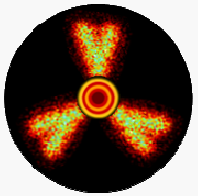
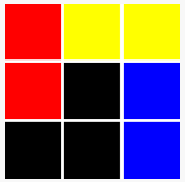
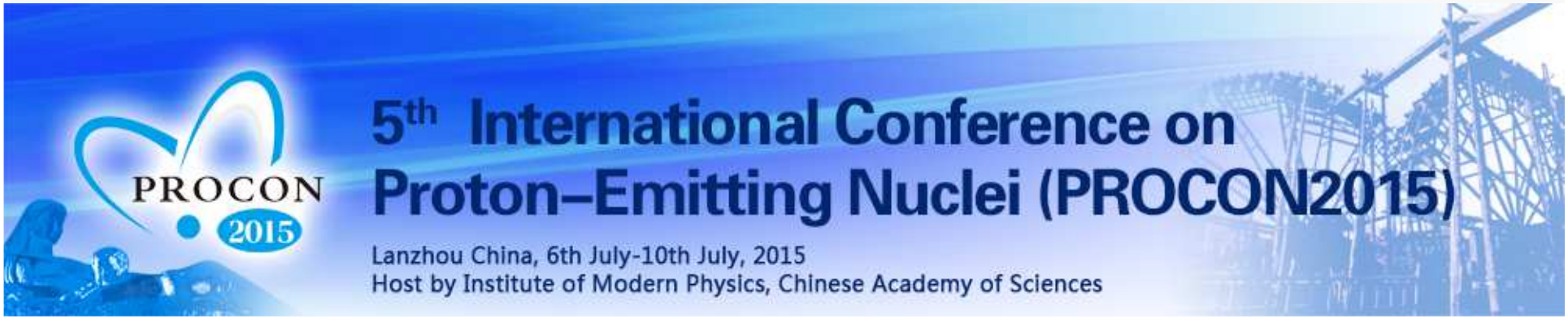
Particle emission at the proton drip-line

