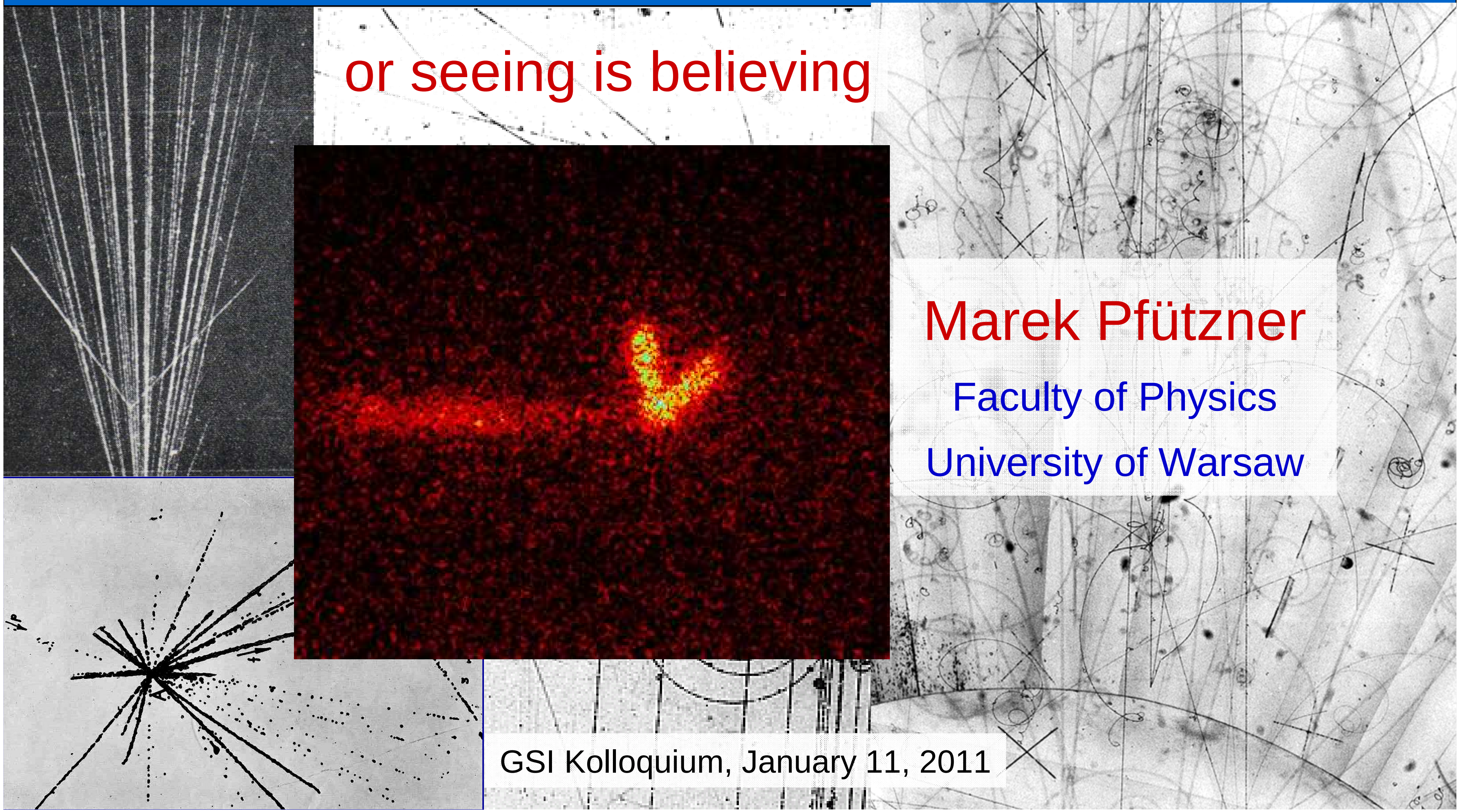
Digital photography at limits of nuclear stability

or seeing is believing



Marek Pfützner

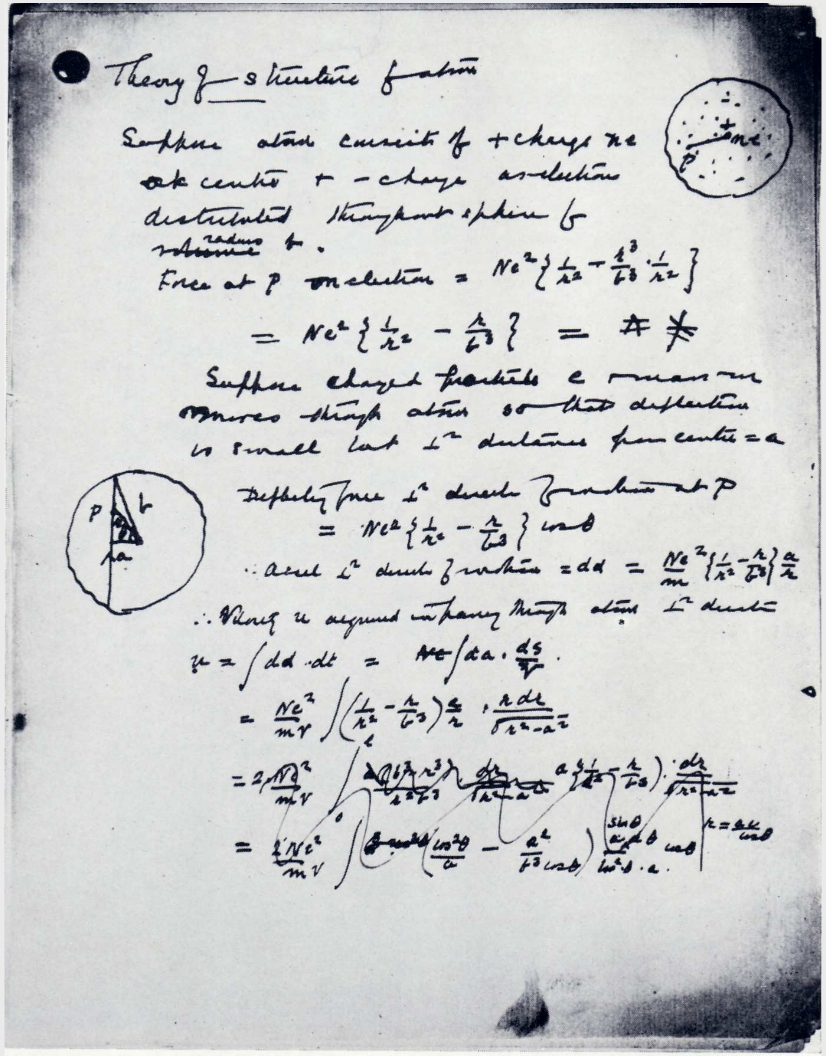
Faculty of Physics

University of Warsaw

GSI Kolloquium, January 11, 2011

100 years ago...

E. Rutherford (1871-1937)



Rutherford's first rough note on the nuclear theory of atomic structure; written, probably, in the winter of 1910–11

The scattering of the α rays...

The first public announcement of the atomic nucleus:

The Scattering of the α and β Rays and the Structure of the Atom

by Professor E. Rutherford, F.R.S.

Proc. of the Manchester Literary and Philosophical Society, IV, 55, pp.18-20.

presented on March 7, 1911

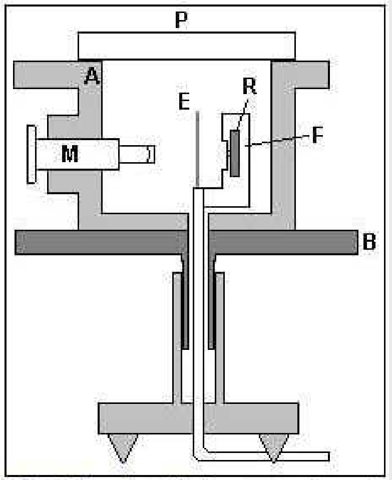
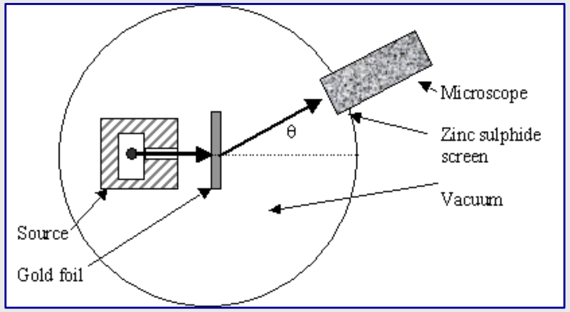
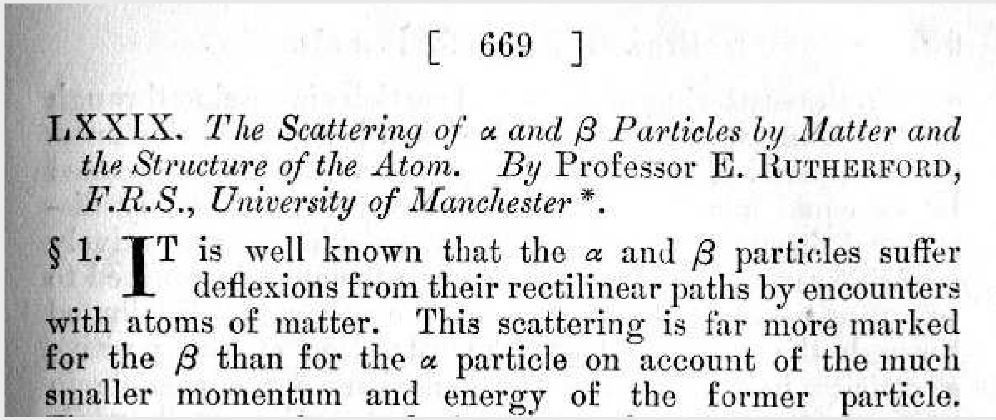


Fig1. Marsden-Geiger experiment.

$$P(\theta) \propto \frac{1}{\sin^4 \theta/2}$$





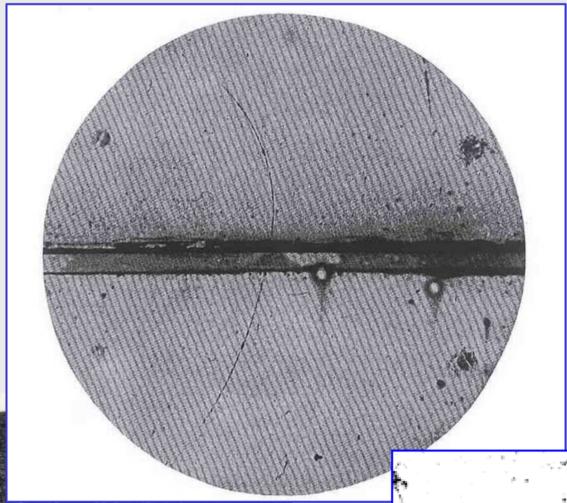
[669]

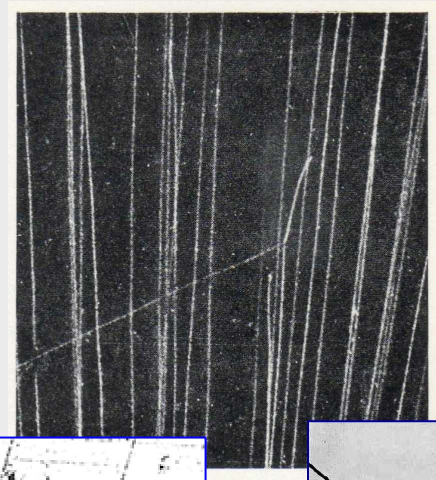
LXXIX. *The Scattering of α and β Particles by Matter and the Structure of the Atom.* *By* Professor E. RUTHERFORD, *F.R.S., University of Manchester* *.

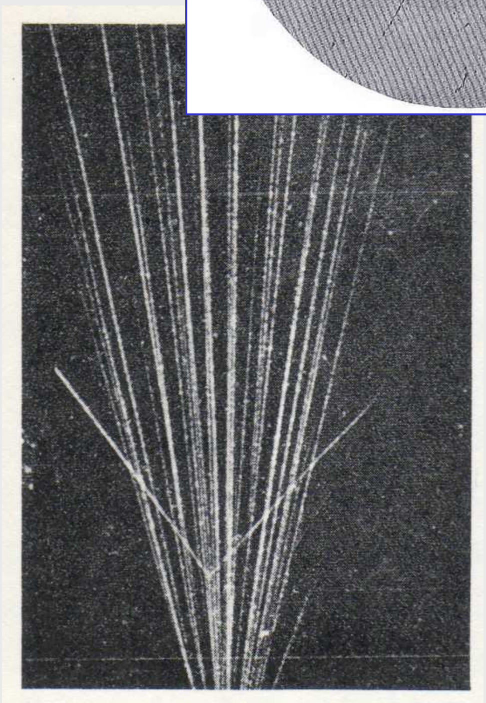
§ 1. IT is well known that the α and β particles suffer deflexions from their rectilinear paths by encounters with atoms of matter. This scattering is far more marked for the β than for the α particle on account of the much smaller momentum and energy of the former particle.

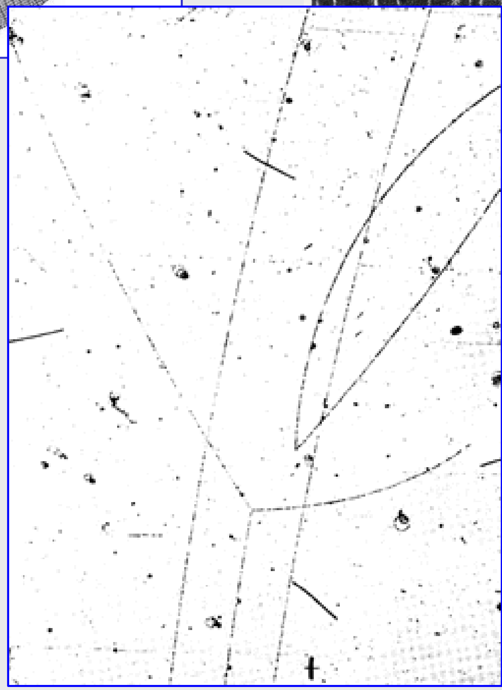
Philosophical Magazine, May 1911, ser.6, xxi, pp.669-88

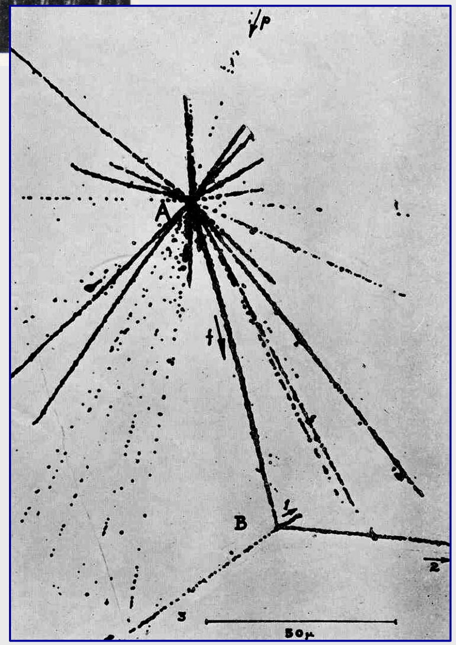
Photography in subatomic physics











In the beginning...

- The whole new world has been discovered accidentally by Antoine Henri Becquerel in 1896 when he exposed a photographic plate to a piece of uranium salt.

- A.H. Becquerel – Nobel Prize 1903 (shared with M. Skłodowska-Curie and P. Curie)

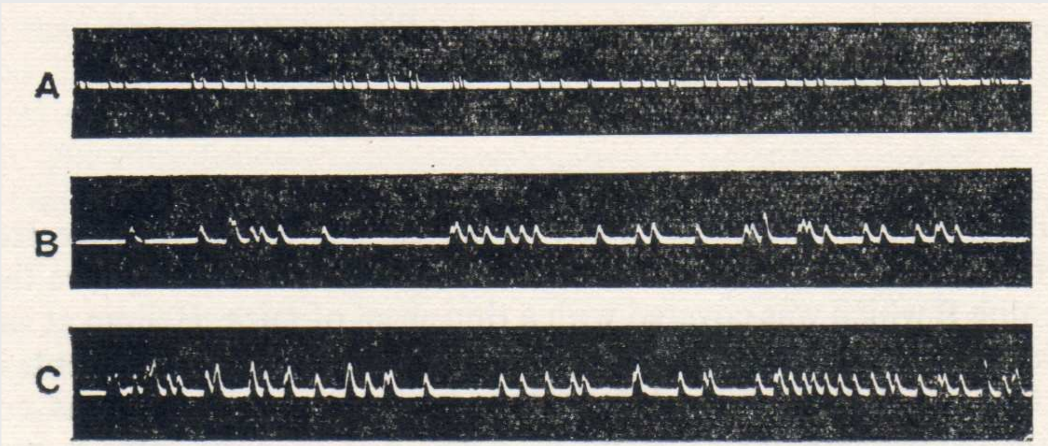
Photos for fast counting

Photographic Registration of α Particles

by Dr. H. Geiger and Professor E. Rutherford, F.R.S.,

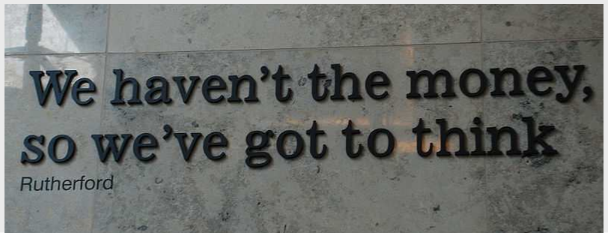
University of Manchester

Philosophical Magazine, October 1912, ser.6, xxiv, pp.618-23



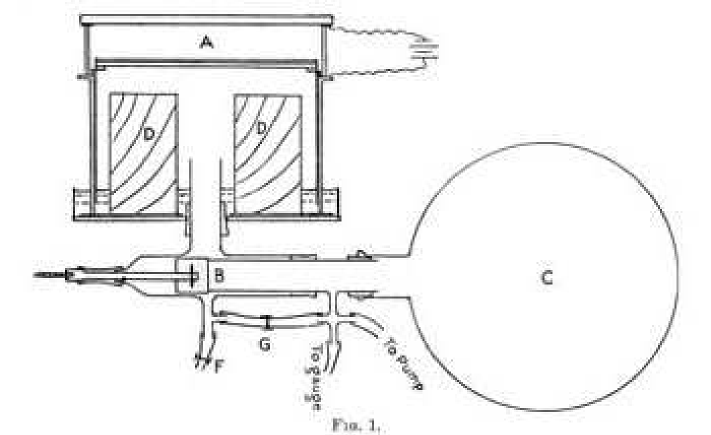
The rapid jumps of an electrometer needle were captured on a moving photographic film (photo-mechanical oscilloscope!).

- Counting rates of up to 1000 α particles per minute could be achieved.

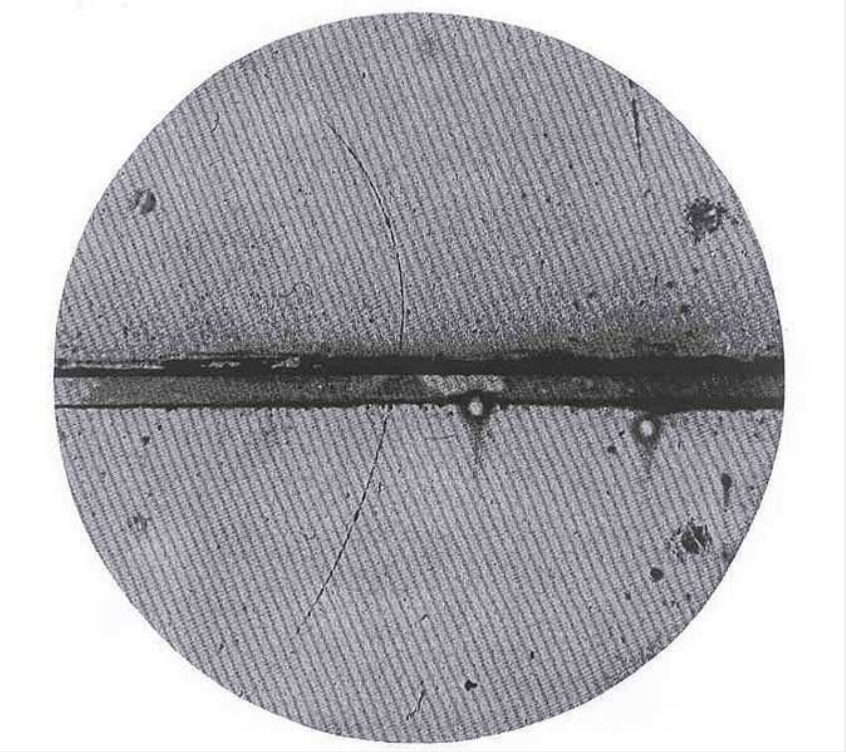


Cloud chamber

In oversaturated vapour droplets condense on ions produced by passing charged particles.



