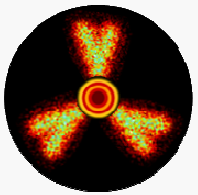
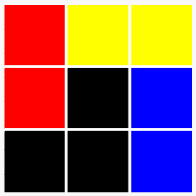
Particle emission at the proton drip-line

Marek Pfützner

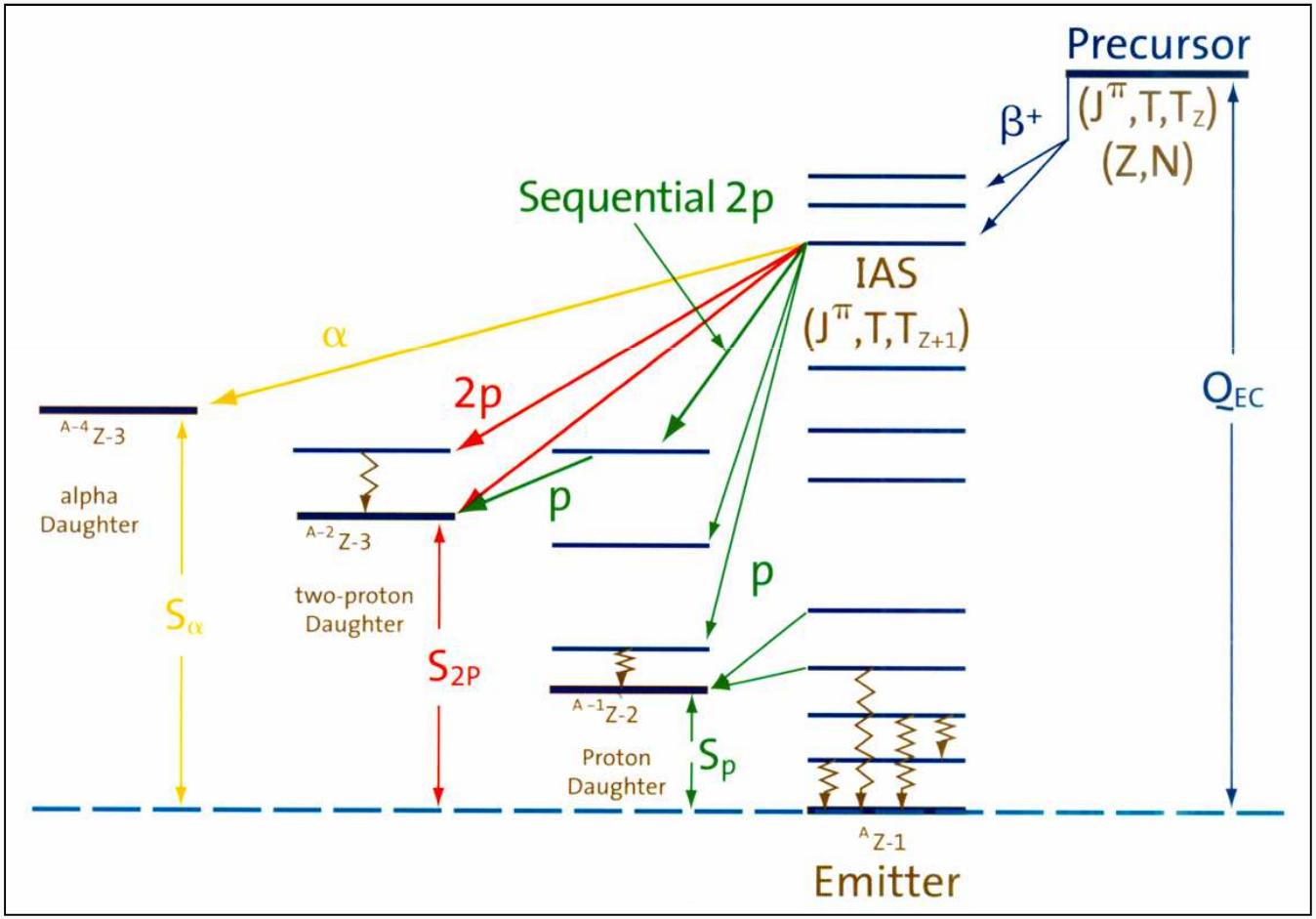




Nuclear Physics Division
University of Warsaw

β-delayed particle emission

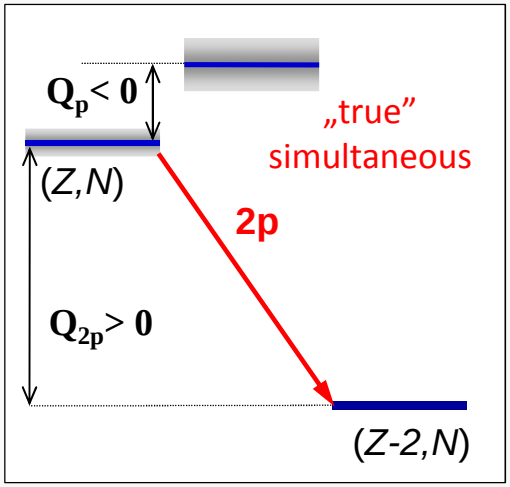
- When the β decay energy is large, many exotic channels are available

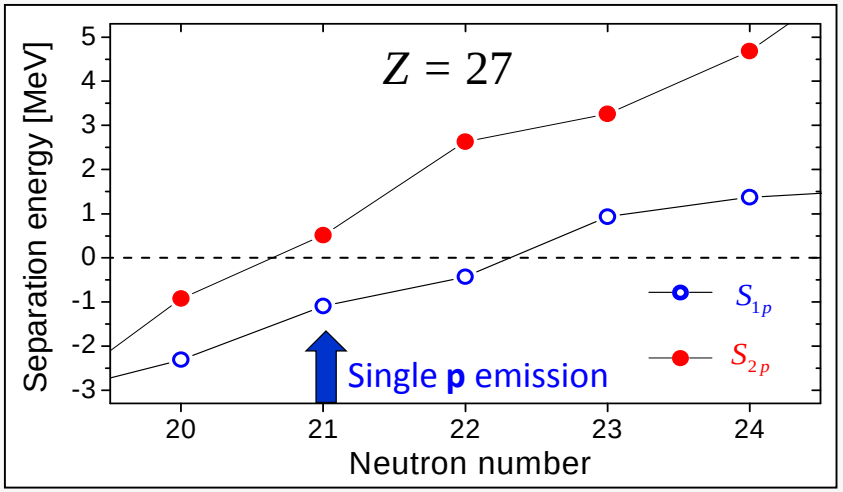


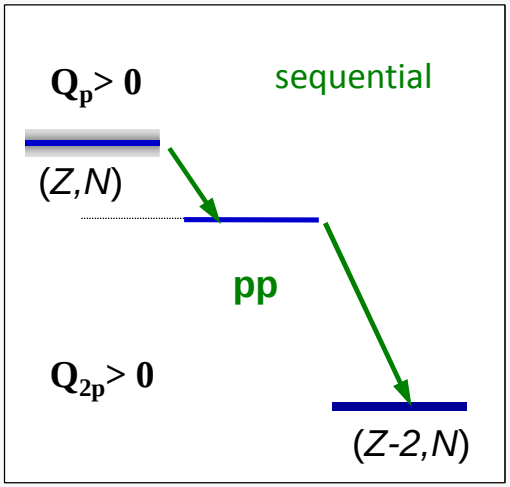
Blank and Borge, Progress in Part. Nucl. Phys. 60 (2008) 403

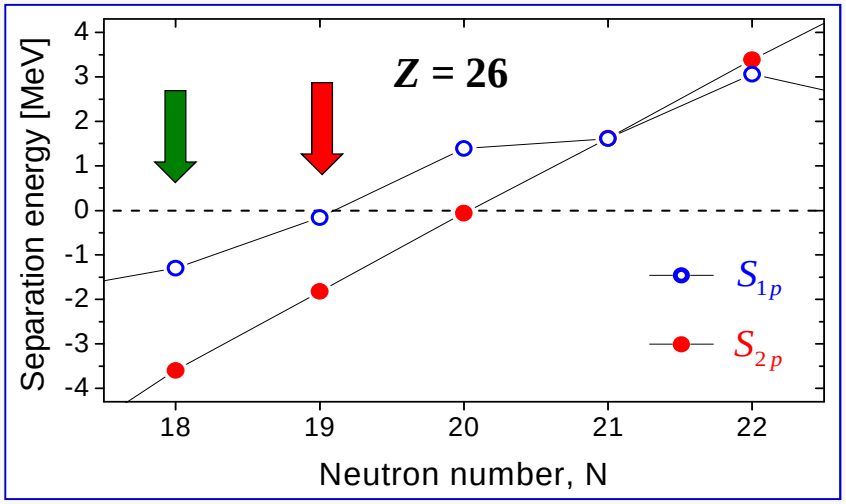
p drip-line is not a limit!

- The limit of „existence" beyond the proton drip-line is determined by emission of protons





