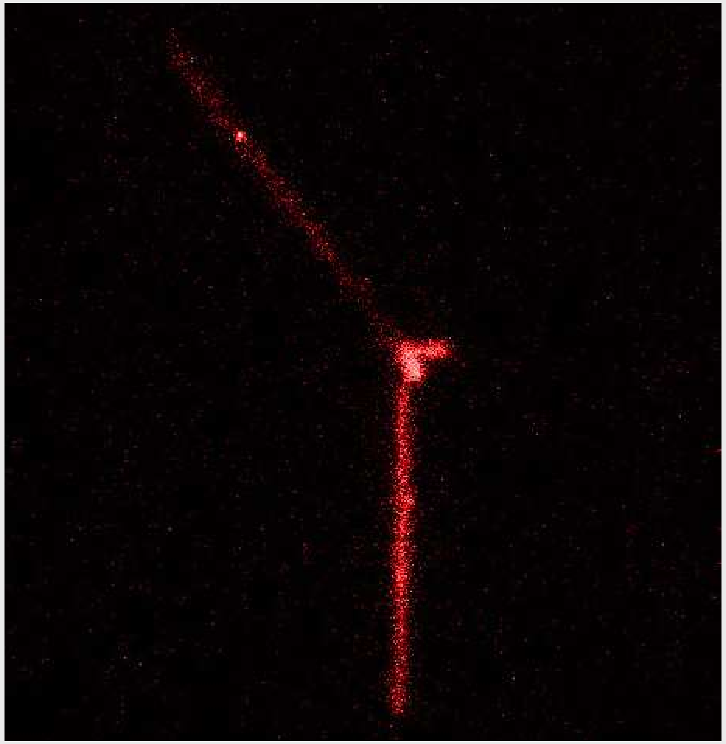
Two-proton radioactivity



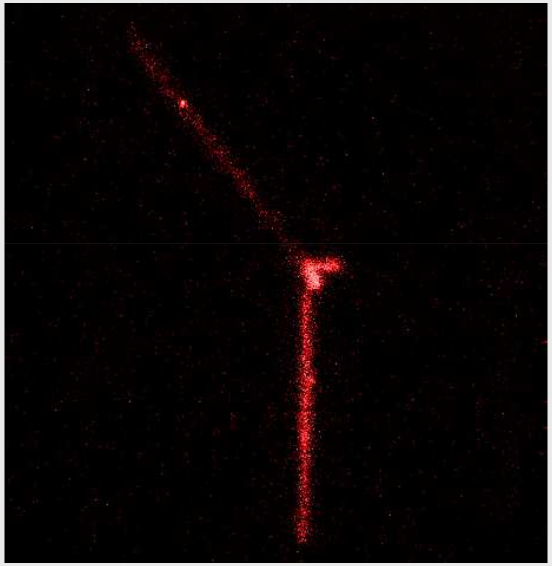
Marek Pfützner

Faculty of Physics

University of Warsaw

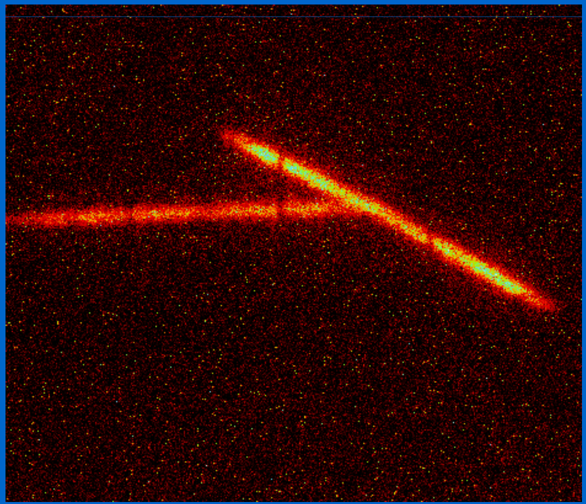
Justus Liebig Universität Giessen
Physikalisches Kolloquium,12.12.2011

Outline

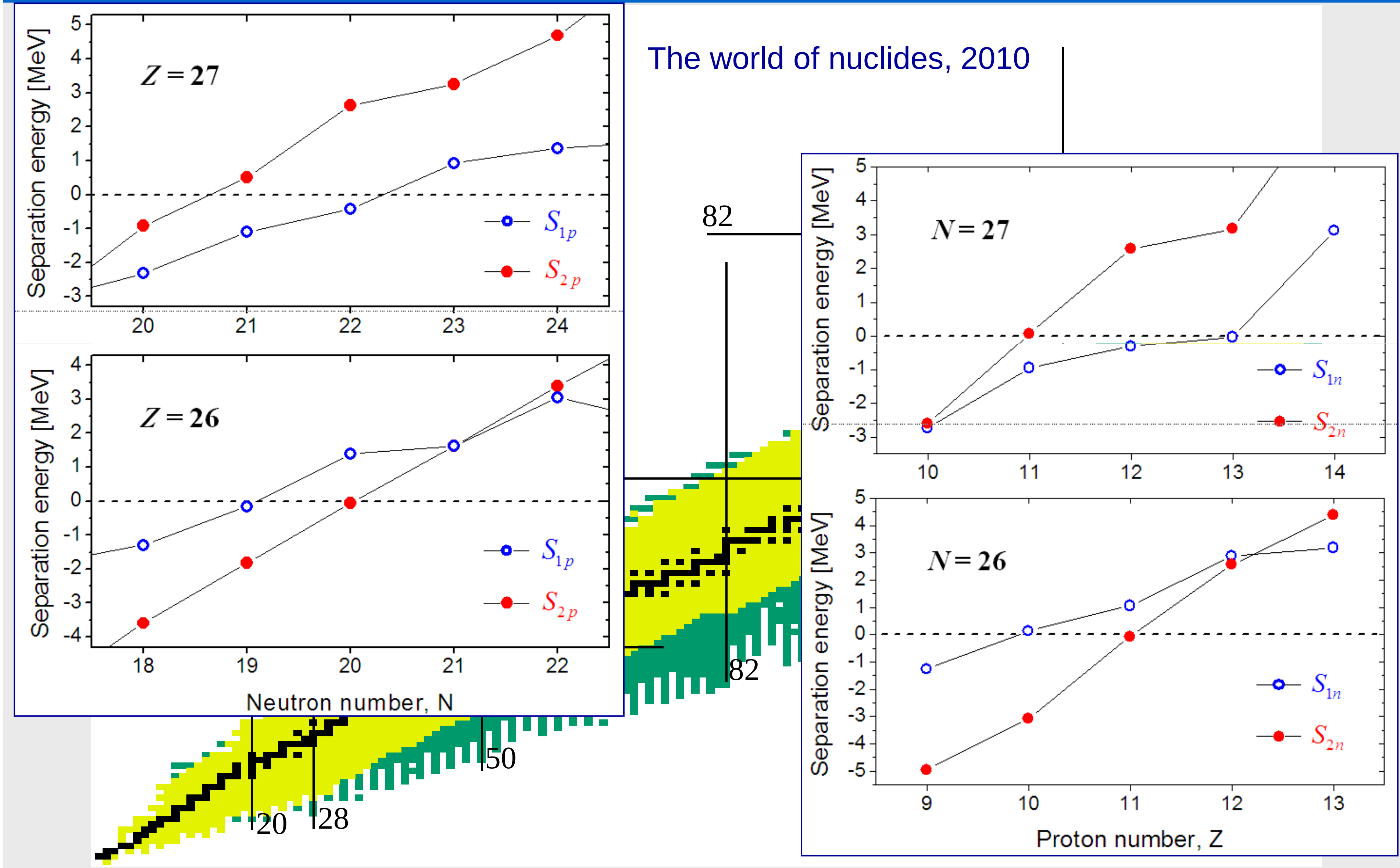


- Decays at the limit of stability
- Production and identification
- Observation of rare decays
- Confrontation with models
- Very fast decays
- Outlook

Decays at the limit of stability

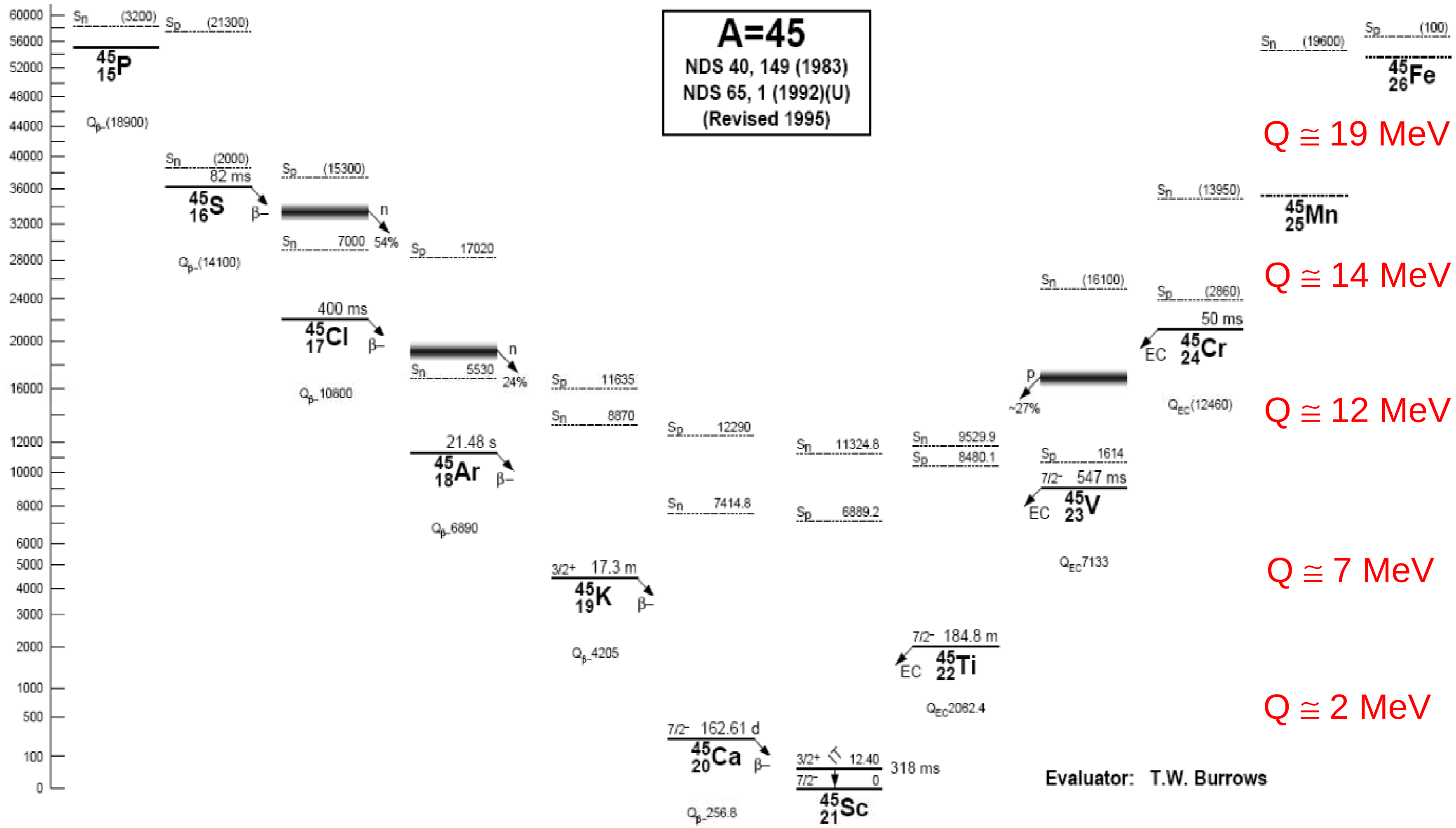


Drip lines



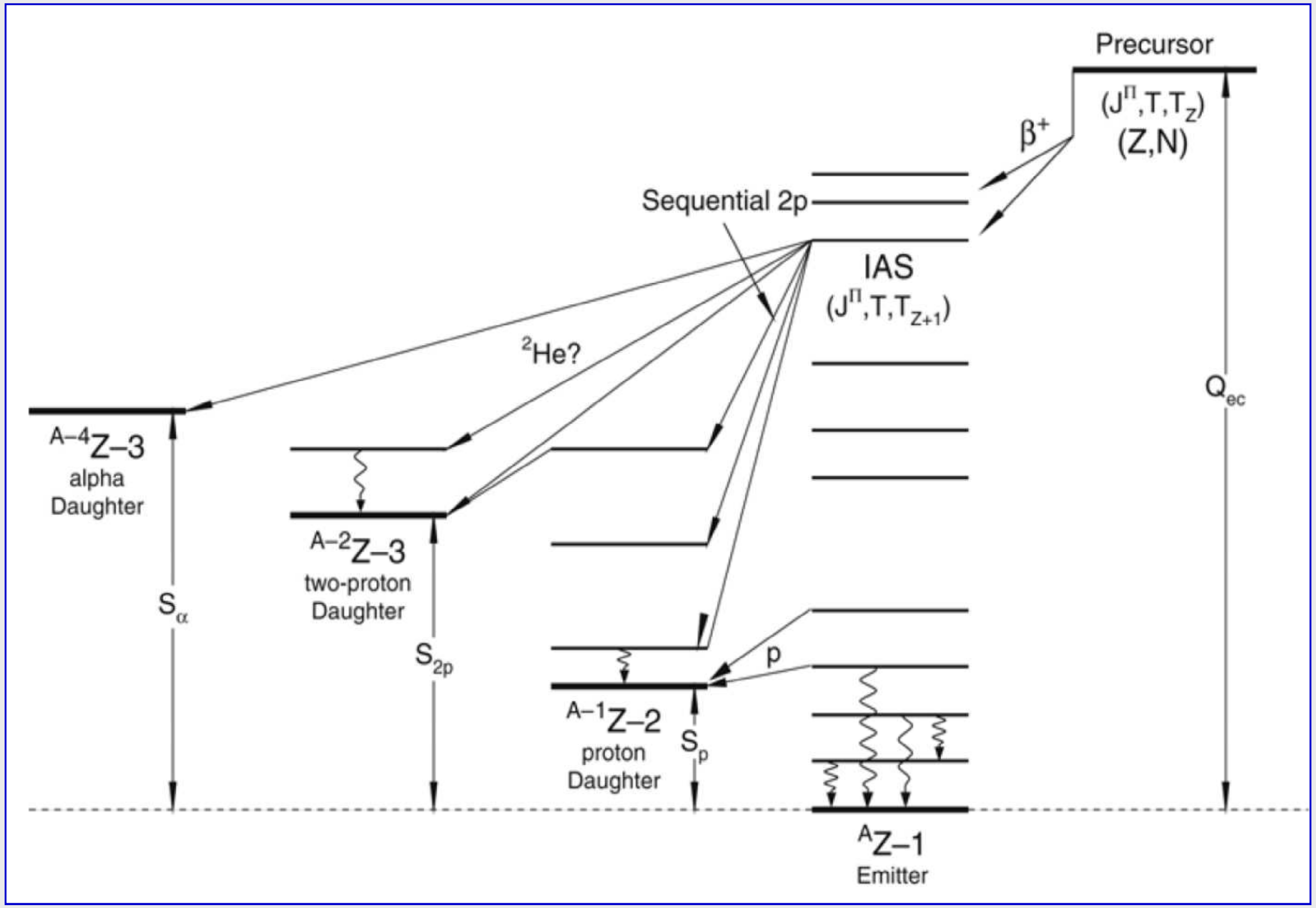
The world of nuclides, 2010
Z = 27
Z = 26
N = 27
N = 26
Separation energy [MeV]
Neutron number, N
Proton number, Z
S_{1p}
S_{2p}
S_{1n}
S_{2n}
20
28
50
82
82

Mass parabola



β-decay and delayed particle emission

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



Beyond the proton drip-line

Competition between two decay modes

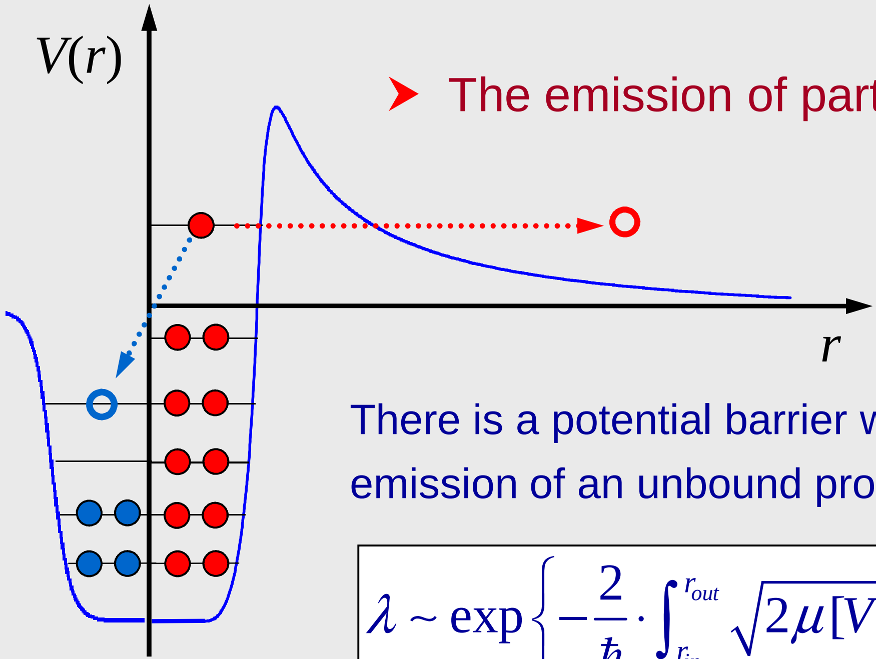
- The β^+ decay

Probability of transition:

$$\lambda \sim Q^5$$

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

→ $T_{1/2} > 1\ \mathrm{ms}$



- 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!