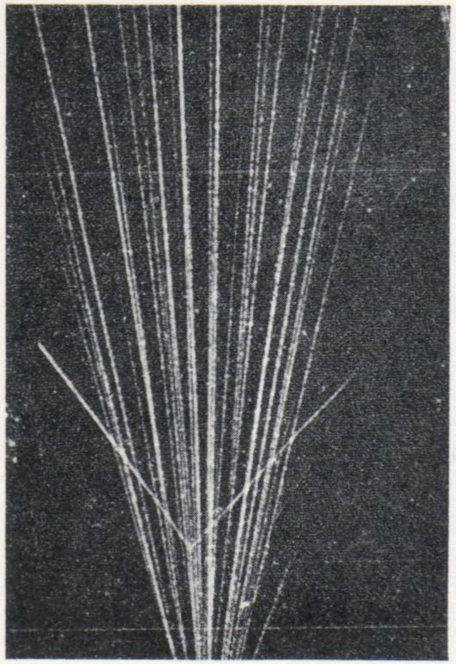
A diagram of Wilson's apparatus. The cylindrical cloud chamber ('A') is 16.5cm across by 3.4cm deep.



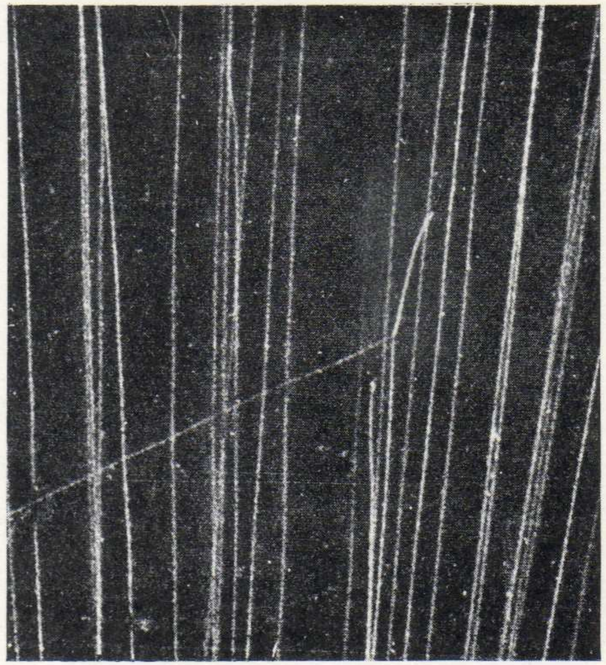
First picture of a positron

- Charles Wilson – first cloud chamber 1900, Nobel Prize 1927
- Carl D. Anderson – discovery of a positron 1932, Nobel Prize 1936

α tracks in helium



Alpha particle strikes helium nucleus and they part at right angles (Blackett)



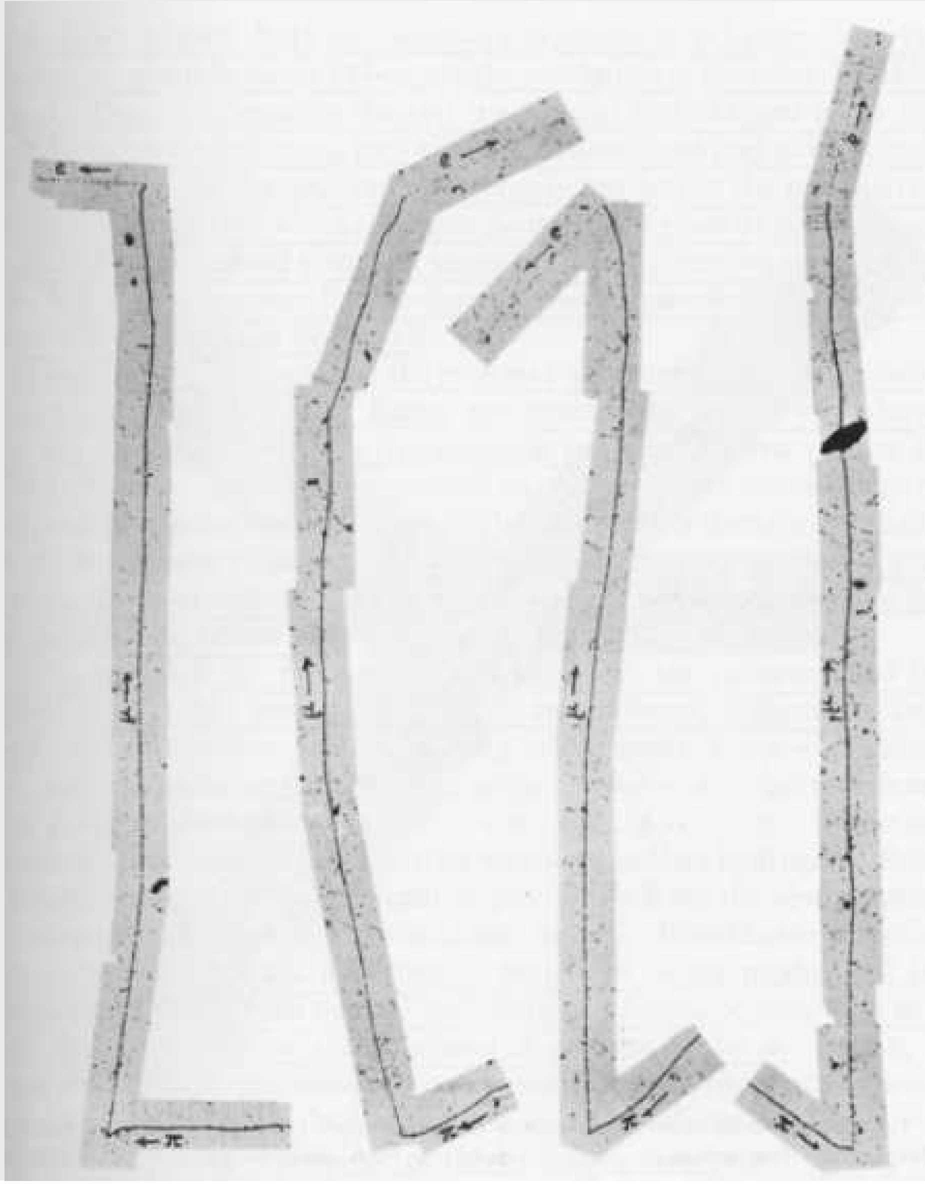
Alpha particle enters nitrogen which ejects proton and becomes oxygen (Blackett)

1923

1925

- To observe the nuclear reaction $\alpha + {}^{14}\mathrm{N} \rightarrow {}^{17}\mathrm{O} + p$
  P. Blackett has taken 23 000 photographs and found 8 events.

Photographic emulsions



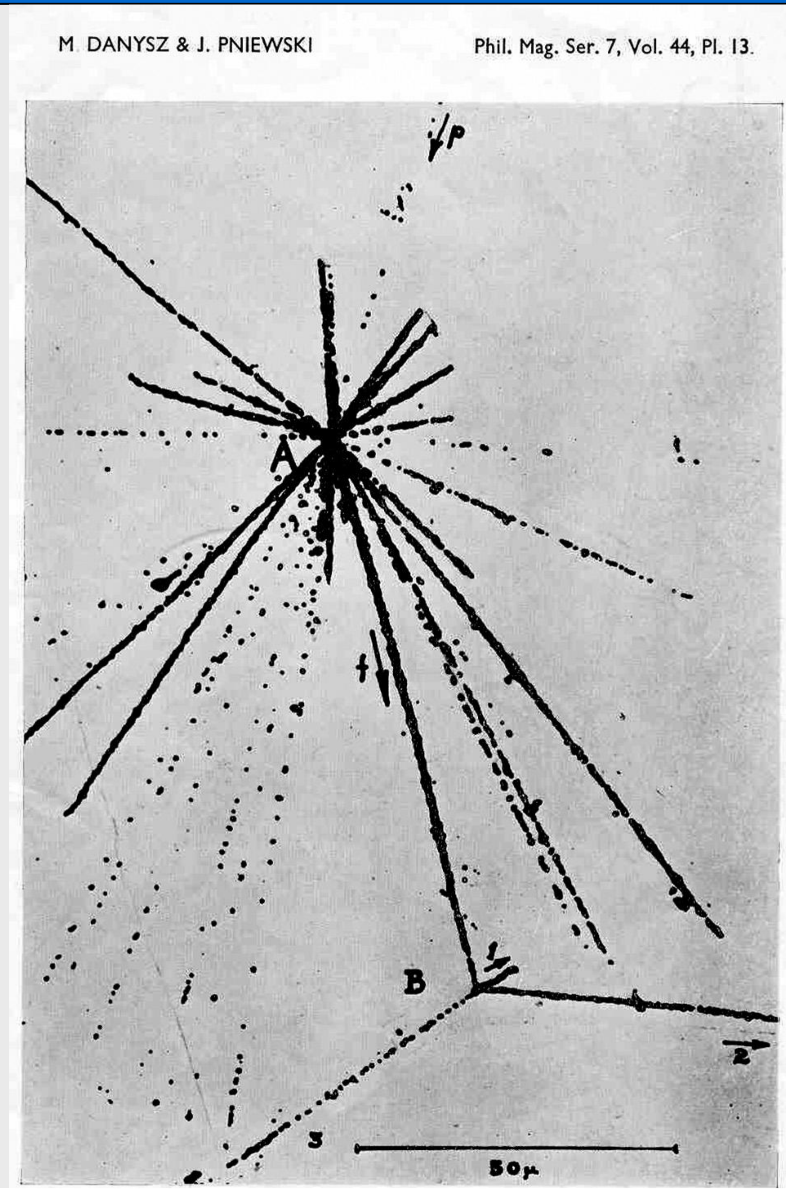
- Pions were discovered in a photographic emulsion exposed to cosmic rays at high altitude in 1947.

- Cecil Powell, Nobel Prize 1950

Hypernucleus

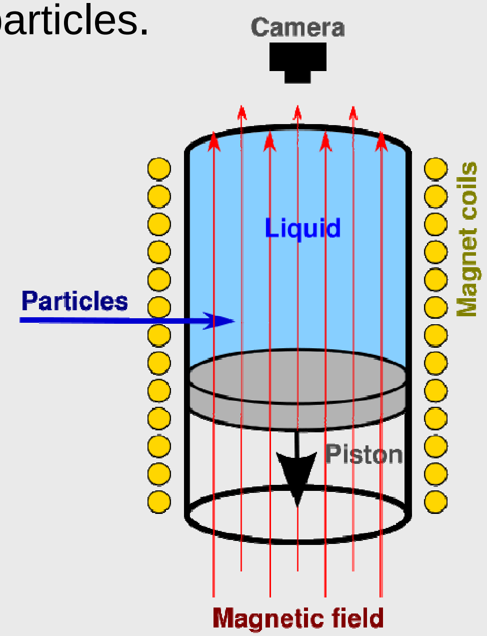
The discovery of a hypernucleus in a photografic emulsion

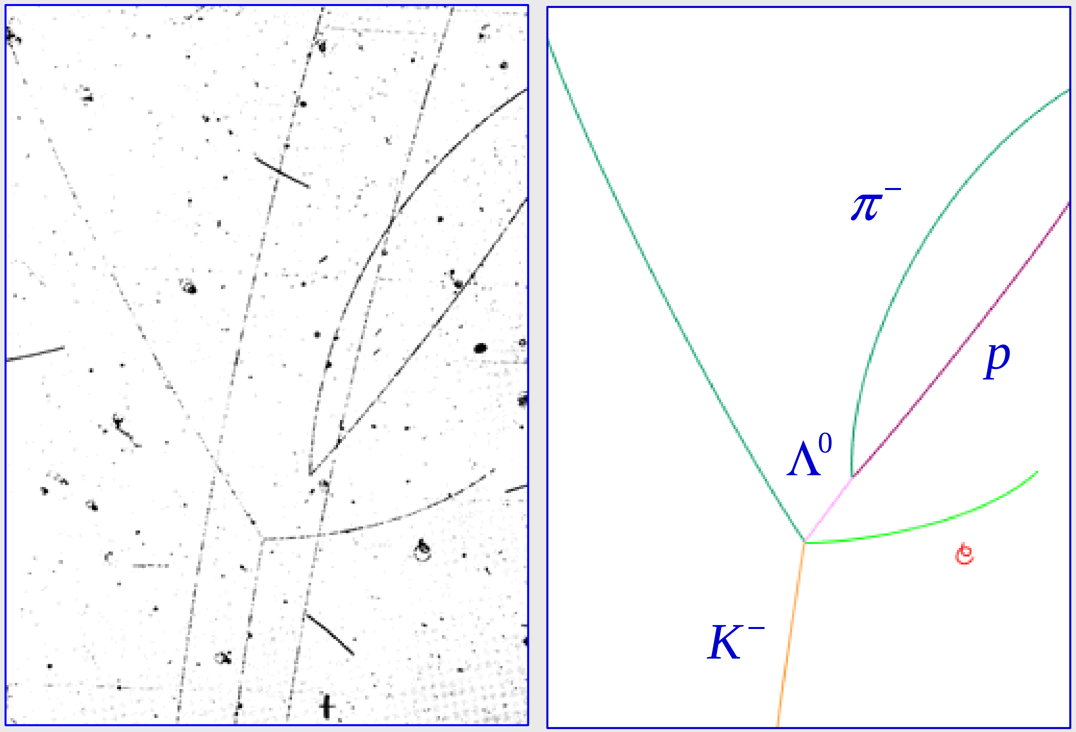
Danysz and Pniewski, 1952



Bubble chamber

In overheated liquid vapour bubbles form around ions produced by passing charged particles.

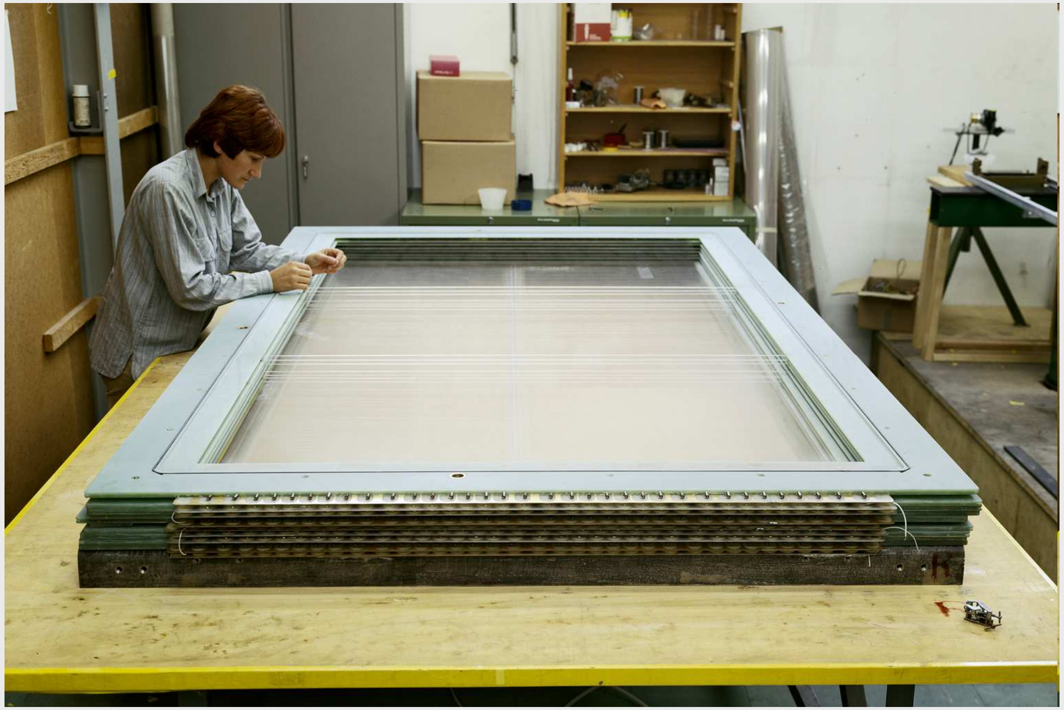


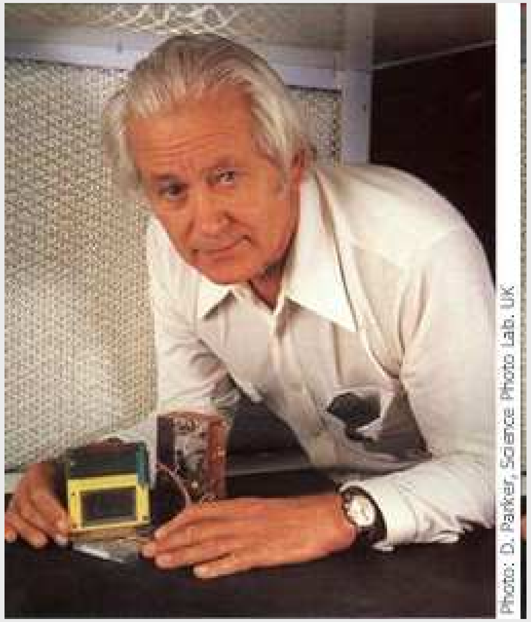


Production and decay of hiperon Λ^0 from $K^- + p$ (CERN)

- Donald D. Glaser – construction of a chamber 1952, Nobel Prize 1960
- Emilio Segre, Owen Chamberlain – discovery of an antiproton, Nobel Prize 1959
- Luis W. Alvarez – discovery of many new particles, Nobel Prize 1968