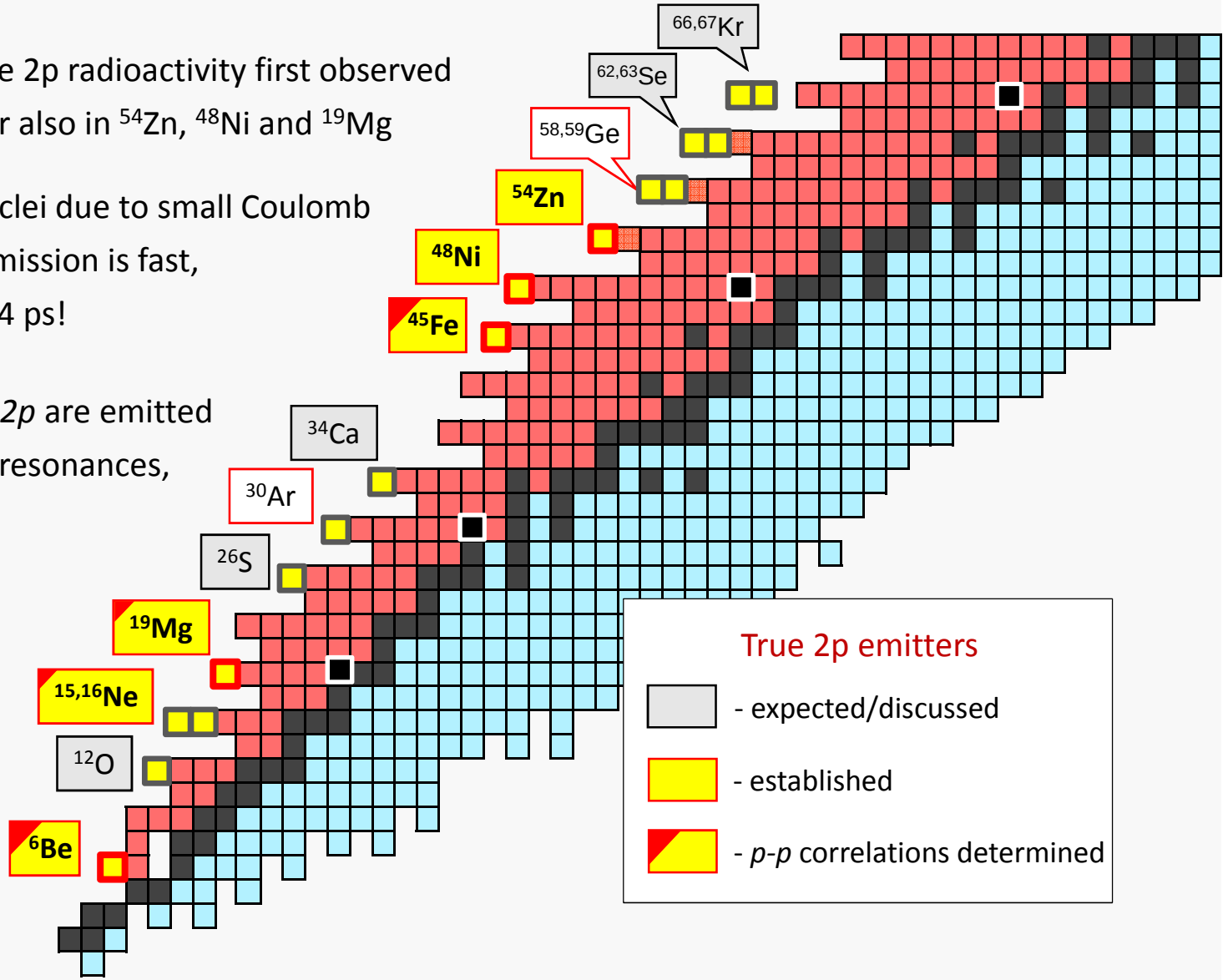




V.I. Goldanskii, Nucl. Phys. 19 (60) 482

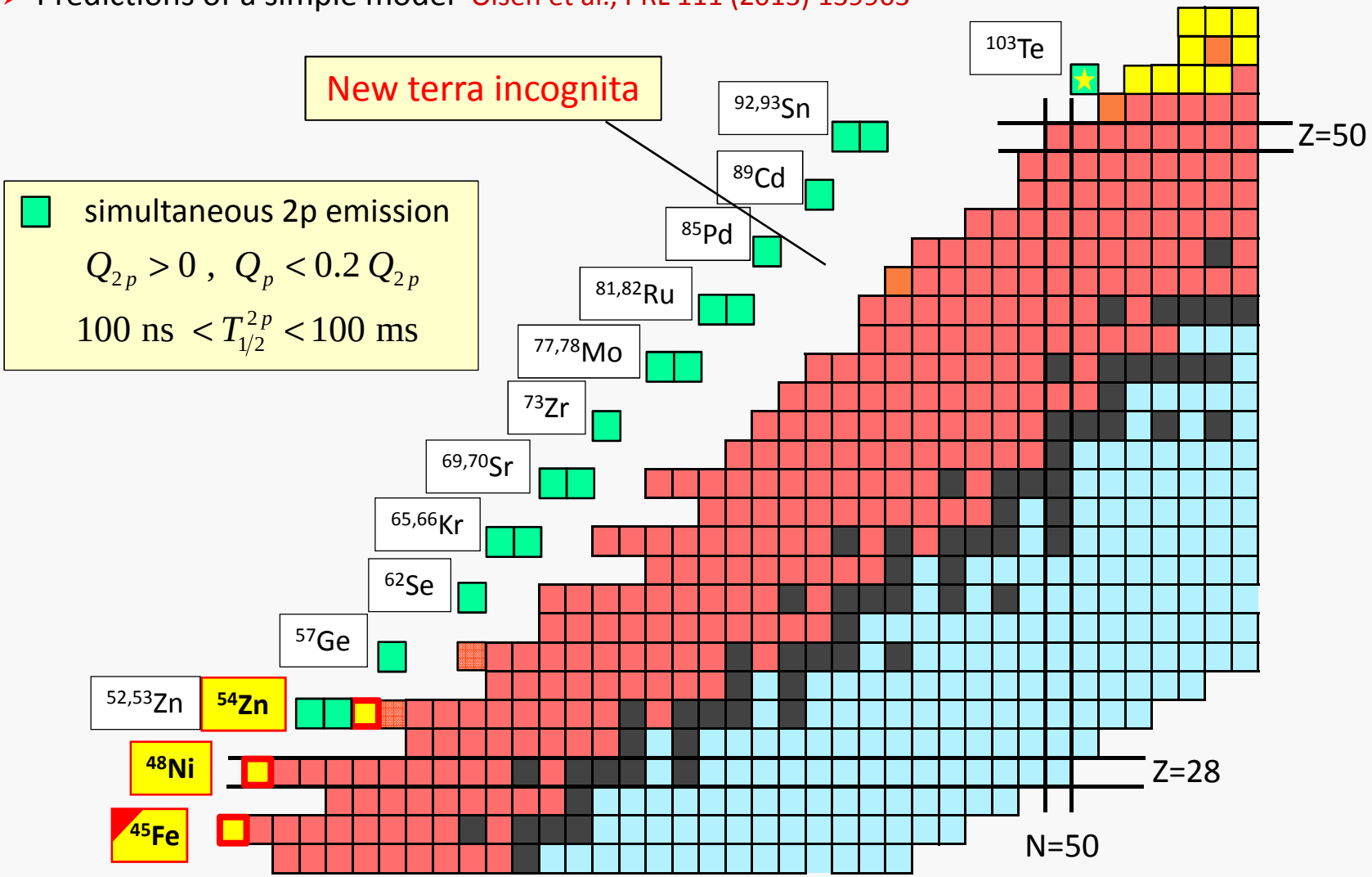
The current status of *2p* emission

- Ground-state 2p radioactivity first observed in ^{45}Fe. Later also in ^{54}Zn, ^{48}Ni and ^{19}Mg
- In lighter nuclei due to small Coulomb barrier *2p* emission is fast, $T_{1/2}(^{19}\mathrm{Mg})$ = 4 ps!
- Below ^{19}Mg *2p* are emitted from broad resonances, like ^{6}Be



Up to tellurium

- Predictions of a simple model Olsen et al., PRL 111 (2013) 139903



Between tellurium and lead

- Predictions of a simple model

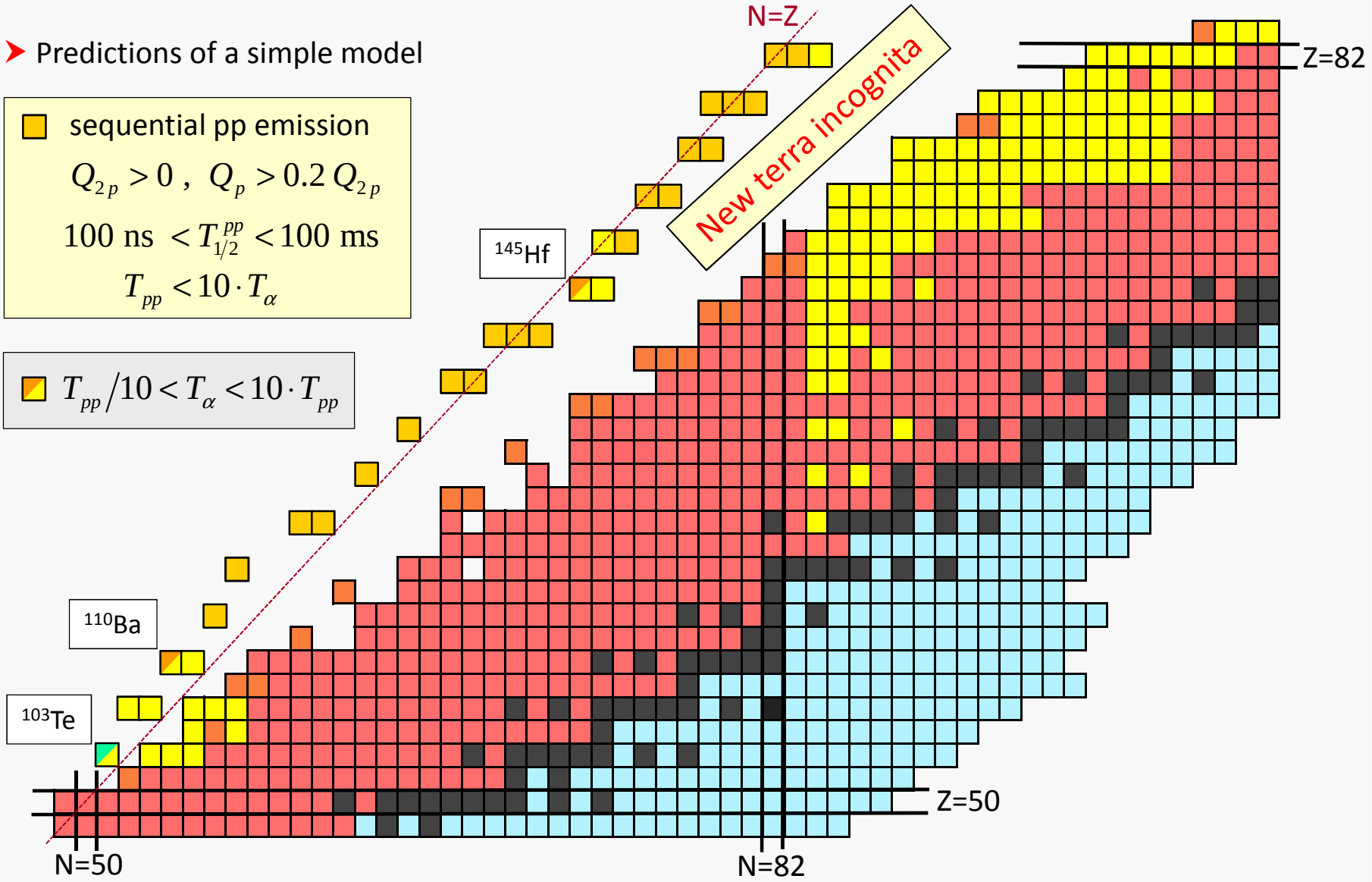
sequential pp emission

$$Q_{2p} > 0\ ,\ Q_p > 0.2\,Q_{2p}$$

$$100\ \text{ns} < T_{1/2}^{pp} < 100\ \text{ms}$$

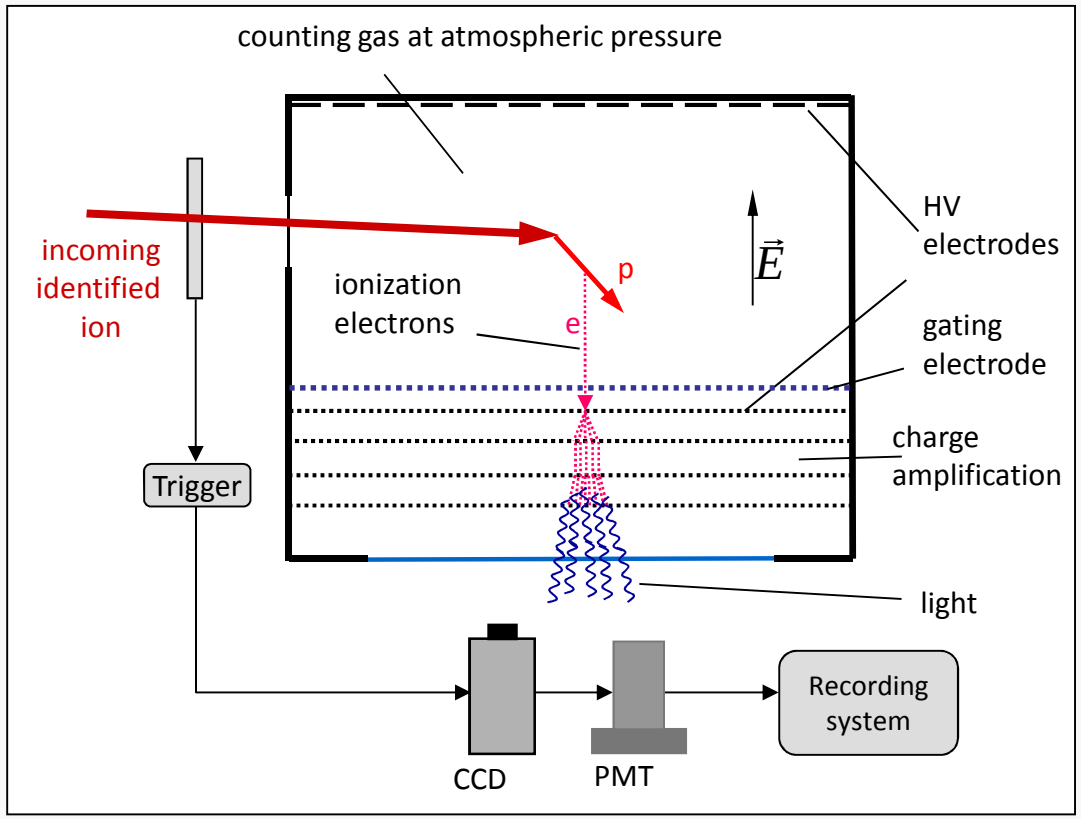
$$T_{pp} < 10 \cdot T_\alpha$$

$$T_{pp}/10 < T_\alpha < 10 \cdot T_{pp}$$

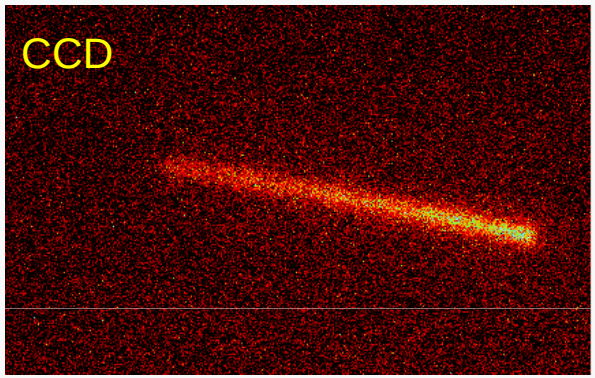


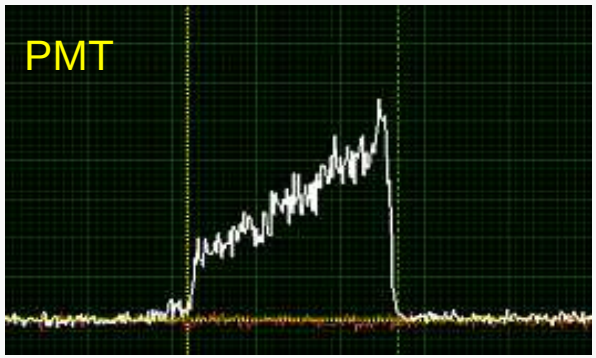
TPC detector

Time projection chamber with optical readout (OTPC)