Marek Pfützner

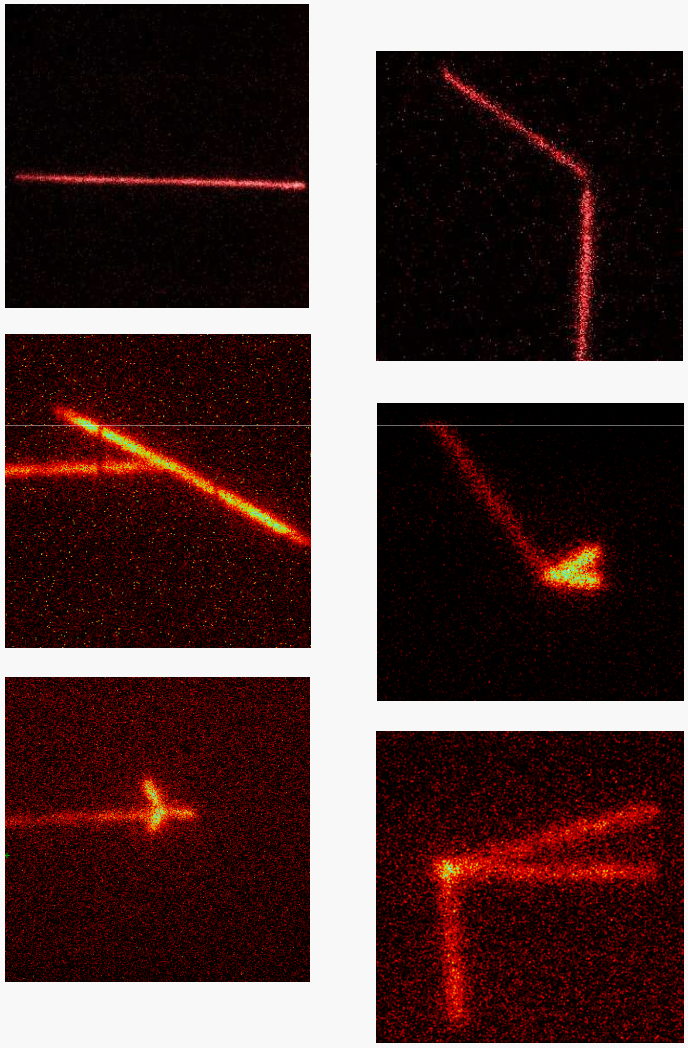




Nuclear Physics Division
University of Warsaw



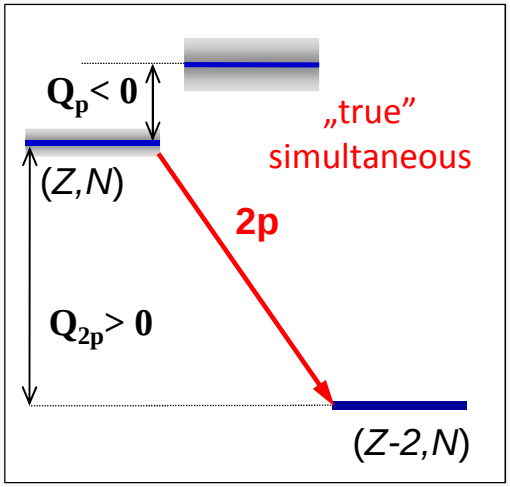
Outline

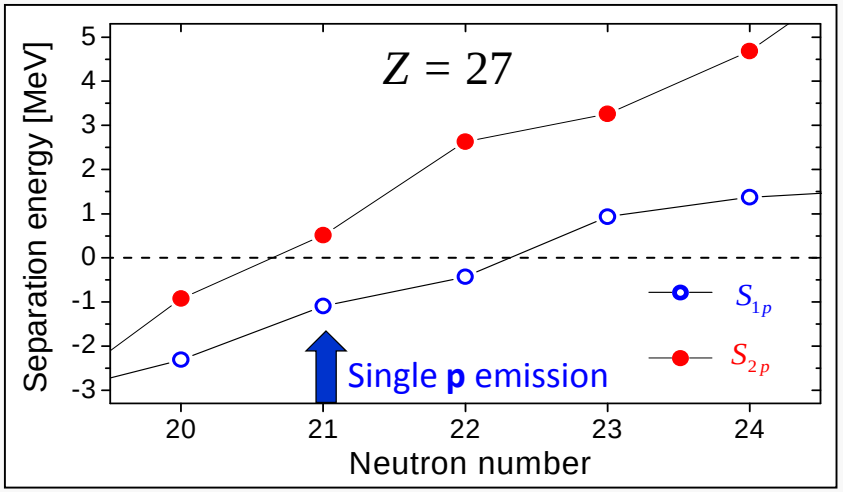


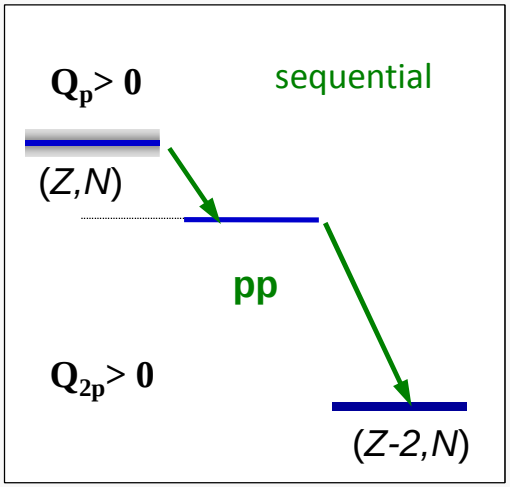
- Nuclei at the proton drip-line and beyond
- Optical TPC
- Reminder of ^{45}Fe
- Decay study of ^{48}Ni (and ^{46}Fe, ^{44}Cr)
- Attractive digression
- Search for new Ge isotopes