Electronics takes over

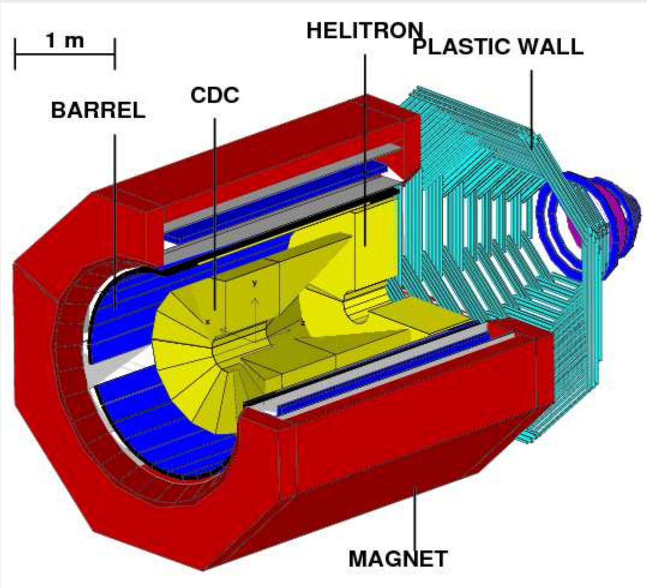




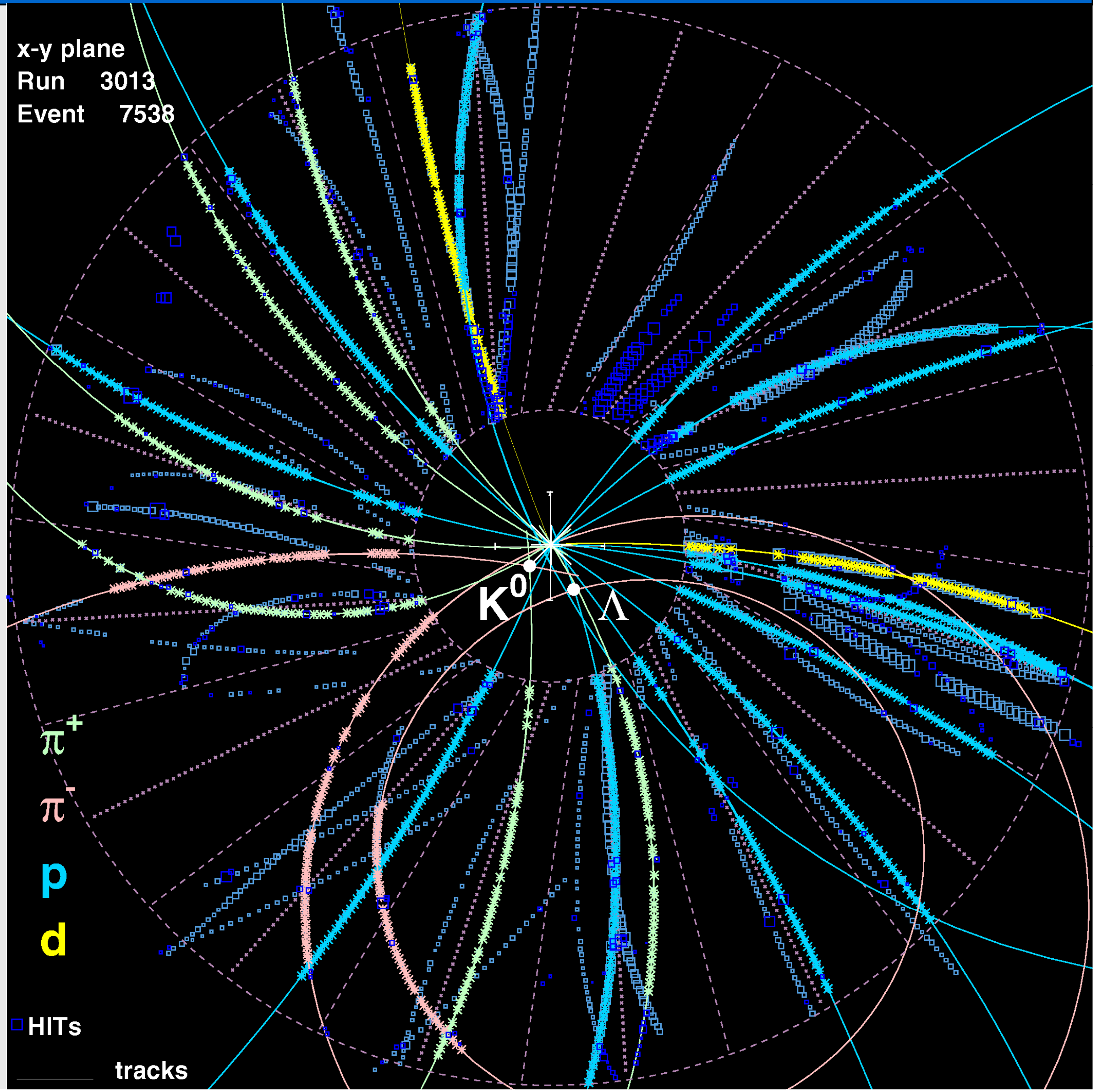
- Georges Charpak – the first multiwire proportional chamber 1968, Nobel Prize 1992

Modern particle tracking

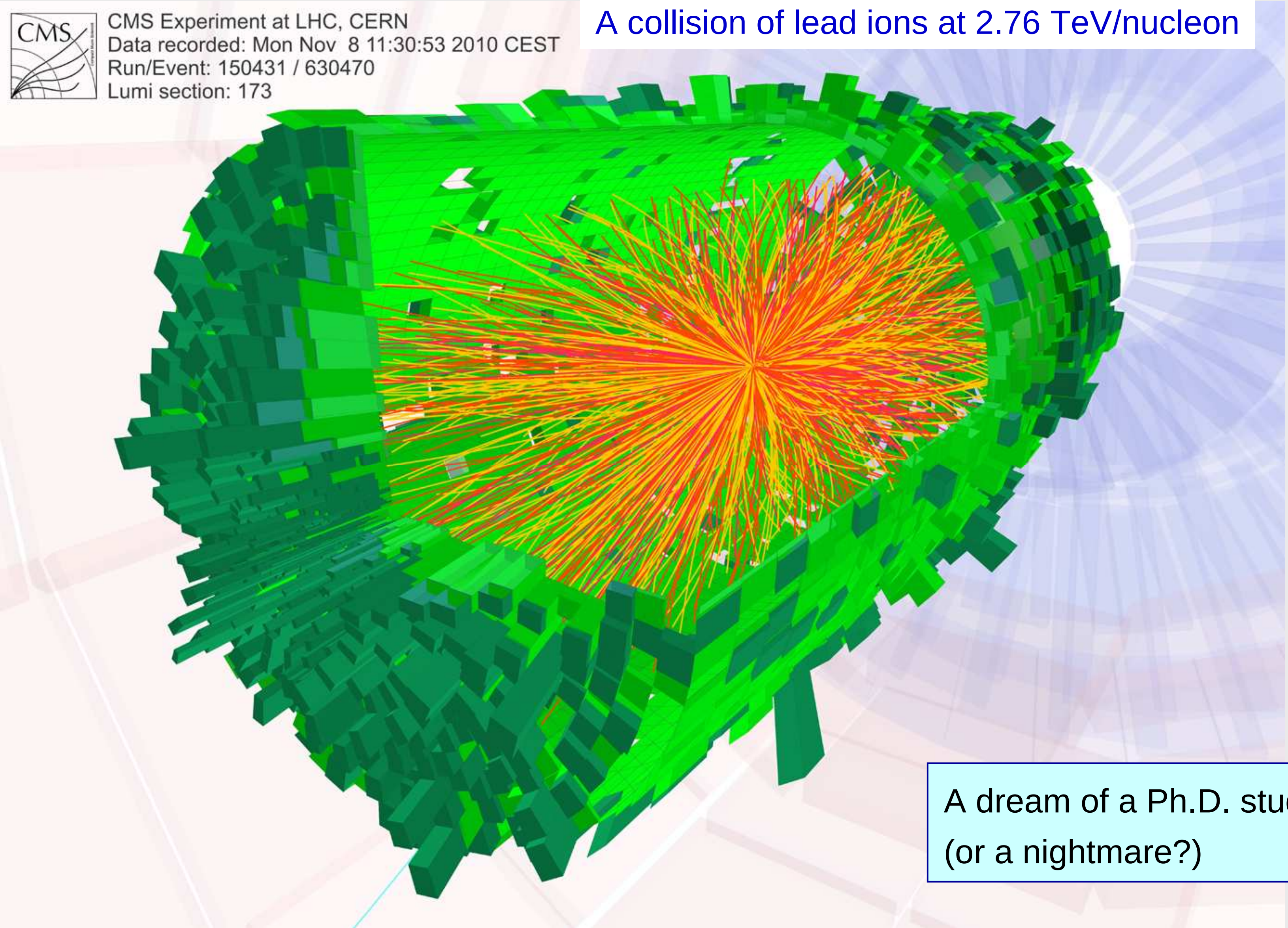
FOPI @ GSI



$$\pi^- + p \; @ \; 1.15 \, \mathrm{GeV}/c$$



CMS event



A collision of lead ions at 2.76 TeV/nucleon

A dream of a Ph.D. student
(or a nightmare?)

New 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

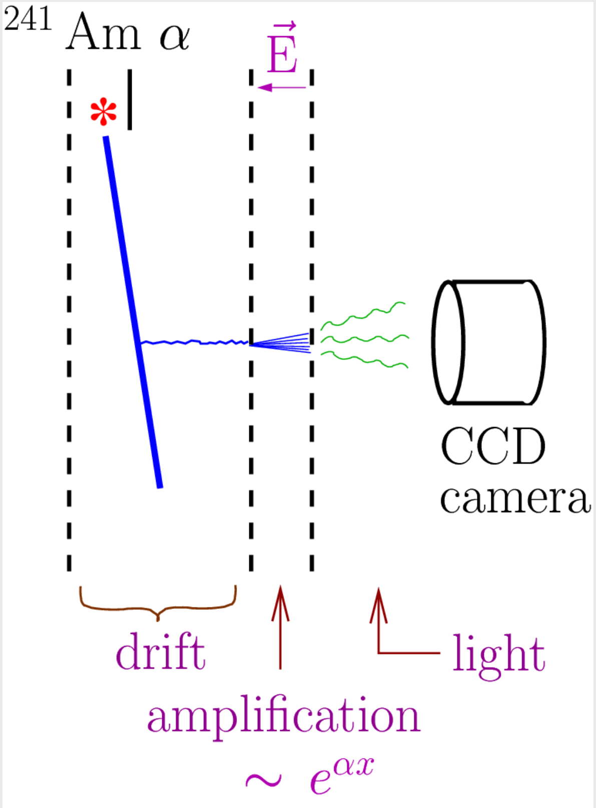
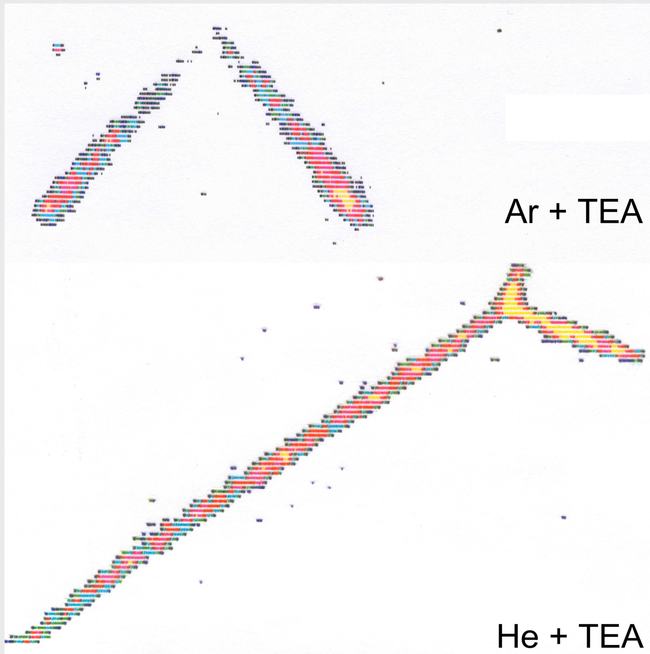
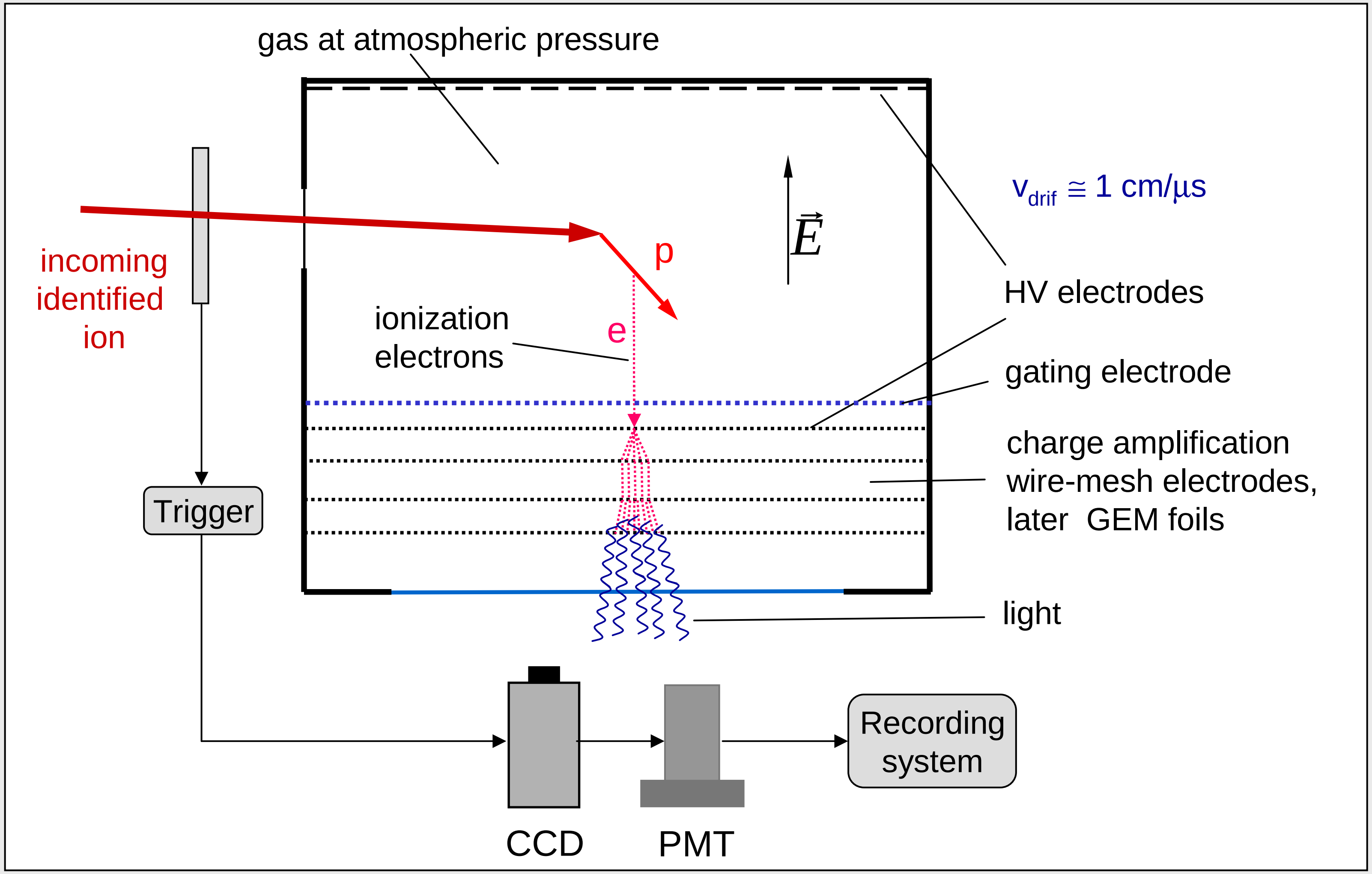


Image examples of α-particle tracks



TEA = Triethylamine $N(C_2H_5)_3$

Optical Time Projection Chamber



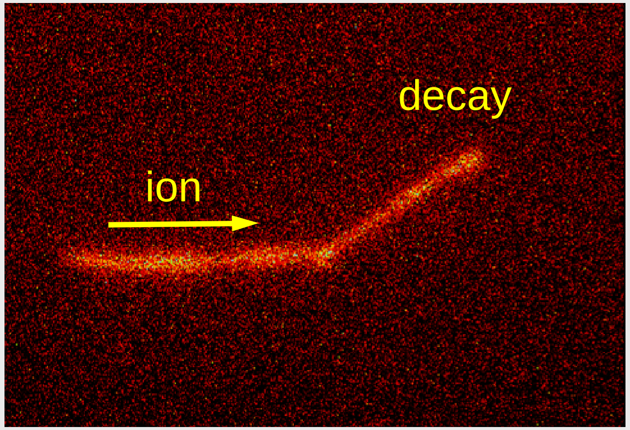
M. Ćwiok et al., IEEE TNS, **52** (2005) 2895

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

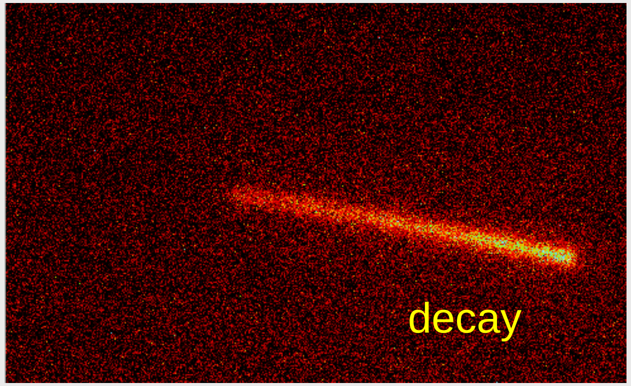
Event reconstruction

CCD image

tracks of the ion and emitted particle(s)

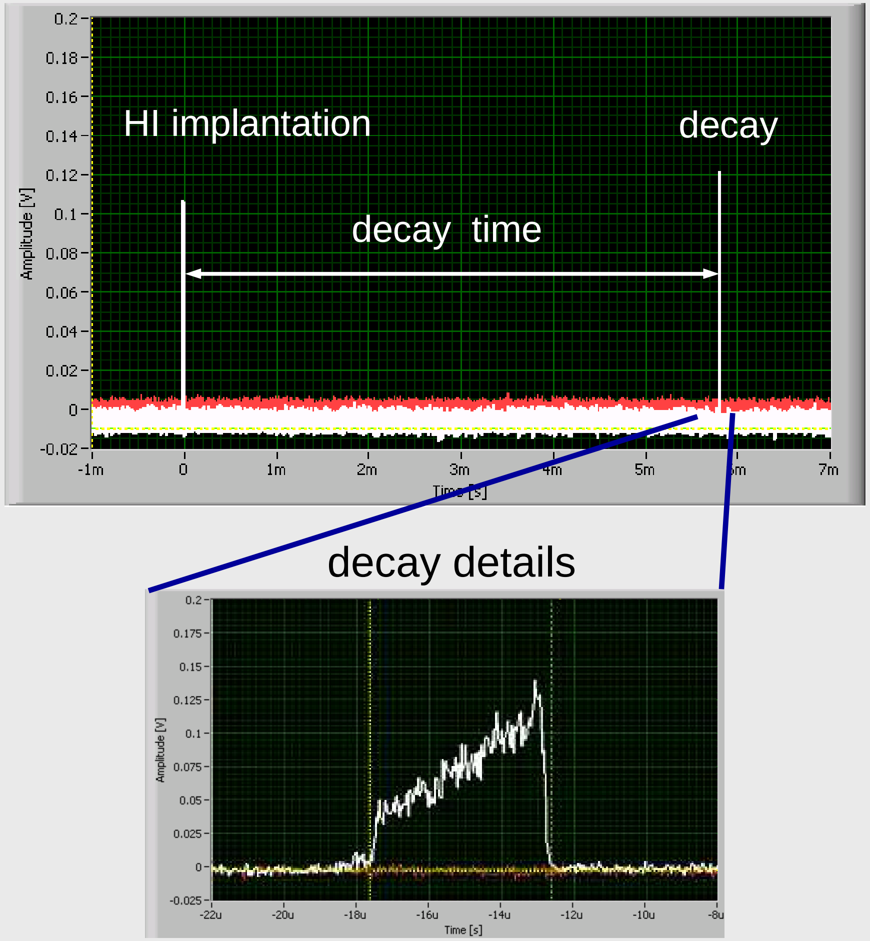


or only emitted particle(s)

