne (50 MeV/u) + Be →...



β*p* emission from ^{13}O

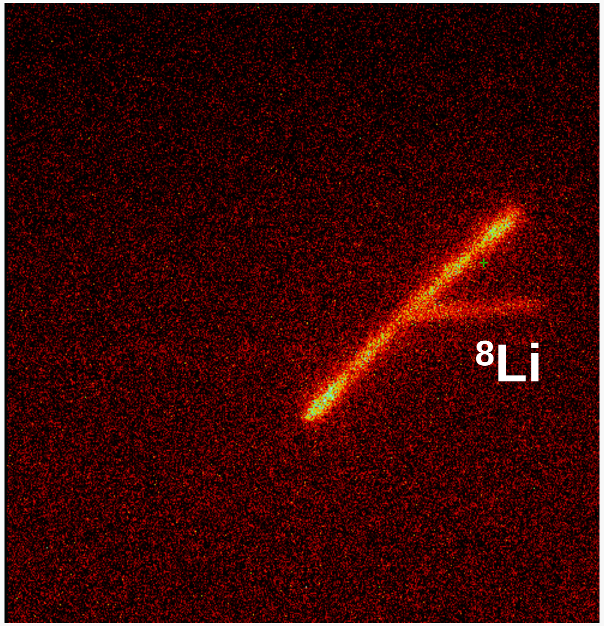
$$^{13}\mathrm{O} \xrightarrow[8\,\mathrm{ms}]{\beta} {}^{13}\mathrm{N}^{*} \rightarrow {}^{12}\mathrm{C} + \mathrm{p}$$