Predicting masses

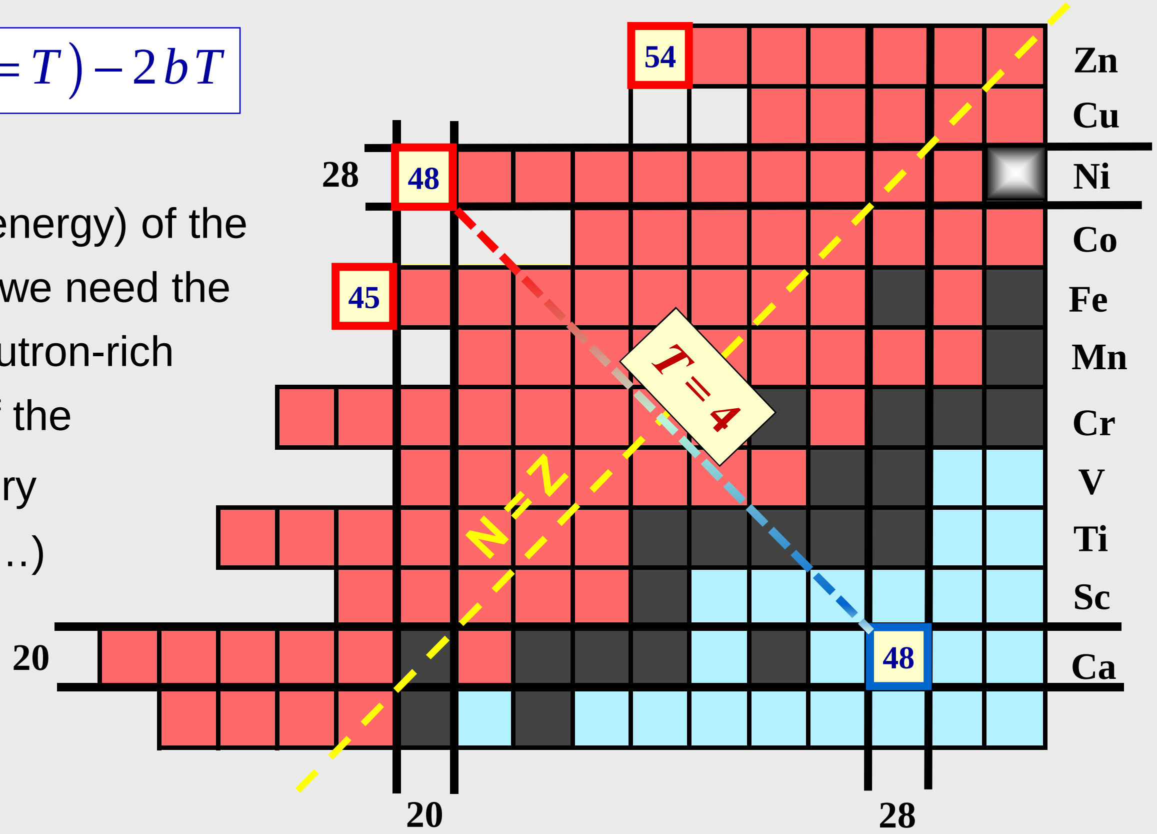
- Global mass models are not precise enough to determine the decay mode. However, there is a trick based on the Isobaric Multiplet Mass Equation (IMME):

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

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

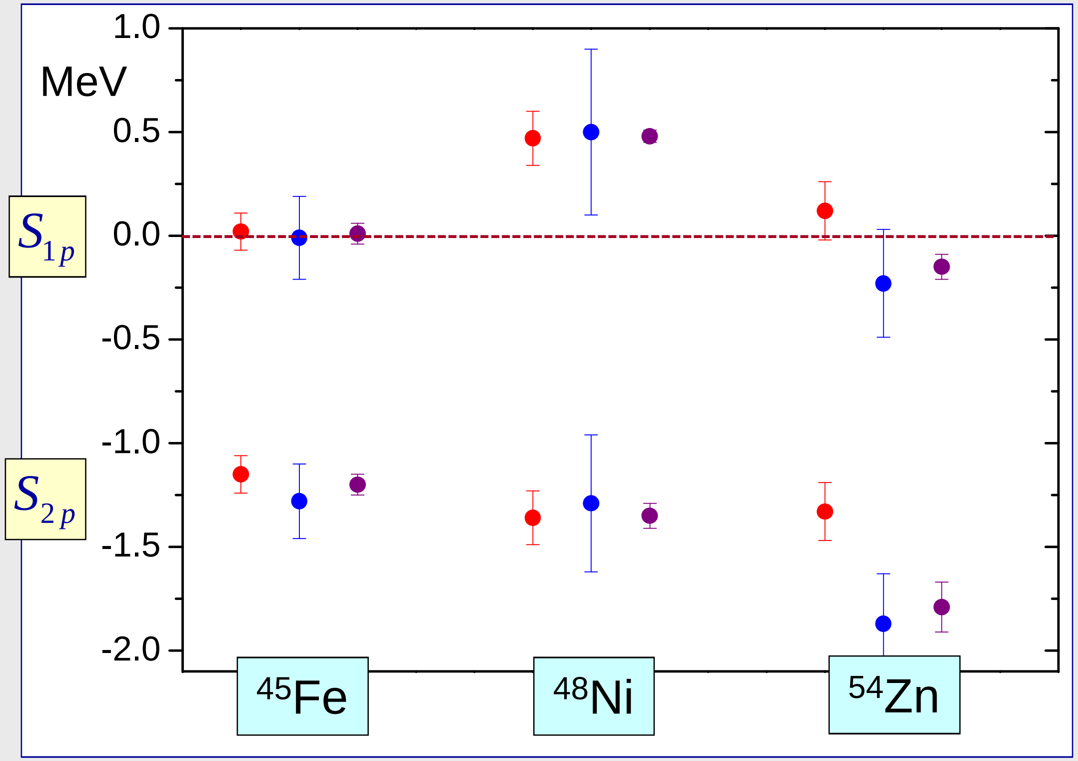
$$BE(T_z = -T) = BE(T_z = T) - 2bT$$

- 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…)

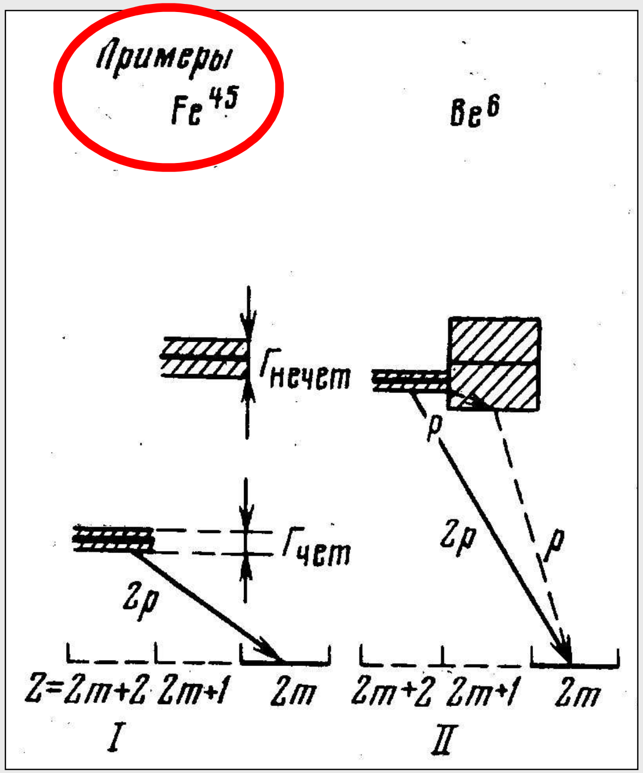


2*p* candidates

Predicted 1p and 2p separation energies



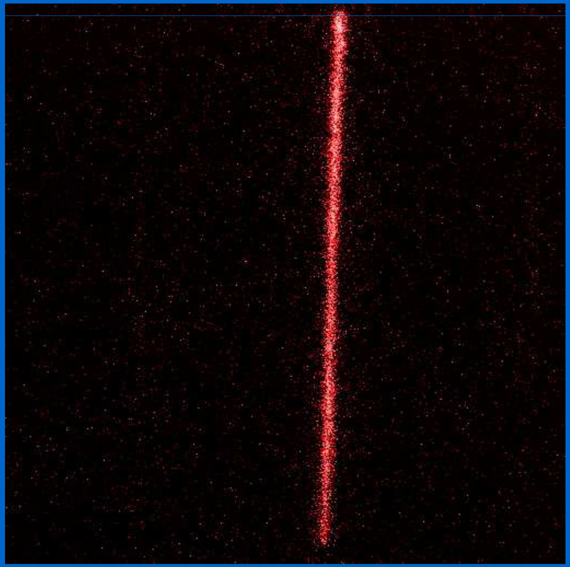
Pattern predicted by Goldansky



- B.A. Brown, PRC 43 (91) R1513
- W.E. Ormand, PRC 55 (97) 2407
- B.J. Cole, PRC 54 (96) 1240

V.I. Goldanskii, Nucl. Phys. 19 (60) 482

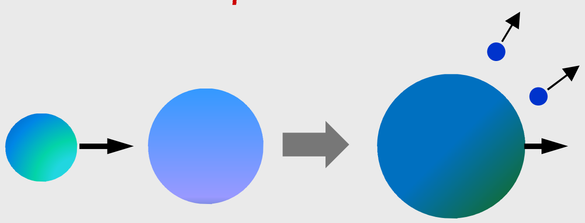
Production and Identification of exotic ions



Production methods

- To produce short-lived radioactive nuclei at the proton drip-line two nuclear reactions are useful

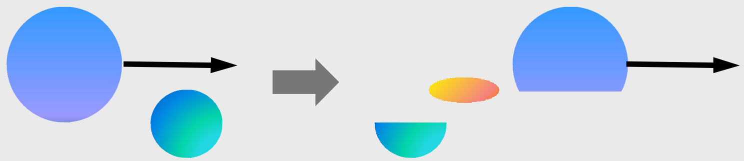
- fusion-evaporation
  reactions between heavy-ions
  GSI, Argonne, Oak Ridge, Jyväskylä,...
  recoil separators



Low energy: ~ Coulomb barrier

- large beam intensity
- thin target
  identification by decays

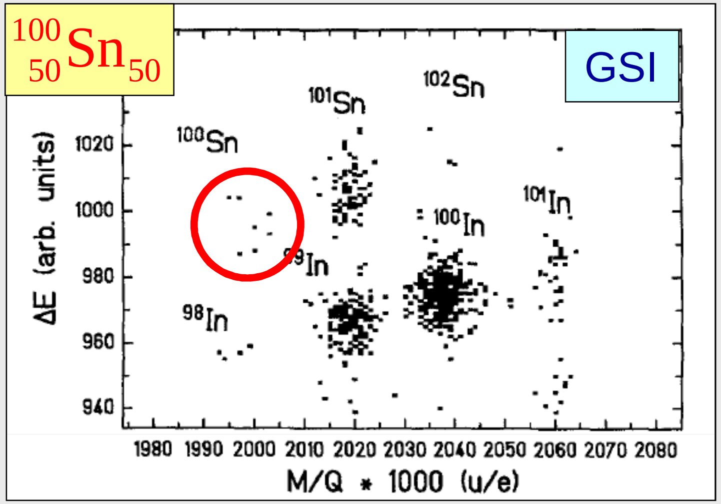
- fragmentation
  of relativistic heavy-ions
  GSI, NSCL, GANIL, RIKEN,…
  fragment separators



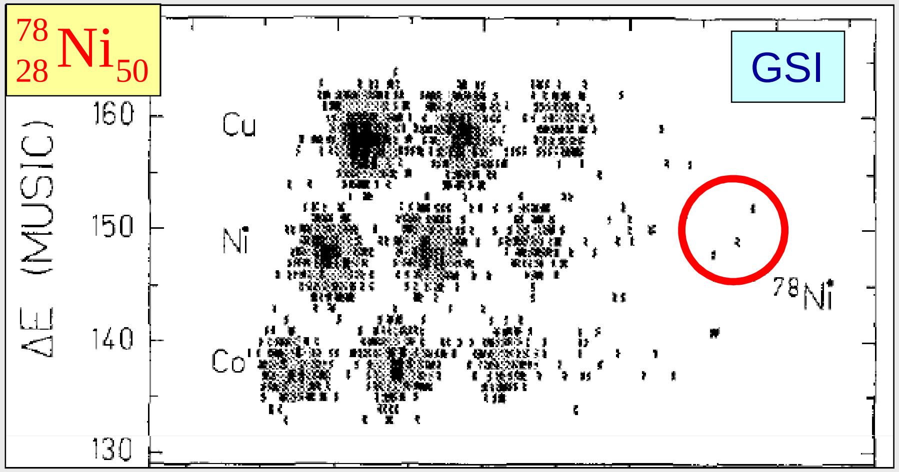
High energy: ~ above Fermi energy

- lower beam intensity
- thick target
  identification in-flight
  single ion sensitivity

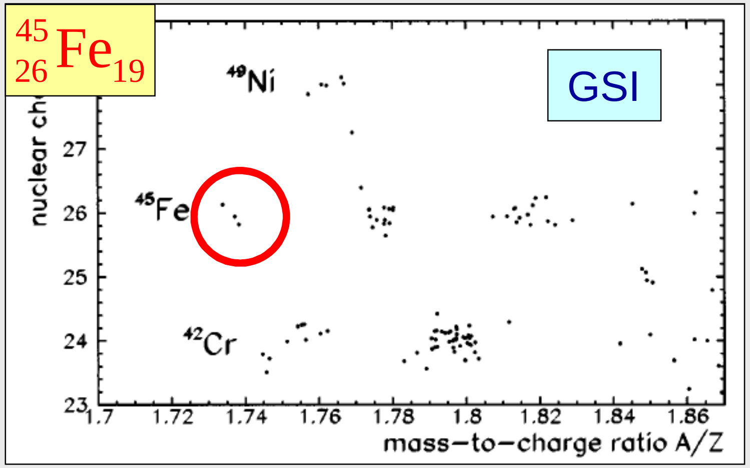
Fragmentation milestones



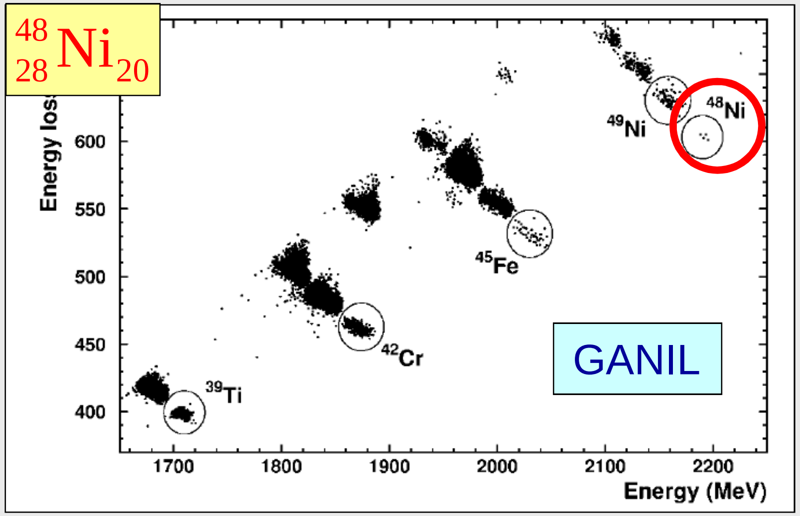
R. Schneider et al., Z. Phys. A 348 (94) 241



Ch. Engelmann et al., Z. Phys. A352 (95) 351



B. Blank et al., PRL 77 (96) 2893

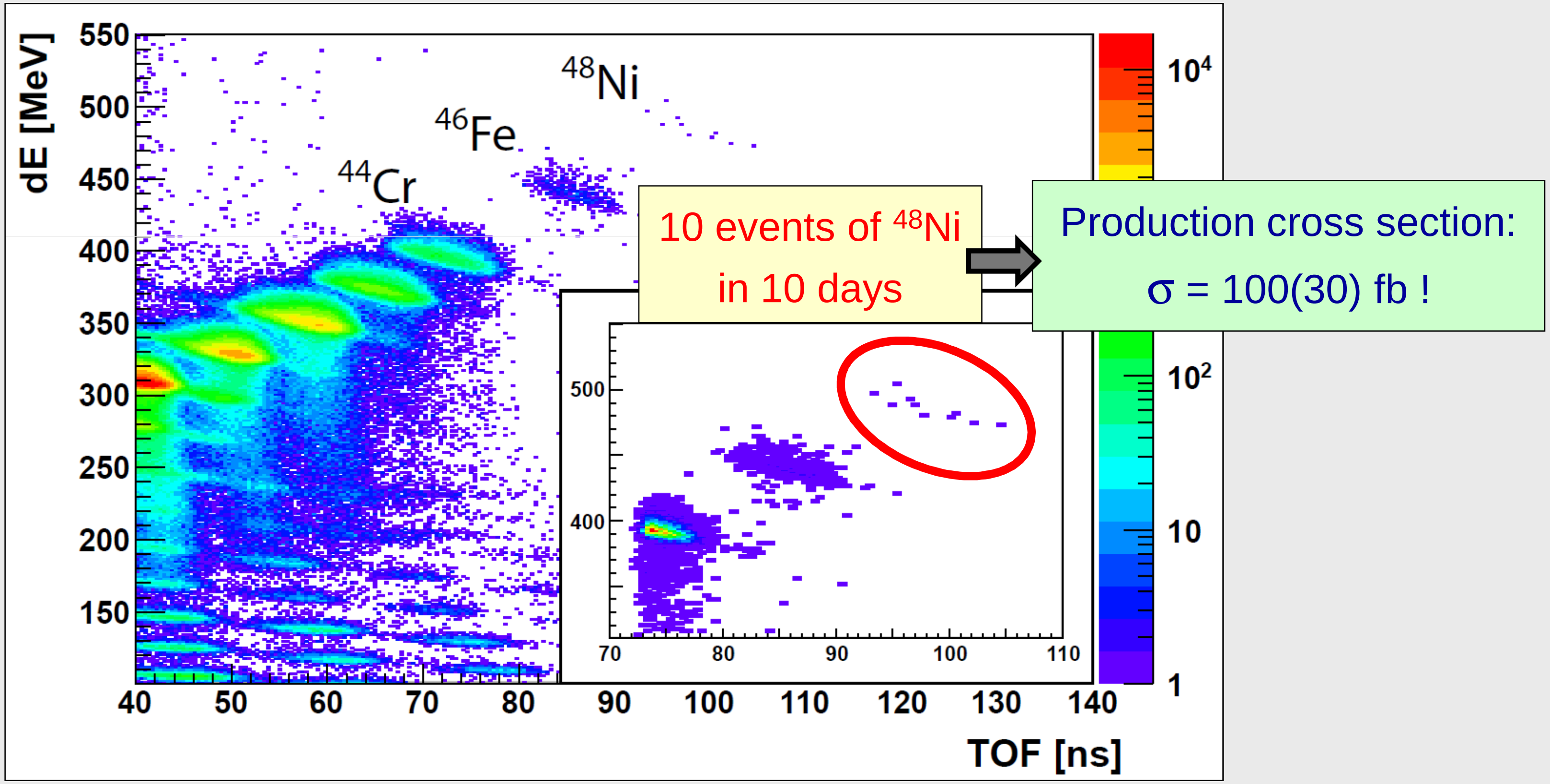


B. Blank et al., PRL 84 (00) 1116

^{48}Ni benchmark

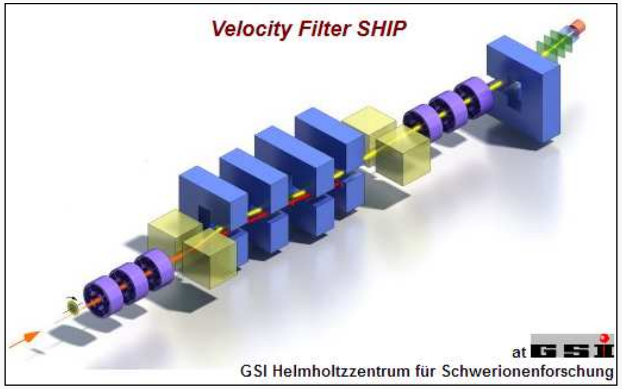
Experiment in March 2011, A1900 fragment separator at NSCL/MSU