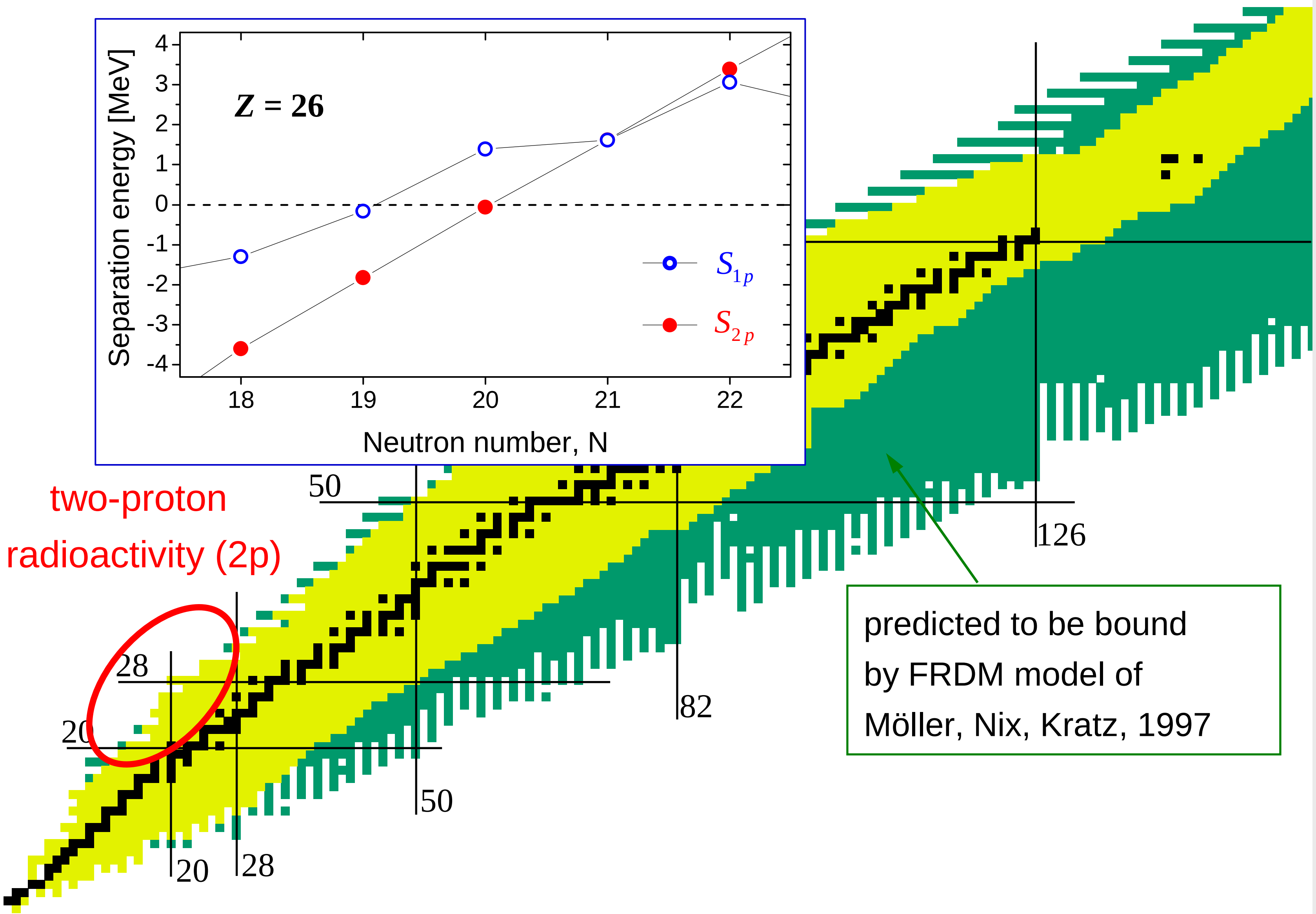


PMT signal sampled

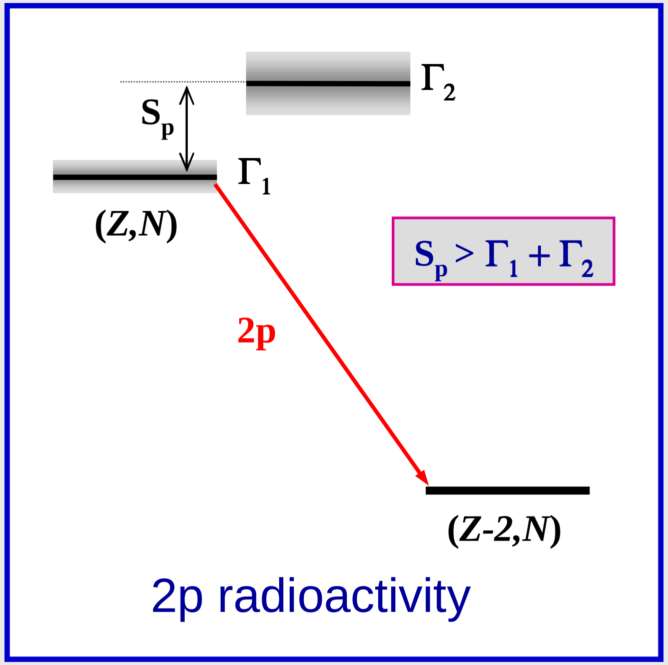
time sequence of events



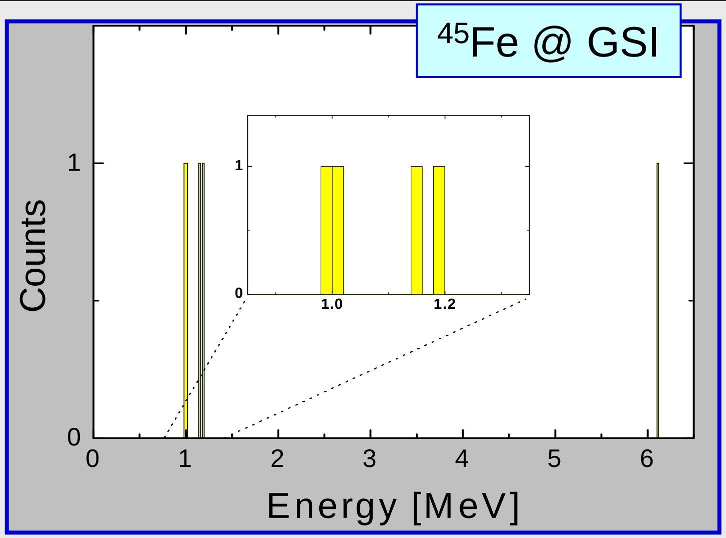
The world of nuclides, 2010

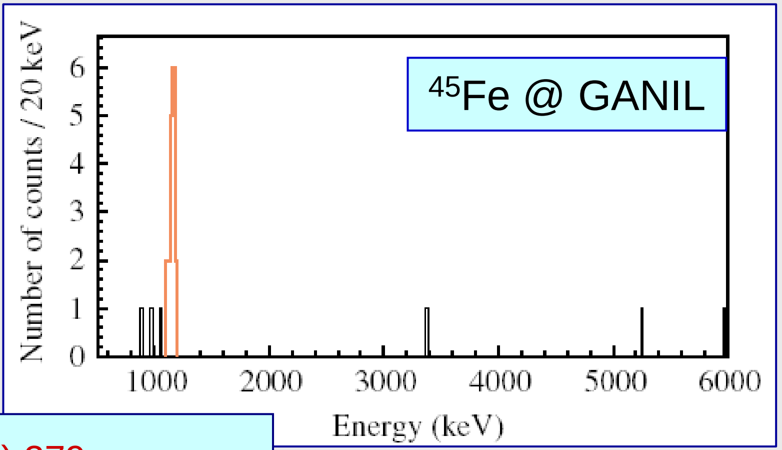


2p radioactivity



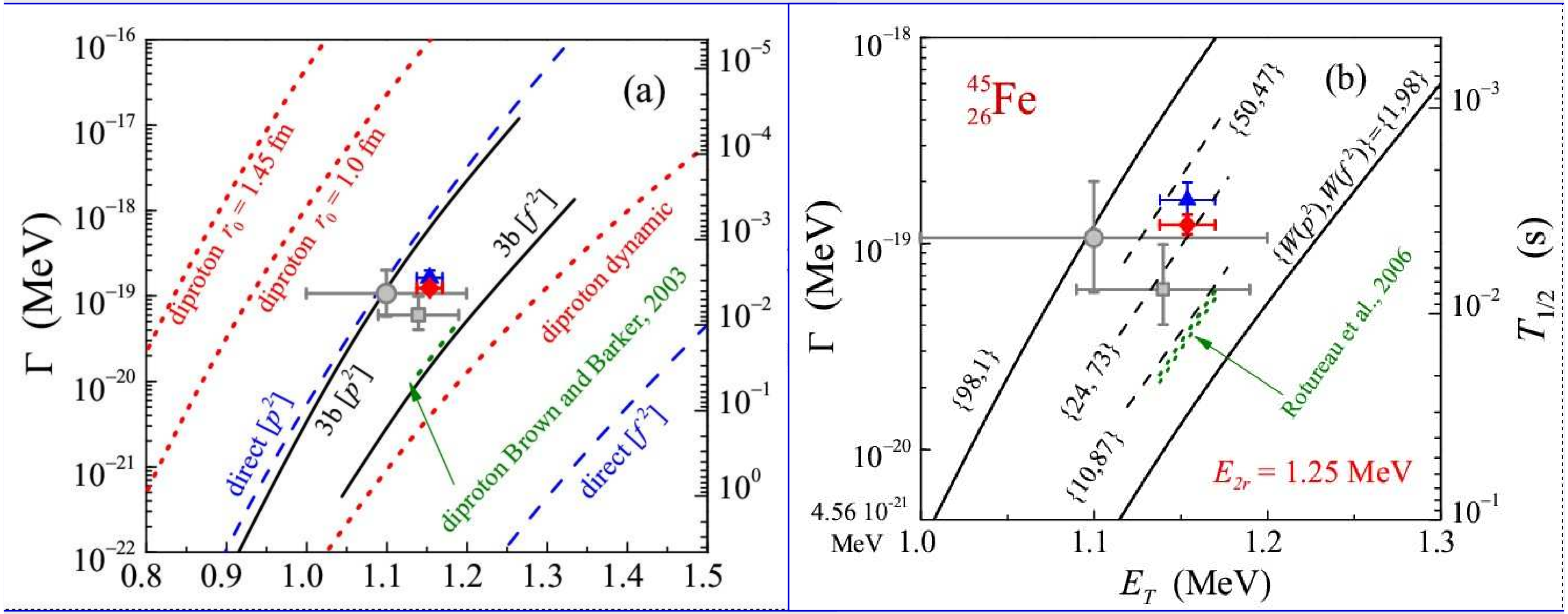
- **Observed for ^{45}Fe, ^{54}Zn, ^{19}Mg**
- **Predicted for ^{48}Ni, ...**





M. P. et al., EPJ A **14** (2002) 279
J. Giovinazzo et al., PRL **89** (2002) 102501
C. Dossat et al., PRC **72** (2005) 054315

Lifetime vs. energy



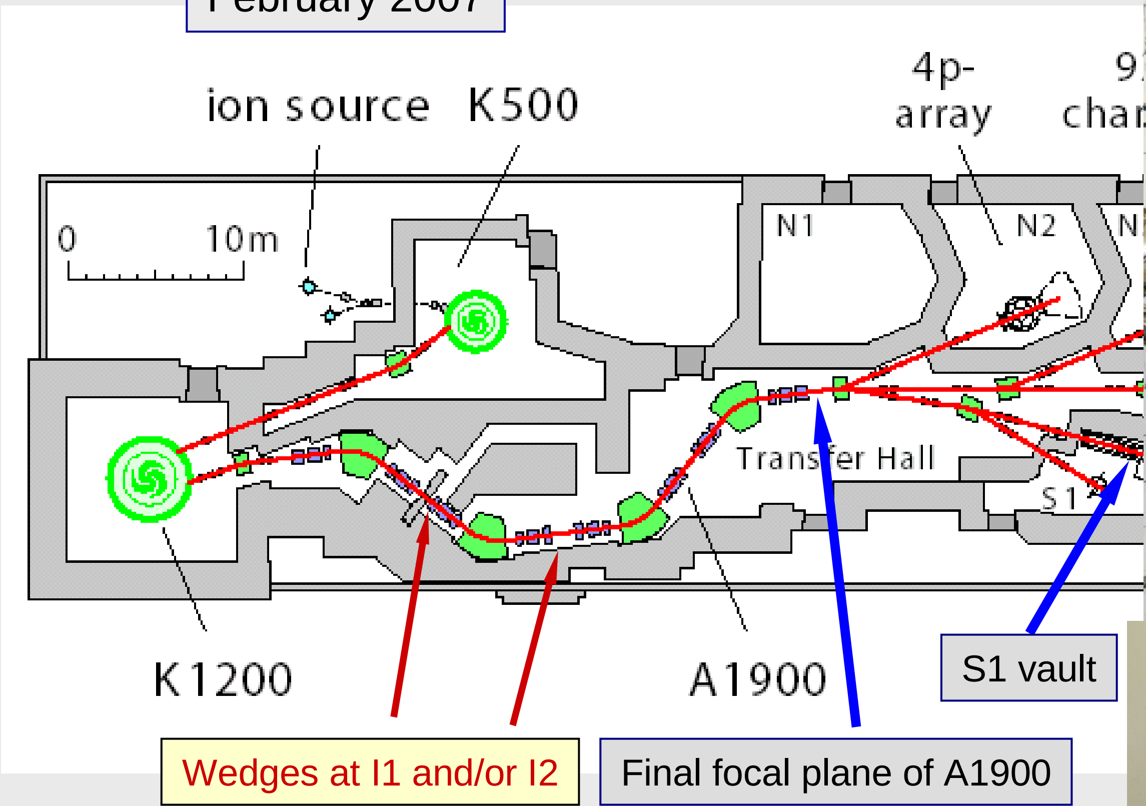
from L. Grigorenko

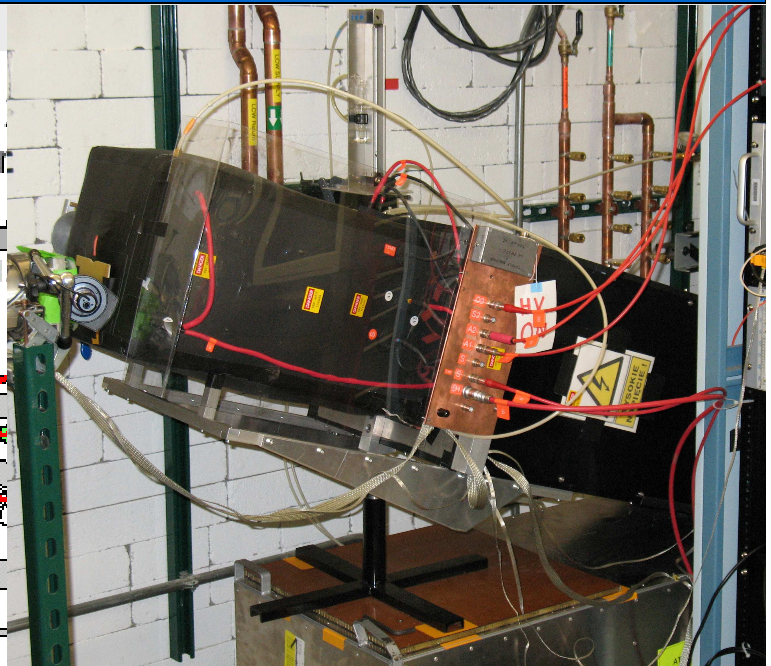
In the first experiments only the decay energy and time were measured

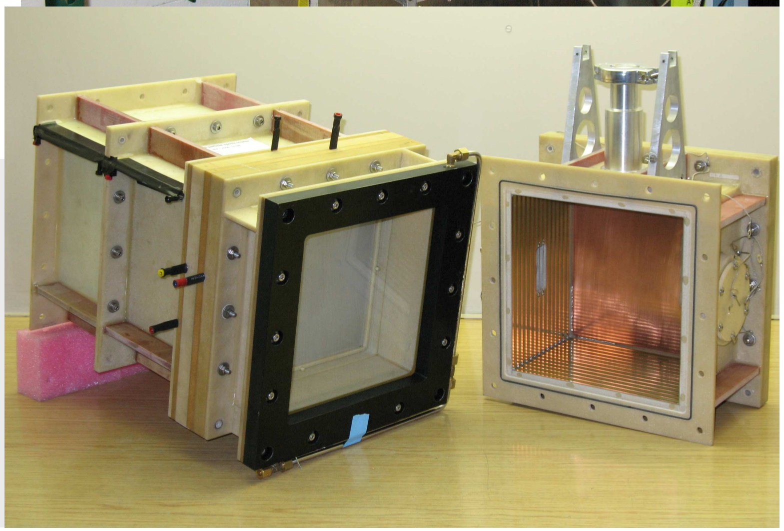
➤ A lot of information is still hidden in the correlations between protons !

OTPC at NSCL/MSU

February 2007



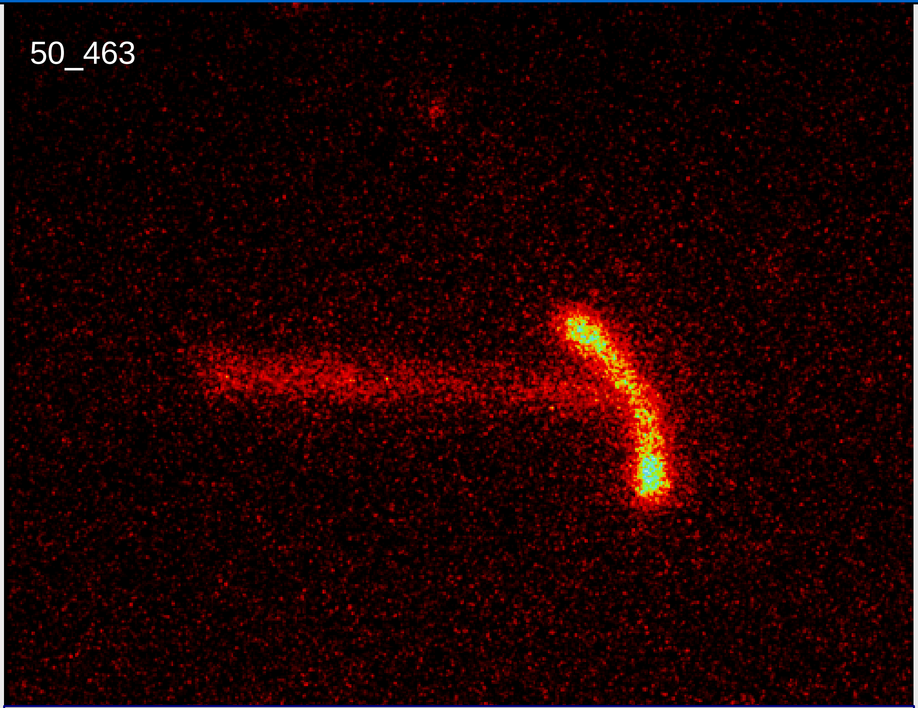


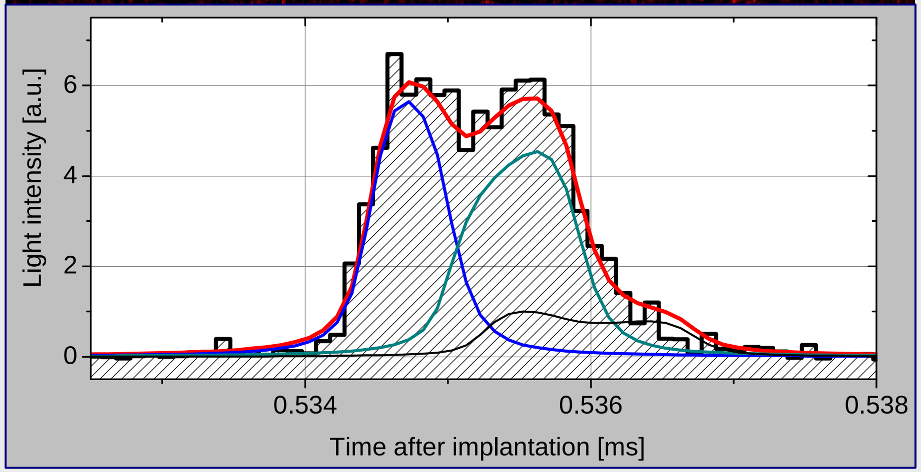


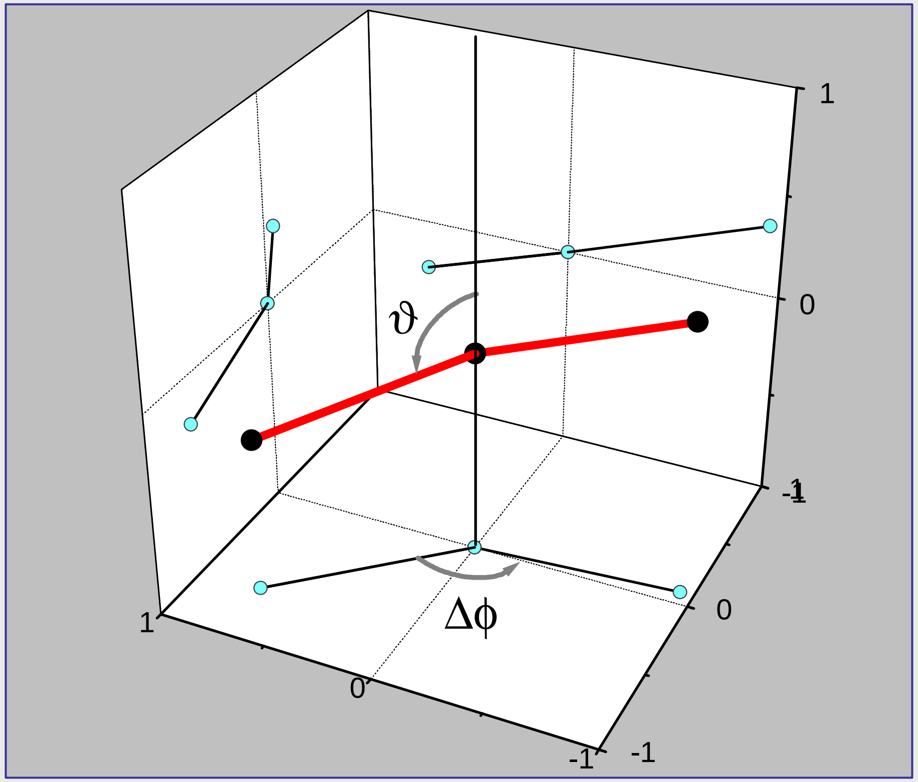
Reaction: ^{58}Ni at 161 MeV/u + ^{nat}Ni → ^{45}Fe