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



β3α decay of ^{12}N

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

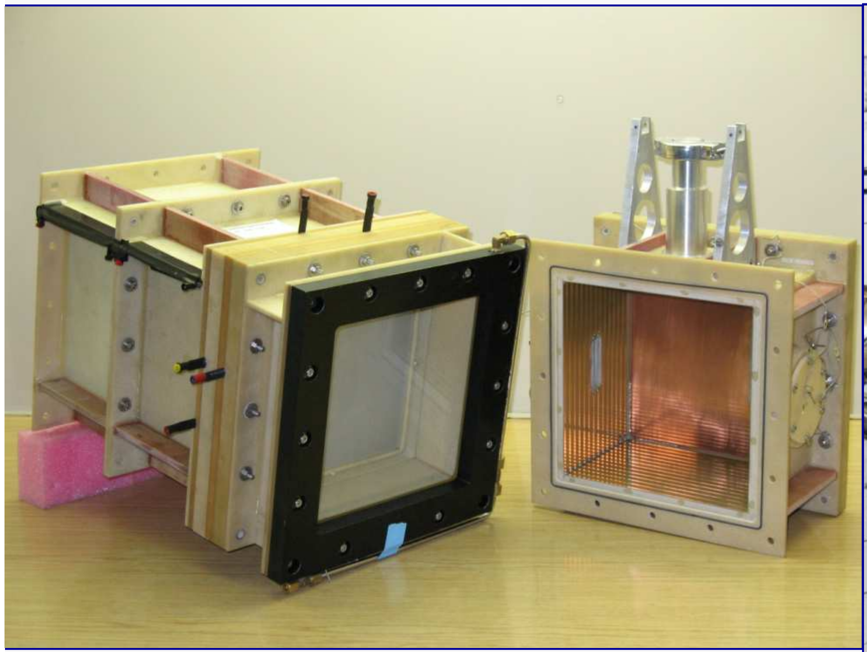


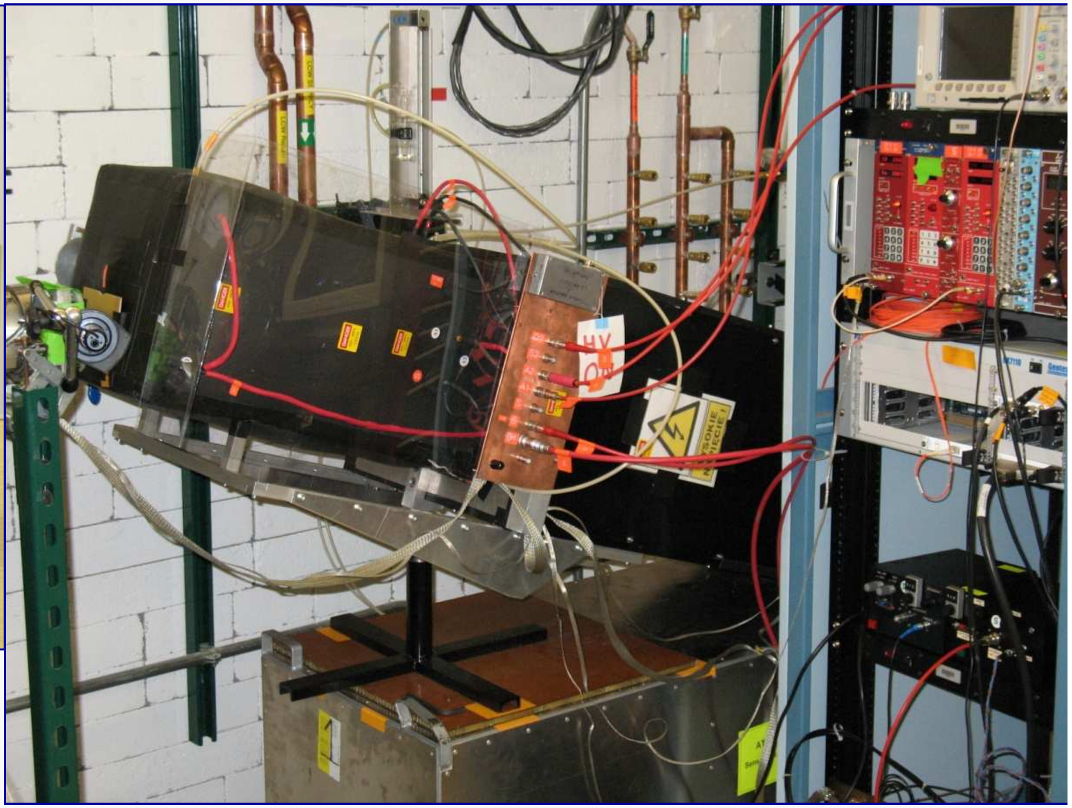
β2α decay of ^{8}Li