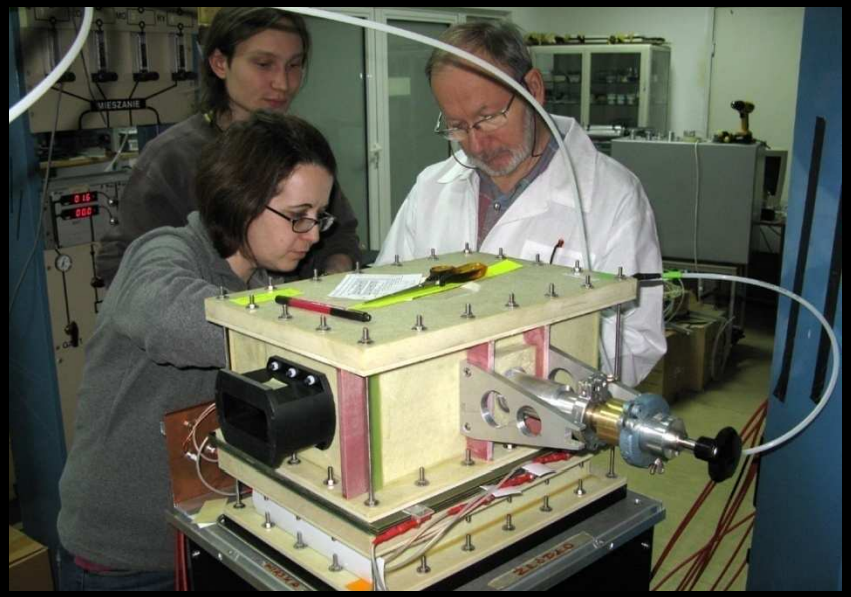
α particle

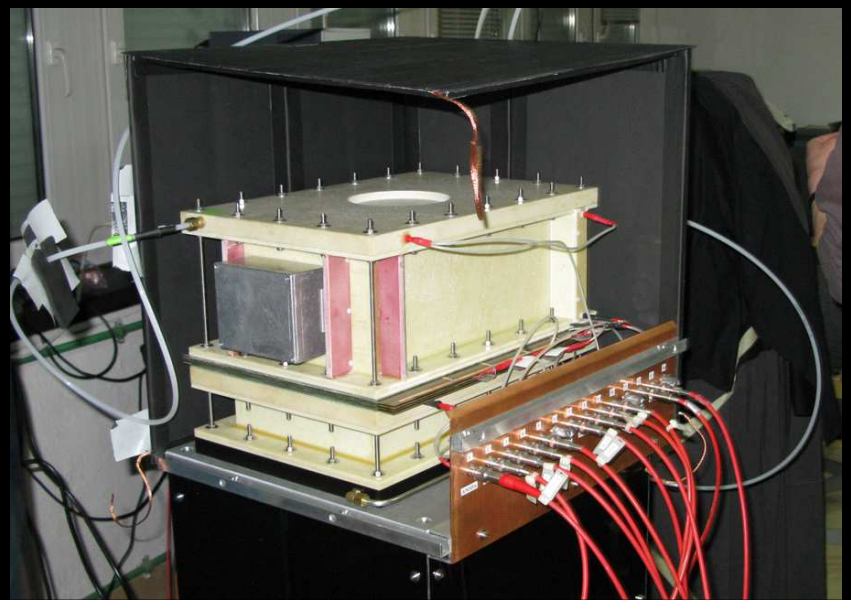


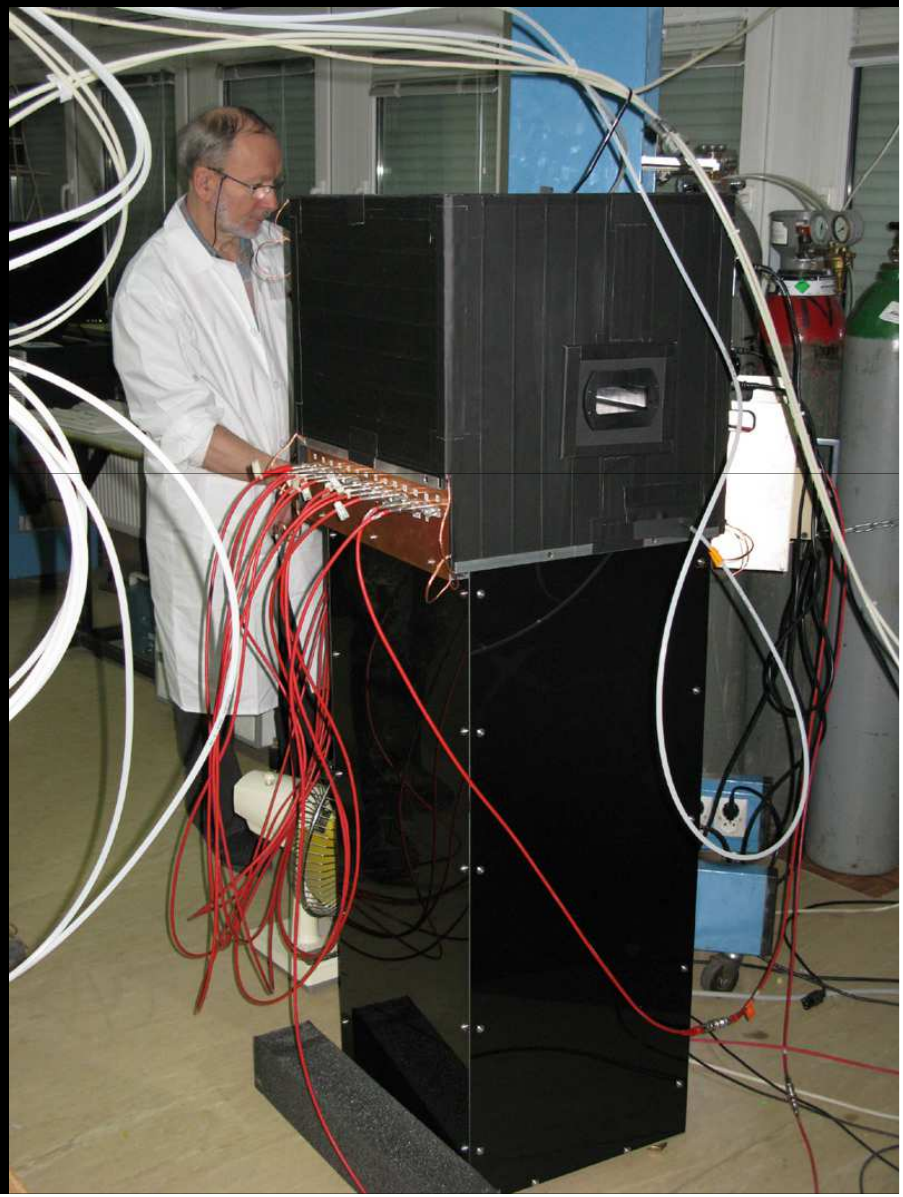


- Combination of the CCD image with the PMT waveform allows to fully reconstruct the track in three dimensions