Ion identification in-flight : ΔE + TOF

Emission of *2p* from ^{45}Fe



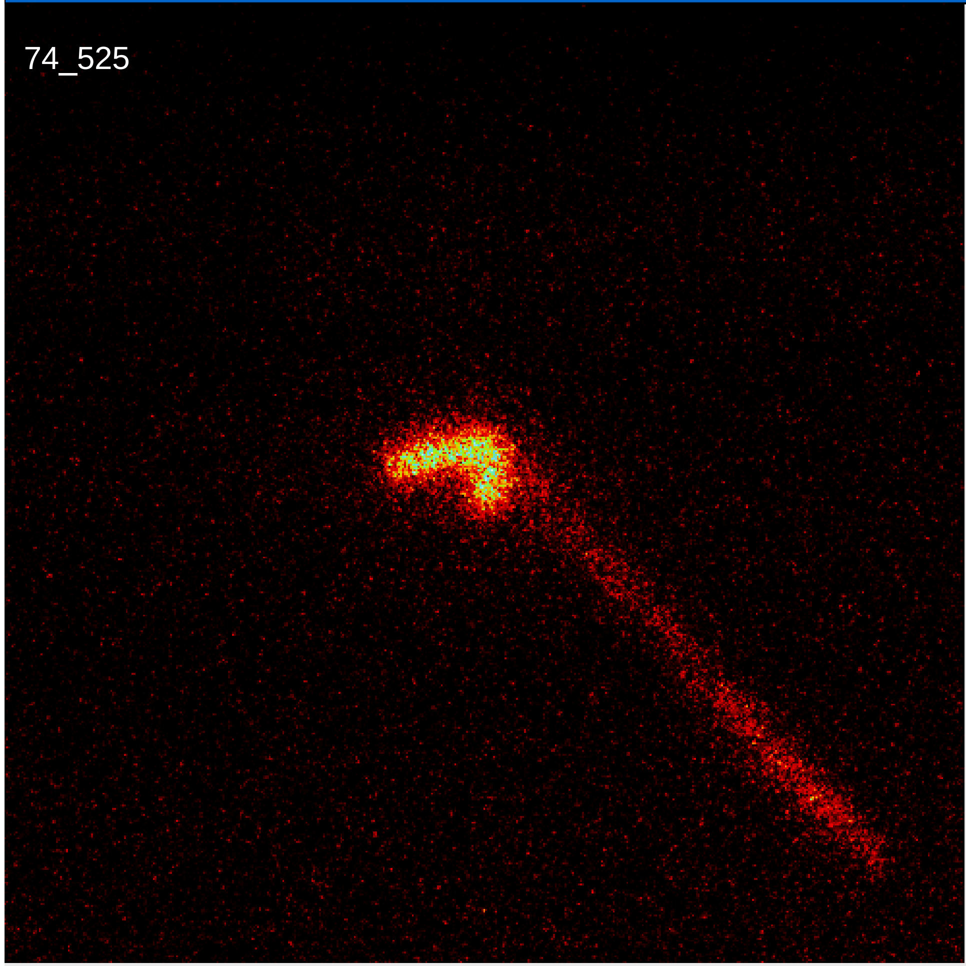


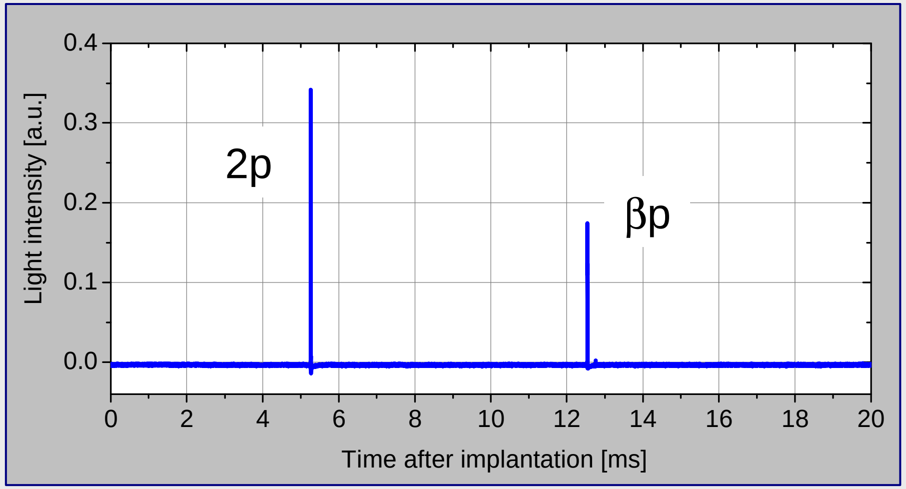


ϑ_1 = (104 ± 2)°, ϑ_1 = (70 ± 3)°

$\Delta\phi$ = (142 ± 3)° → θ_{pp} = (143 ± 5)°

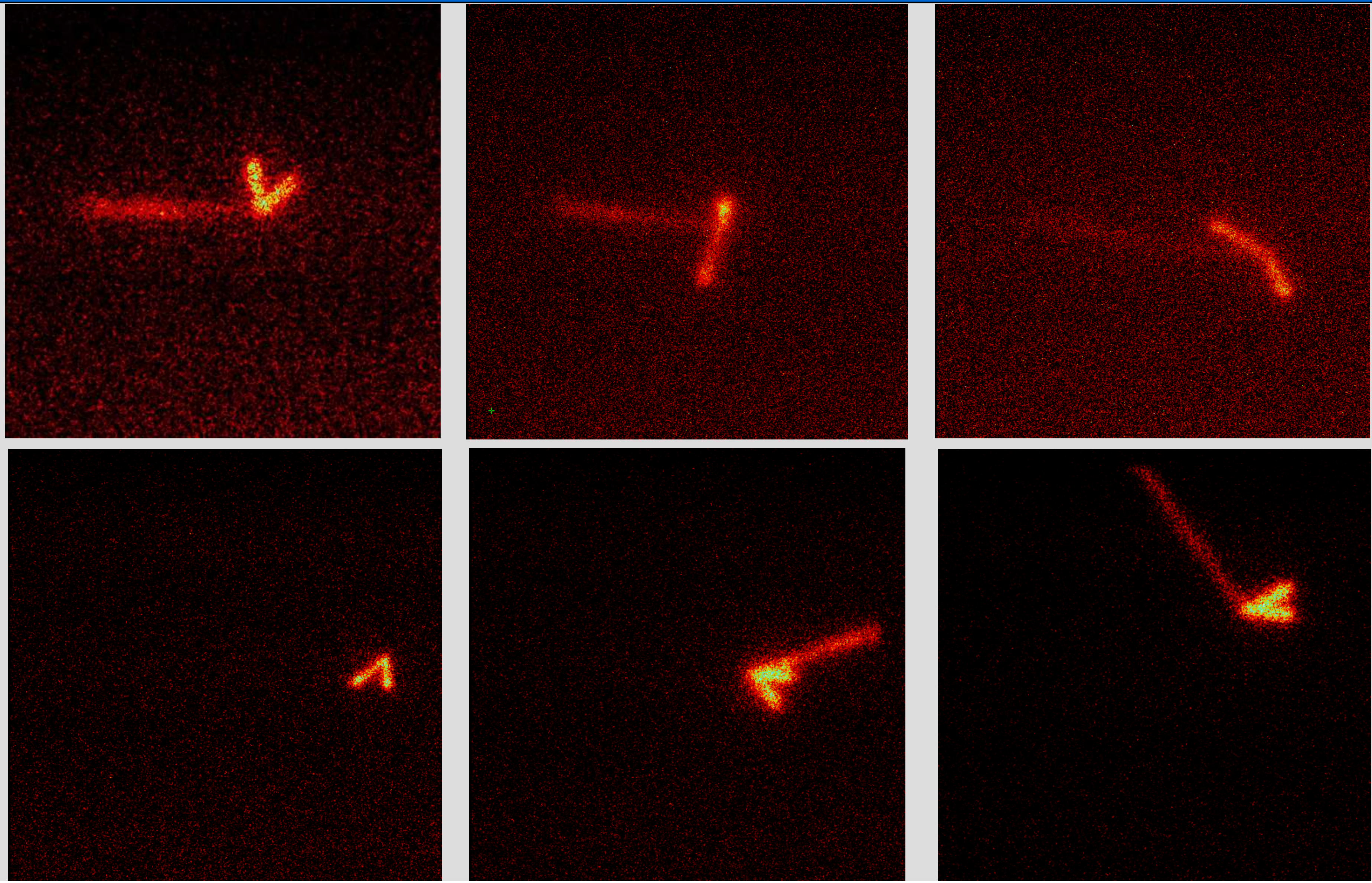
2p followed by β*p*



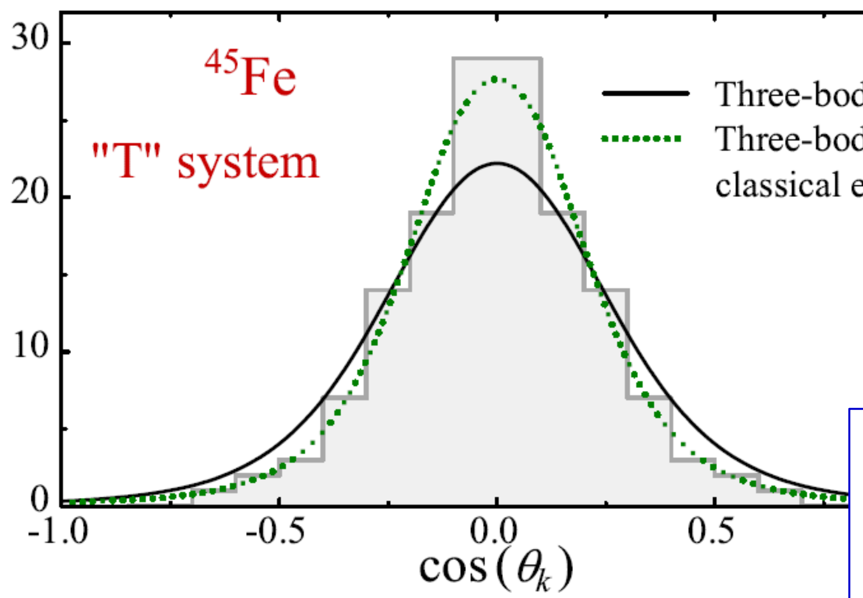


Synchronous mode ⇨ ion track not seen

2p events



p-p correlations



θ_k is the angle between vectors:

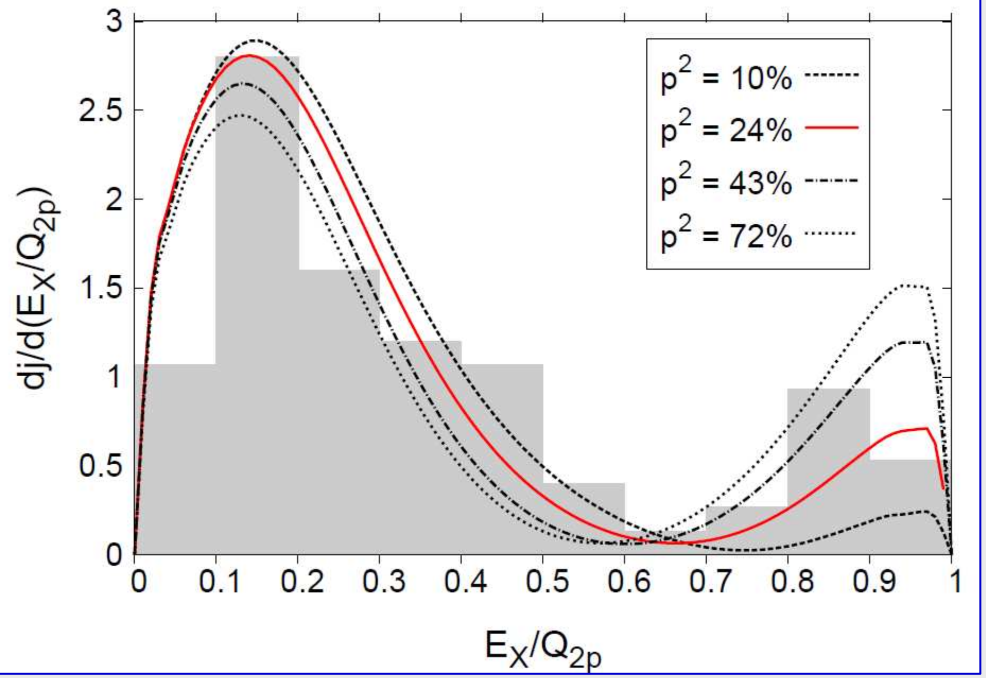
$(\vec{k}_1 - \vec{k}_2)$ and $(\vec{k}_1 + \vec{k}_2)$

$\vec{k}_1, \vec{k}_2$ - protons' momenta in CM

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

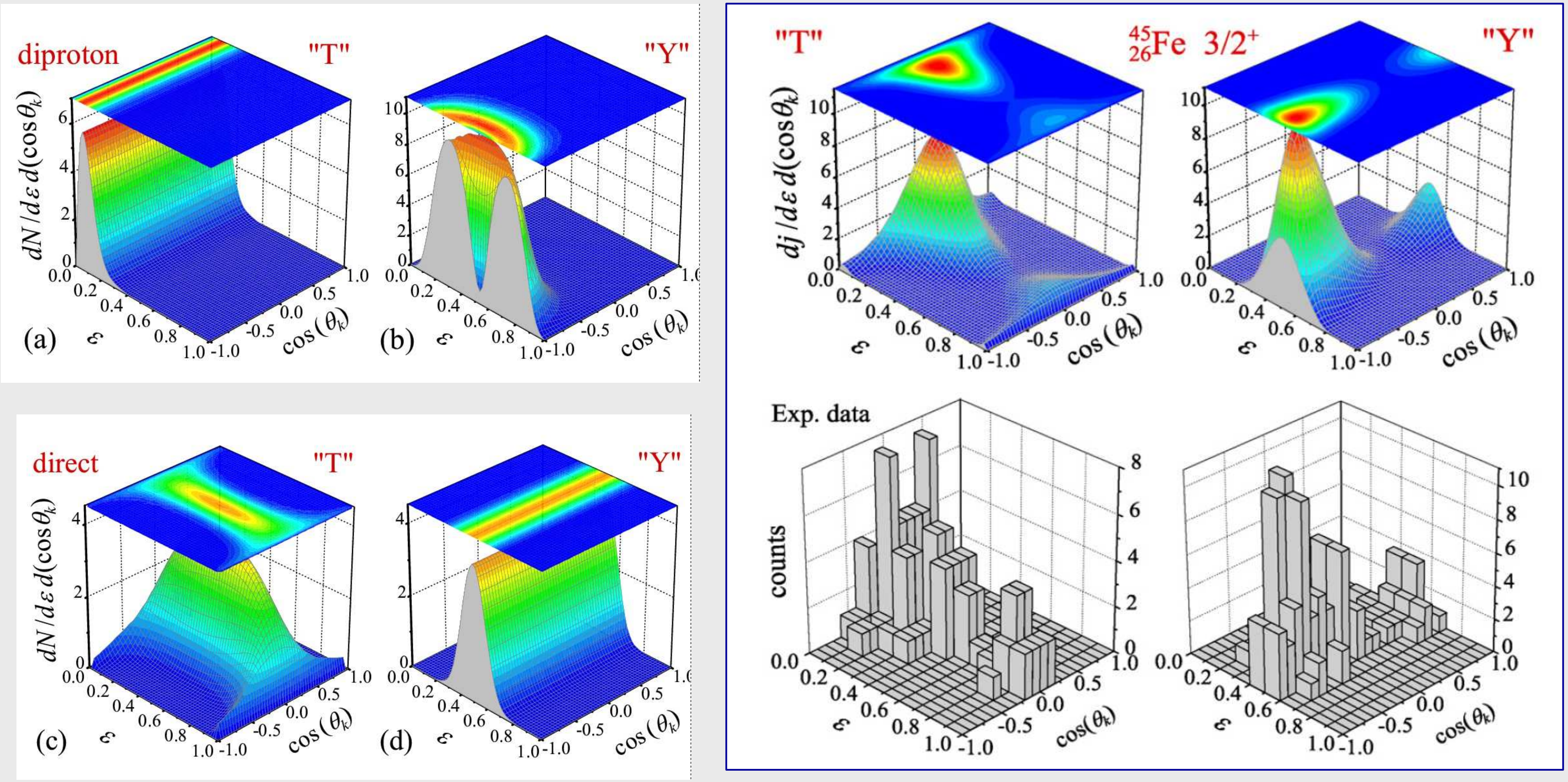
Classical extrapolation:

quantum-mechanical w-f is propagated to a distance of 1000 fm. Further, classical trajectories are followed up to 50 000 fm.



L.V. Grigorenko et al., Phys. Lett. B **677** (2009) 30

p-*p* correlations in ^{45}Fe

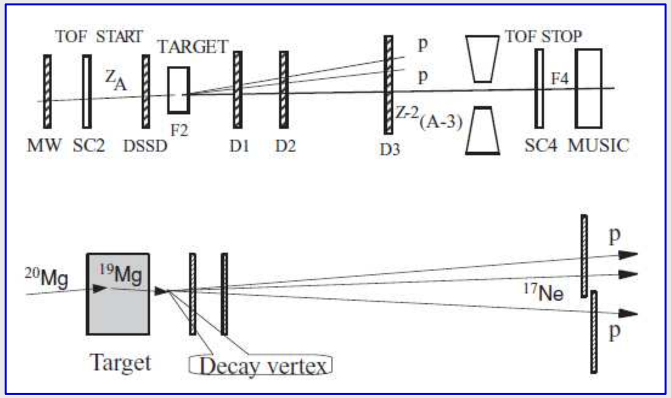


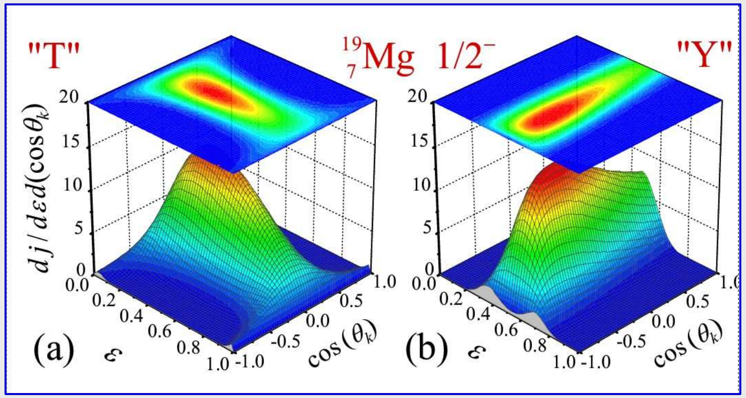
L.V. Grigorenko et al., Phys. Lett. B **677** (2009) 30

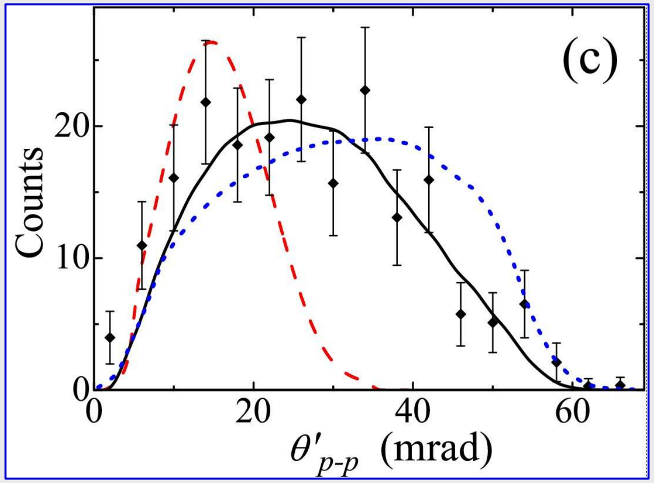
... in ^{19}Mg,...