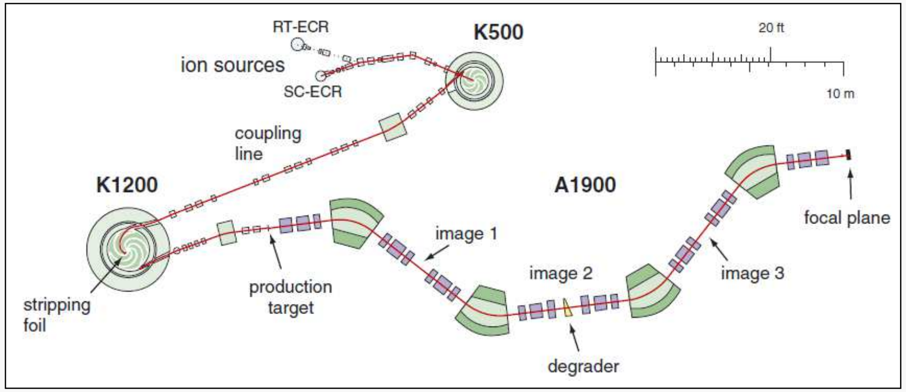
^{58}Ni @ 160 A·MeV + ^{nat}Ni → ^{48}Ni



M. Pomorski et al., PRC 83 (11) 061303(R)

Sensitivity





- Hunt for element 120 at SHIP

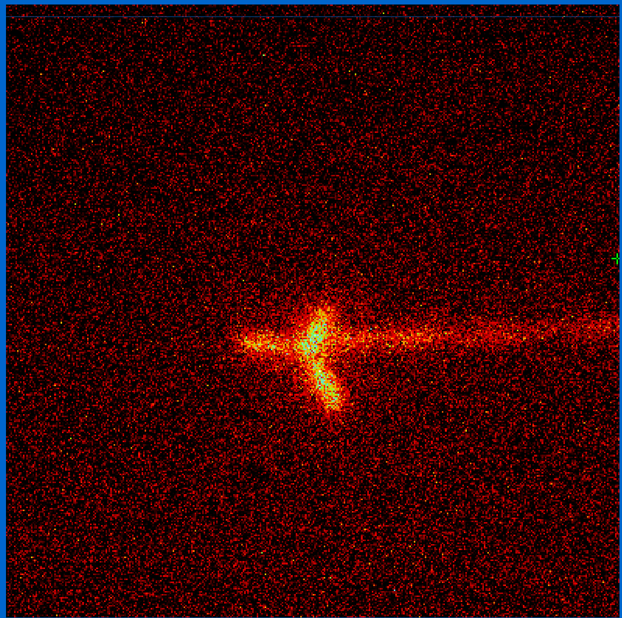
fusion ^{54}Cr + ^{248}Cm → ^{302}120*

- Production of ^{48}Ni at NSCL

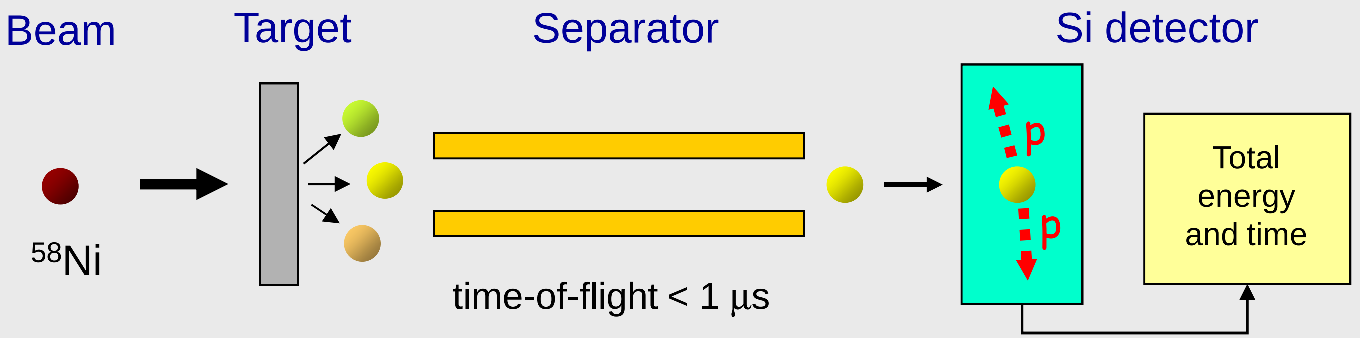
fragmentation ^{58}Ni + ^{nat}Ni → ^{48}Ni

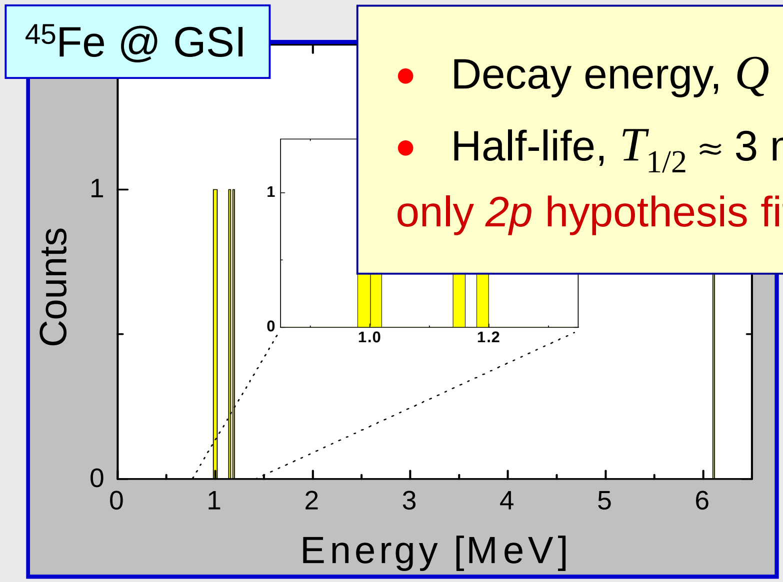
	SHIP	NSCL	
Cross section:	≈ 90 fb	≈ 100 fb	
Beam intensity:	750 pnA	20 pnA	38 times weaker
Running time (1 event):	≈100 days	≈1 day	100 times shorter
Total dose:	≈ $4\cdot10^{19}$ part.	≈ $1\cdot10^{16}$ part.	4000 times smaller
Target thickness:	0.5 mg/cm^2	580 mg/cm^2	

Observation of rare decay channels



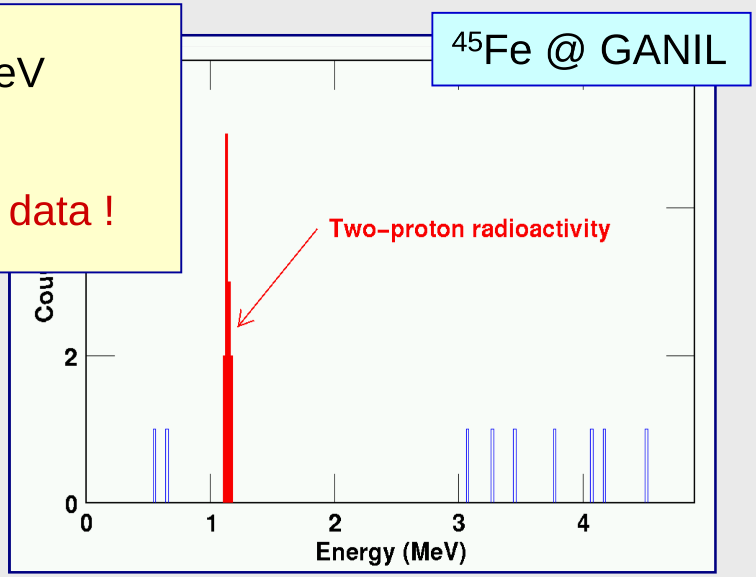
First evidence of *2p* emission





- Decay energy, Q = 1.1 MeV
- Half-life, $T_{1/2} \approx$ 3 ms

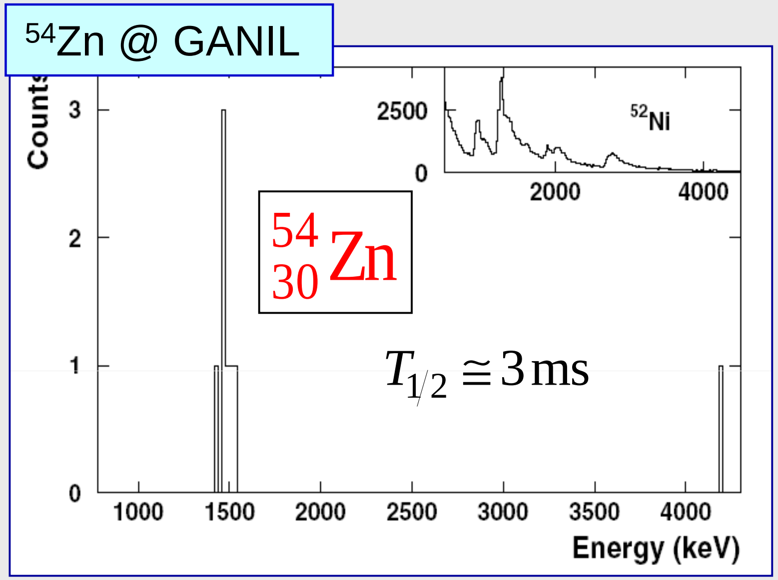
only *2p* hypothesis fits these data !

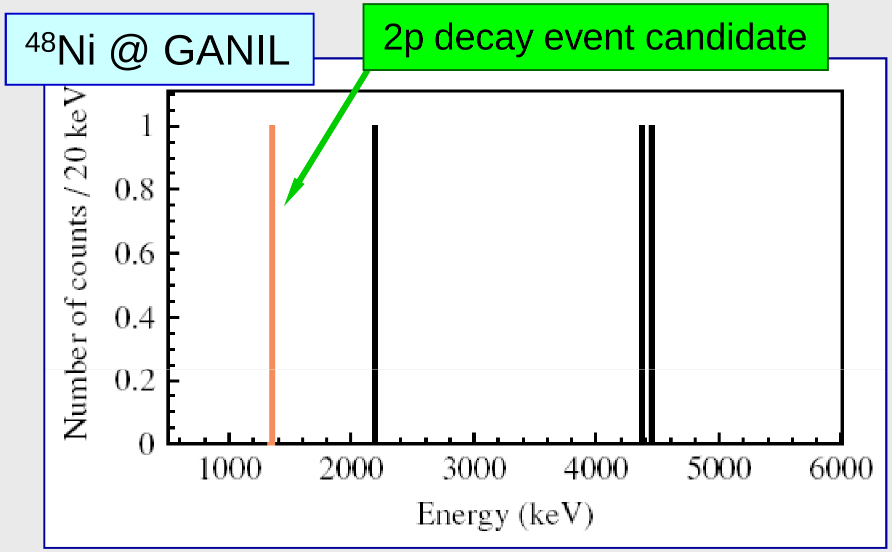


M. P. et al., EPJ A 14 (02) 279

J. Giovinazzo et al., PRL 89 (02) 102501

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

- Interpretation is made by comparing measured decay energy and half-life with models. There is no direct proof for the emission of two protons!

Search for β-delayed *3p*

PHYSICAL REVIEW C VOLUME 45, NUMBER 1 JANUARY 1992

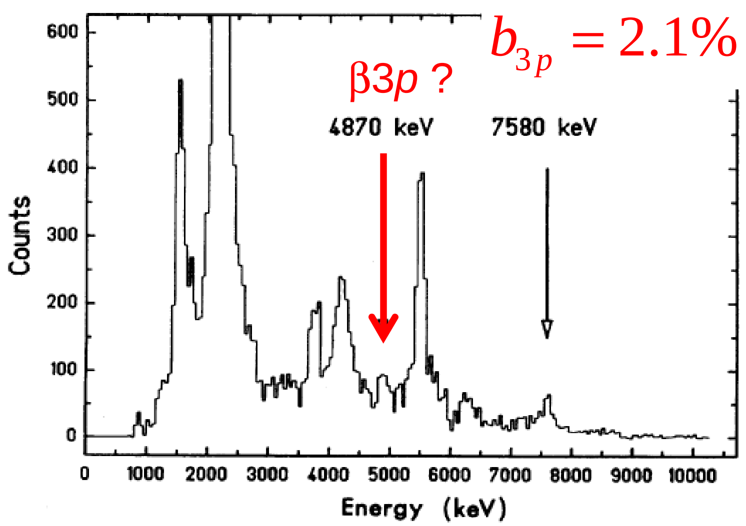
Decay modes of ^{31}Ar and first observation of β-delayed three-proton radioactivity

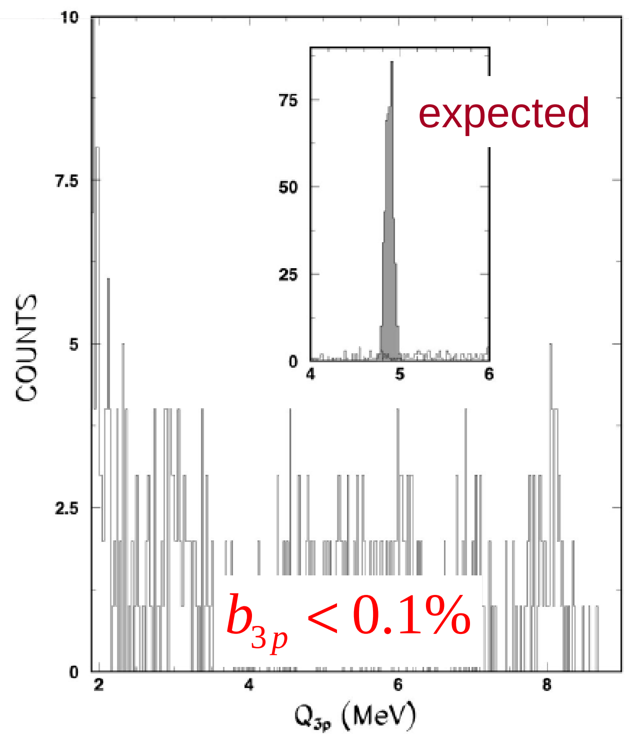
D. Bazin,* R. Del Moral, J. P. Dufour, A. Fleury, F. Hubert, and M. S. Pravikoff
Centre d'Etudes Nucléaires de Bordeaux–Gradignan, Le Haut Vigneau 33175 Gradignan CEDEX, France

PHYSICAL REVIEW C VOLUME 59, NUMBER 4 APRIL 1999

^{31}Ar examined: New limit on the β-delayed three-proton branch

H. O. U. Fynbo,[1] L. Axelsson,[2] J. Äystö,[3] M. J. G. Borge,[4] L. M. Fraile,[4] A. Honk
A. Jokinen,[3] B. Jonson,[2] I. Martel,[5,†] I. Mukha,[1,‡] T. Nilsson,[2,§] G. Nyman,[2] M. Oin
M. H. Smedberg,[2] O. Tengblad,[4] F. Wenander,[2] and the ISOLDE

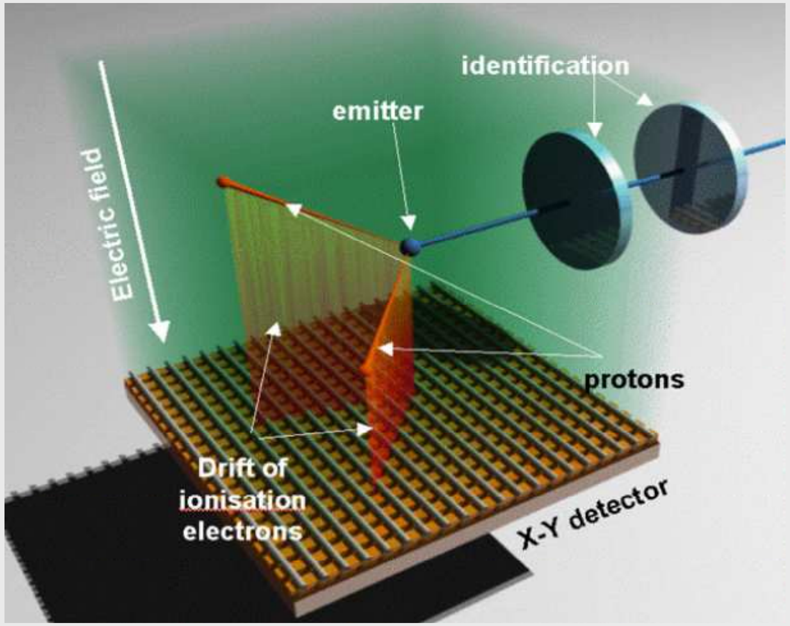


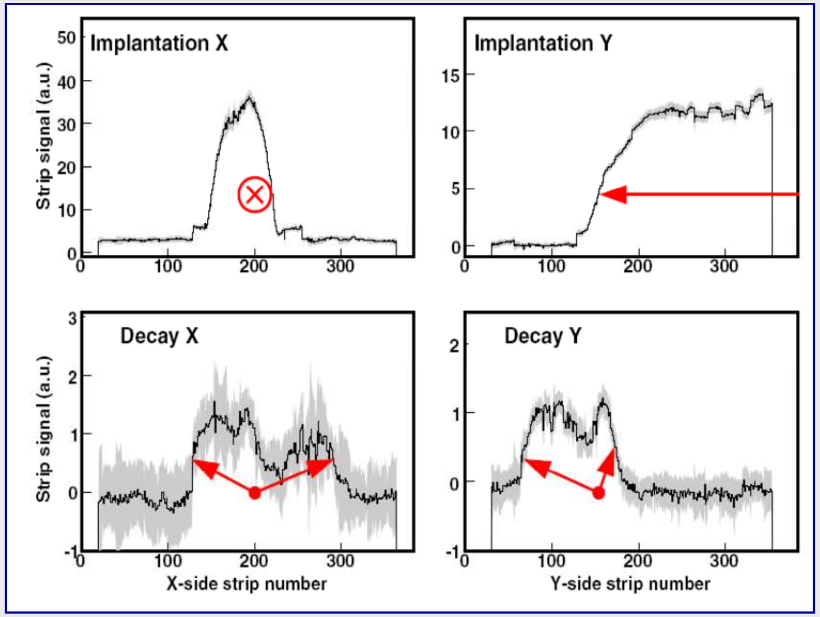


TPC principle

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.