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

Experiment at NSCL/MSU

February 2007





Gas mixture:

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

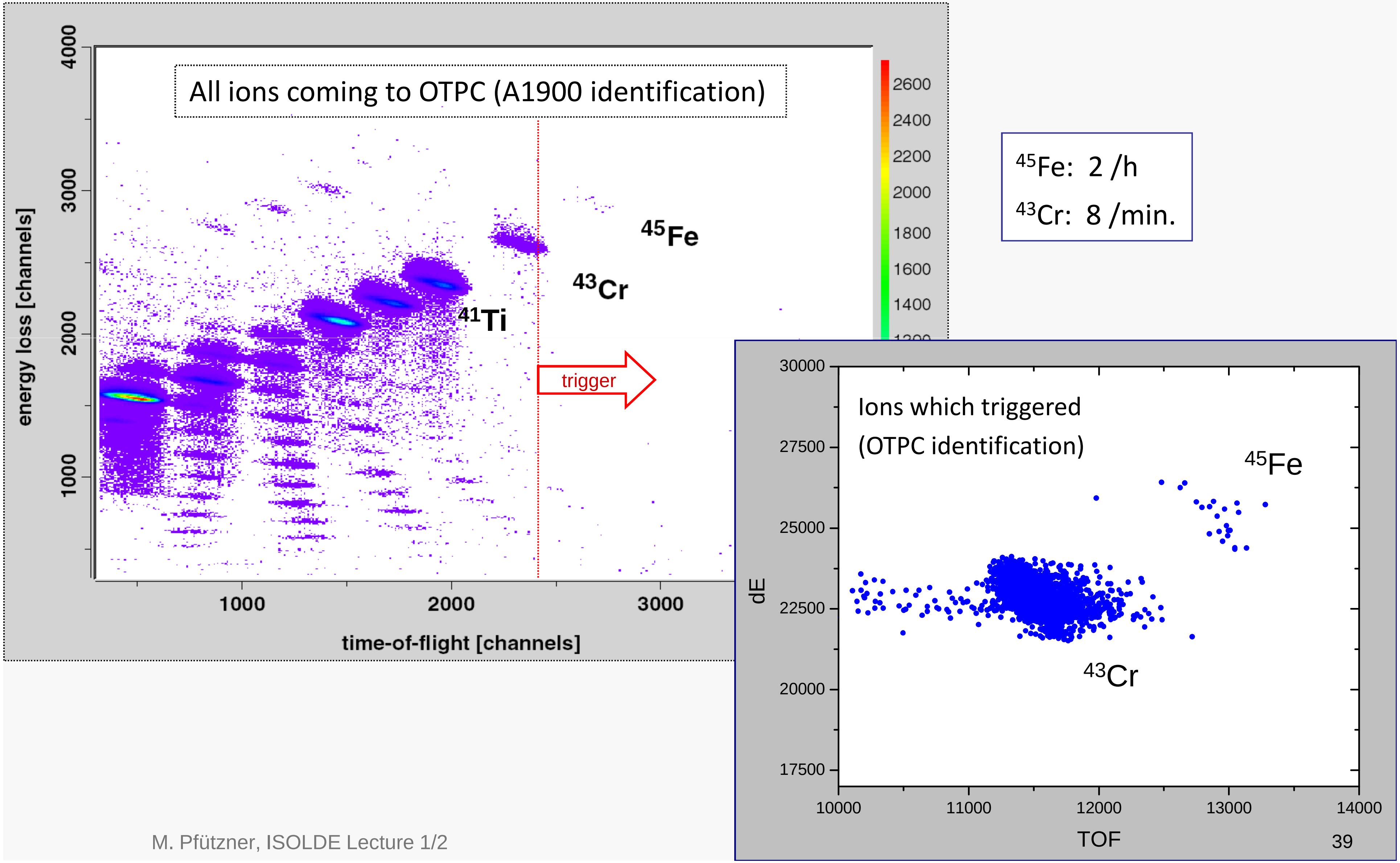
- ➤ range of 550 keV proton ≈ 2.3 cm
- ➤ range spread of ^{45}Fe ion ≈ 50 cm