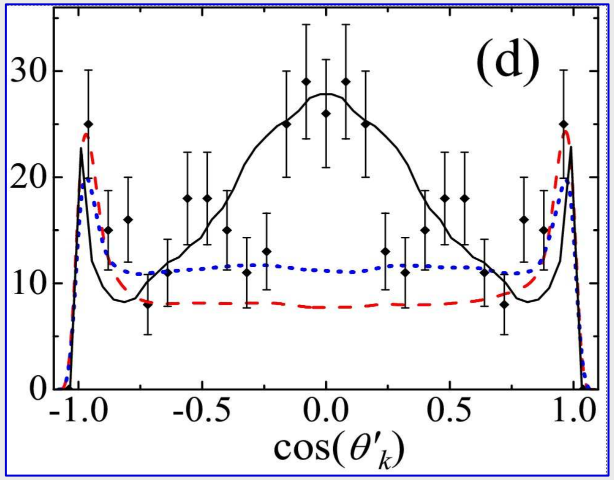
The tracking experiment at GSI/FRS

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







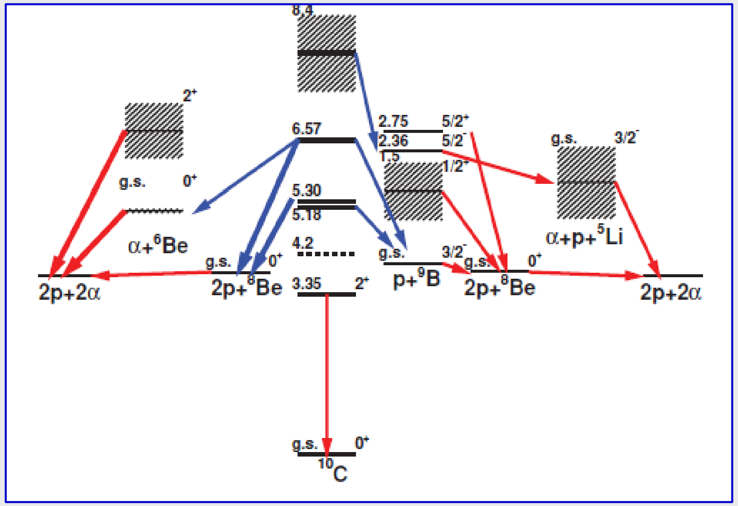


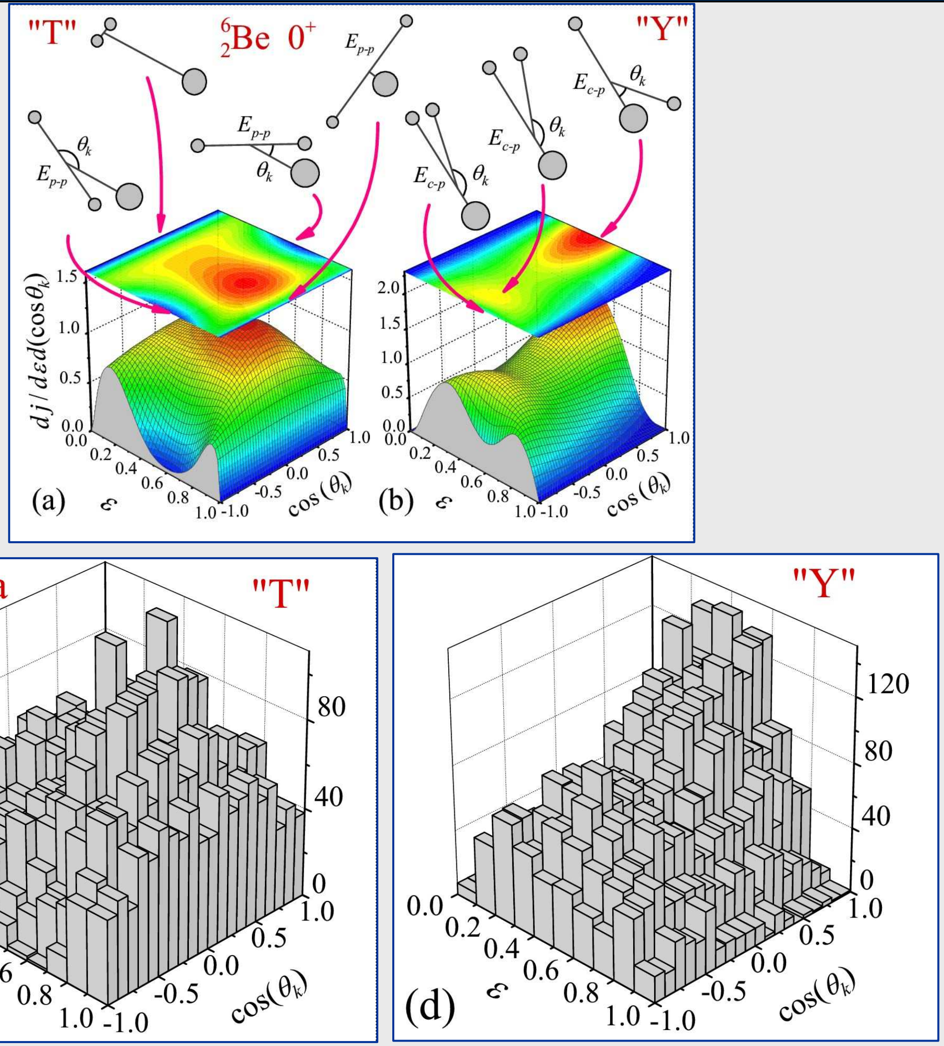
I. Mukha et al., Phys. Rev. C **77** (2008) 061303(R)

I. Mukha et al., Phys. Rev. Lett. **99** (2007) 182501

...and in ^{6}Be

^{10}C inelastic scattering at
Texas A&M University



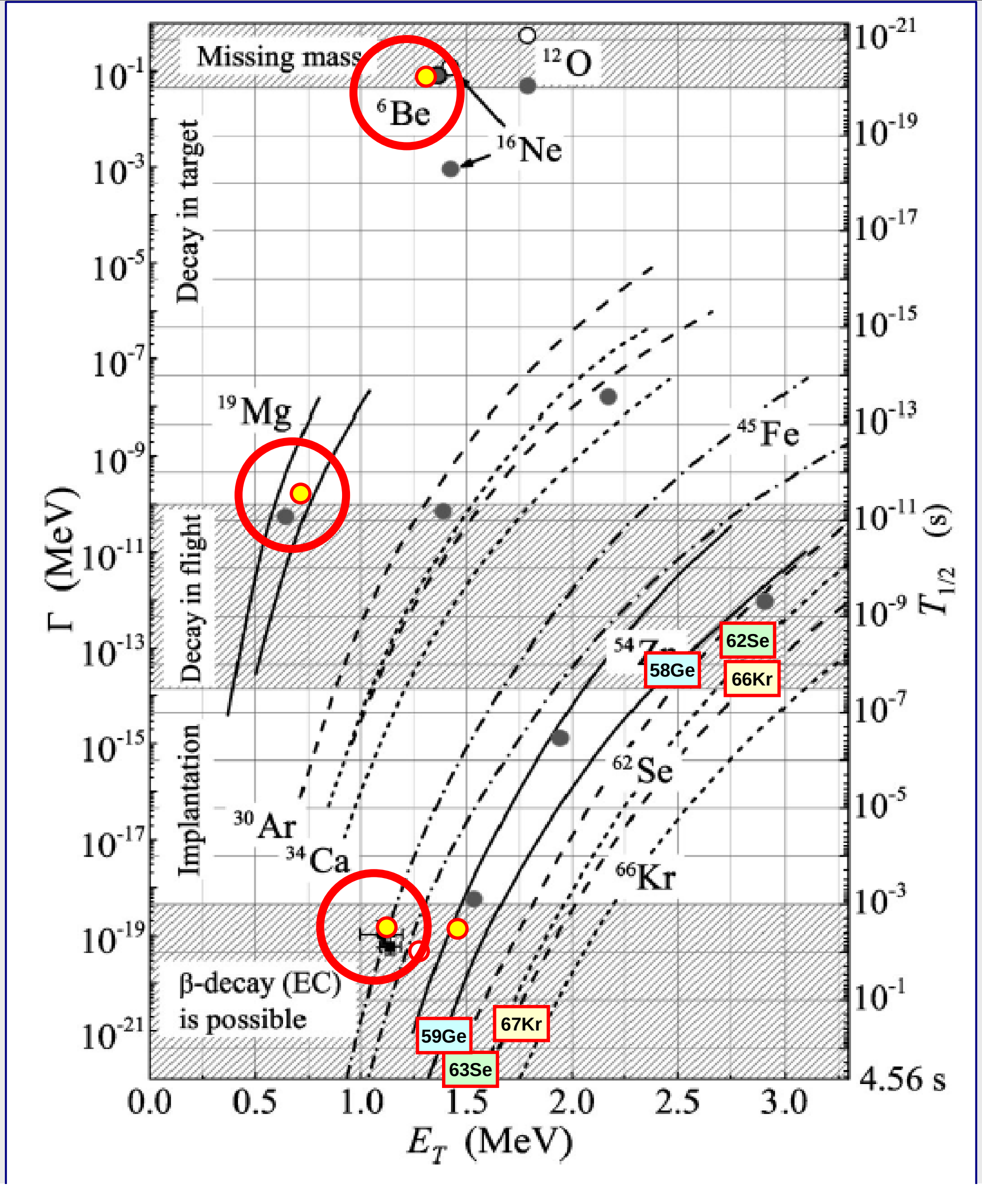


K. Mercurio et al., Phys. Rev. C **78** (2008) 031602(R)
L. Grigorenko et al., Phys. Lett. B **677** (2009) 30

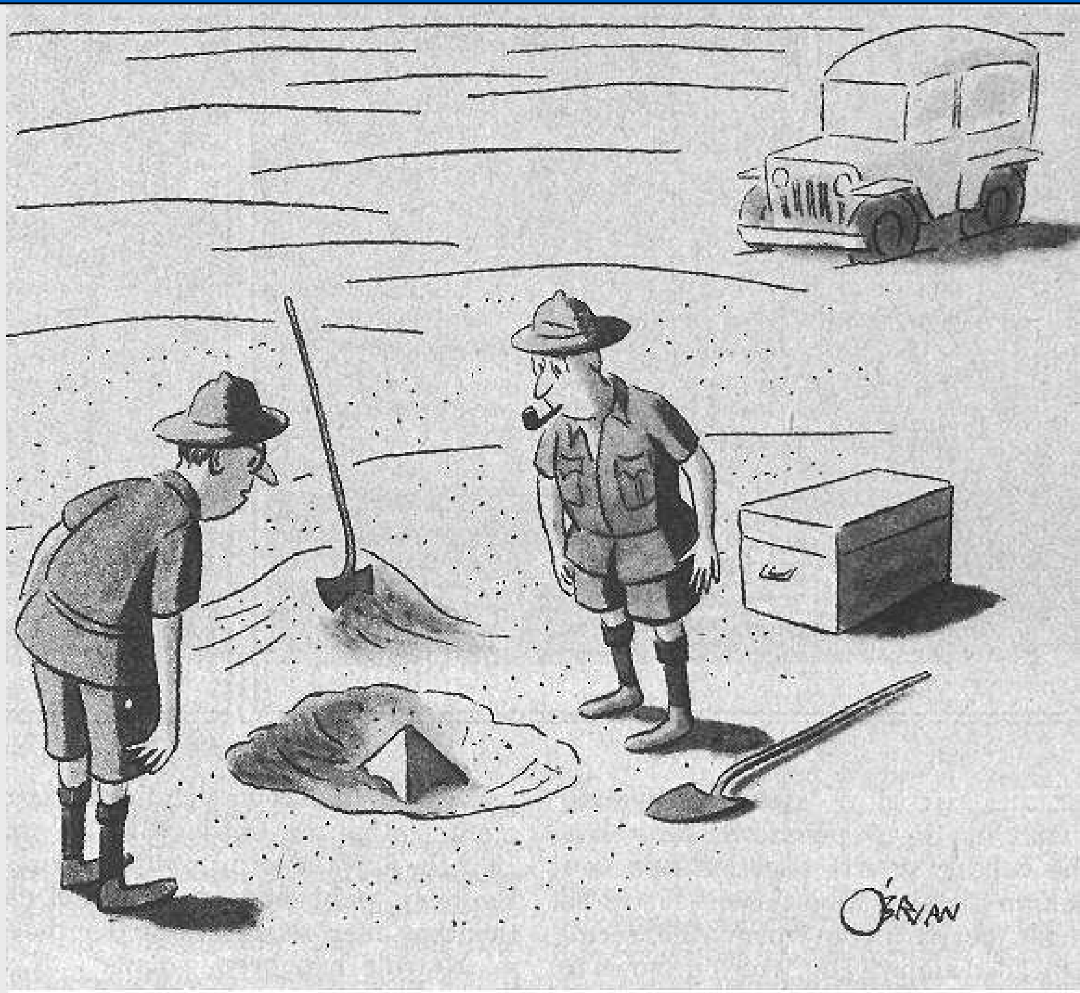
Three lifetime regimes

- Invariant mass method for broad resonanses
  $T_{1/2} \leq 10^{-19}$ s
- In-flight decays
  $T_{1/2}$ = 5 ps – 50 ns
- Implantation method
  $T_{1/2} > 50$ ns

L.V. Grigorenko and M.V. Zhukov,
PRC 68 (2003) 054005

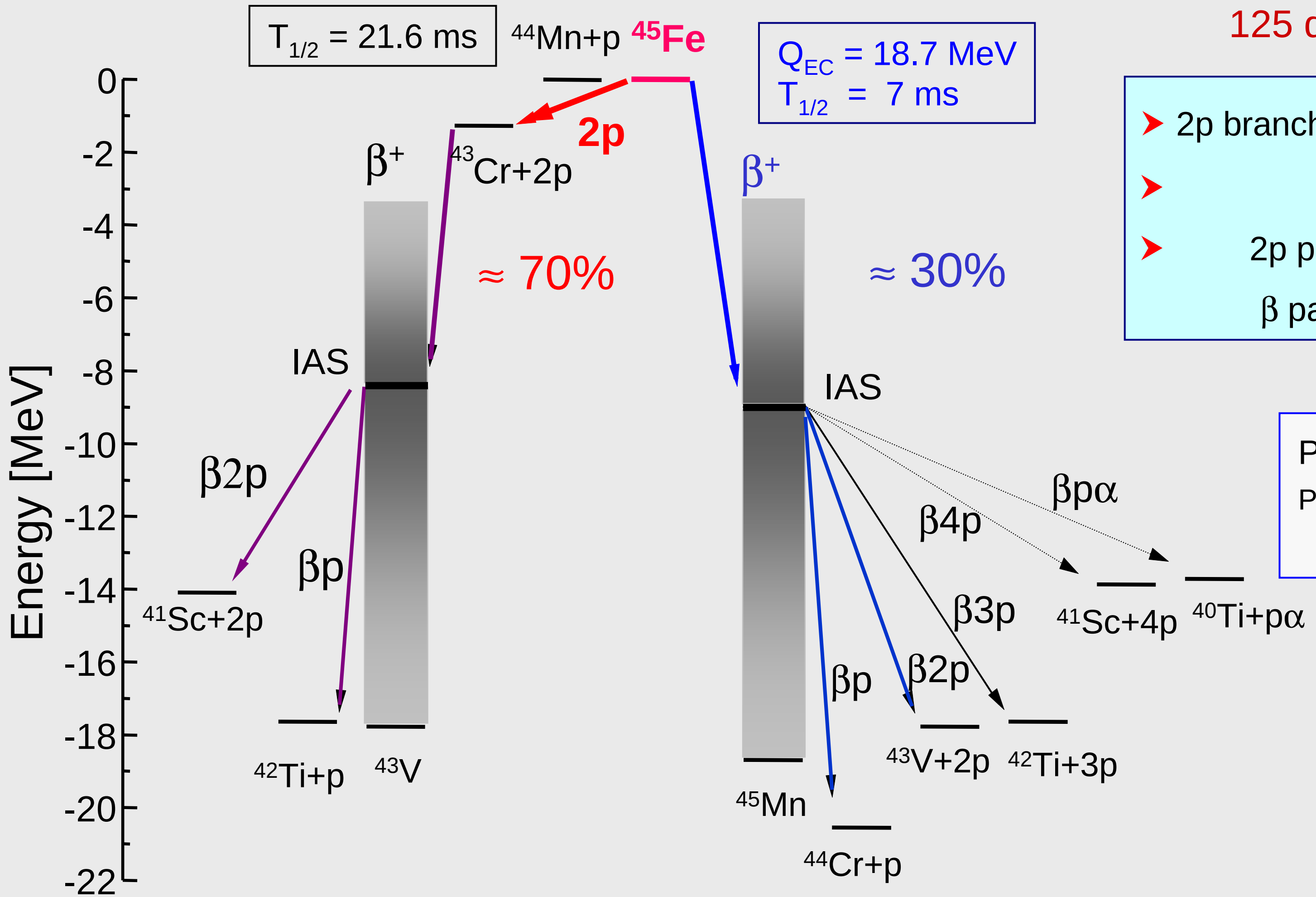


☺



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

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



125 decays recorded

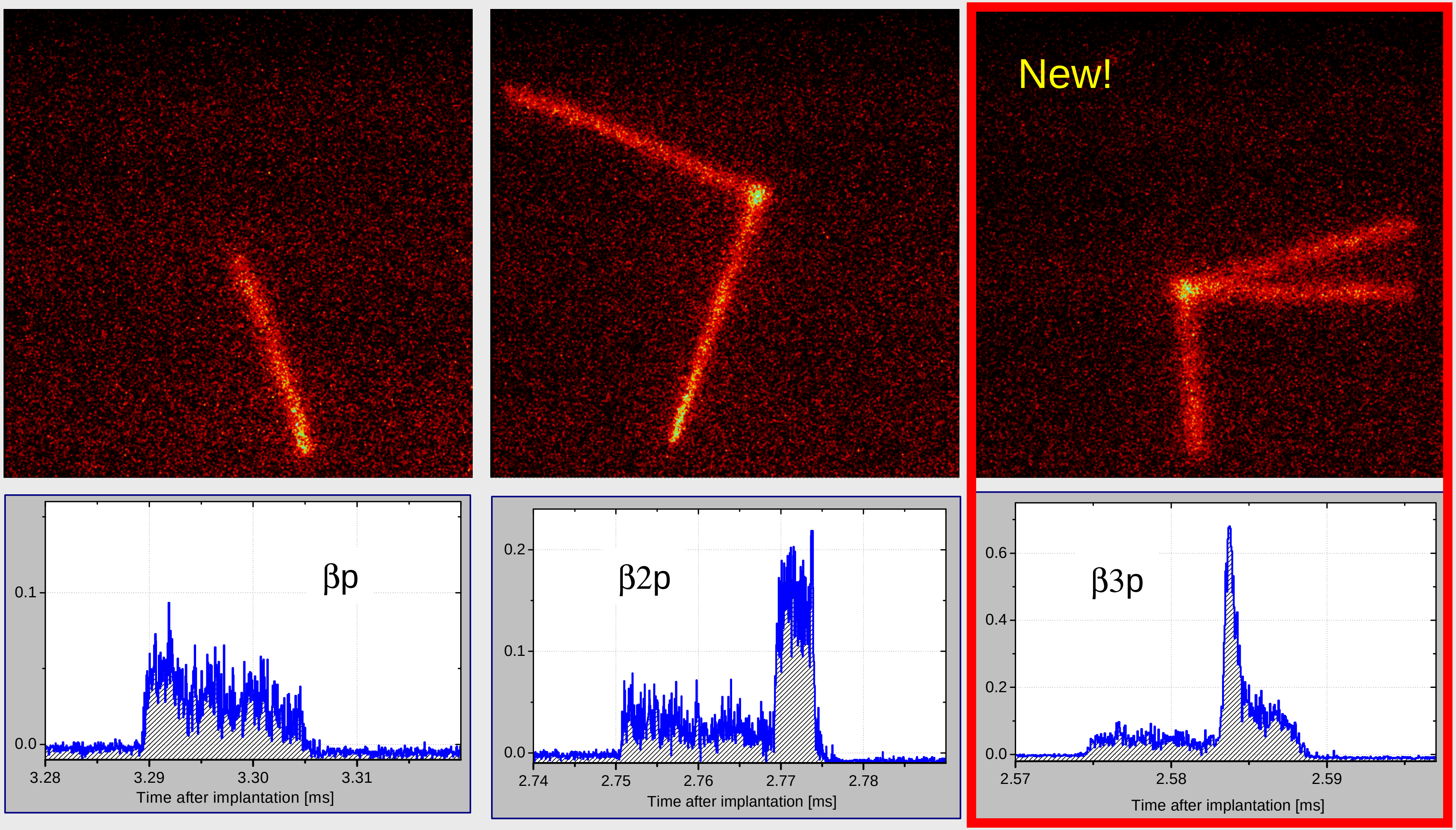
- 2p branching ratio: 0.70 ± 0.04
- half-life: 2.6 ± 0.2 ms
- 2p partial $T_{1/2}$: 3.7 ± 0.4 ms