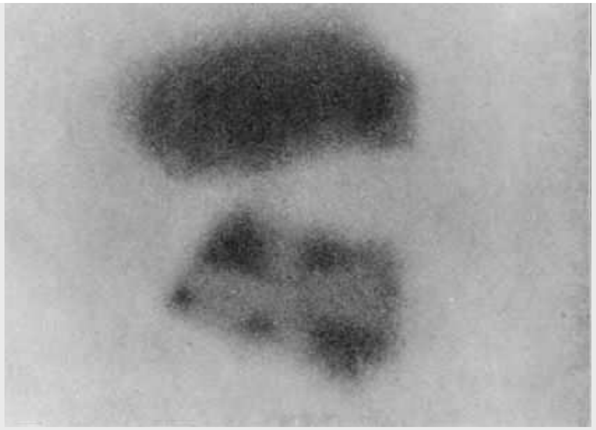
A decay event of ^{45}Fe

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

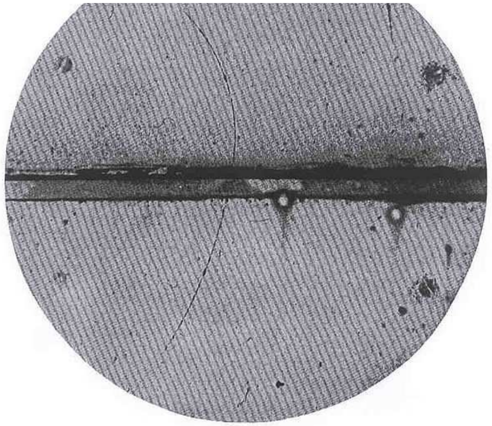
J. Giovinazzo et al., PRL 99 (2007) 102501

Photography in subatomic physics

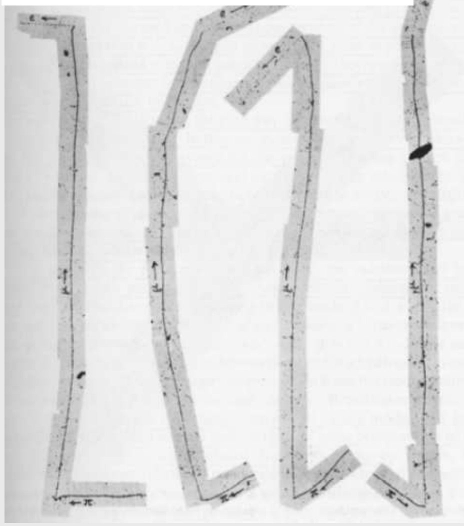
Radioactivity (Becquerel, 1896)



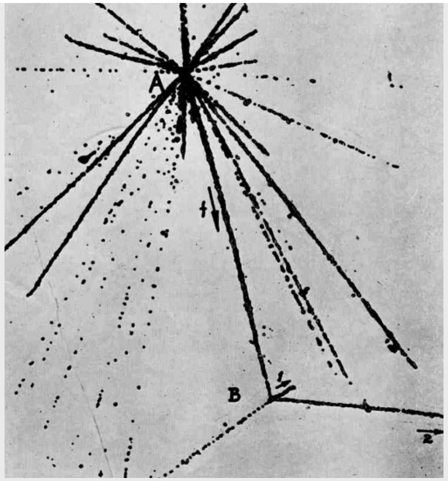
Positron (Anderson, 1932)



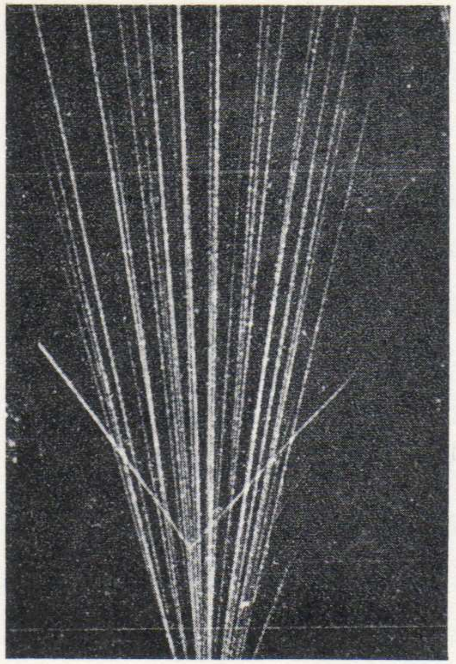
Pion (Powell, 1947)



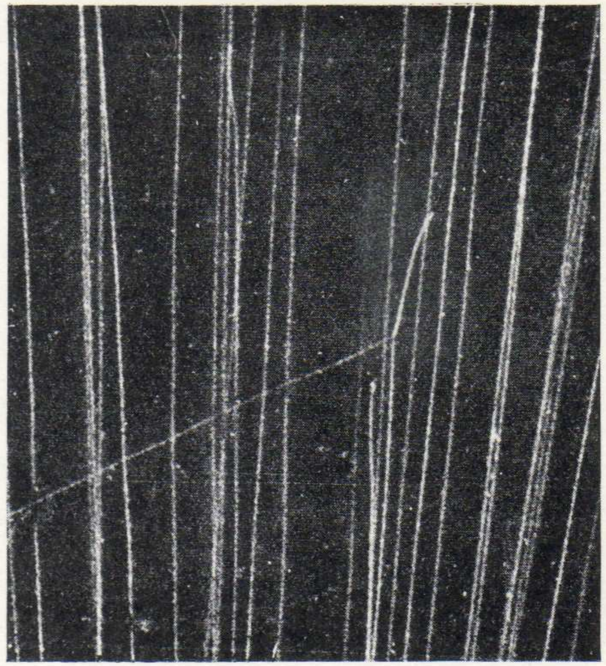
Hypernucleus
(Danysz, Pniewski, 1952)



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)

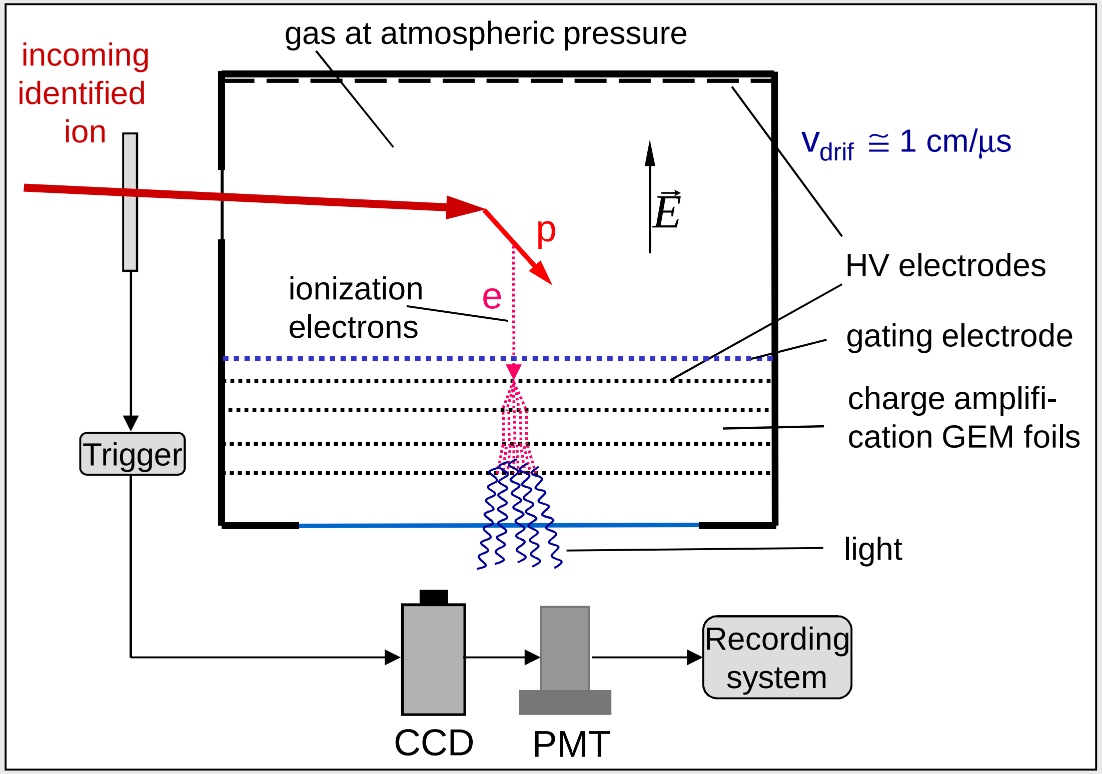
1923

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.

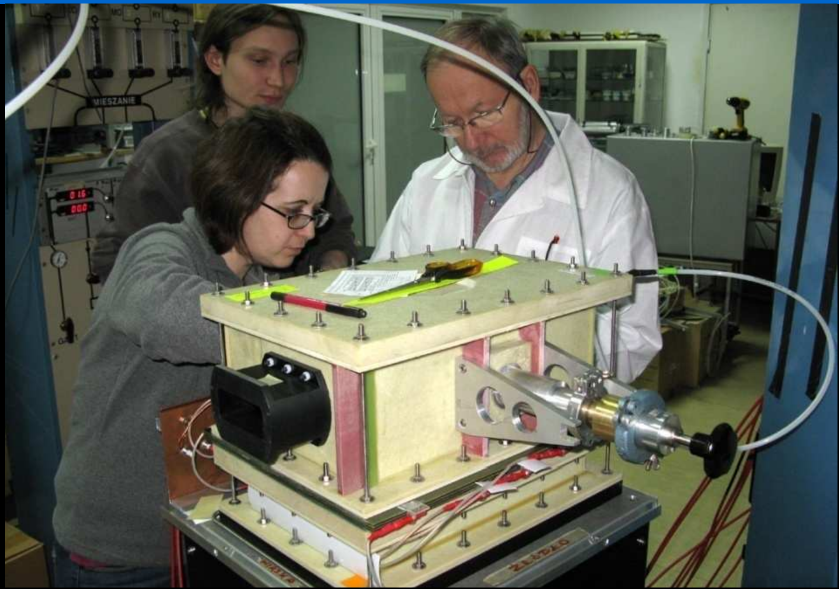
New idea – TPC with optical readout

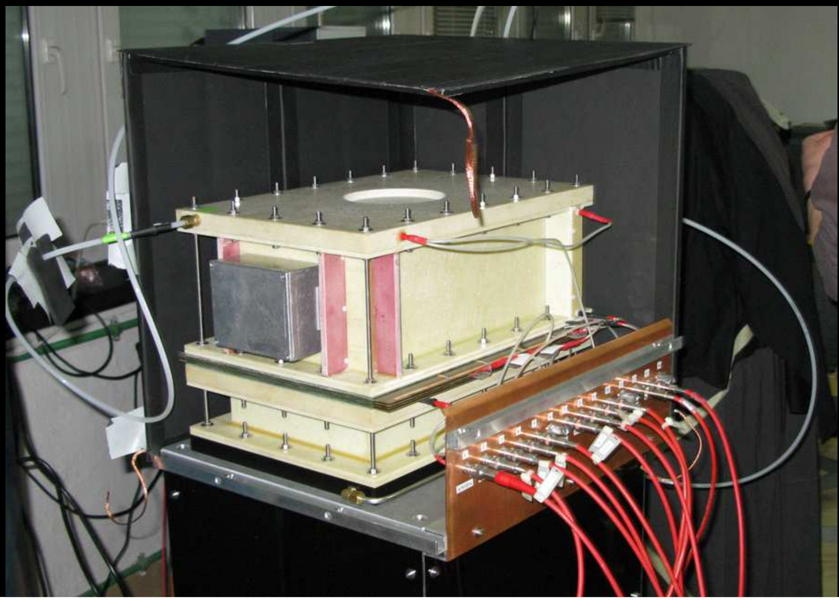
OTPC – Optical Time Projection Chamber

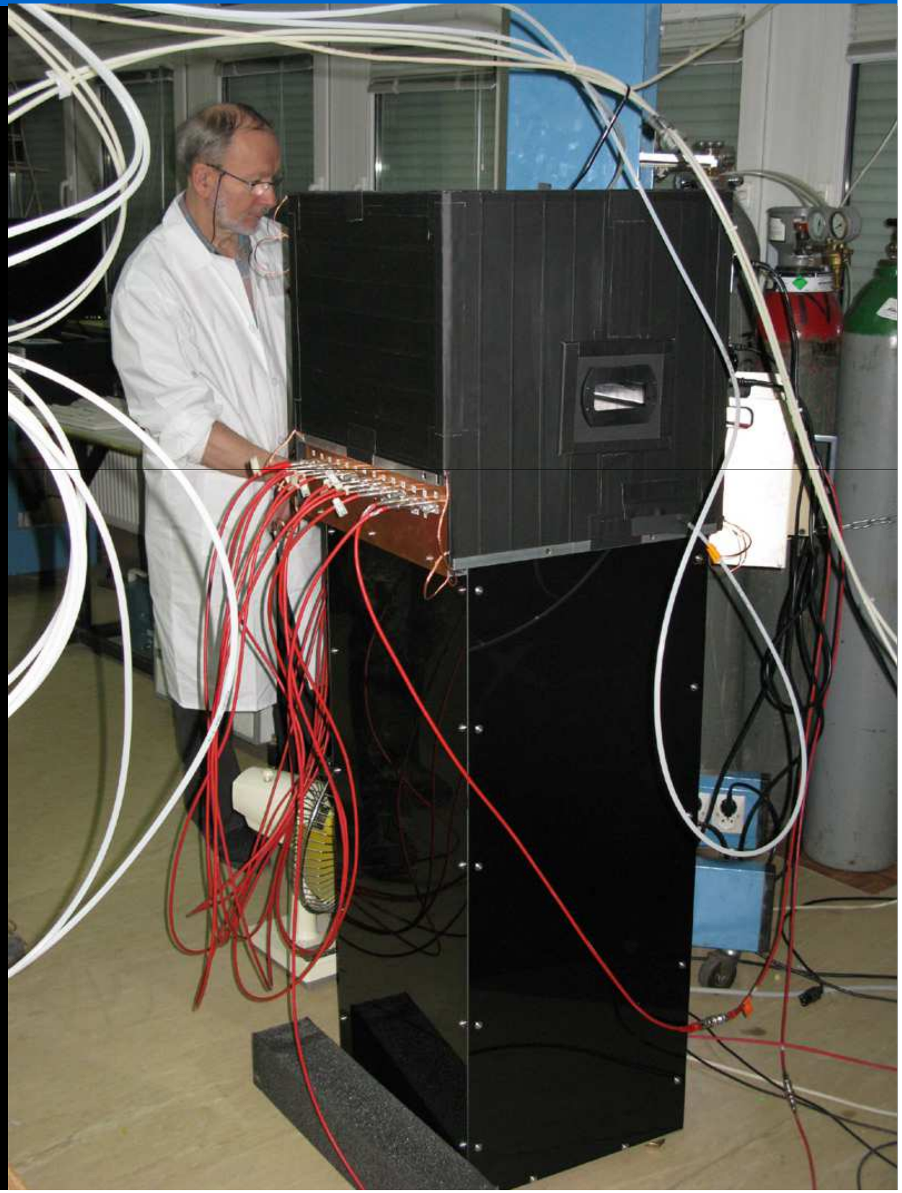


K. Miernik et al., NIM A581 (07) 194

OTPC



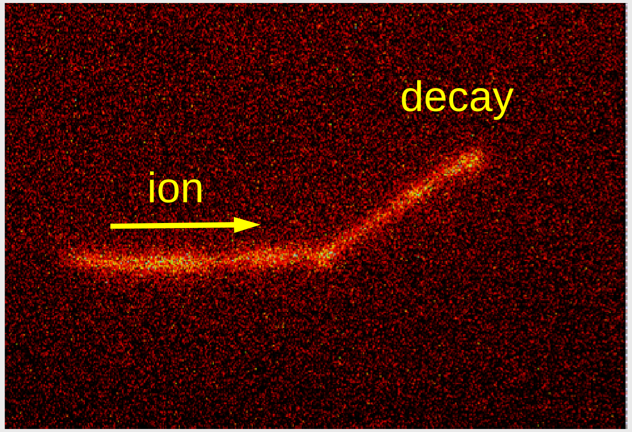




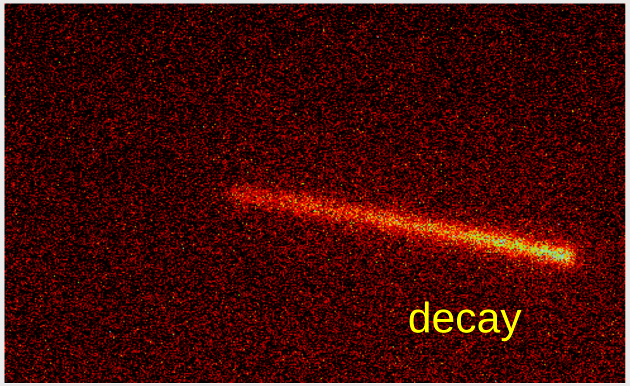
Principle of operation

CCD image

tracks of the ion and emitted particle(s)

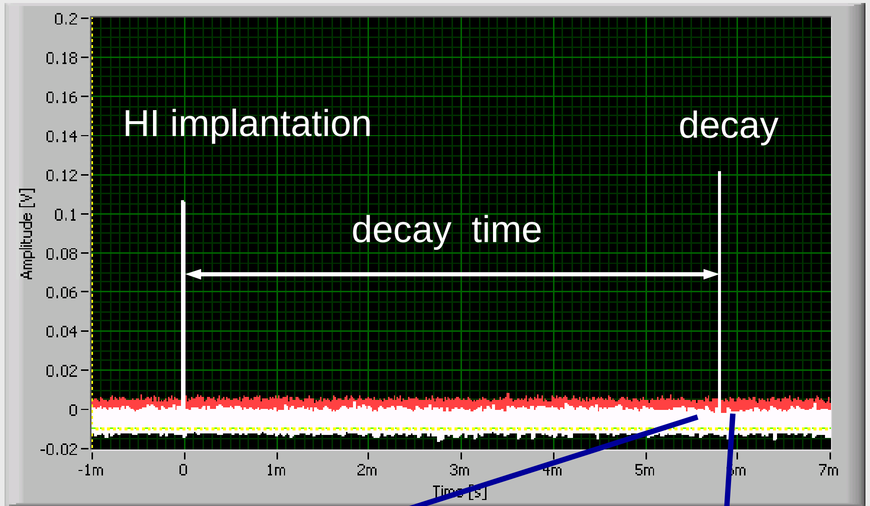


or only emitted particle(s)