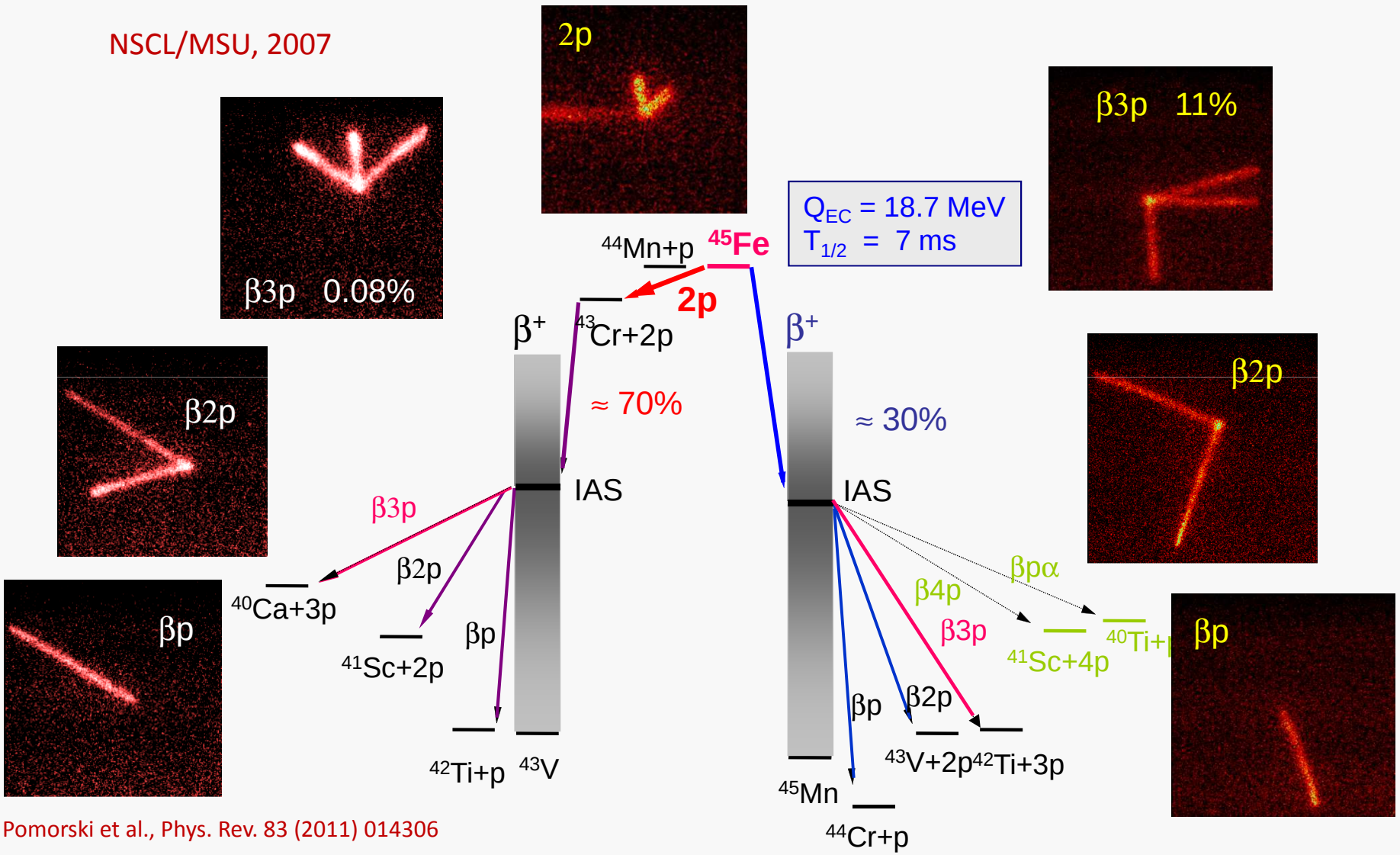
OTPC







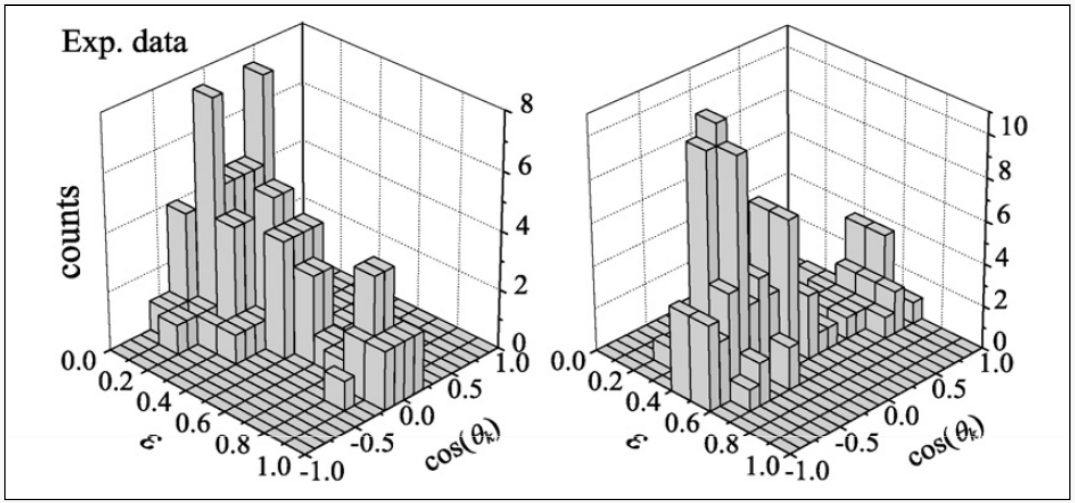
Decays of ^{45}Fe and ^{43}Cr

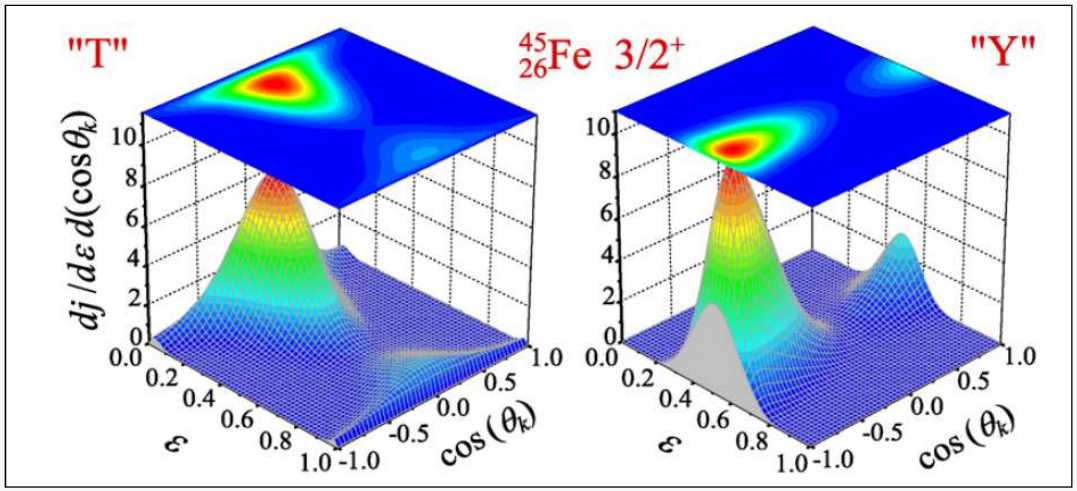


Pomorski et al., Phys. Rev. 83 (2011) 014306

Miernik et al., PRL 99 (07) 192501

p-p momentum correlations for ^{45}Fe



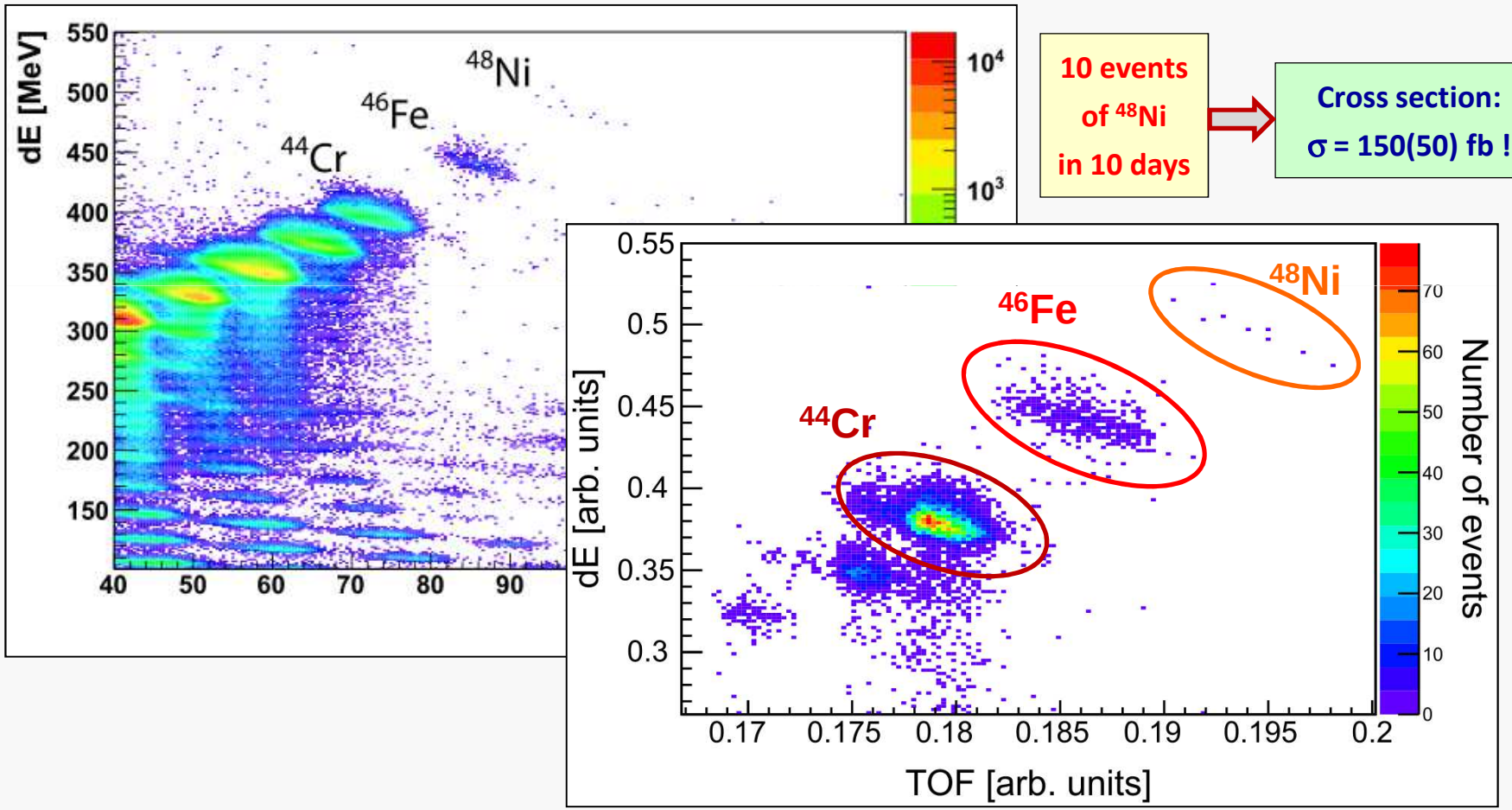


- Proton-proton momentum correlations measured for ^{45}Fe are complex and indicate a genuine 3-body phenomenon
- Good agreement with the 3-body model of Grigorenko et al.

Miernik *et al.*, PRL 99 (07) 192501 Grigorenko *et al.*, PLB 677 (2009) 30 MP, Karny, Grigorenko, Riisager, RMP 84 (12) 567

Study of ^{48}Ni

- NSCL/MSU, March 2011: ^{58}Ni at 160 MeV/u + ^{nat}Ni → ^{48}Ni

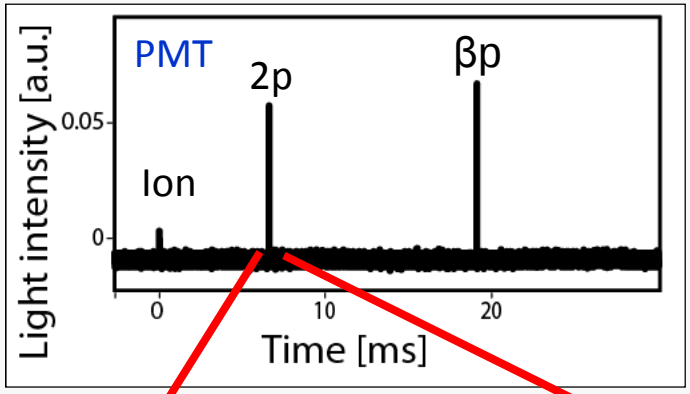


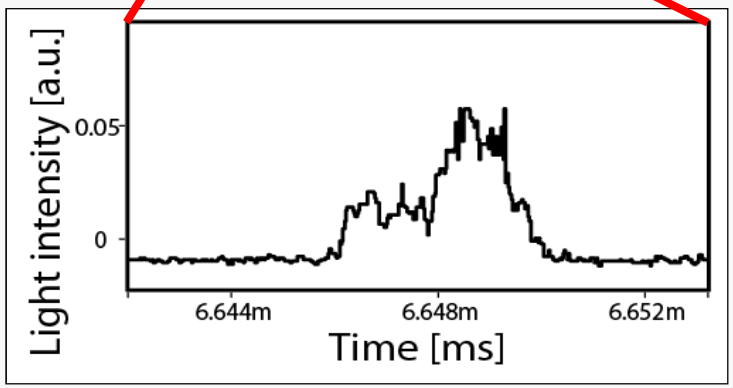
10 events of ^{48}Ni in 10 days

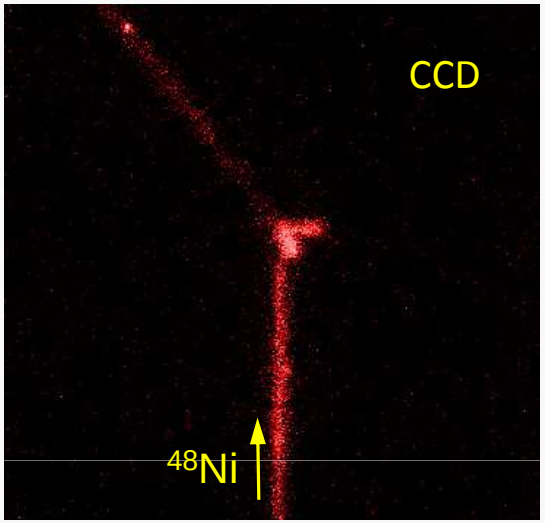
Cross section: σ = 150(50) fb !