β partial $T_{1/2}$: 8.7 ± 1.3 ms

Prediction by E. Ormand
Phys. Rev. C 53 (1996) 214
$T_{1/2}(\beta)$ = 7 ms

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

β^+ decay of ^{45}Fe

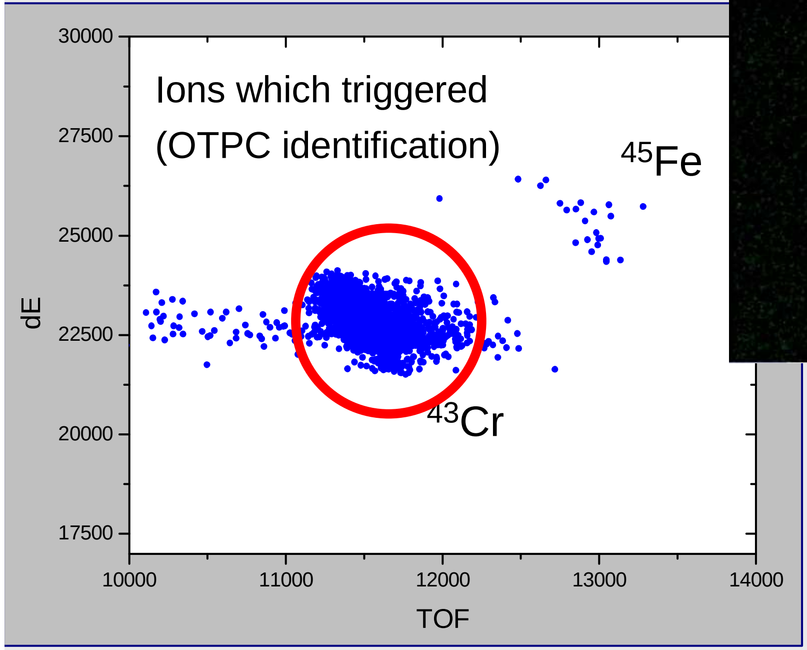


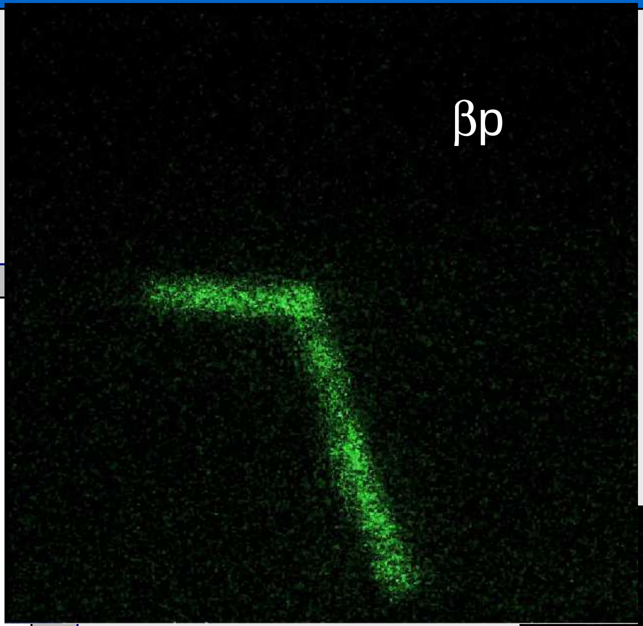
K. Miernik et al., Phys. Rev. C **76** (2007) 041304(R)

β^+ decay of ^{43}Cr

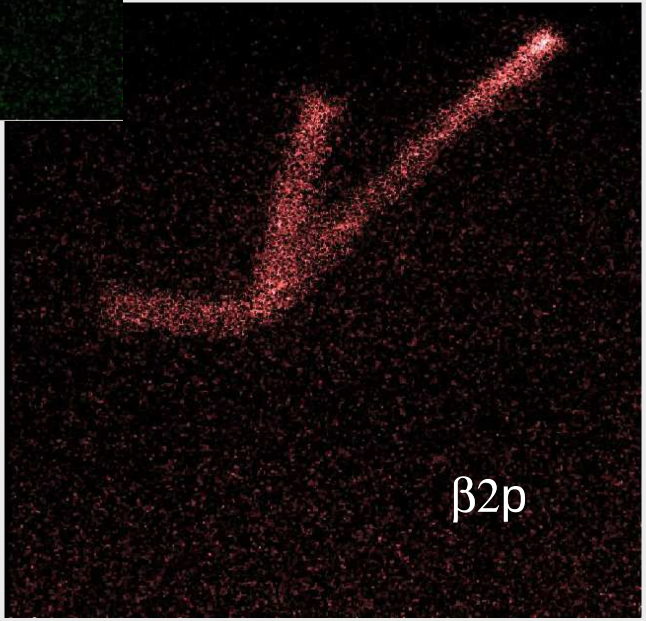
^{45}Fe: 2 /h

^{43}Cr: 8 /min.





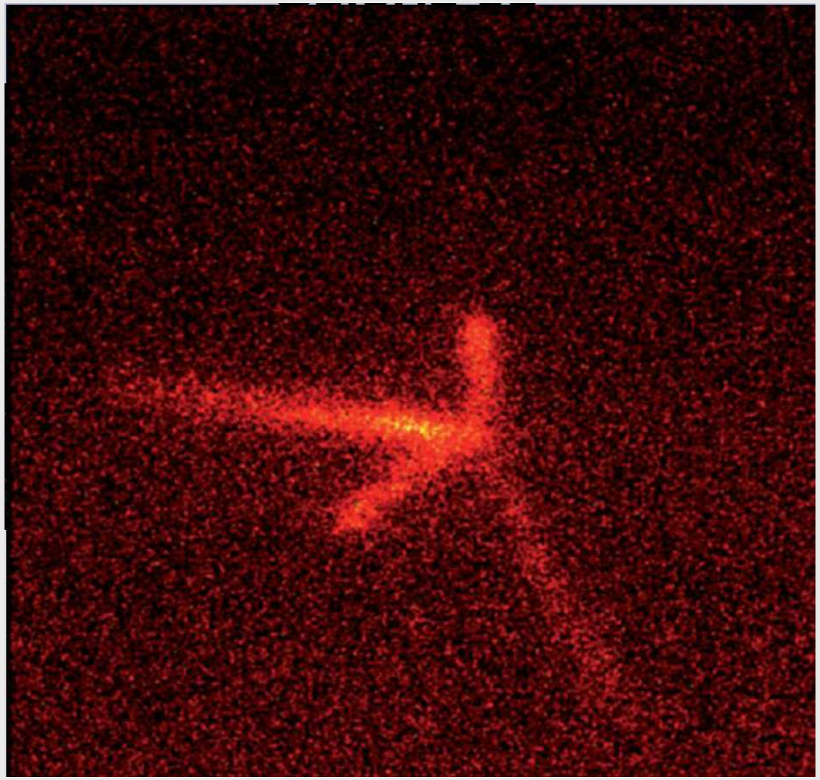
Example events in the asynchronous mode (incoming ^{43}Cr ion visible)



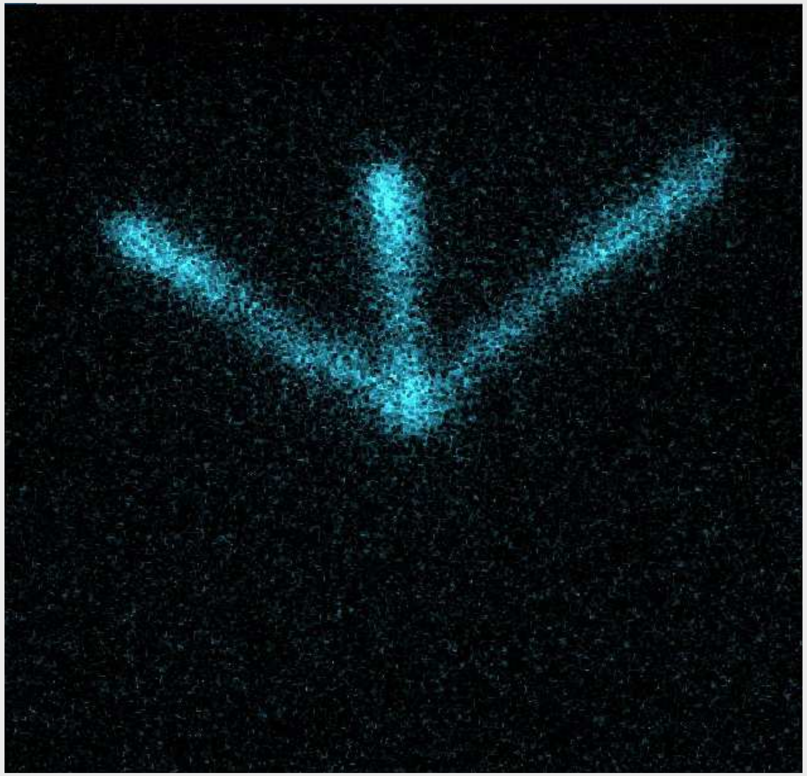
We recorded about 40 000 events of ^{43}Cr

M. Pomorski et al., to be published

^{43}Cr – the second case of β*3p*



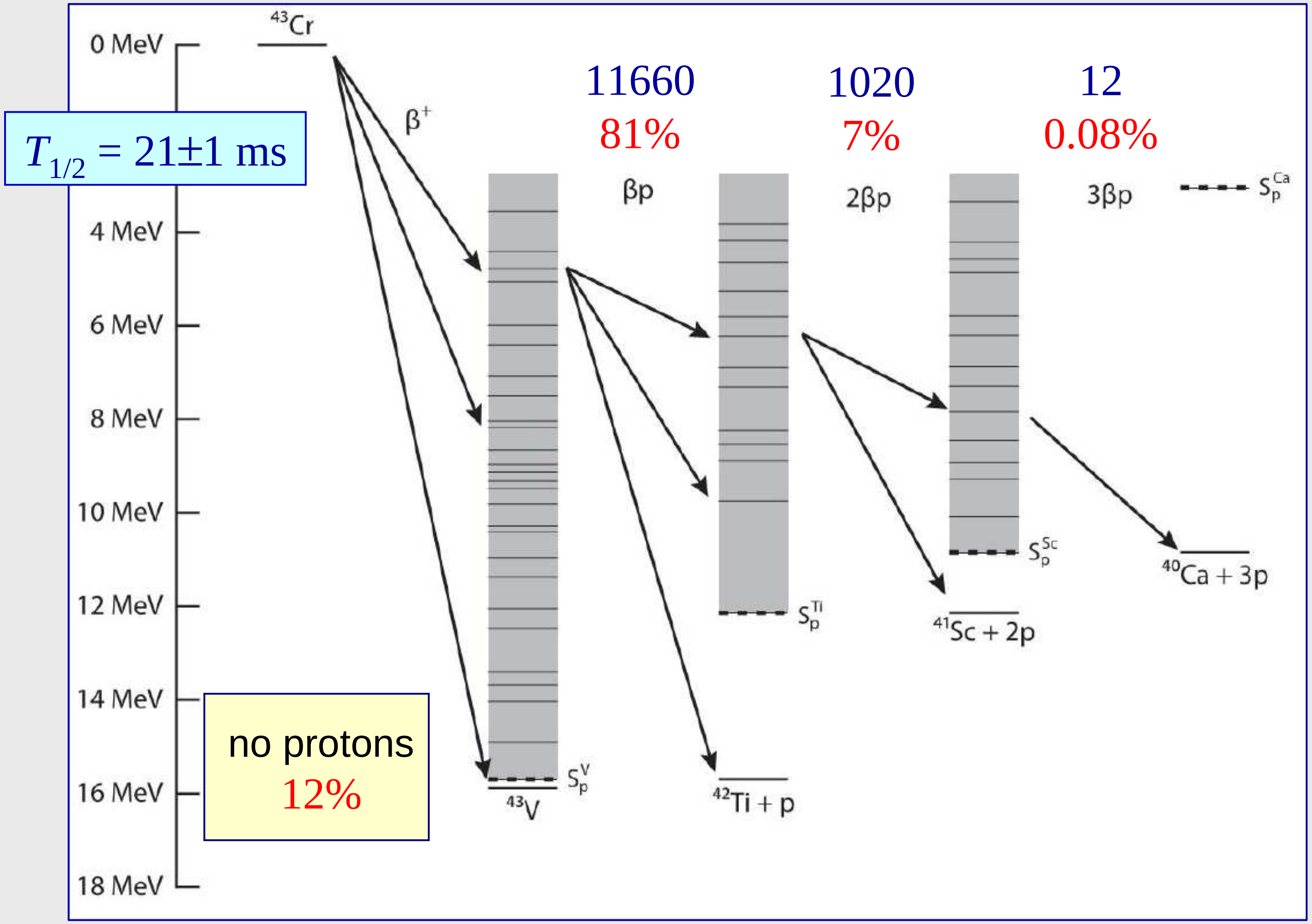
an event in an asynchronous mode



an event in a synchronous mode
(an ion not visible)

- In total 12 such events were observed (the Blackett style ☺)

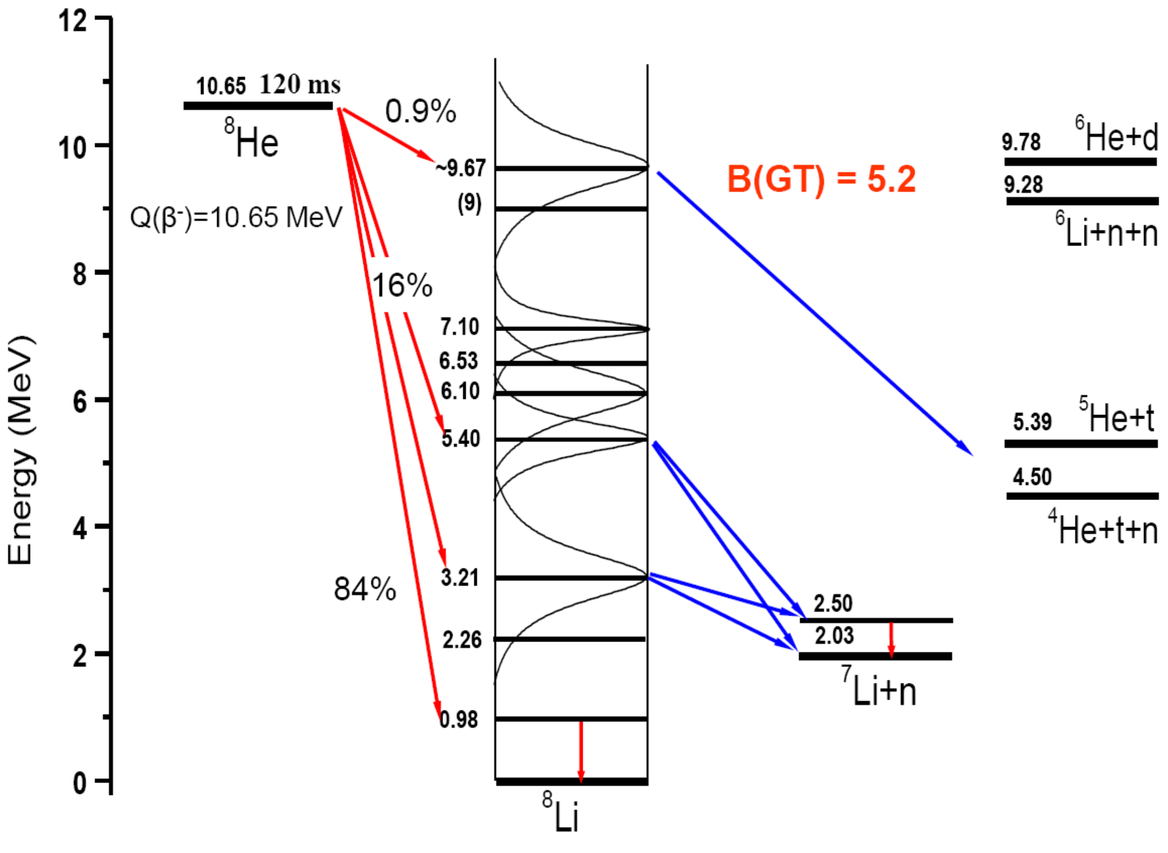
Decay channels of ^{43}Cr



M. Pomorski et al., to be published

Neutron drip-line case: ^{8}He

^{8}He – the most neutron-rich, particle-stable nucleus, attracts lot of interest (NNDC/NSR Data Base shows 225 papers!)



D. R. Tilley et. all, Nucl. Phys. A 745 (2004)

β-delayed t emission measured

$$^{8}\mathrm{He} \rightarrow {}^{8}\mathrm{Li}^{*} \rightarrow \mathrm{t} + \alpha + \mathrm{n}$$

$$b_t = (8.0 \pm 0.5) \times 10^{-3}$$

➔ $B_{GT} \geq 5.2$, log $ft = 2.9$!