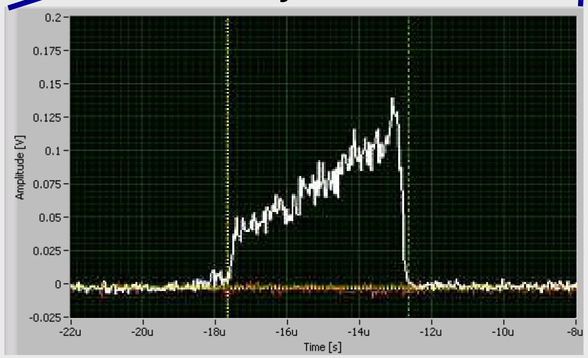


PMT signal sampled

time sequence of events

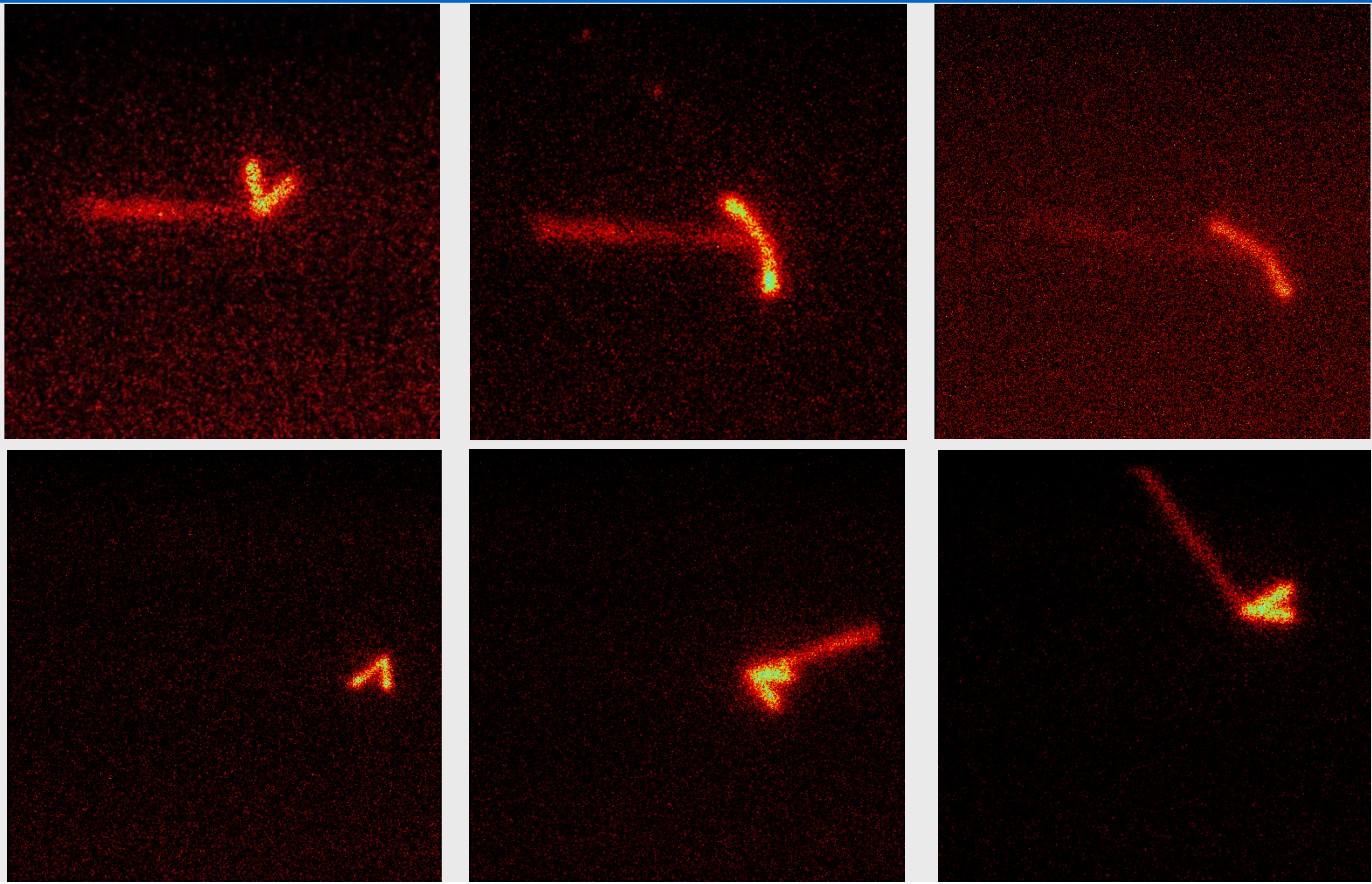


decay details

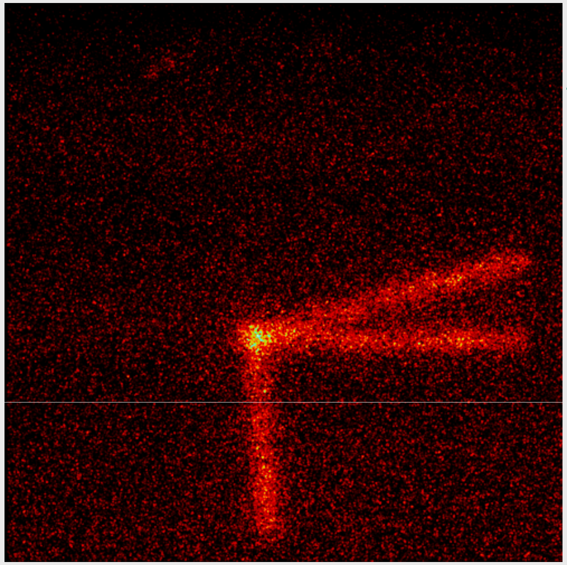


Images of *2p* from ^{45}Fe

NSCL/MSU, February 2007



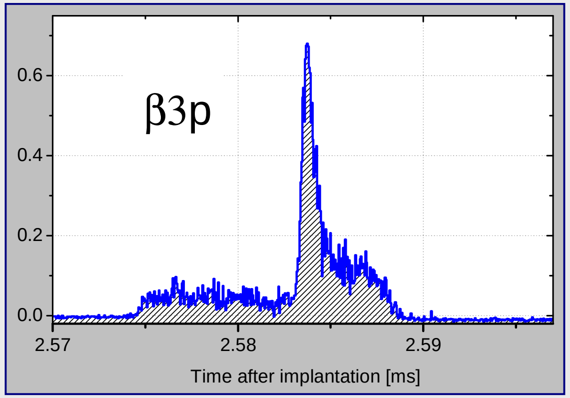
Discovery of β-delayed *3p*



$$^{45}_{26}\mathrm{Fe}_{19} \rightarrow {}^{45}_{25}\mathrm{Mn}^{*}_{20} + e^{+} + \nu_e$$

11% ↳ $^{42}_{22}\mathrm{Ti}_{20} + 3p$

125 ^{45}Fe events
38 β decays
4 β3p

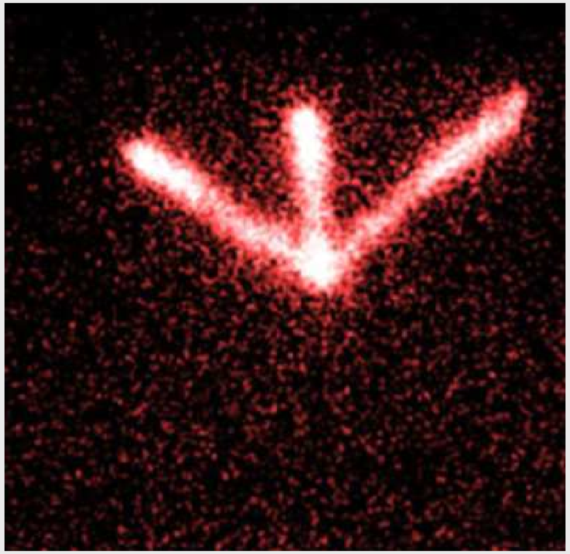


K. Miernik et al., PRC 76 (07) 041304(R)

$$^{43}_{24}\mathrm{Cr}_{19} \rightarrow {}^{43}_{23}\mathrm{V}^{*}_{20} + e^{+} + \nu_e$$

0.08% ↳ $^{40}_{20}\mathrm{Ca}_{20} + 3p$

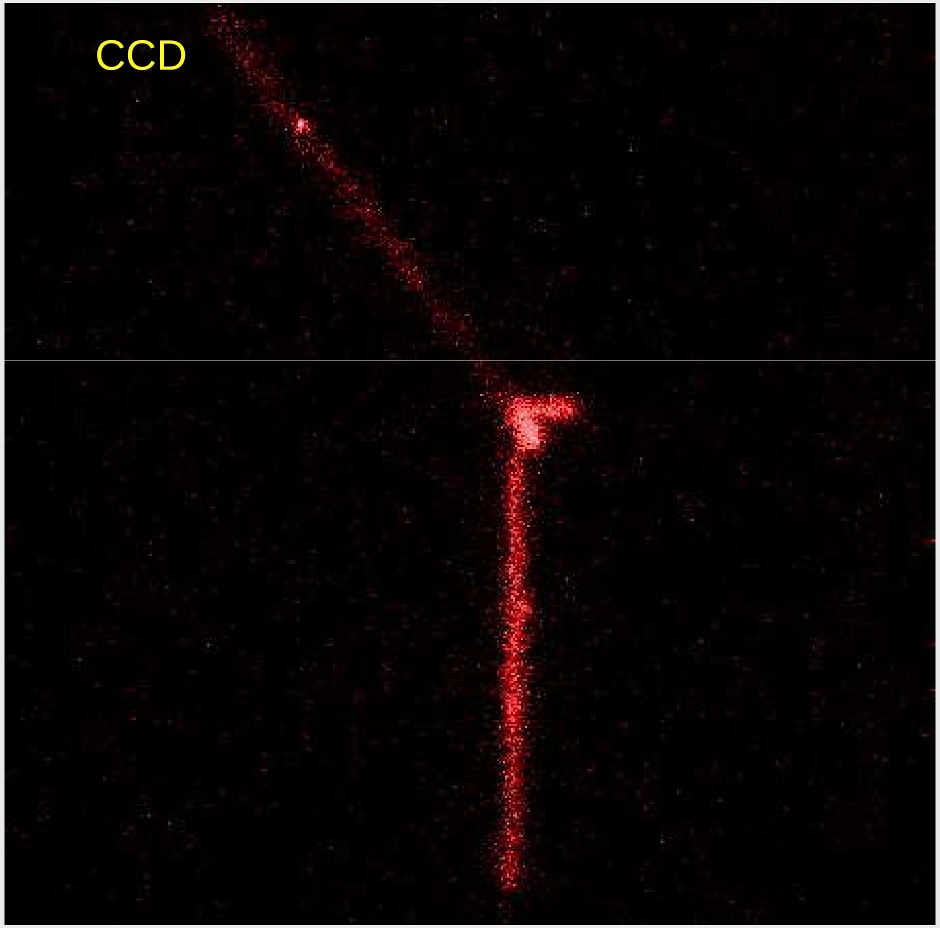
≈40 000 ^{43}Cr events
12 β3p



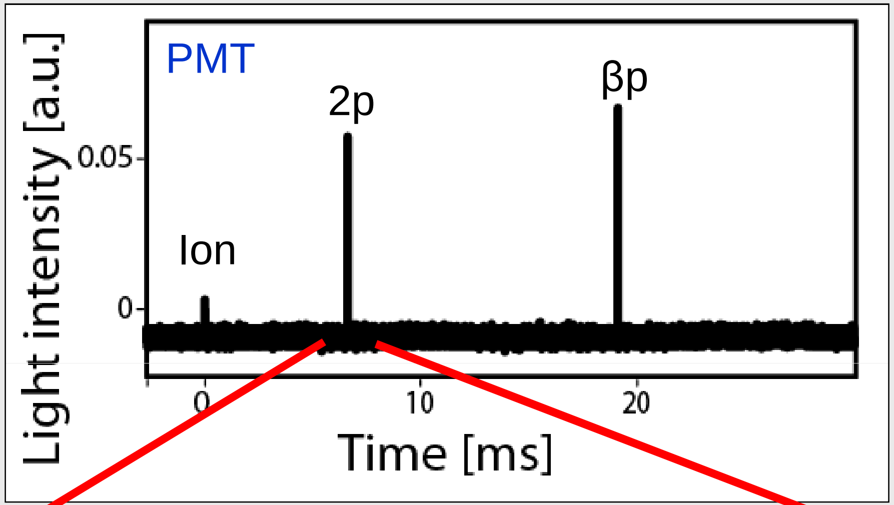
M. Pomorski et al., PRC 83 (11) 014306(R)