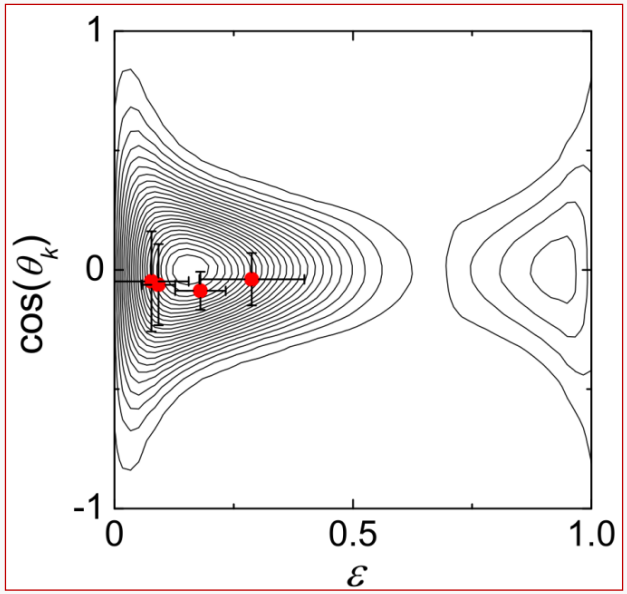
Pomorski et al., PRC 90 (14) 014311

2p decay of ^{48}Ni









Four 2p events of ^{48}Ni ⇒ **Q_{2p} = 1.29 (4) MeV**

Pomorski et al., PRC 90 (14) 014311

β-delayed protons from ^{44}Cr

5542 identified ions of ^{44}Cr

4098 properly stopped

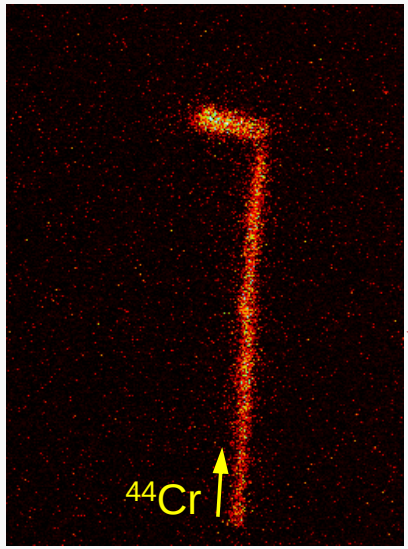
183 decays observed

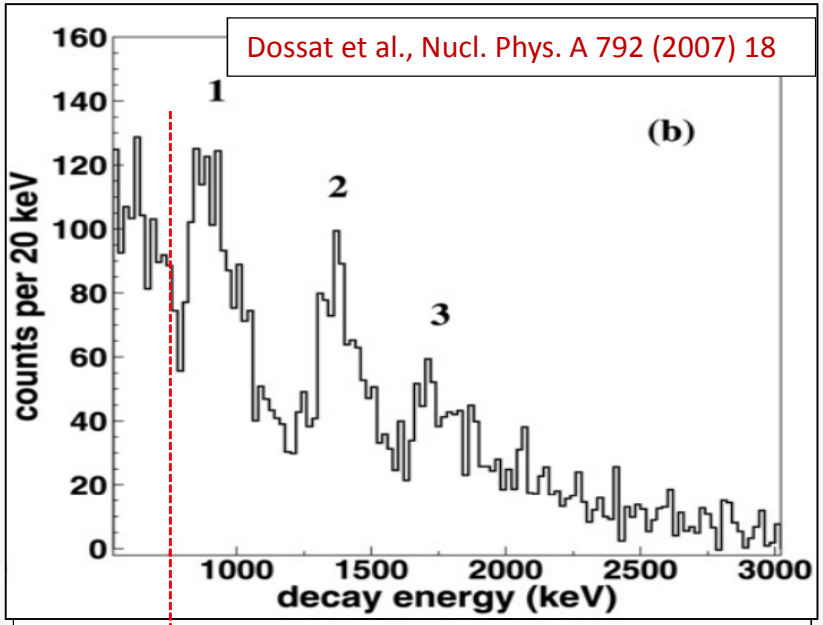
→ $b_p = 10(1)\%$

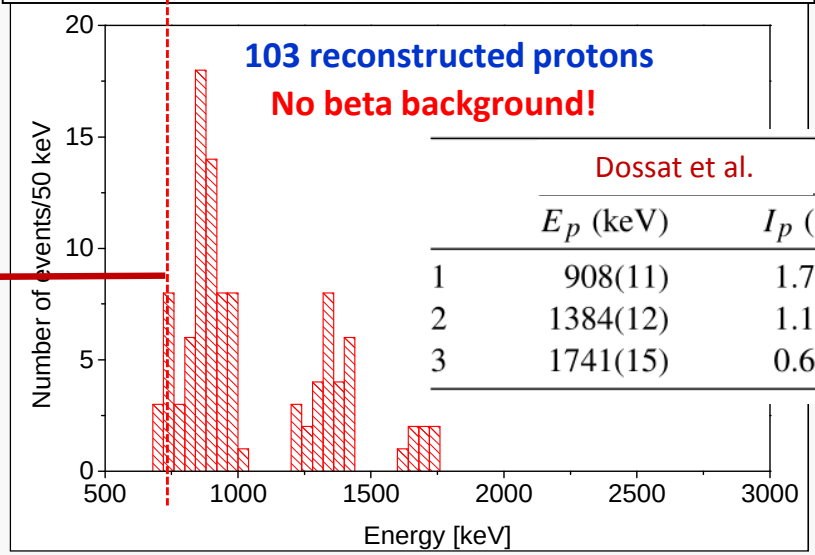
Dossat : $b_p = 14.0(9)\%$

A clear new line at 740(20) keV

$I_p = 0.6(2)\%$





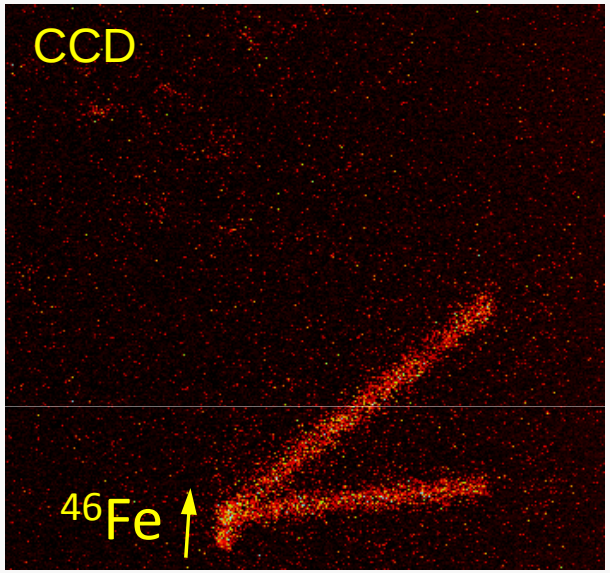


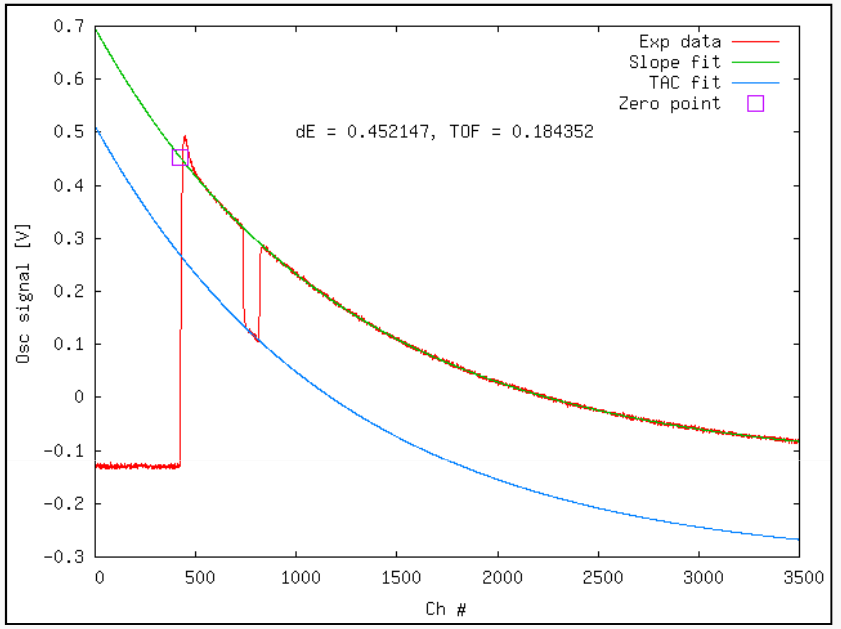
	Dossat et al. E_p (keV)	Dossat et al. I_p (%)	This work
1	908(11)	1.7(3)	**2.7(5)%**
2	1384(12)	1.1(3)	**1.4(3)%**
3	1741(15)	0.6(3)	**0.5(2)%**

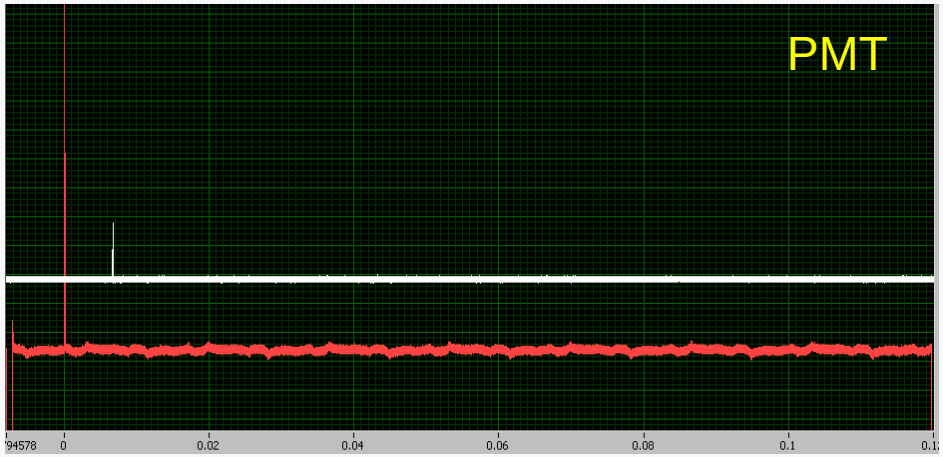
Pomorski et al., PRC 90 (14) 014311

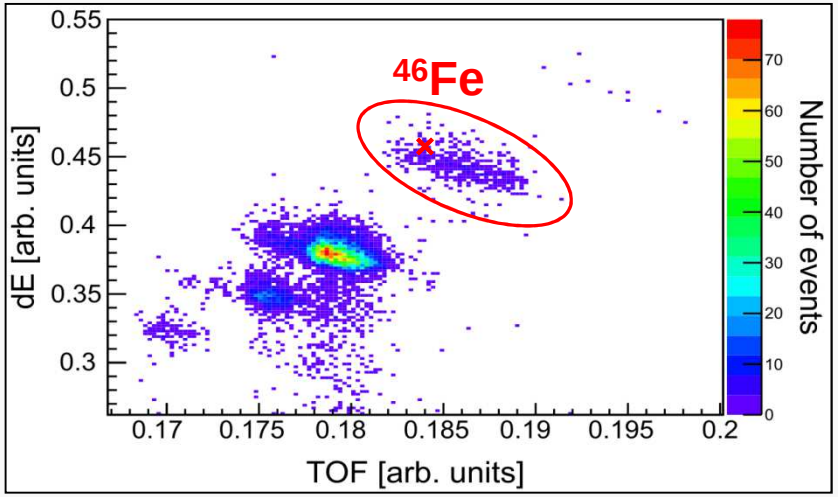
β2p channel in ^{46}Fe

- One good event!

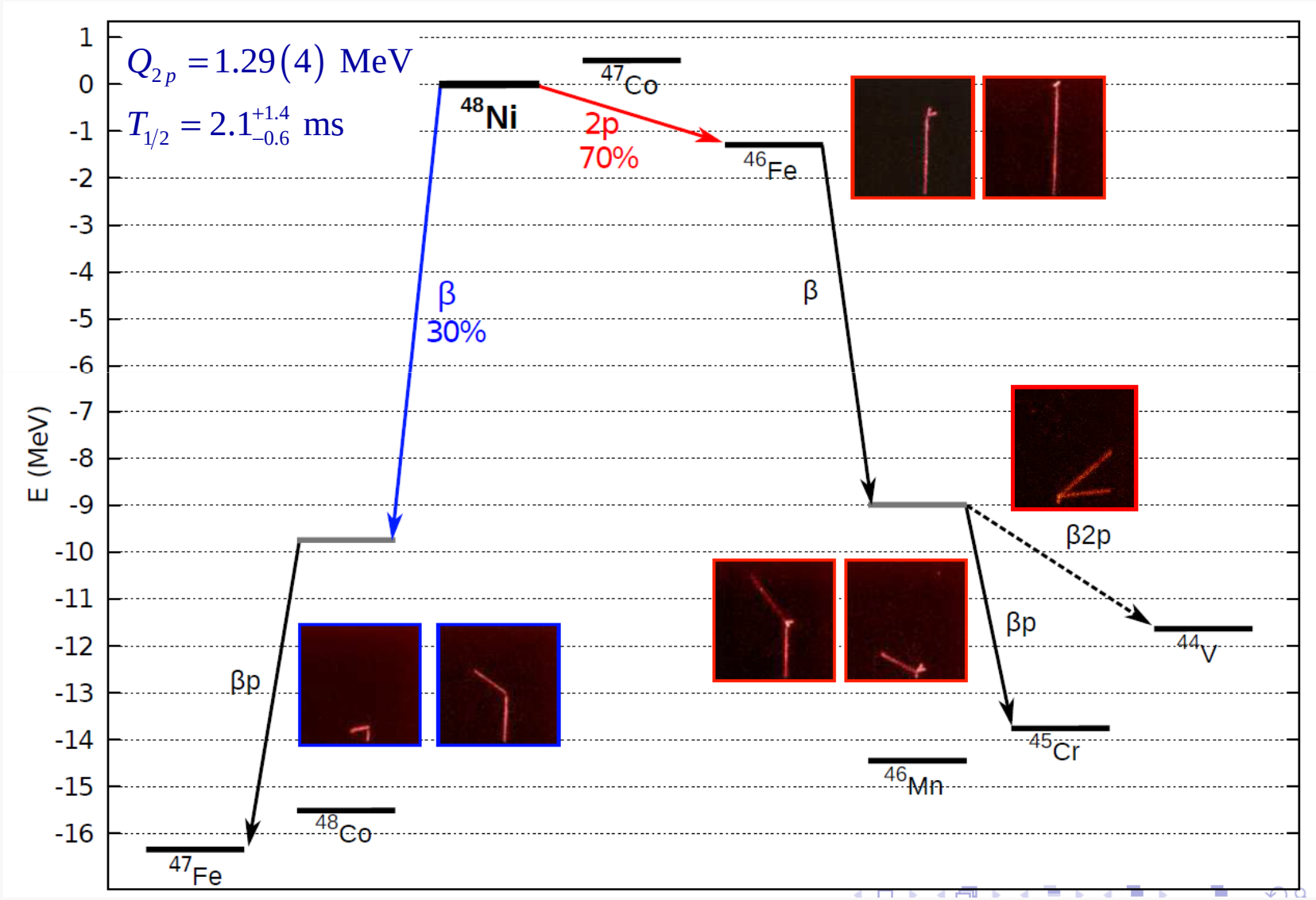








Decay scheme of ^{48}Ni



β3p in ^{31}Ar?

PHYSICAL REVIEW C VOLUME 45, NUMBER 1 JANUARY 1992

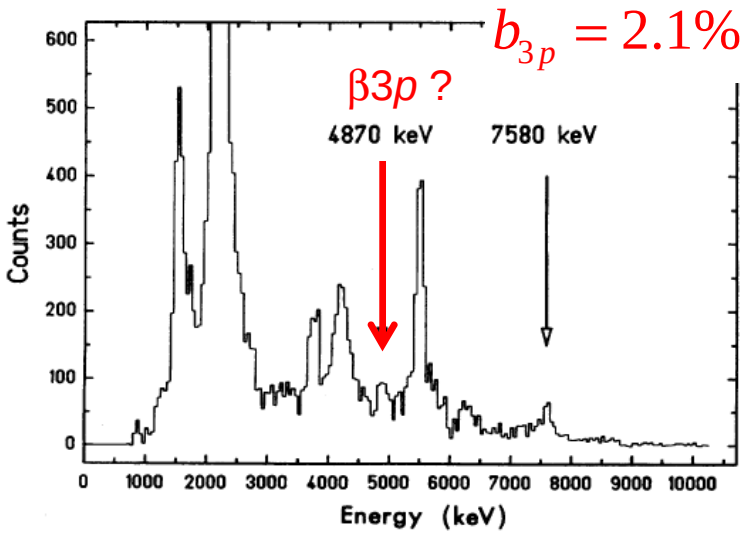
Decay modes of ^{31}Ar and first observation of β-delayed three-proton radioactivity