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

Ion identification

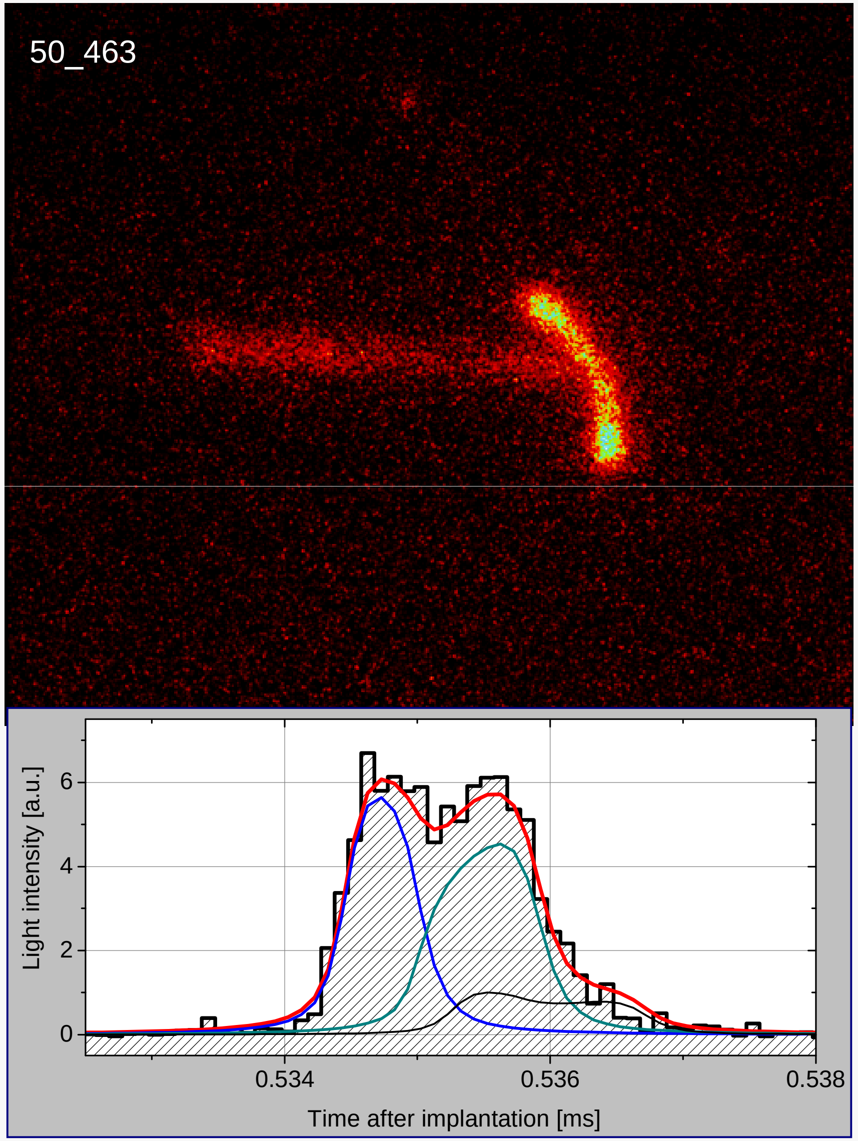


^{45}Fe: 2 /h

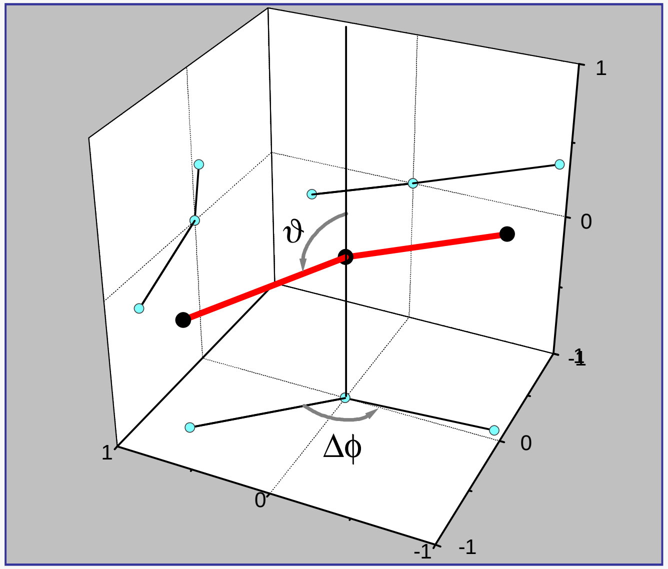
^{43}Cr: 8 /min.