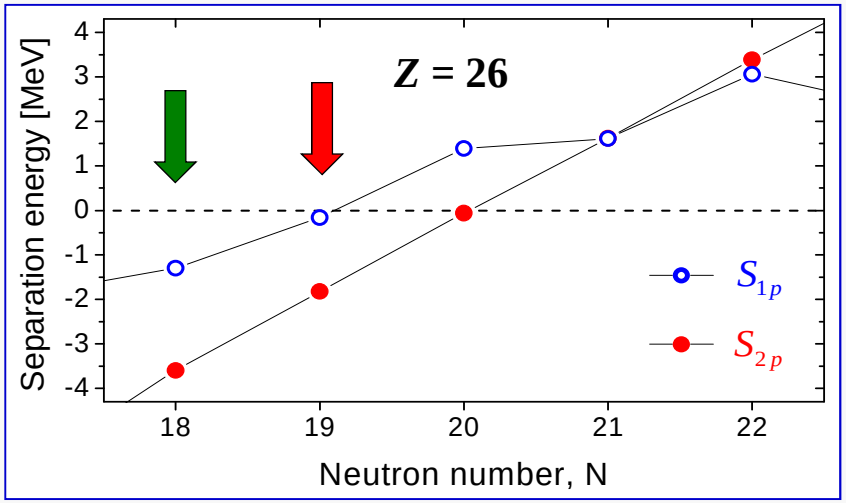
p drip-line is not a limit!