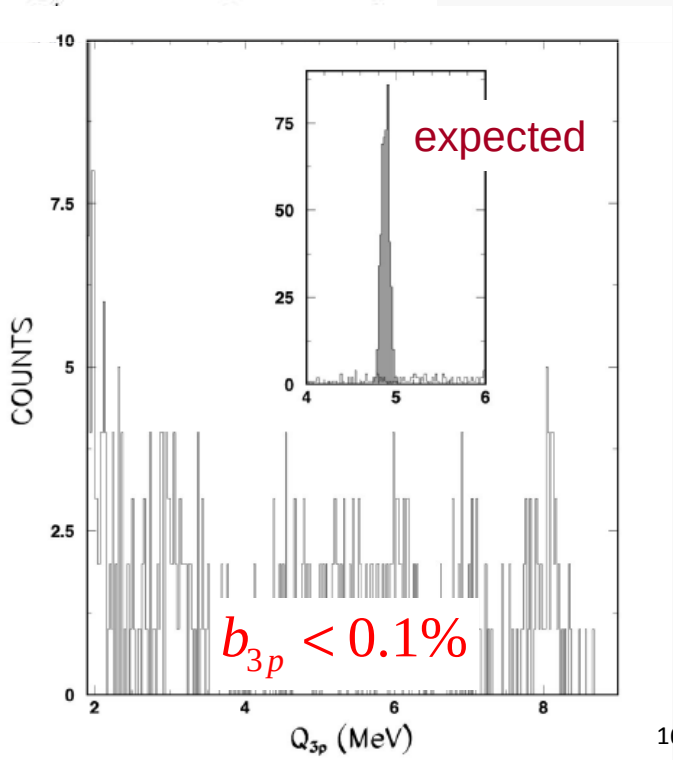
D. Bazin,* R. Del Moral, J. P. Dufour, A. Fleury, F. Hubert, and M. S. Pravikoff
Centre d'Etudes Nucléaires de Bordeaux–Gradignan, Le Haut Vigneau 33175 Gradignan CEDEX, France

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

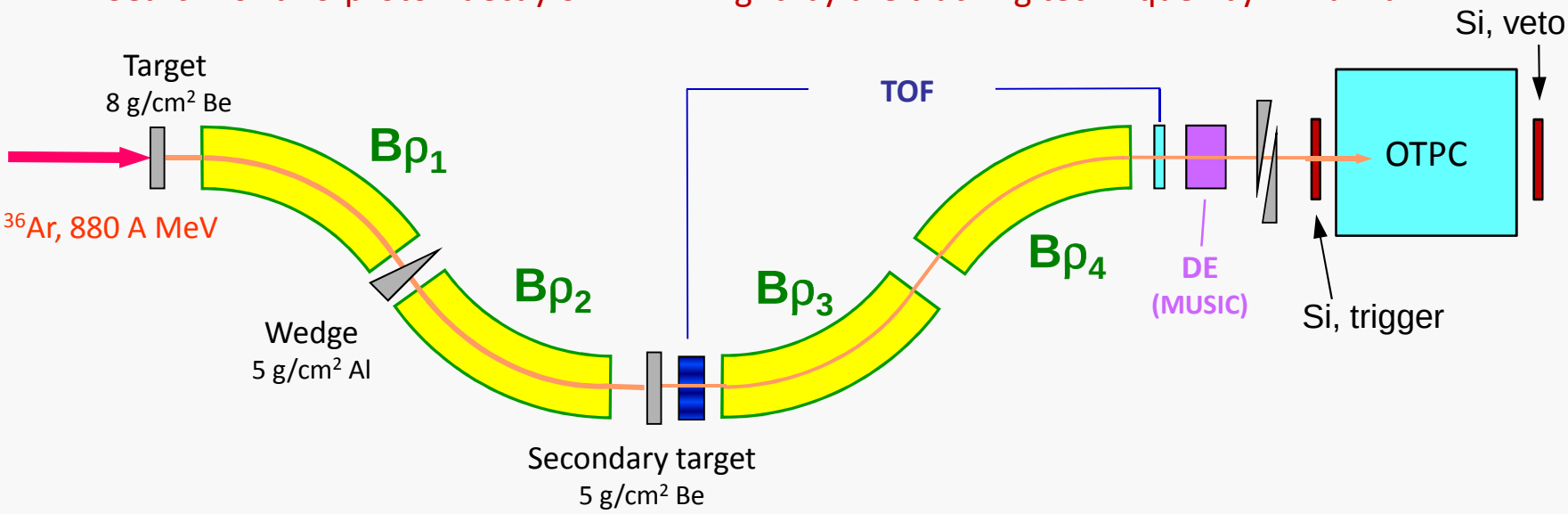


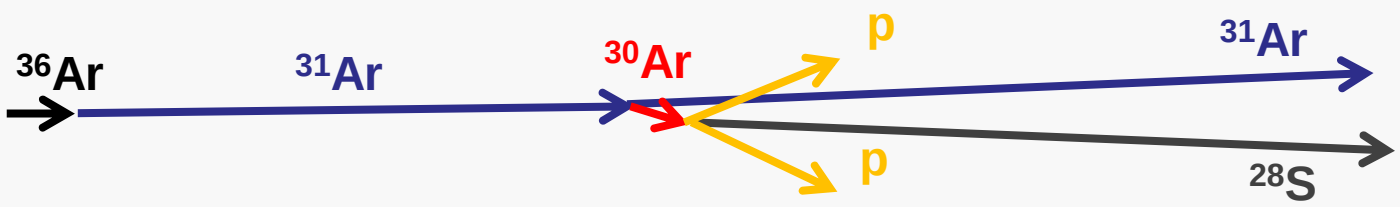


^{31}Ar at the FRS

- Experiment at GSI-FRS, August 2012

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



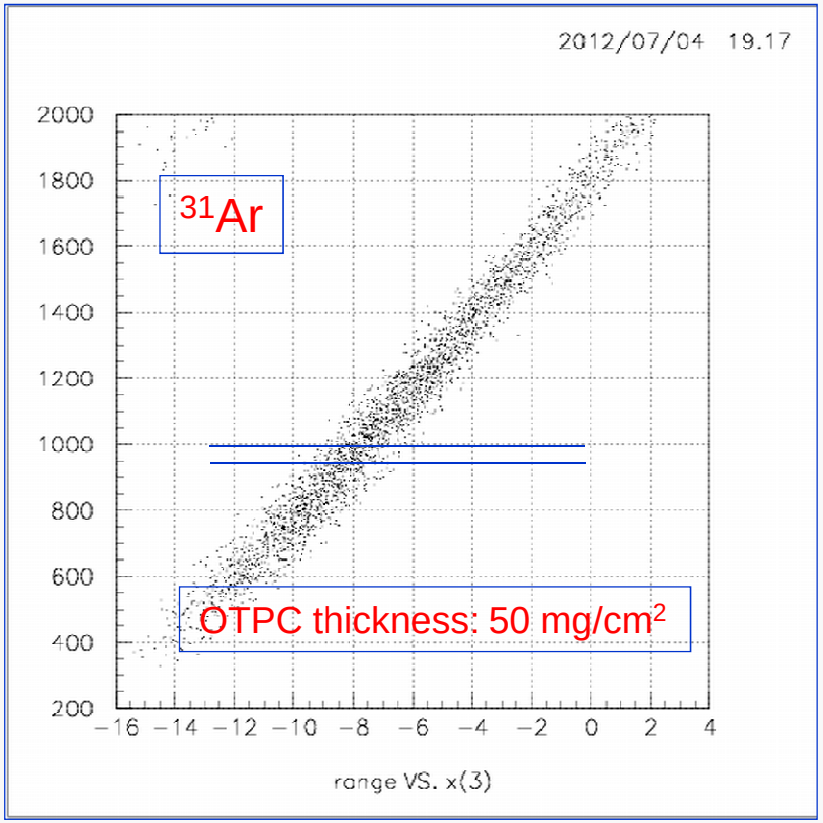


- Many ^{31}Ar ions pass to the S4
  An idea: stop them in the OTPC
  and search for β3*p* channel of ^{31}Ar

- With the beam of 10^{10} proj./spill we hoped for one ^{31}Ar atom/spill stopped.
  If spill every 4 s → 20 000/day

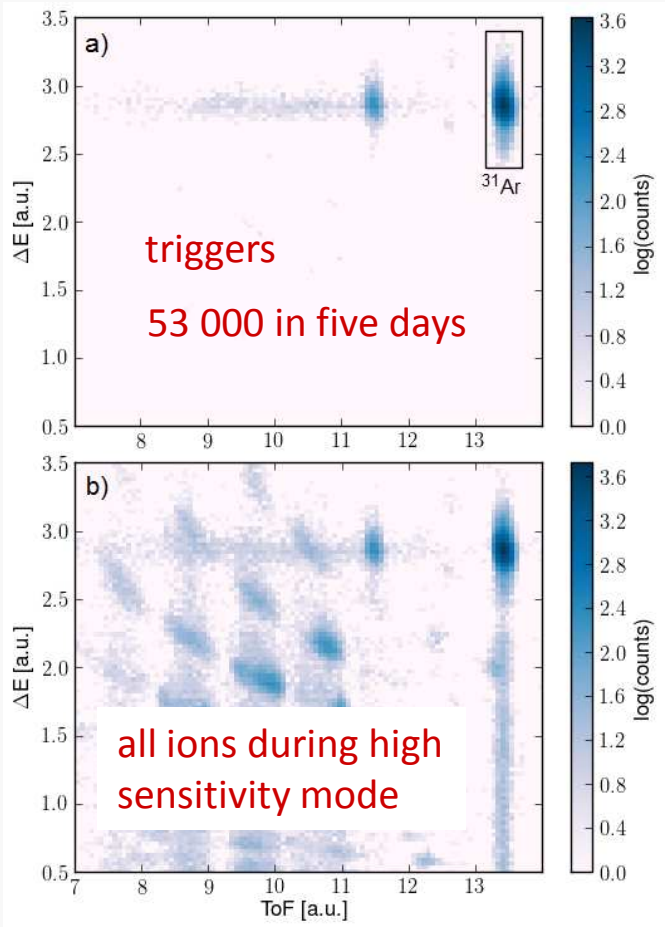
^{31}Ar at the FRS

- For effective stopping, the thickest gas mixture was chosen: 98% Ar + 2% N_2



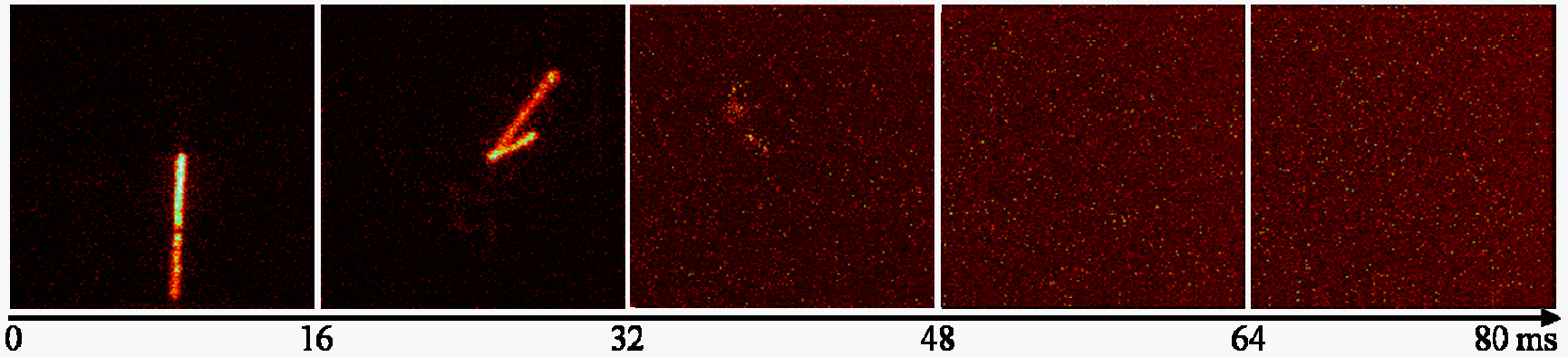
Simulation of the range vs. hor. position

- We could not stop the beam upon arrival of a triggering ion.



Yes, β3p in ^{31}Ar!