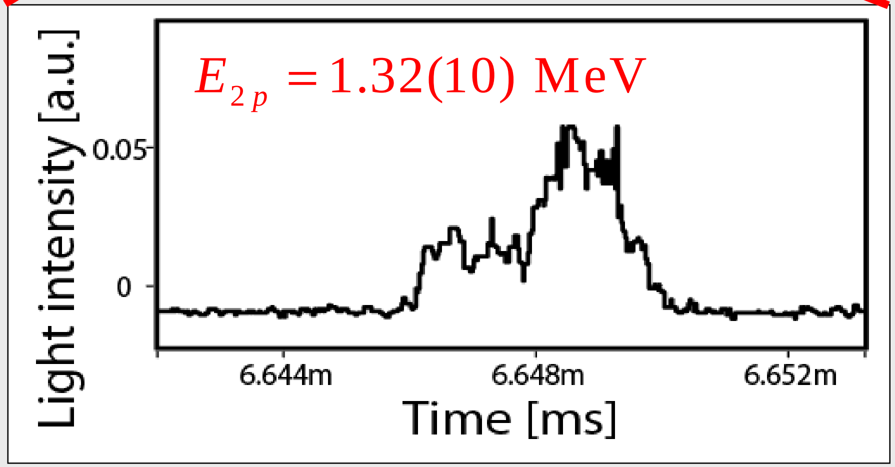
2p radioactivity of ^{48}Ni

NSCL/MSU, March 2011

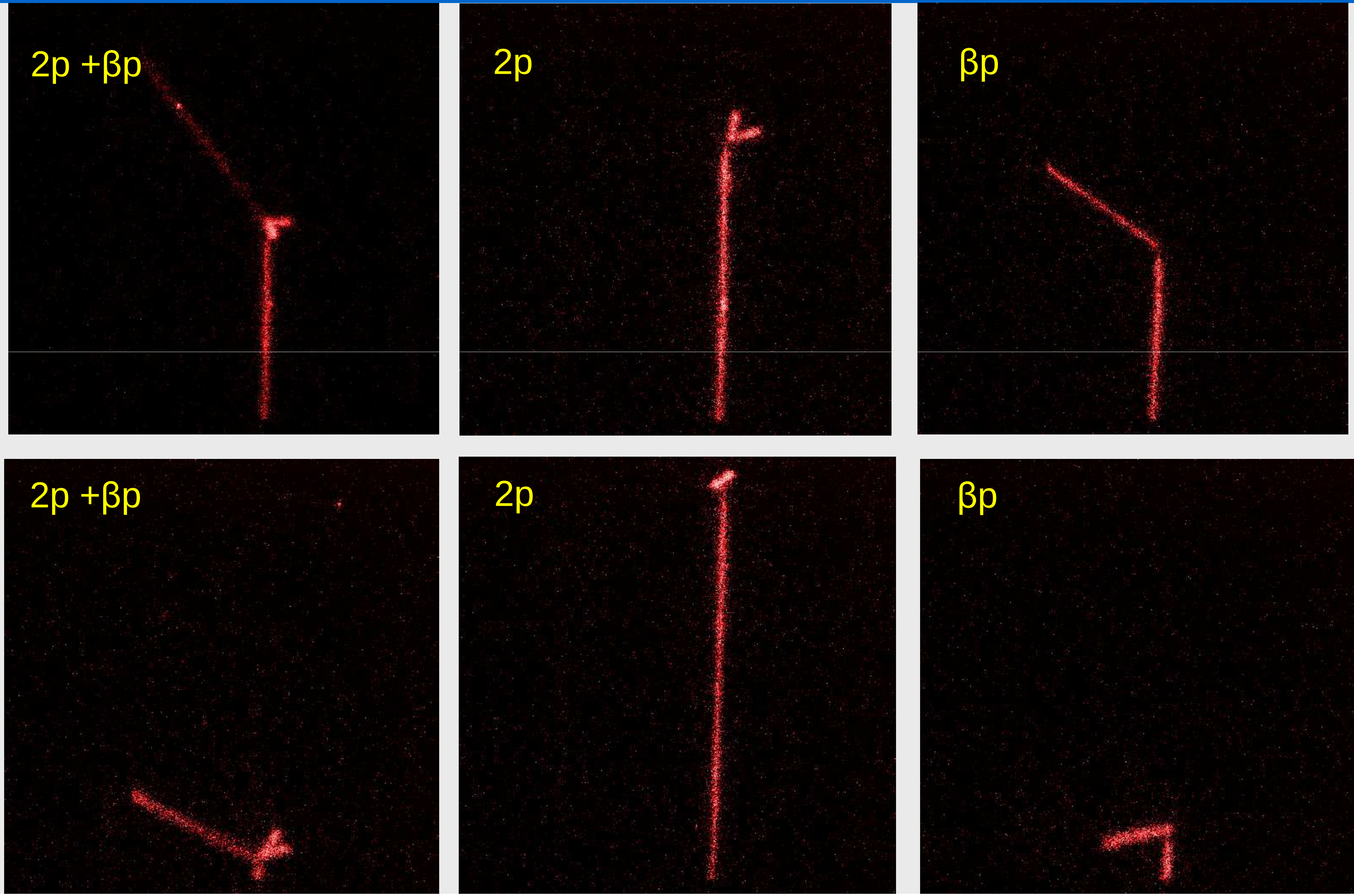


M. Pomorski et al., PRC 83 (11) 061303(R)

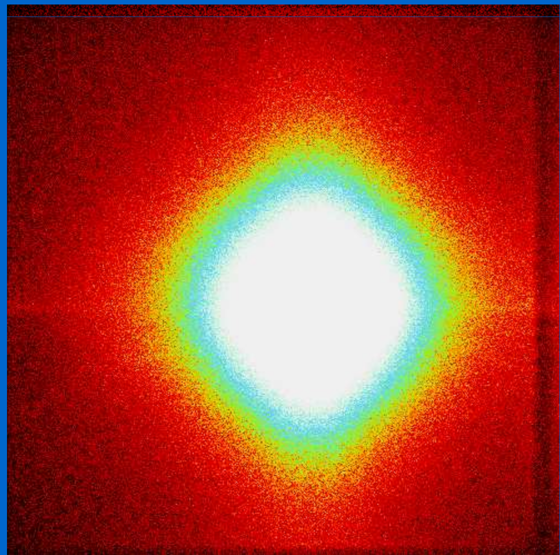




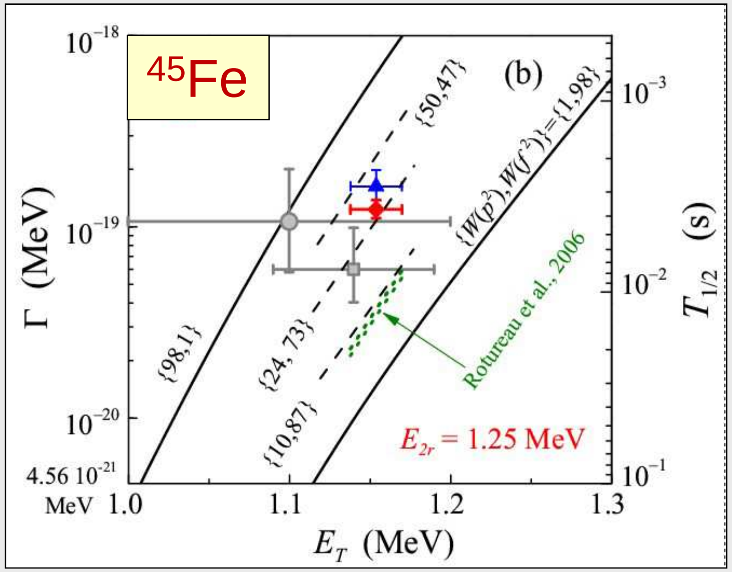
Other decays of ^{48}Ni

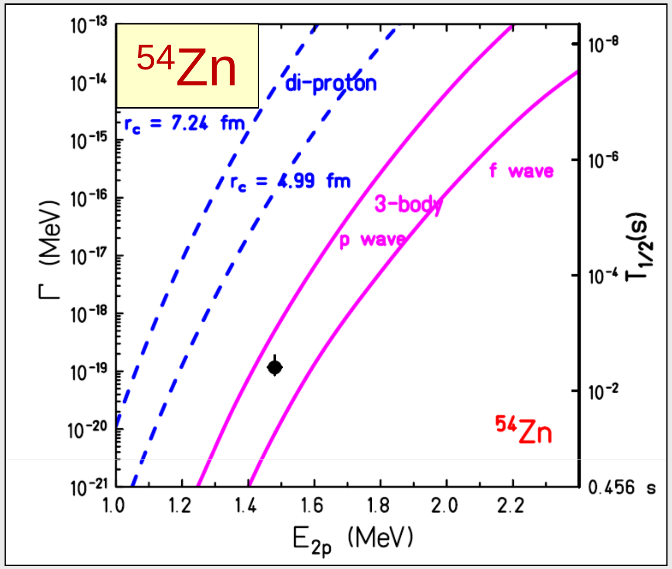


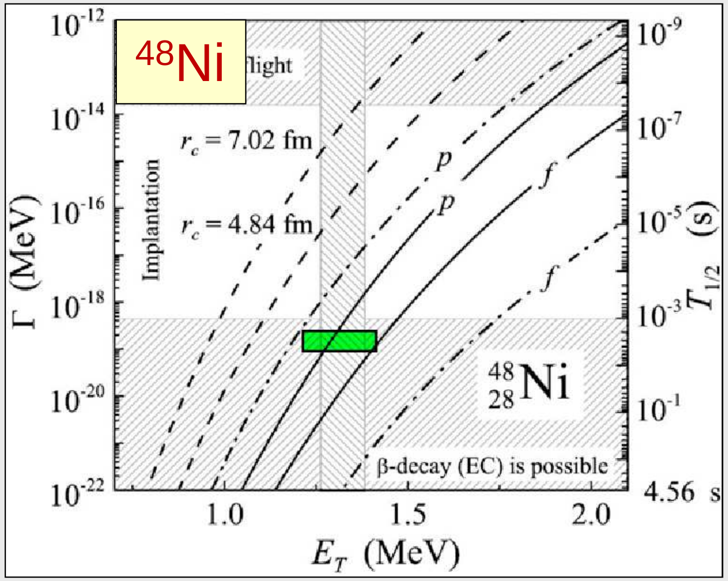
Confrontation with models

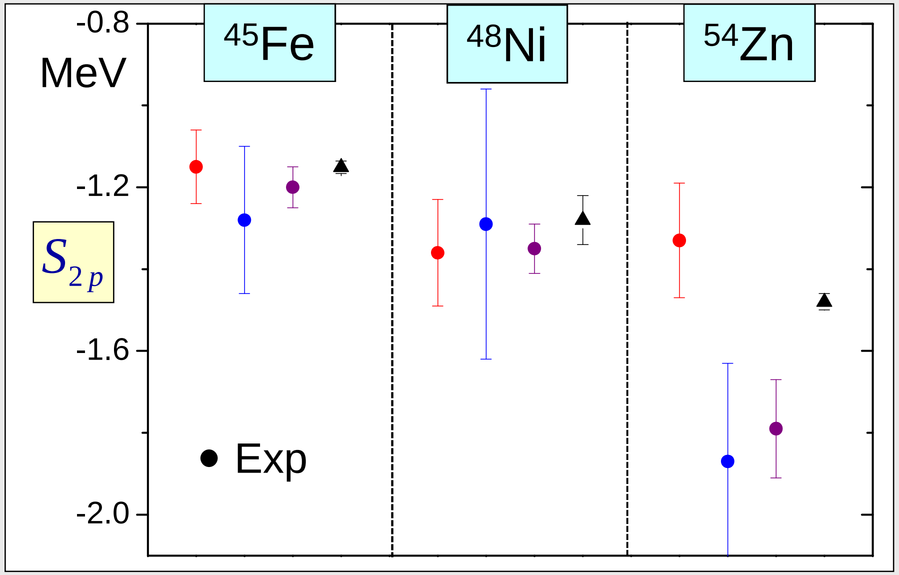


2p decay: energy vs. time

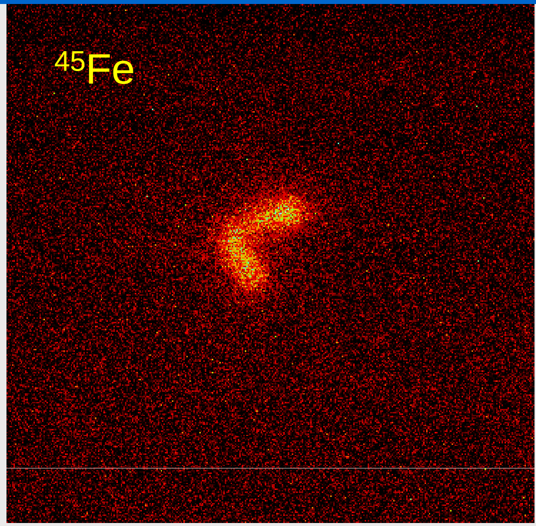


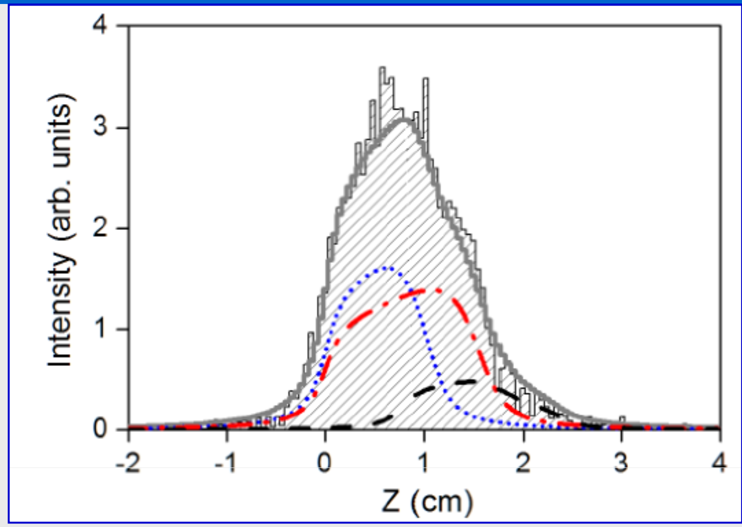


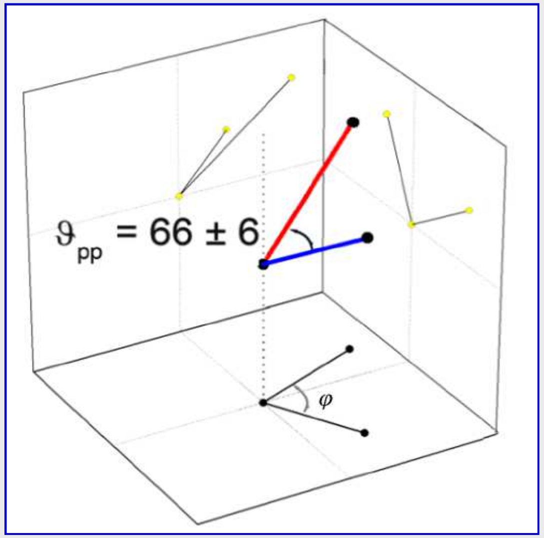


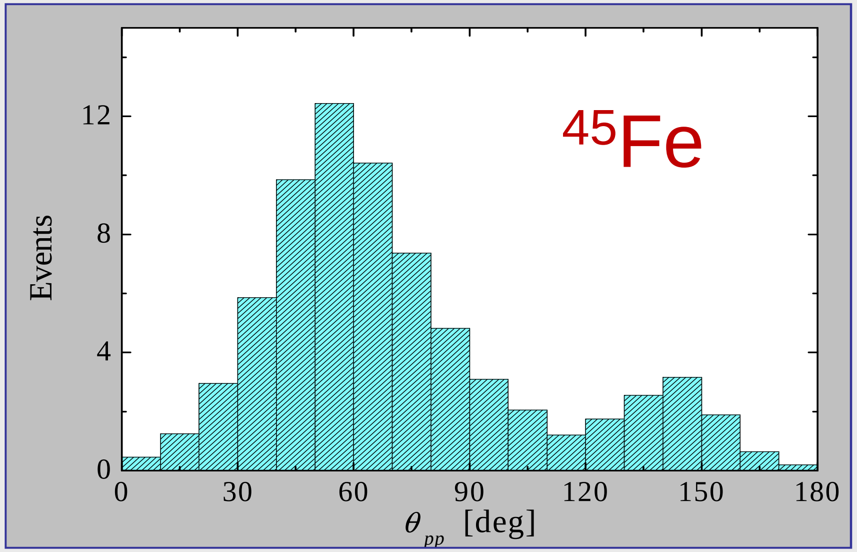


p-p angular correlation



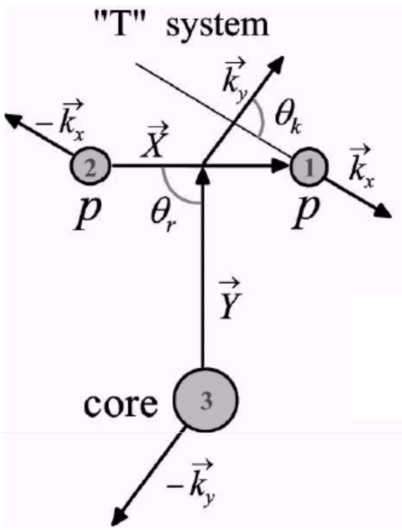


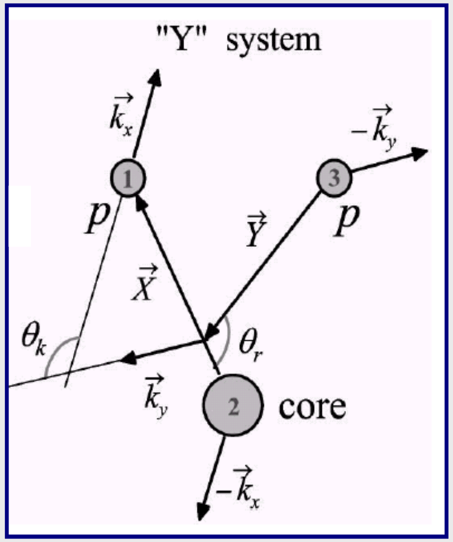




K. Miernik et al., PRL 99 (07) 192501

3-body model in Jacobi coordinates





Transition from CM to Jacobi „T" system is easy

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

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

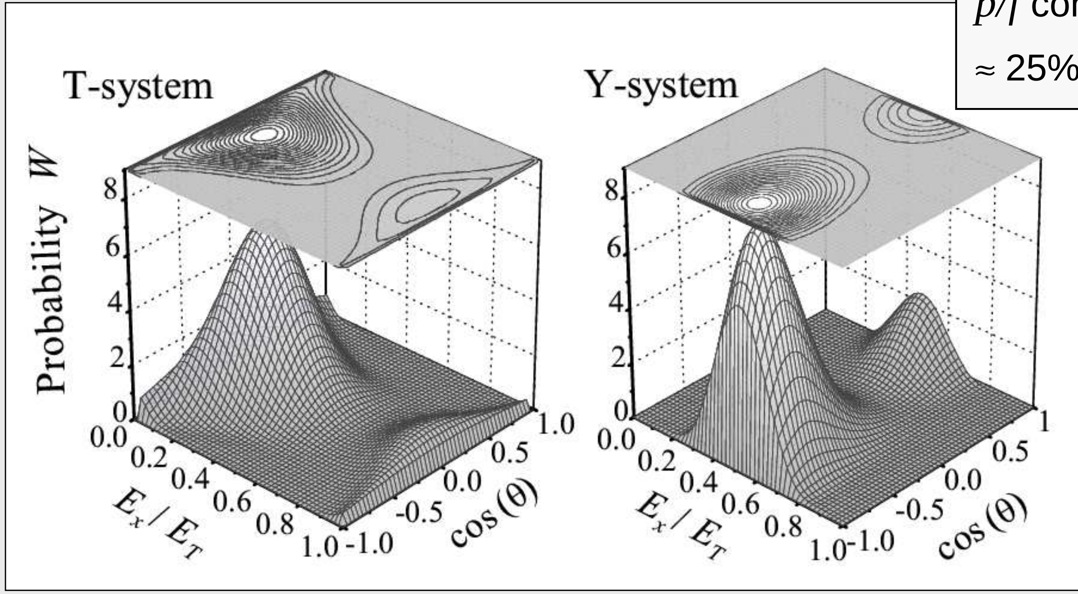
θ_k is the angle between vectors:

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

^{45}Fe

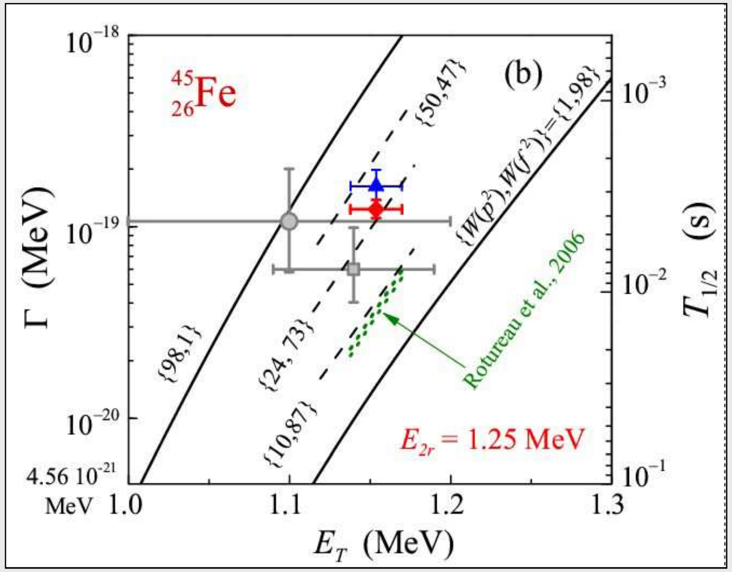
p/f configurations

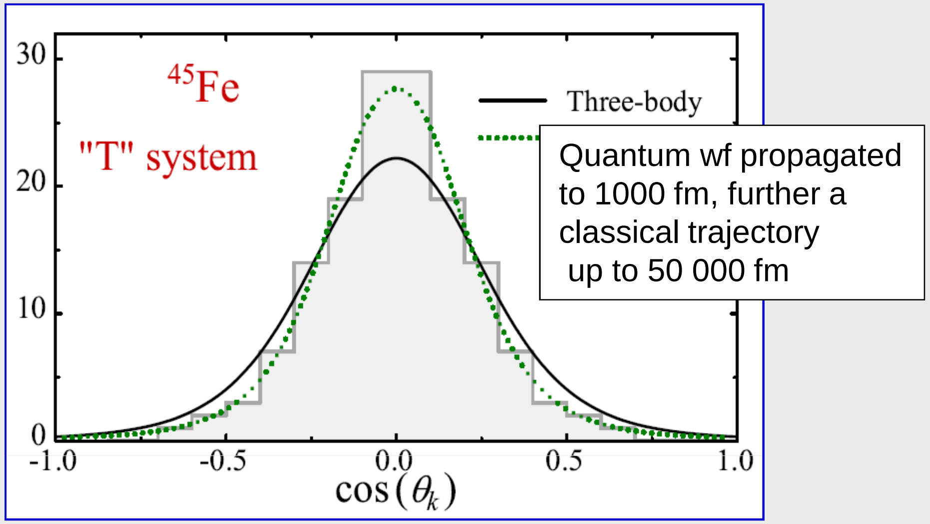
$\approx 25\%\ p^2 + 75\%\ f^2$



L.V. Grigorenko and M.V. Zhukov, PRC 68 (03) 054005

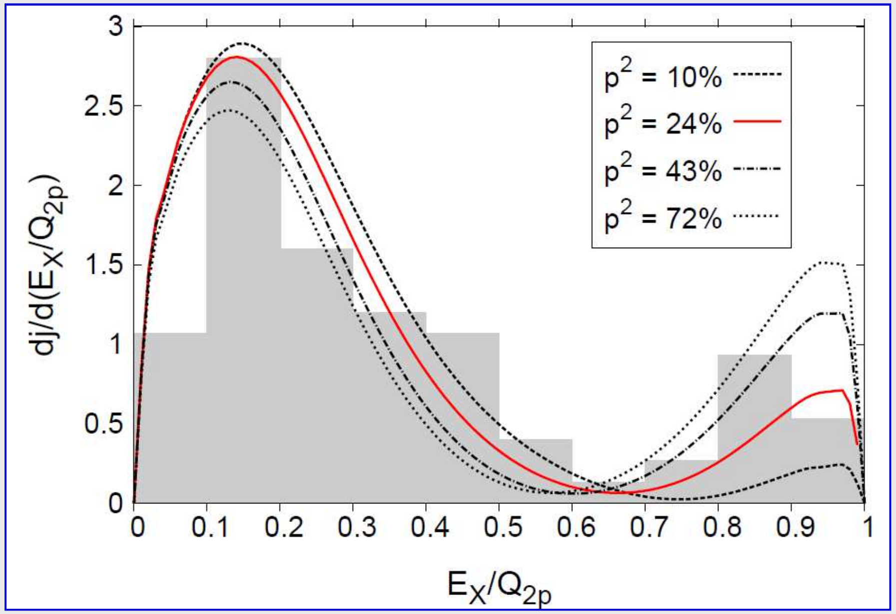
p-p correlations in ^{45}Fe





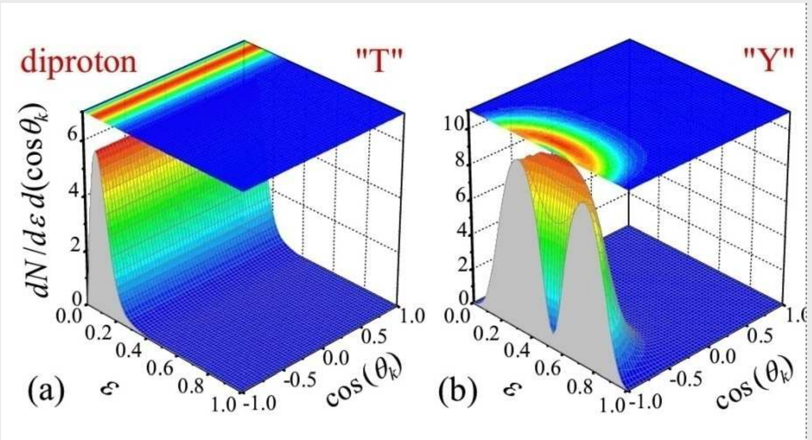
- ➤ *2p* radioactivity offers more observables than *1p* emission (correlations!)
  - → Better test of nuclear models