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



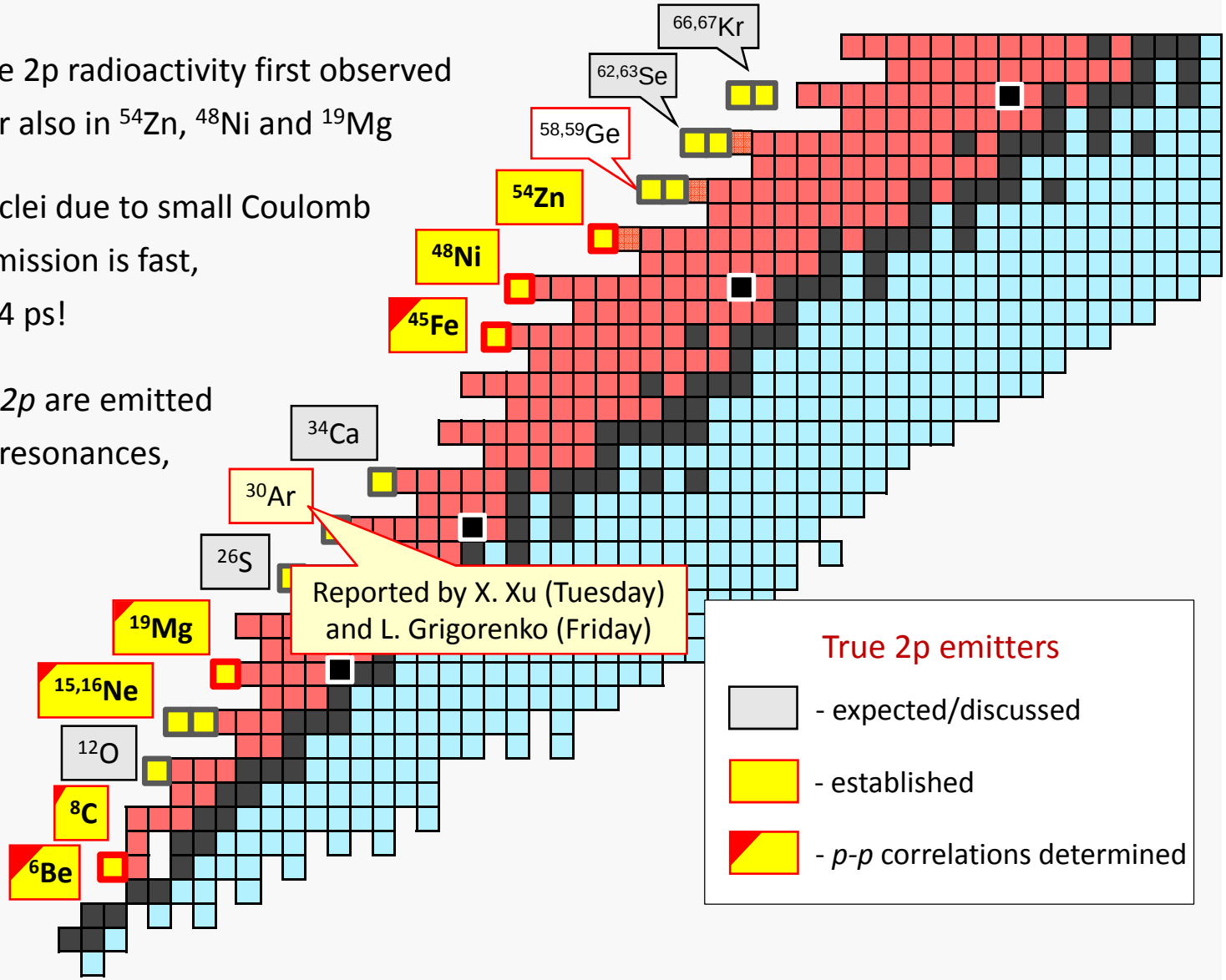






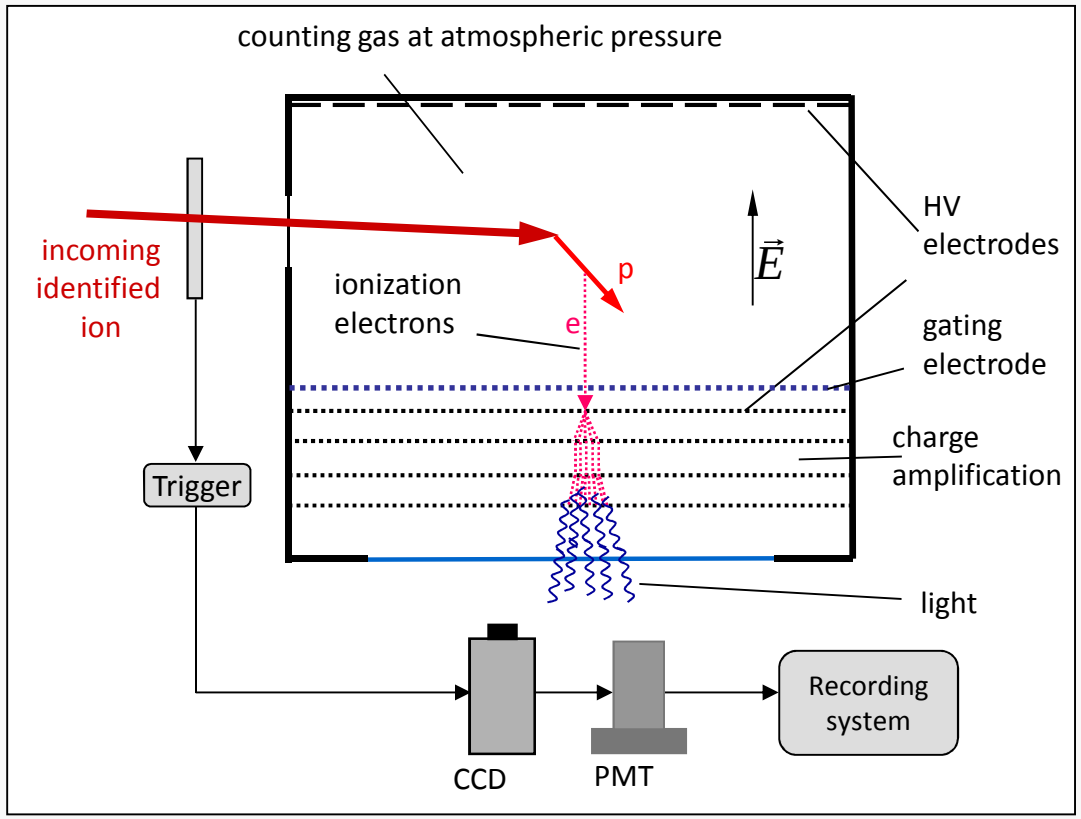
The status of *2p* emission

- 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