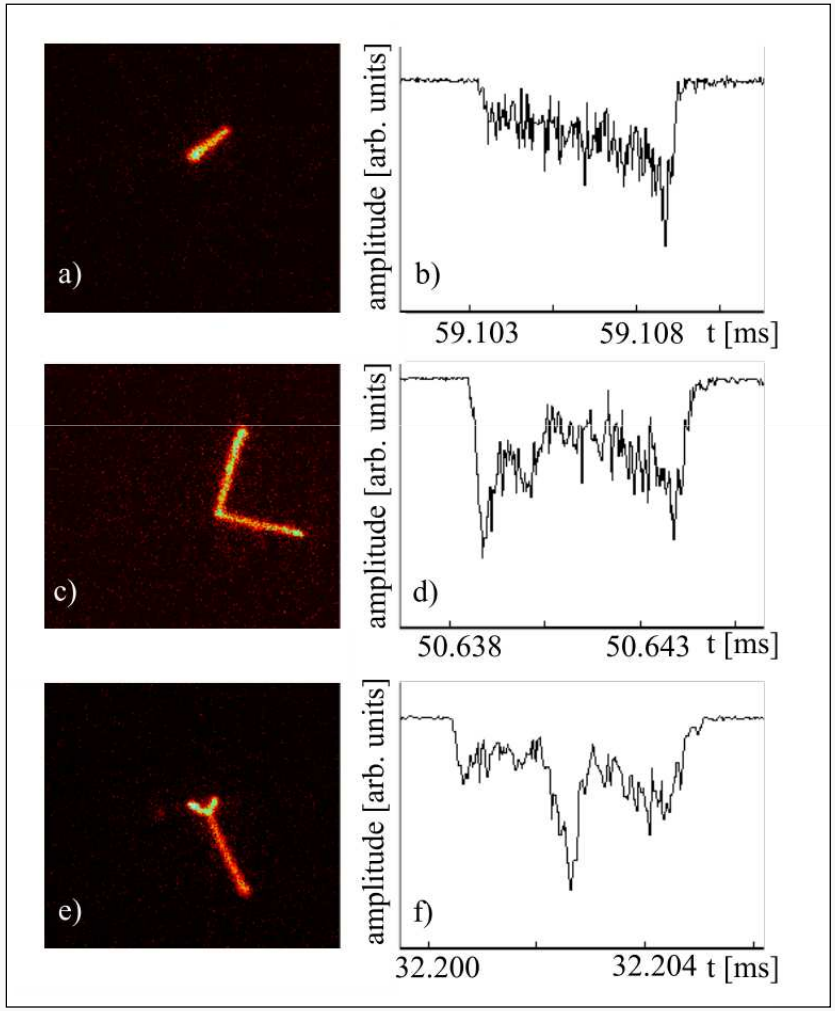
- A new acquisition mode – a series of shorter expositions („movie")



- Selection of events: in the first frame no other ions than well stopped ^{31}Ar present

21 000 events,
all inspected individually
by Ola Lis

β3p in ^{31}Ar



Lis et al., PRC 91, 064309 (2015)

- 13 events of β3p decay of ^{31}Ar was observed

TABLE I. The total branching ratios for the observed decays of ^{31}Ar. The given uncertainties are statistical.

Channel	Events	Branching [%]
$\beta 0p$	5984	22.6(3)[a]
$\beta 1p$	13157	68.3(3)
$\beta 2p$	1729	9.0(2)
$\beta 3p$	13	0.07(2)

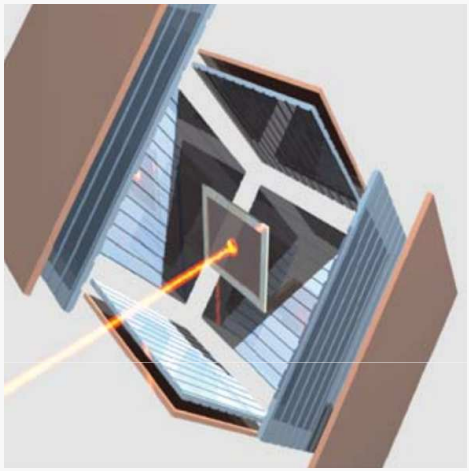
Only 3 cases of β3p known:

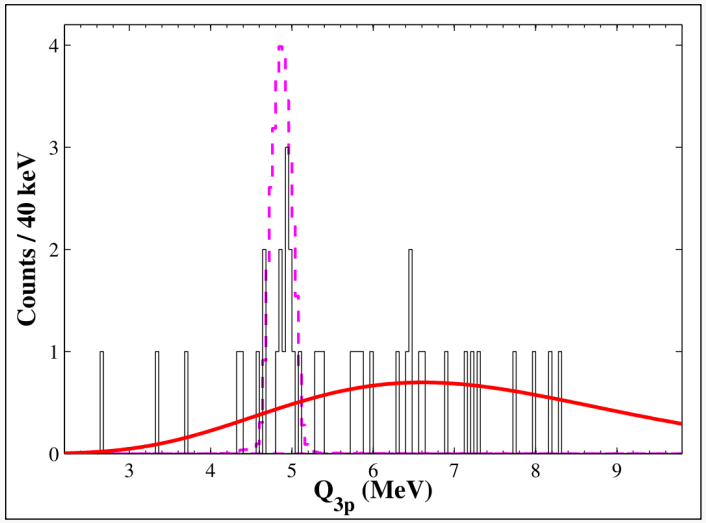
- ^{45}Fe (Miernik et al., PRC76, 2007)
- ^{43}Cr (Pomorski et al., PRC83, 2011)
- ^{31}Ar (Lis et al., PRC, 2015)

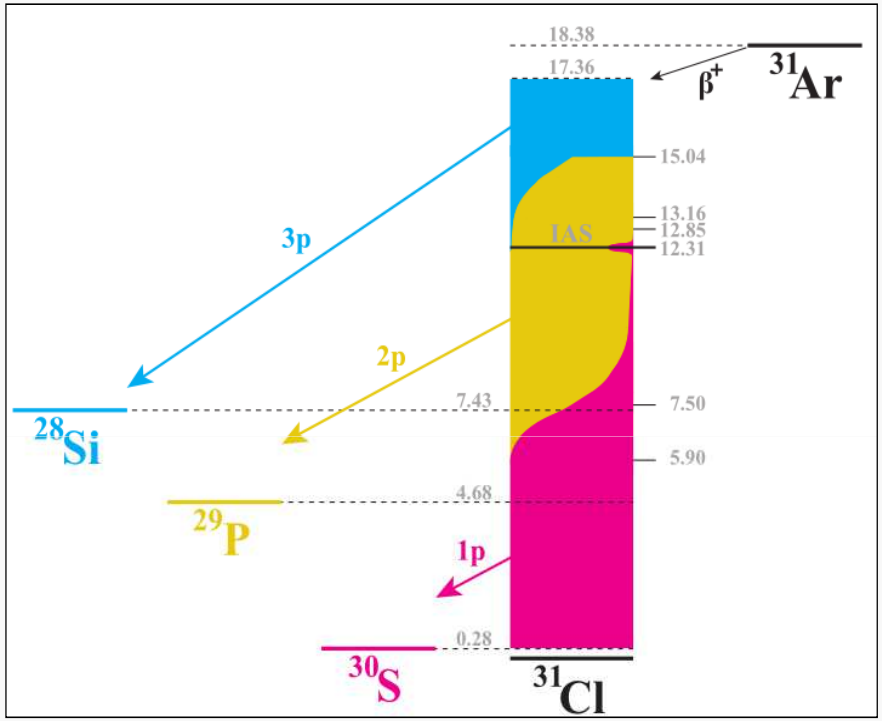
All discovered with the OTPC!

β3p in ^{31}Ar

- β3p decay channel of ^{31}Ar confirmed by ISOLDE using Si Cube







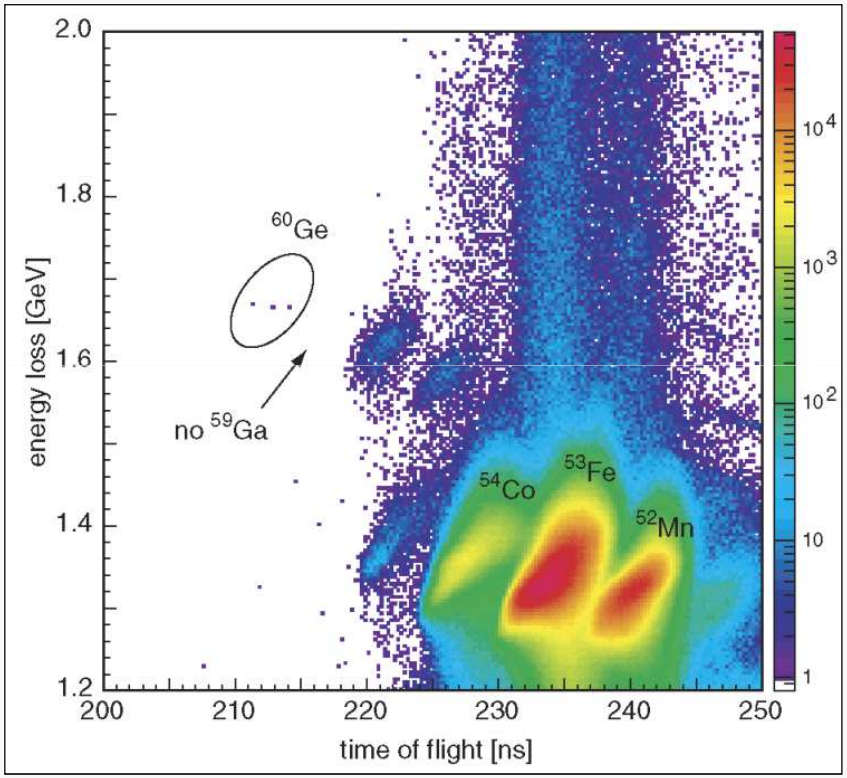
Koldste et al., PRC 89 (2014) 064315

➔ The estimated β3p branching: 0.08(4)%

➔ The β3p transitions responsible for 30% of the total Gamow-Teller strength in ^{31}Ar!

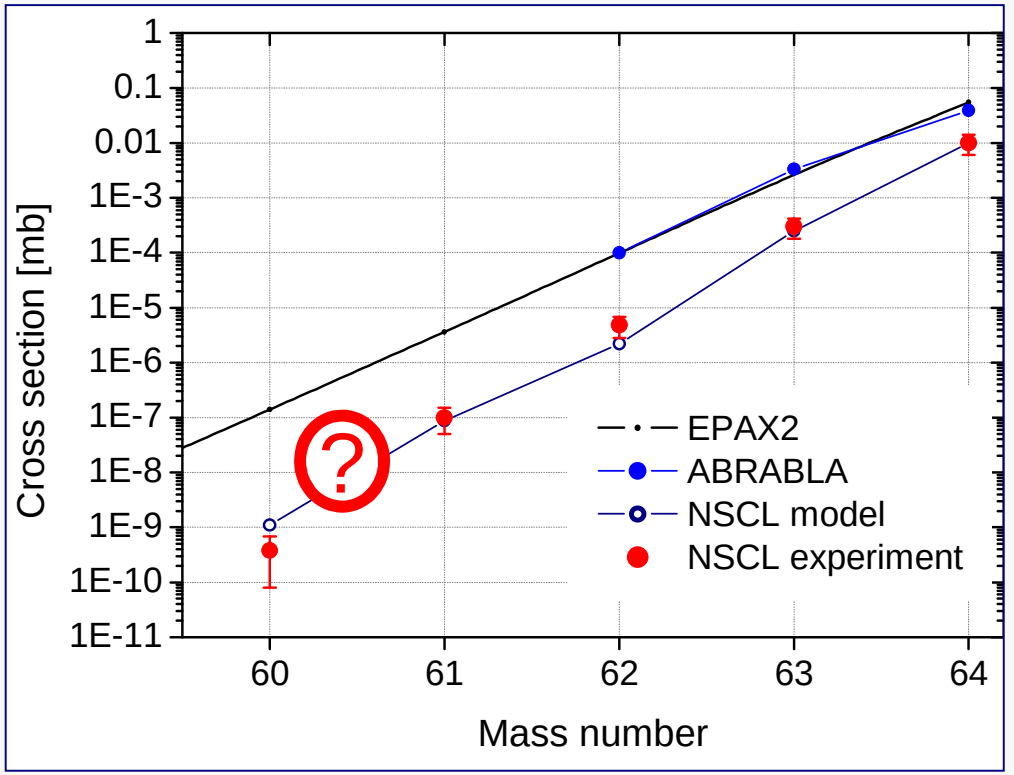
Ge isotopes at the proton drip-line

- ^{60}Ge discovered at NSCL/MSU in 2004



Stolz et al., Phys. Lett. B 627 (2005) 32

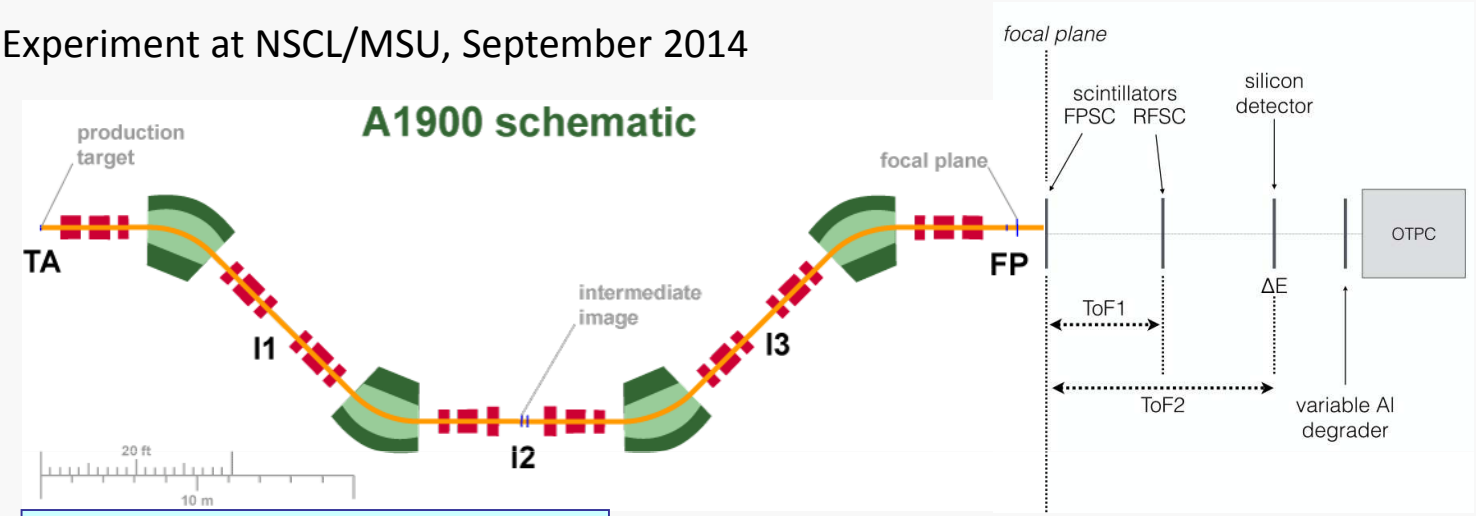
A1900: ^{78}Kr @ 140 MeV/u + Be



Lower cross section for the production of ^{60}Ge than expected → does it indicate very short half-life?