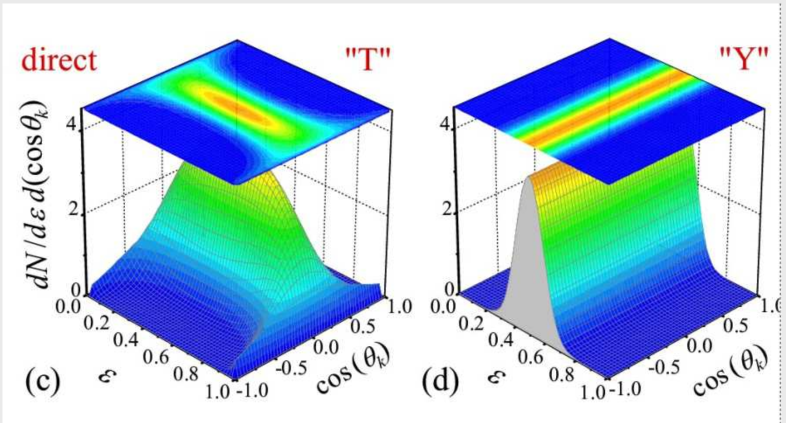
- ➤ 3-body model consistently reproduces all observables for certain composition of an initial wave function

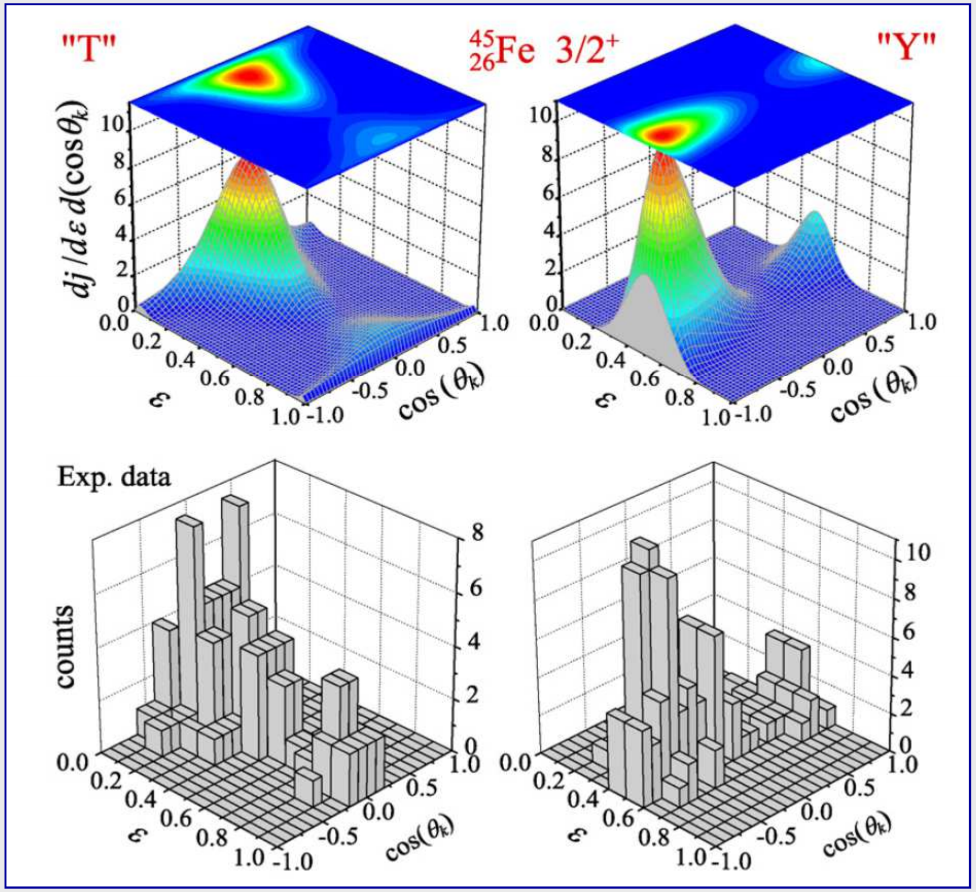


K. Miernik *et al*., EPJA 42 (09) 431

Full picture for ^{45}Fe

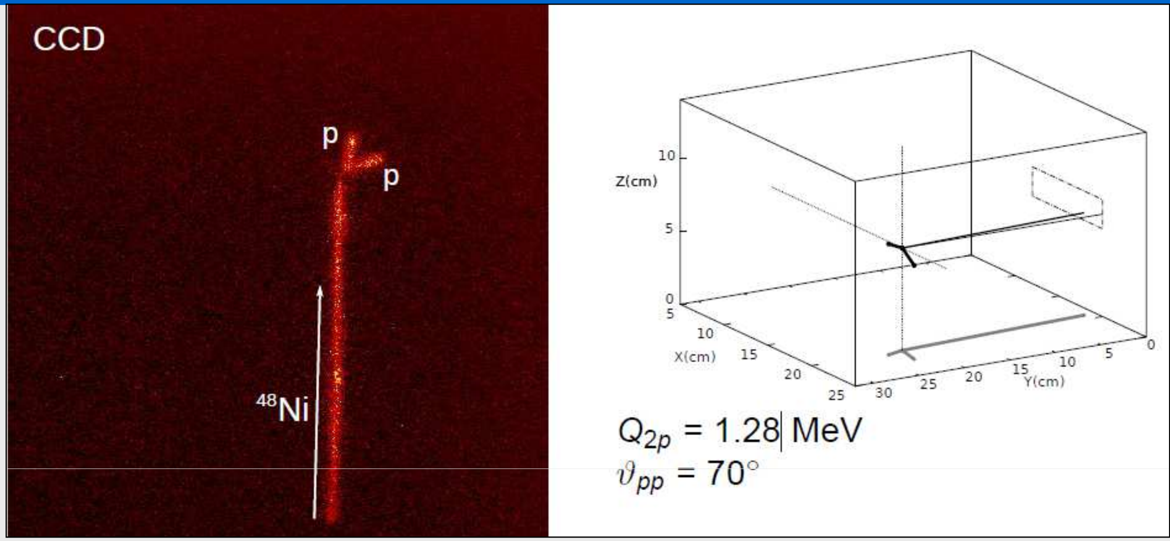


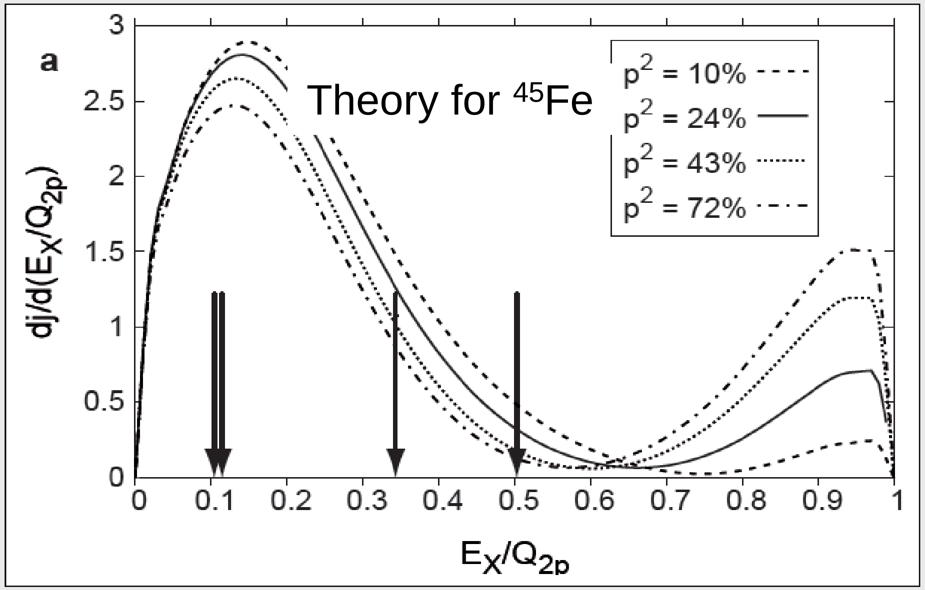




L.V. Grigorenko *et al*., PLB 677 (09) 30

p-p correlations in ^{48}Ni



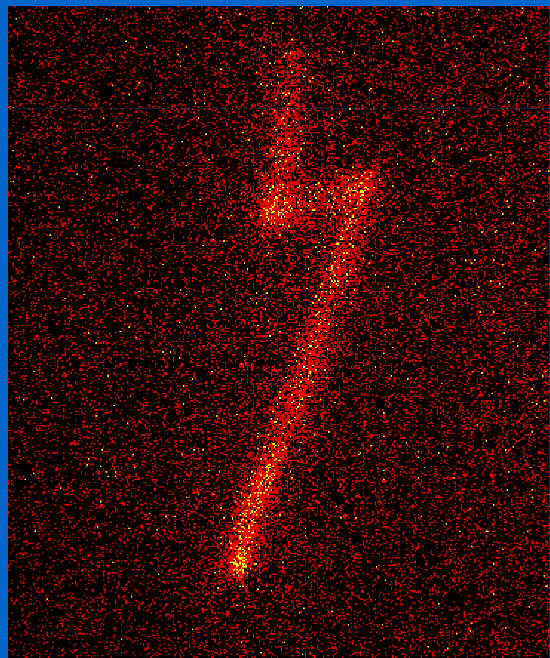


- 3-body prediction for ^{48}Ni still missing ☹

Anyway, more statistics is needed for meaningful comparison ☺

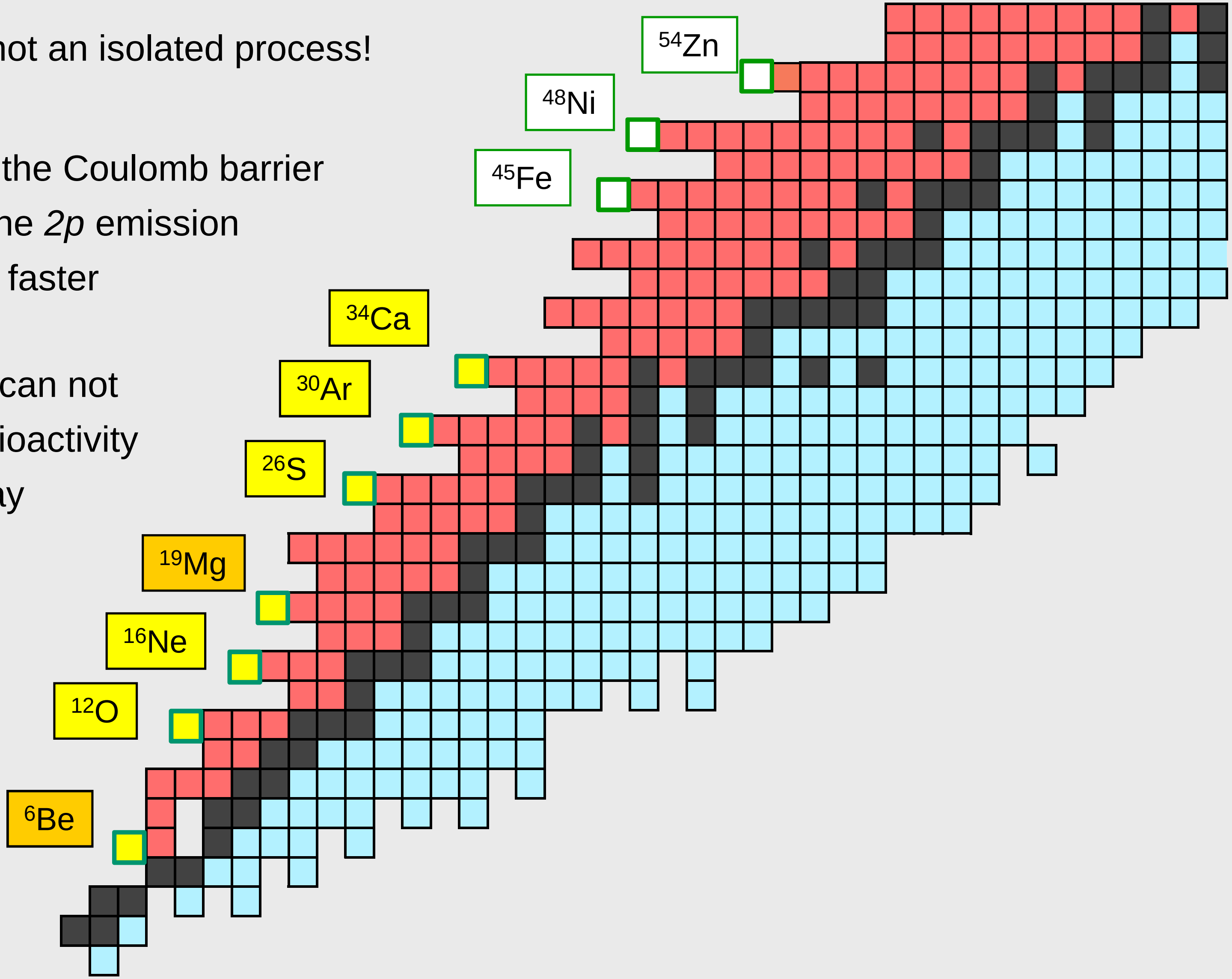
M. Pomorski et al., to be published in Acta Phys. Pol. B (2012)

Very fast decays



Light *2p* emitters

- *2p* emission is not an isolated process!
- In lighter nuclei the Coulomb barrier is smaller and the *2p* emission proceeds much faster
- Below ^{19}Mg we can not speak of *2p* radioactivity there is *2p* decay of resonances