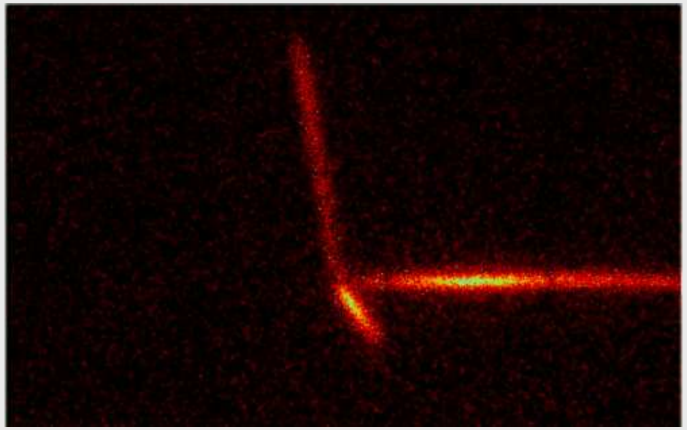
ISOLDE (1992)

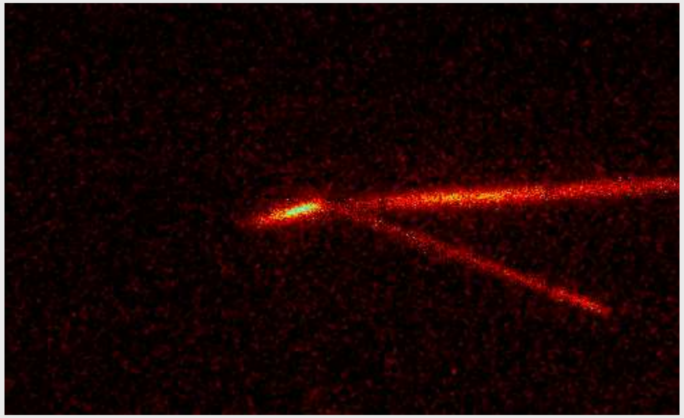
M. Borge et al., NP A 560 (1993) 664

^{8}He decay study @ JINR, Dubna

We see the tritium channel

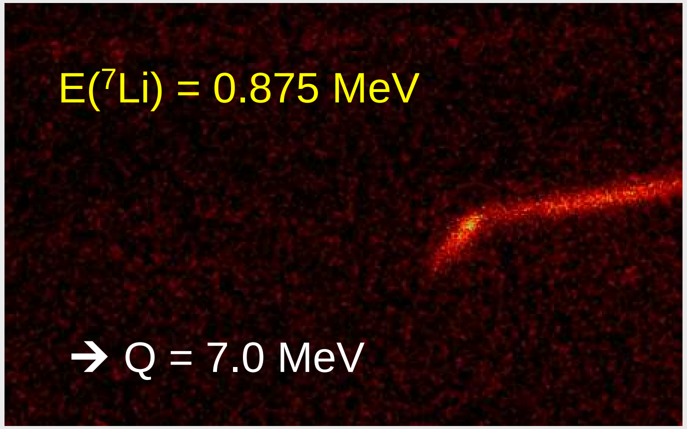
$$^{8}\mathrm{He} \rightarrow {}^{8}\mathrm{Li}^{*} \rightarrow \alpha + \mathrm{n} + \mathrm{t}$$

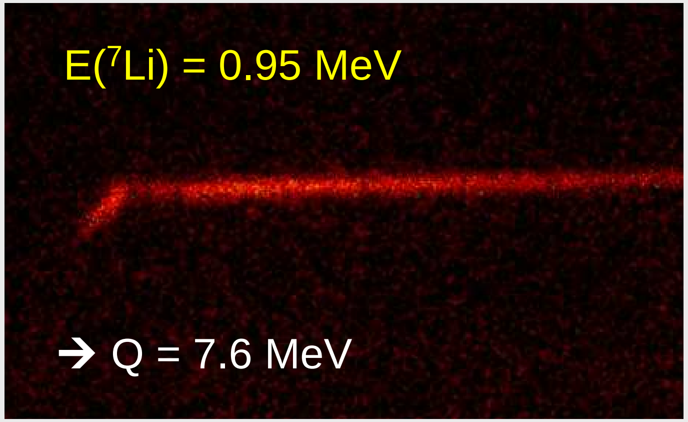




but also the recoil of ^{7}Li !

$$^{8}\mathrm{He} \rightarrow {}^{8}\mathrm{Li}^{*} \rightarrow {}^{7}\mathrm{Li} + \mathrm{n}$$



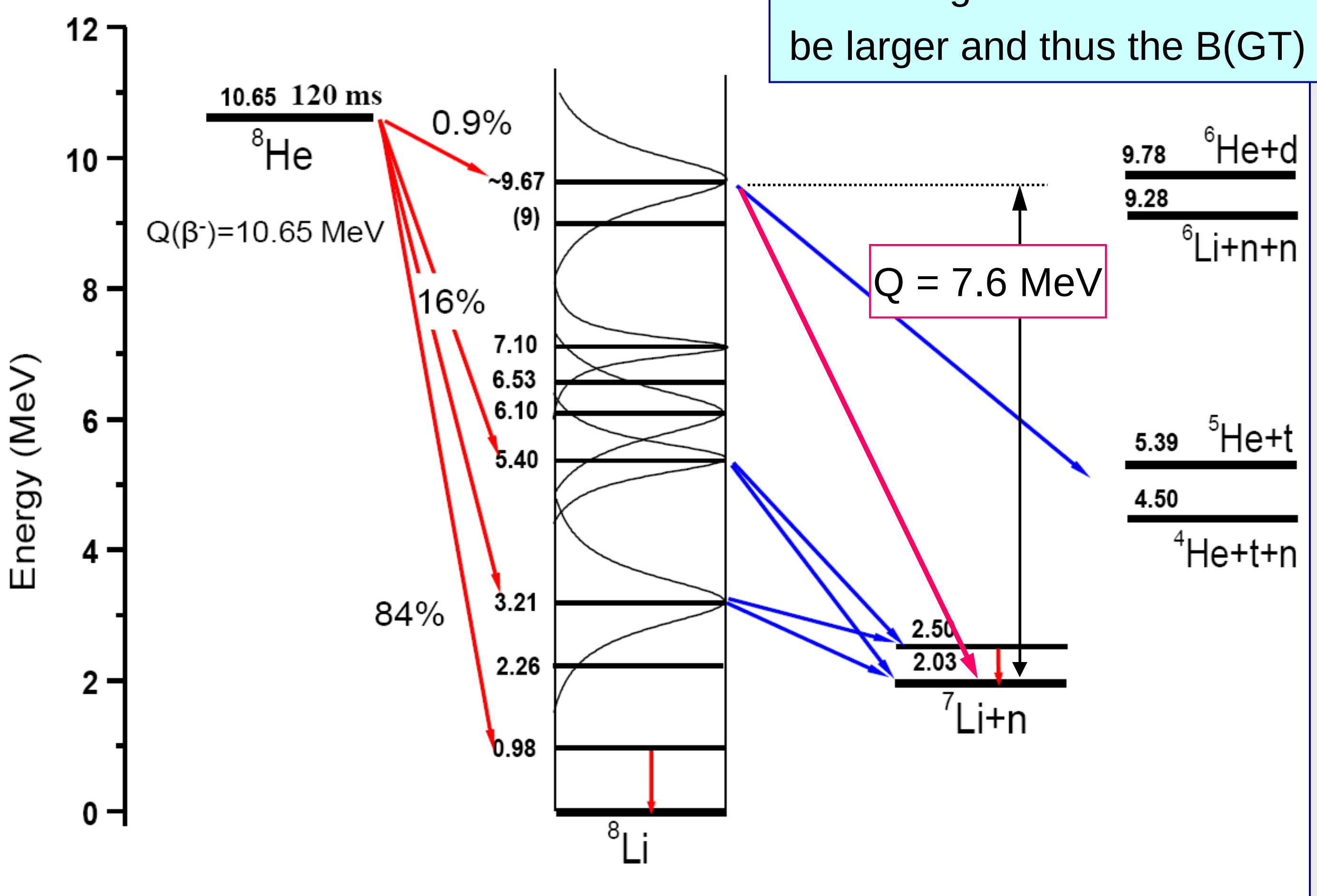


S. Mianowski

A new decay branch

preliminary!

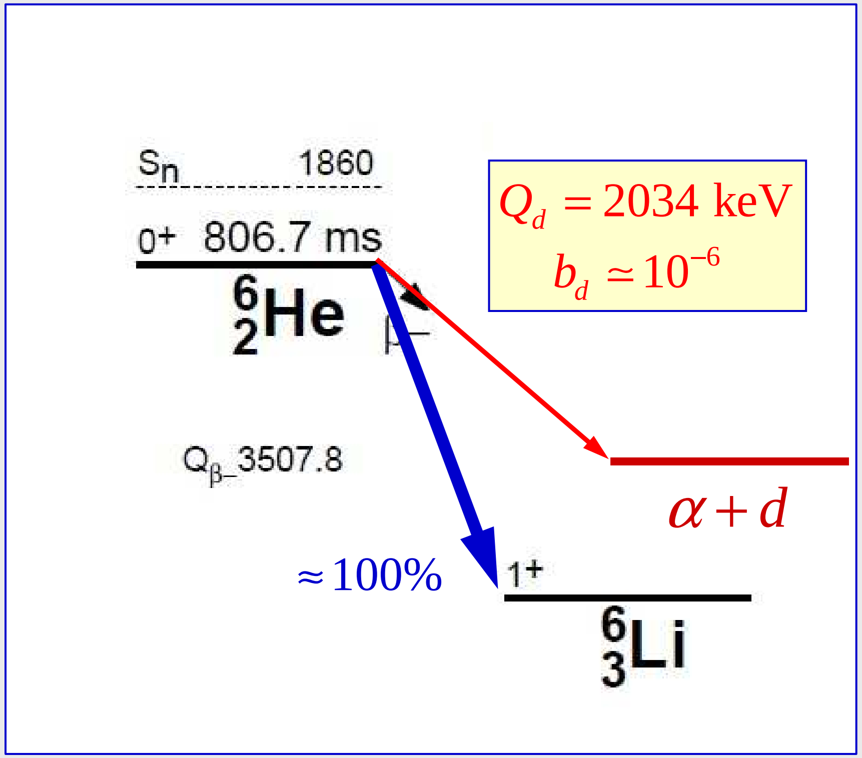
Branching to the 9.67 MeV state must be larger and thus the B(GT) too!

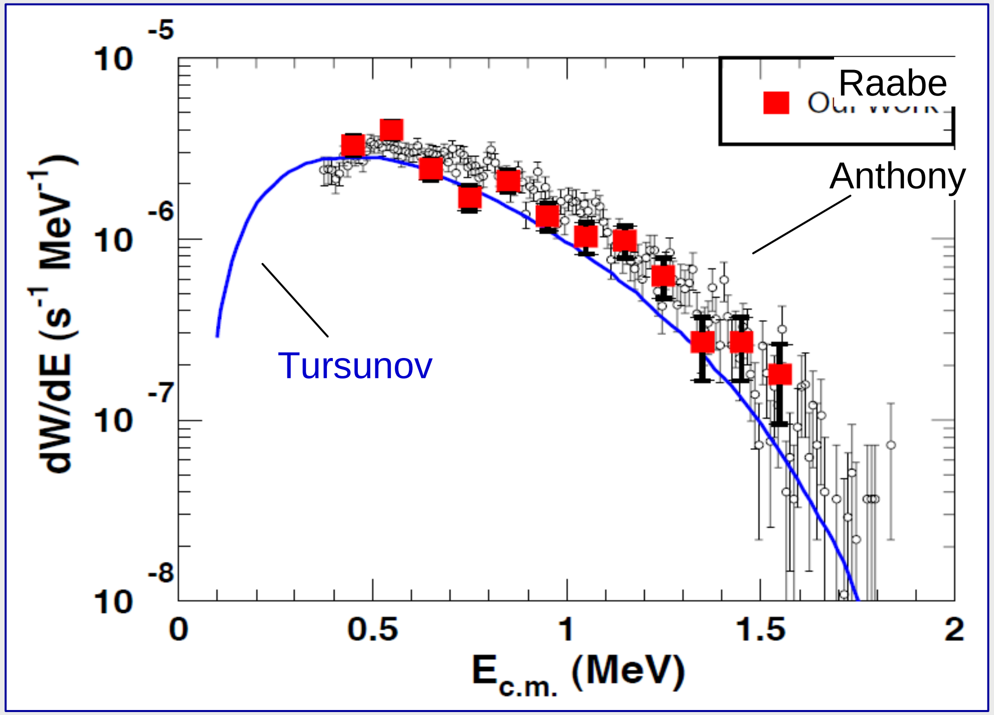


D. R. Tilley et. all, Nucl. Phys. A 745 (2004)

The next case: ^{6}He

- ^{6}He has a very weak decay branch to $\alpha + d$



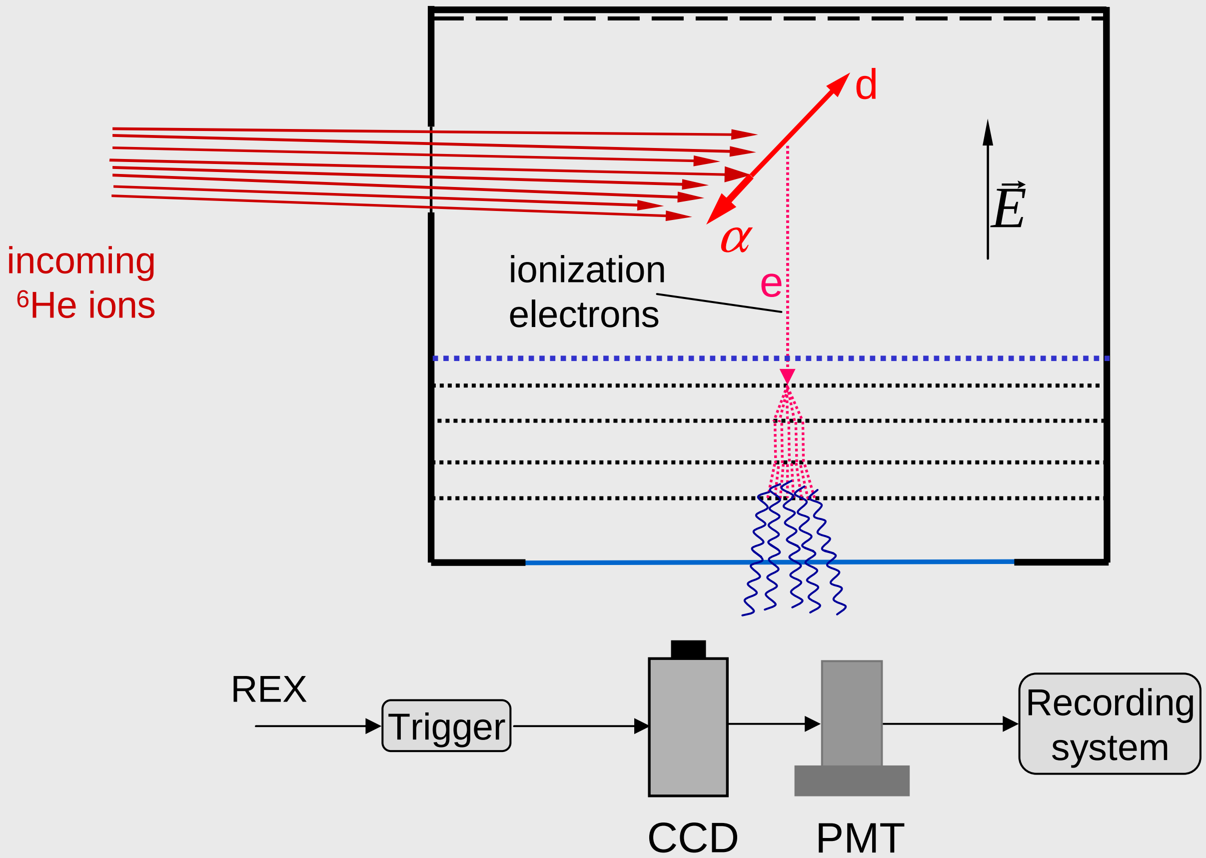


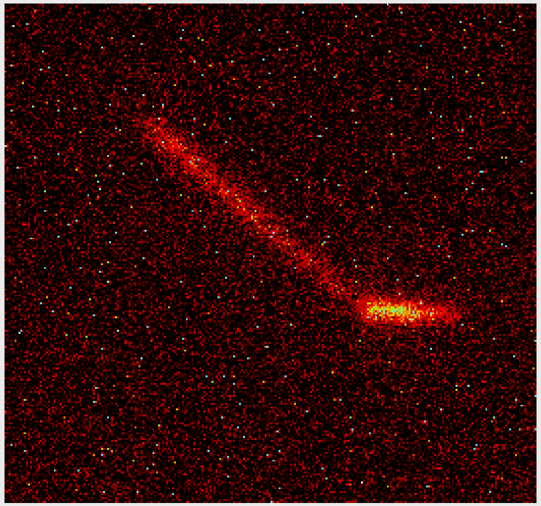
- Due to β-background, it was not possible to determine the spectrum below $E_{CM} \cong$ 400 keV!

An idea for the OTPC

Using REX ISOLDE we plan to implant a bunch of ≅ 10^5 ^{6}He ions and wait for the decay signal. Sometimes we will see α + d particles.

- The OTPC is not sensitive to electrons!

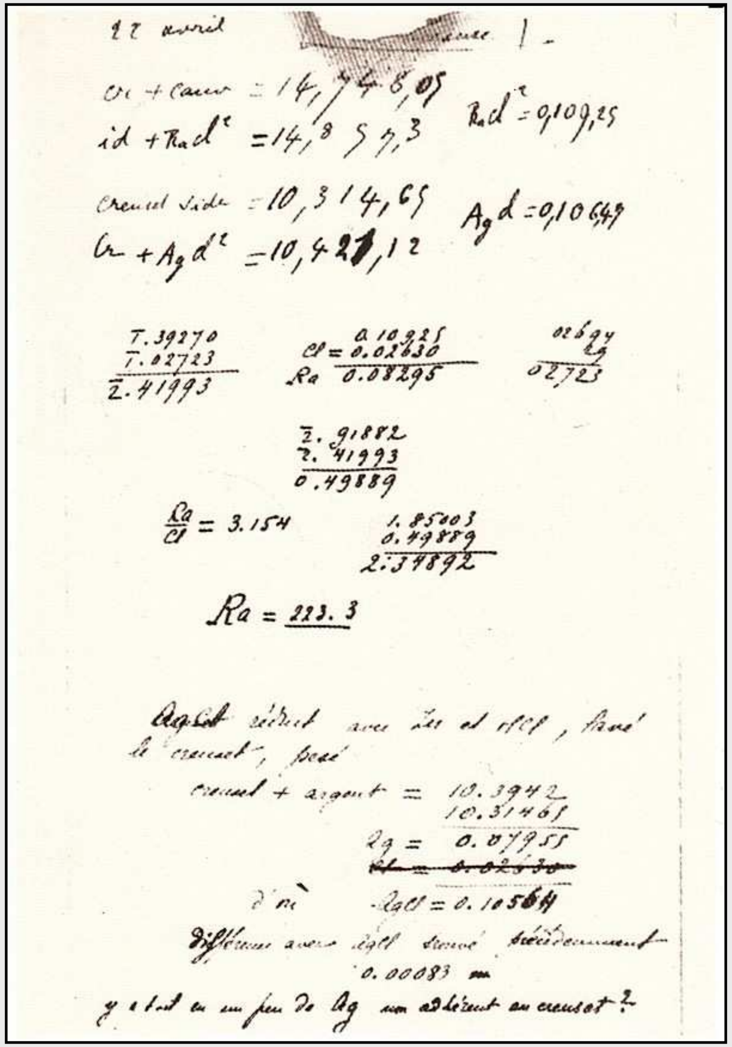




Summary

- The idea of optical recording of charged particles' tracks does work!
  Return of photographic techniques to nuclear science!
- This idea implemented as OTPC brought new results
  - *p-p* correlations in the decay of ^{45}Fe
  - *β3p* emission in two nuclei
  - possibly a new decay channel of ^{8}He
- Remarkable sensitivity – one good event suffices!
- Much cheaper and simpler than electronic TPC
- Present version has limitations
  - rather slow
  - limited to simple decays (2 tracks can be reconstructed)
  - not sensitive enough to see *β* particles
- Measurement on ^{8}He is being analyzed. A run on ^{6}He is planned

2011 – Year of Chemistry



Paris, 11 rue Pierre-et-Marie-Curie

The Nobel Prize in Chemistry 1911 was awarded to Marie Curie *"in recognition of her services to the advancement of chemistry by the discovery of the elements radium and polonium, by the isolation of radium and the study of the nature and compounds of this remarkable element"*.

http://nobelprize.org/nobel_prizes/chemistry/laureates/1911/


Mazurian Lakes Conference on Physics
Legacy of Maria Skłodowska-Curie – 100 years after discovery of atomic nucleus,
September 11 – 18, 2011, Piaski, POLAND
www.mazurian.fuw.edu.pl

Thank you for attention!