2p events from ^{45}Fe

3D reconstruction



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

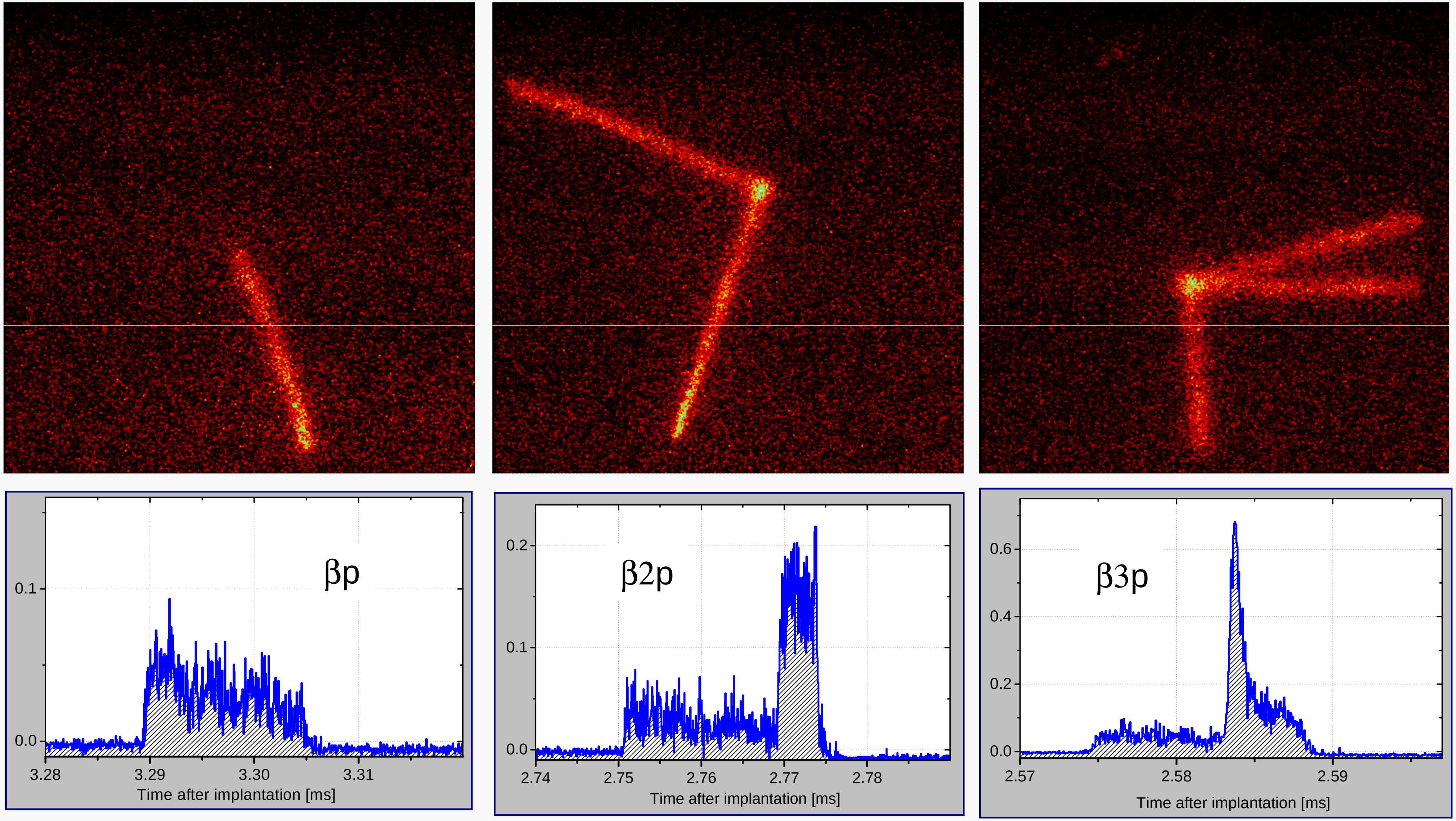


$\vartheta_1 = (104 \pm 2)^\circ$, $\vartheta_1 = (70 \pm 3)^\circ$

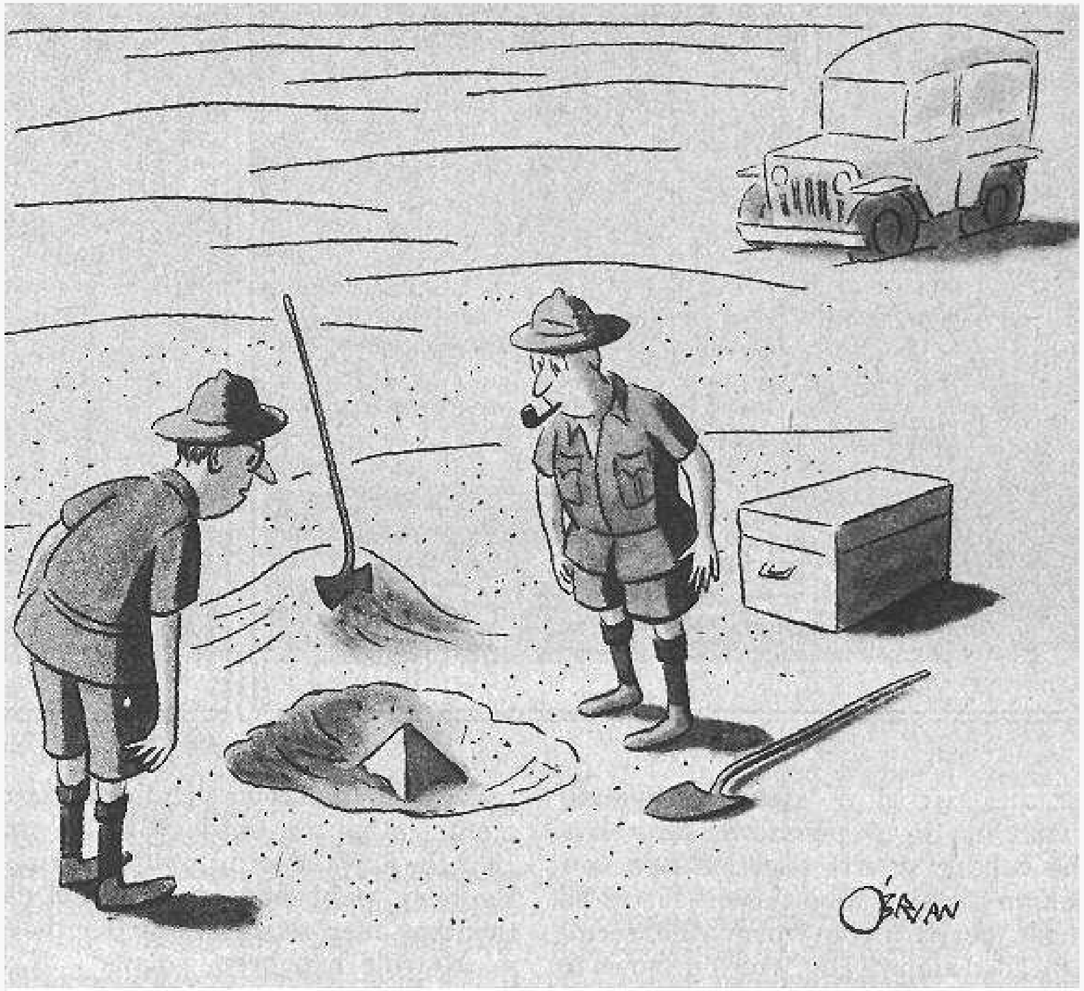
$\Delta\phi = (142 \pm 3)^o \rightarrow \theta_{pp} = (143 \pm 5)^o$

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

β delayed protons from ^{45}Fe



Thanks and see you tomorrow ☺



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