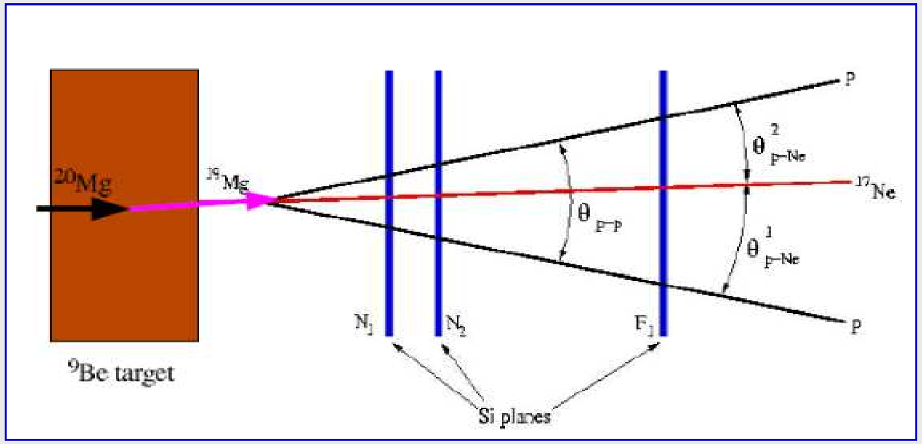
A short-lived case of ^{19}Mg

- The tracking technique for very short-lived *2p* decays was pioneered at GSI

Production with a radioactive beam

^{24}Mg @ 600 MeV/u + Be → ^{20}Mg

^{20}Mg + Be → ^{19}Mg

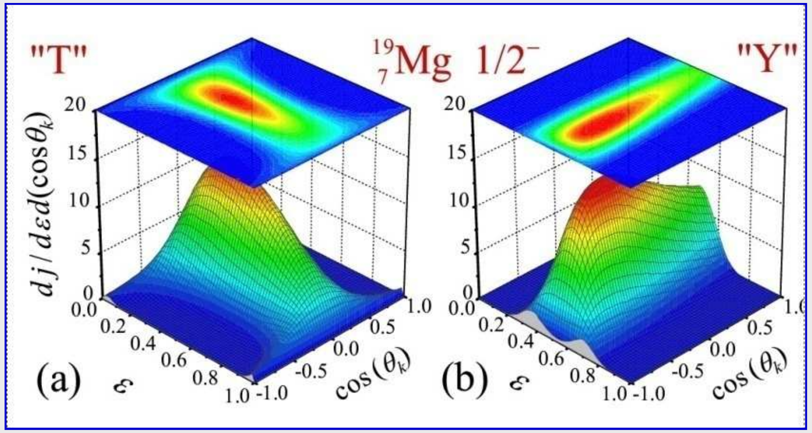


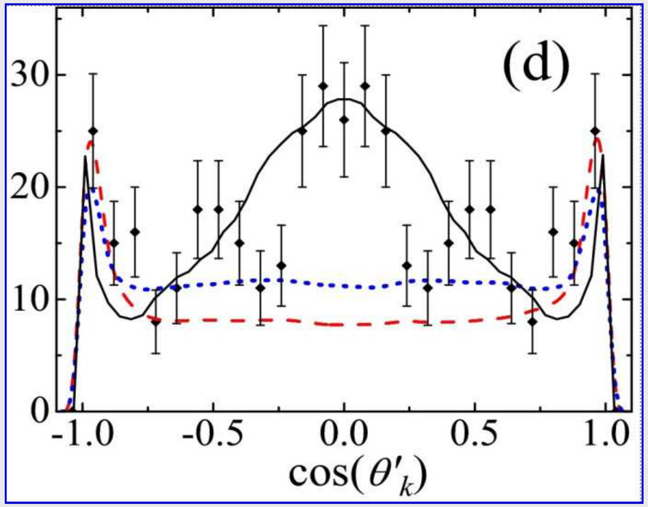
I. Mukha et al., PRL. 99 (2007) 182501

I. Mukha et al., PR C 77 (2008) 061303(R)

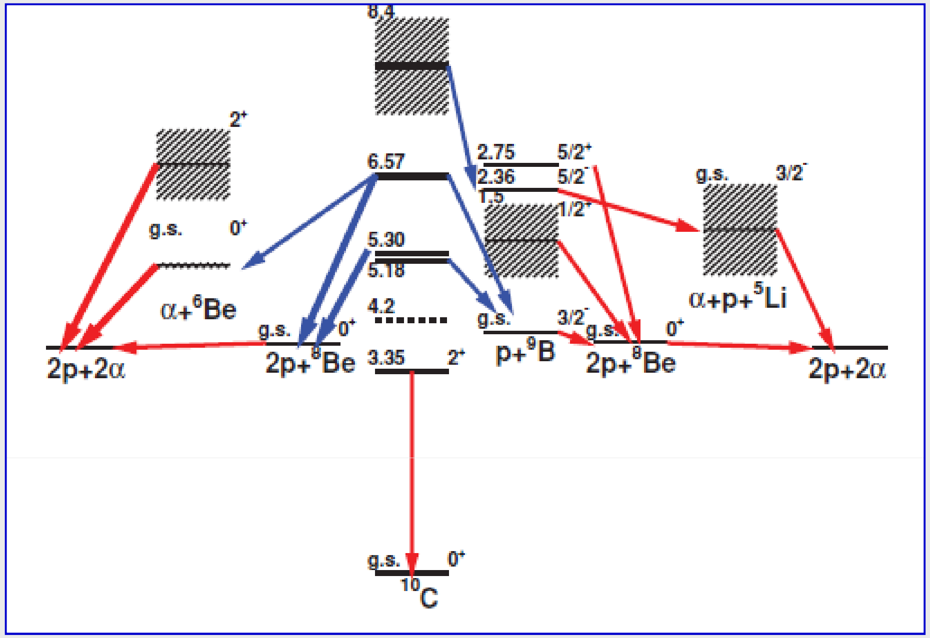
I. Mukha et al., EPJA 42 (2009) 421

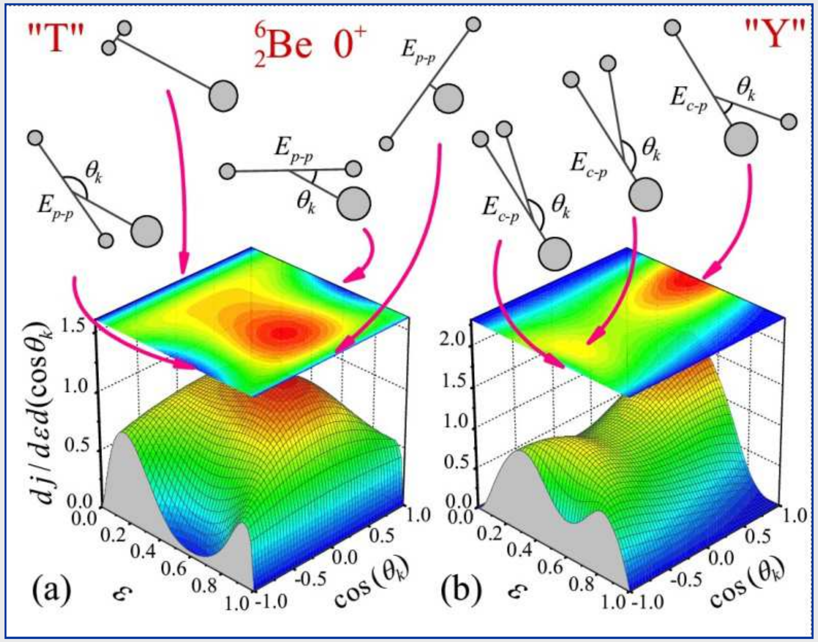
$T_{1/2}$ = 4.0(15) ps





Decay of ^{6}Be resonance

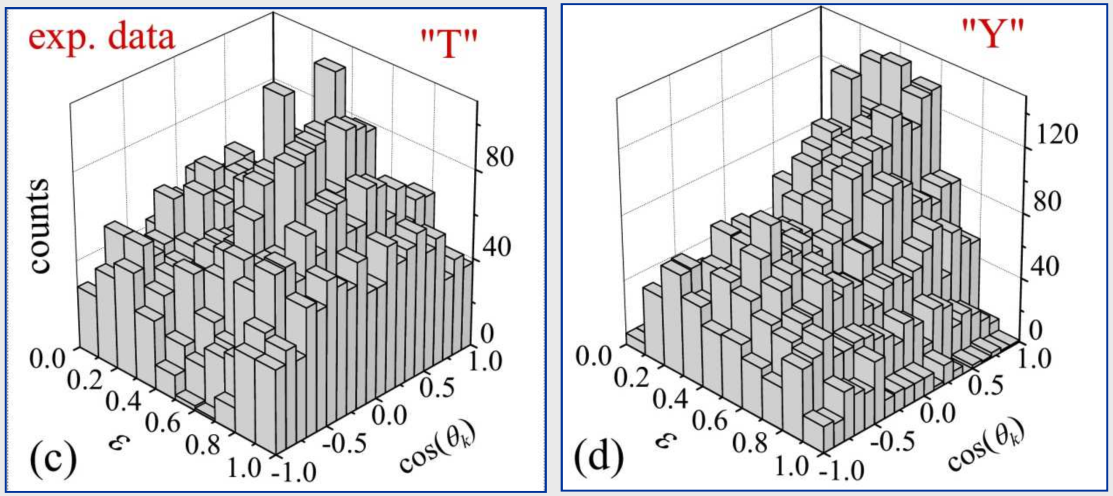




^{10}C inelastic scattering at
Texas A&M University

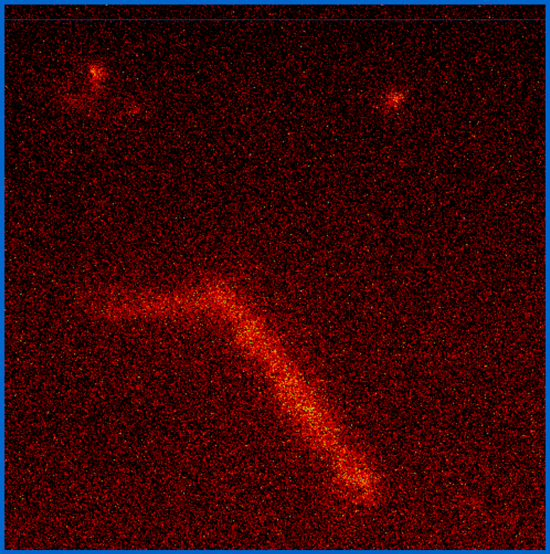
❶ p (^{10}B, ^{10}C) n @15 MeV/u

❷ 11 MeV/u ^{10}C + C/Be → ^{10}C*



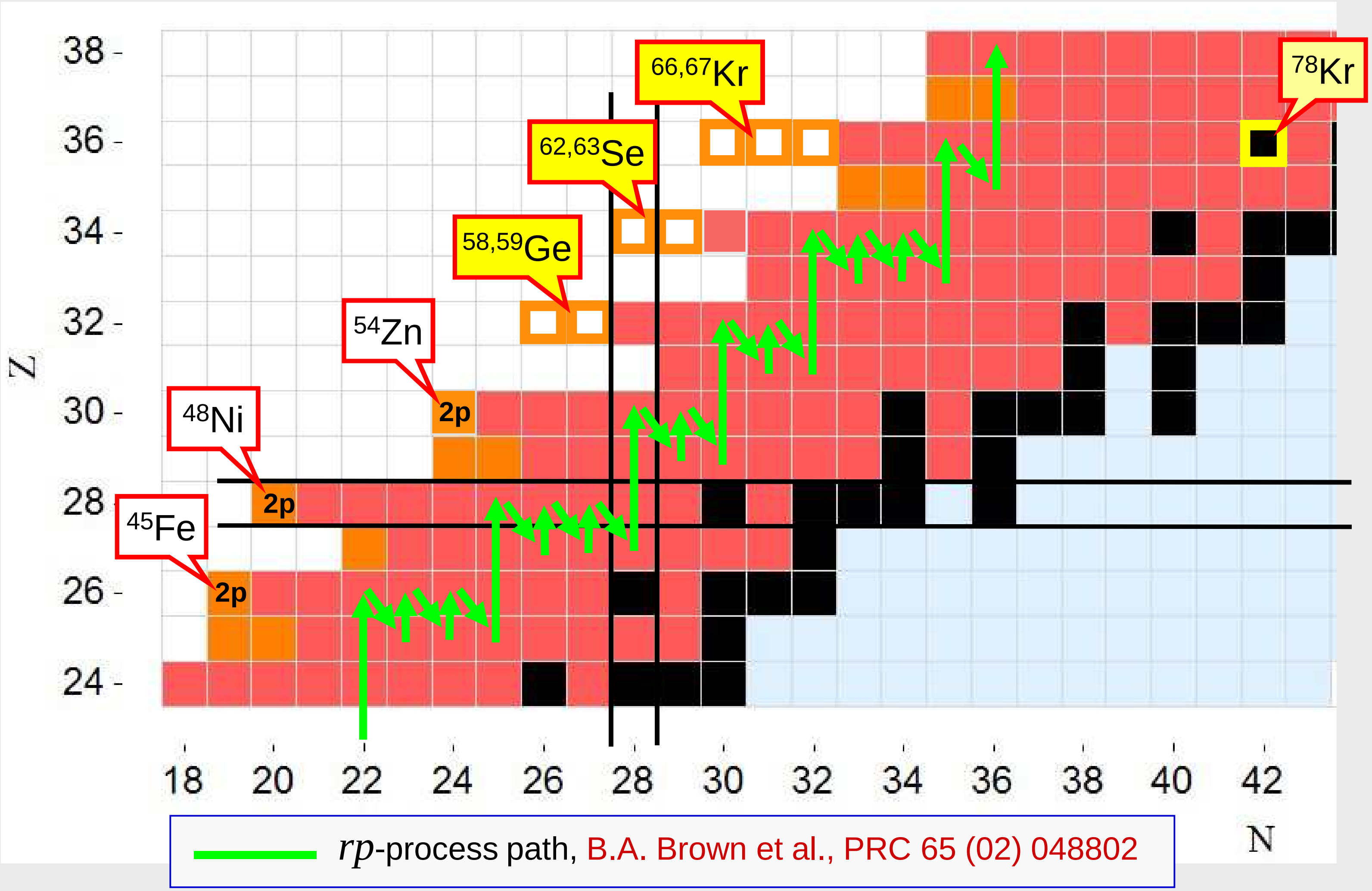
K. Mercurio et al., PRC 78 (08) 031602(R)
L. Grigorenko et al., PLB 677 (2009) 30

Outlook



Heavier 2p emitters

- Search for ^{59}Ge planned in RIKEN and NSCL

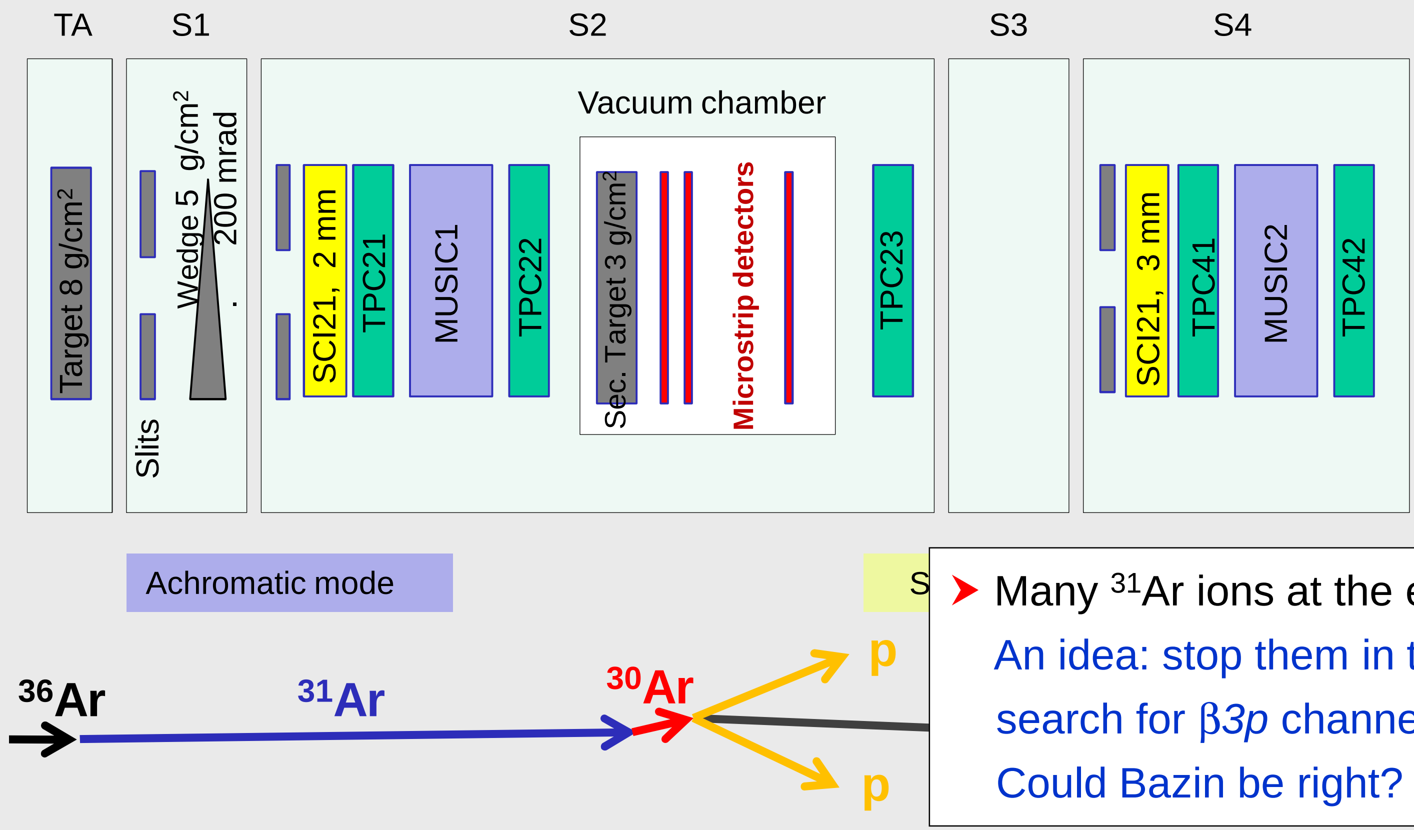


Search for ^{30}Ar

GSI/FRS Experimental Proposal S388

"Search for two-proton decay of ^{30}Ar in flight by the tracking technique"

By I. Mukha



- Many ^{31}Ar ions at the end of FRS

  An idea: stop them in the OTPC

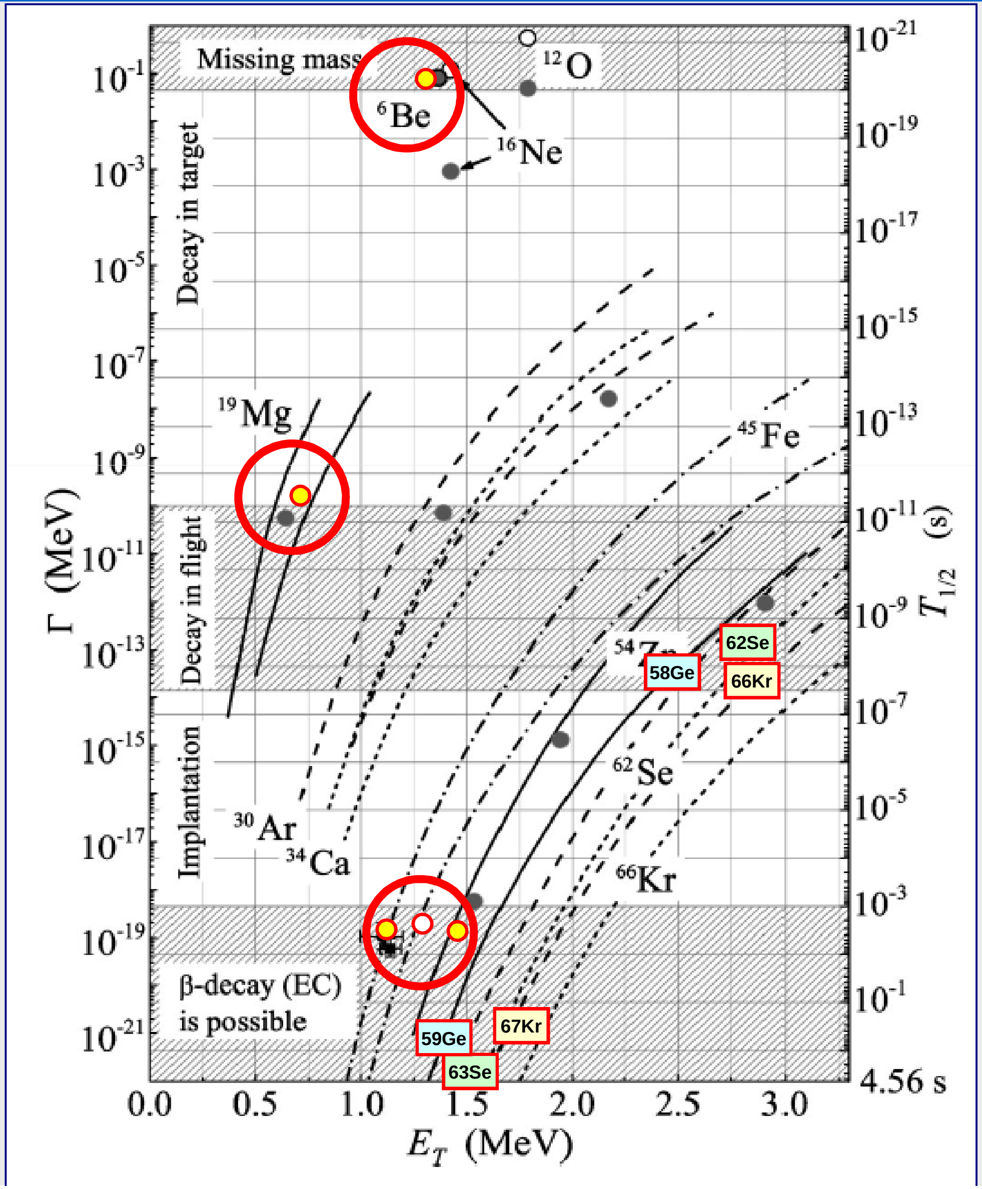
  search for $\beta 3p$ channel of ^{31}Ar

  Could Bazin be right?

Three lifetime regimes

- 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

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



Summary

- The idea of optical recording of charged particles' tracks proved to be very successful.

- This idea implemented in the OTPC brought new results
  - *p-p* correlations in the decay of ^{45}Fe
  - first observation of *β3p* emission in ^{45}Fe and ^{43}Cr
  - first observation of *2p* decay of ^{48}Ni

- The direct ground-state *2p* emission established for ^{6}Be, ^{16}Ne, ^{19}Mg, ^{45}Fe, ^{48}Ni, and ^{54}Zn

- The *p-p* correlations obtained for ^{6}Be, ^{19}Mg, ^{45}Fe are in good agreement with the 3-body model of Grigorenko and Zhukov

- The 3-body model is presently the only one predicting the correlations, however, it has to be refined to describe the initial state in a realistic way

- The field is progressing, search for other cases of *2p* emission continues…

Thank you for attention!