Ten years after…

- Experiment at NSCL/MSU, September 2014

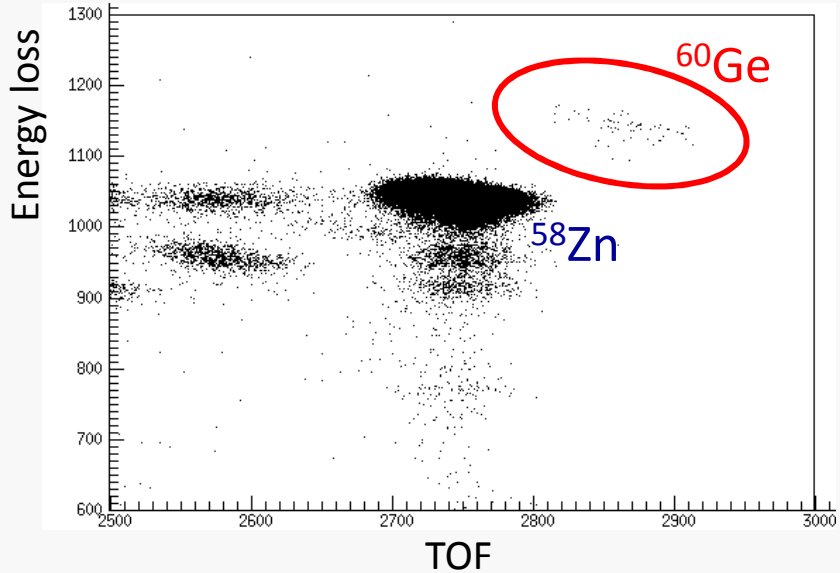


A1900: ^{78}Kr @ 150 MeV/u + Be

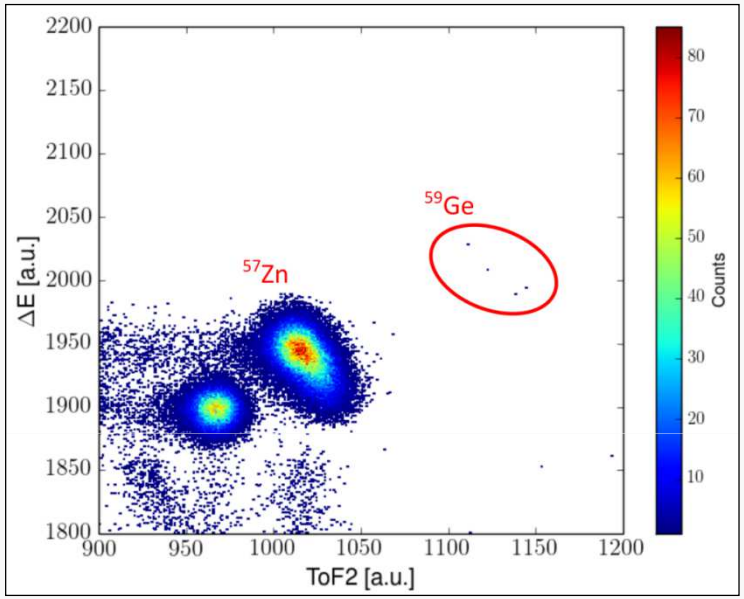
→ 73 atoms of ^{60}Ge identified!
Delayed protons observed, analysis in progress

→ Cross section measured for ^{60,61,62}Ge

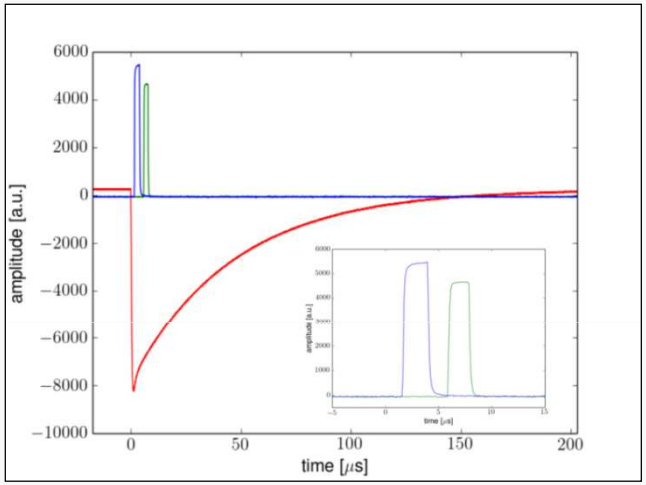
→ Search for ^{59}Ge

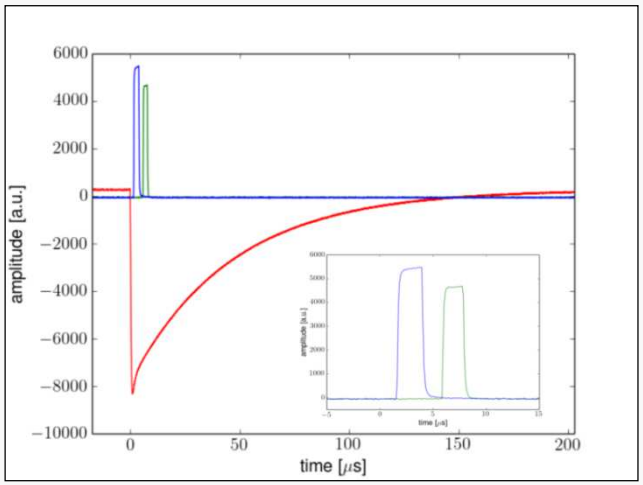


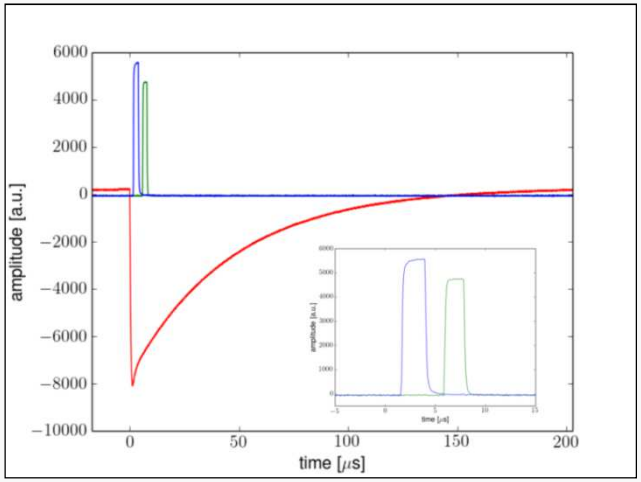
First observation of ^{59}Ge



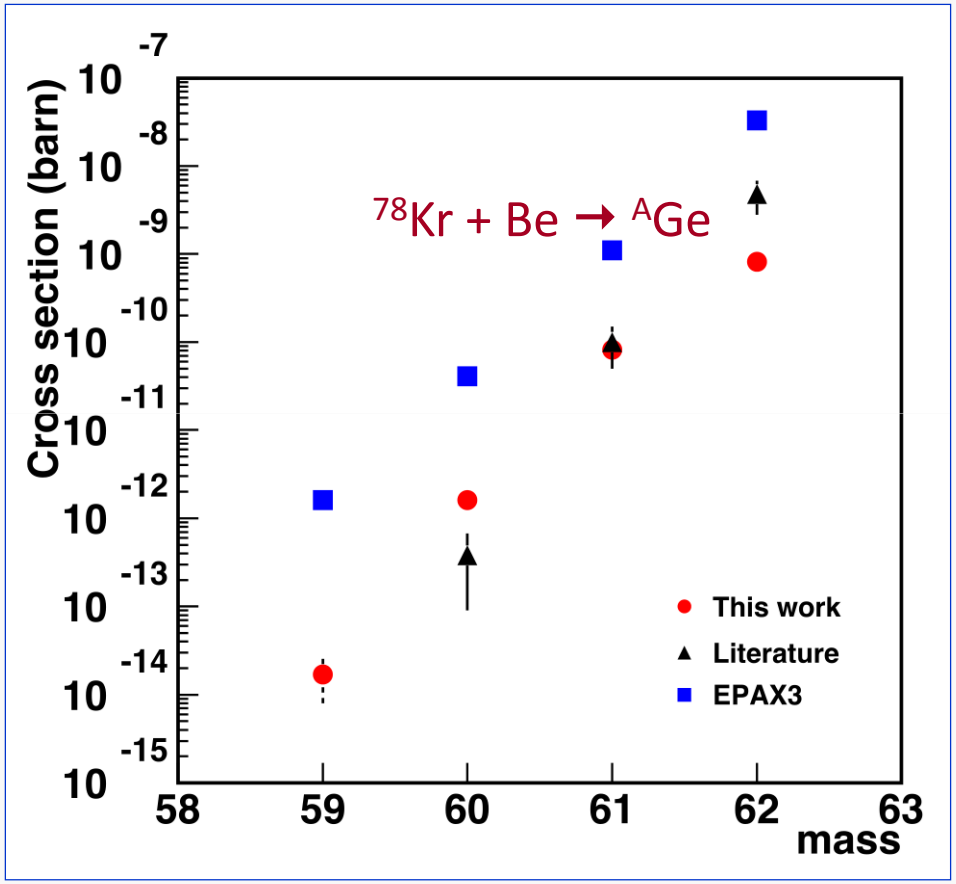
Ciemny et al., submitted to PRC as RC

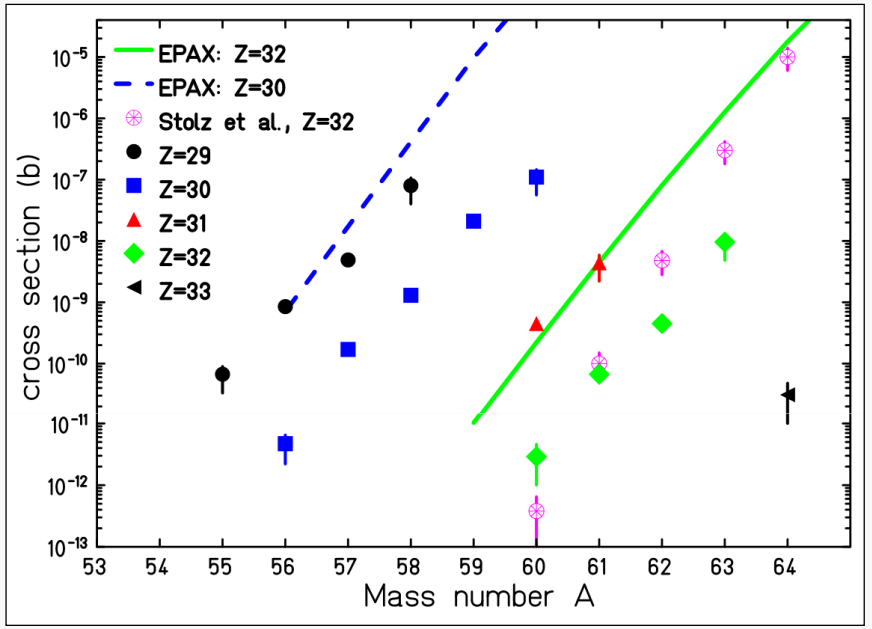






Cross section for Ge isotopes





Blank et al., EPJ A 31 (2007) 267

➔ ^{70}Ge @ 70 A·MeV on ^{nat}Ni target produces ^{60}Ge with larger cross section (×2)!

➤ Decay studies of ^{59}Ge possible. Perhaps at RIKEN one can go even further…?

Summary

- Beyond proton drip-line there is a large territory of beta decaying nuclei waiting for discovery (*terra incognita nova*)
- The OTPC detector is a very efficient tool to search for very rare multiparticle decays or to investigate particle decays obscured by beta background.
- Can provide precise branching ratios for β-delayed particle channels. Although the energy resolution is worse than for Si detectors, yields complementary data for low-energy particles.
- Non-trivial 3-body character of 2p decay of ^{45}Fe discovered. 2p decay of ^{48}Ni discovered.
- New decay channels, like β3p (^{45}Fe, ^{43}Cr, ^{31}Ar), observed for the first time. β2p emission discovered in ^{46}Fe based on one atom decay!
- New neutron-deficient isotope ^{59}Ge identified, first decay data for ^{60}Ge collected.

Thank you!