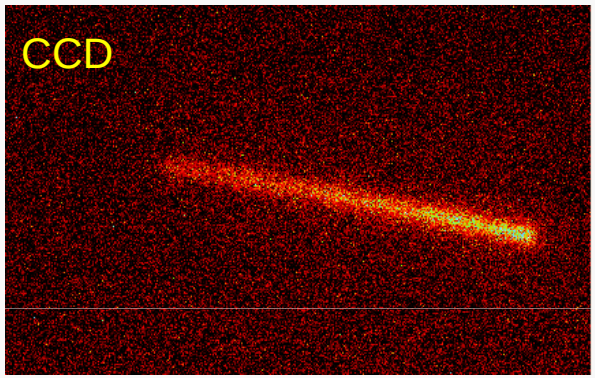


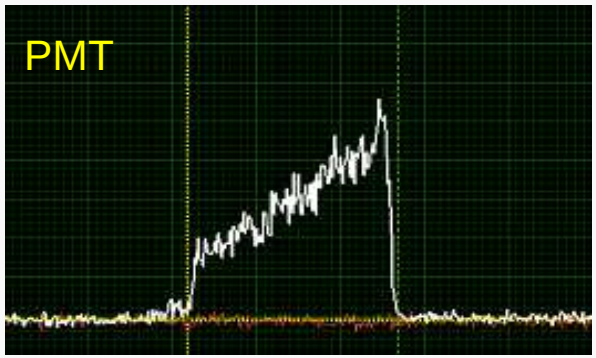
TPC detector

Time projection chamber with optical readout (OTPC)



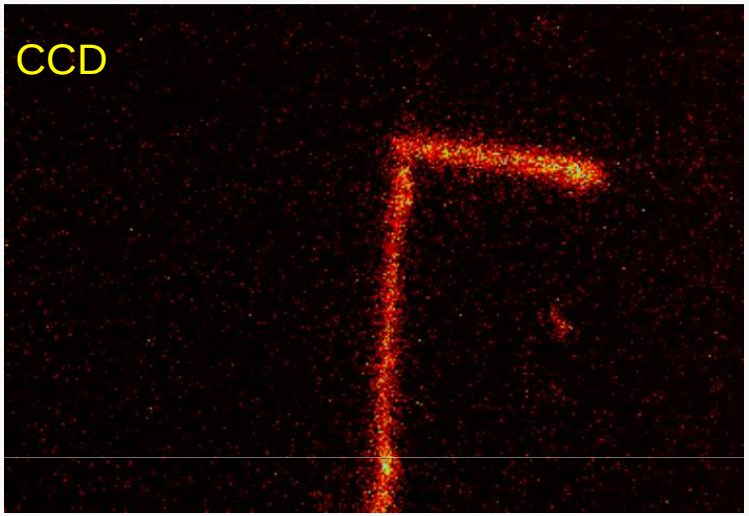
α particle

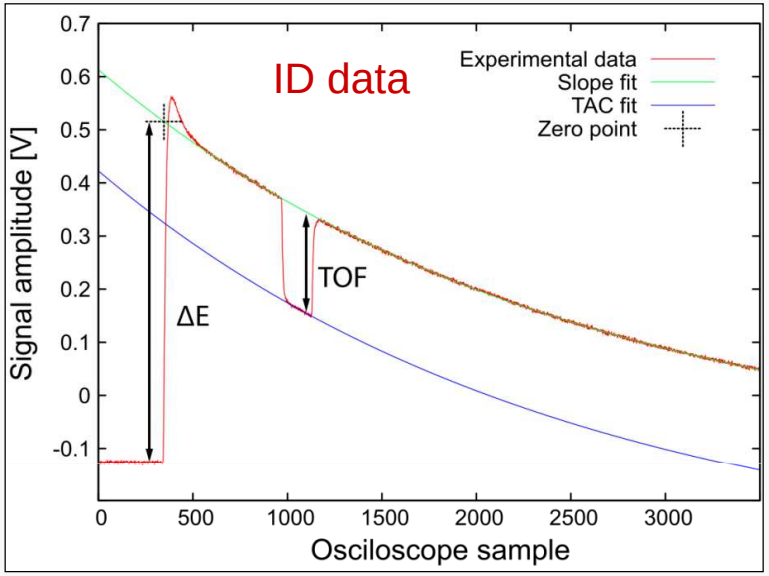


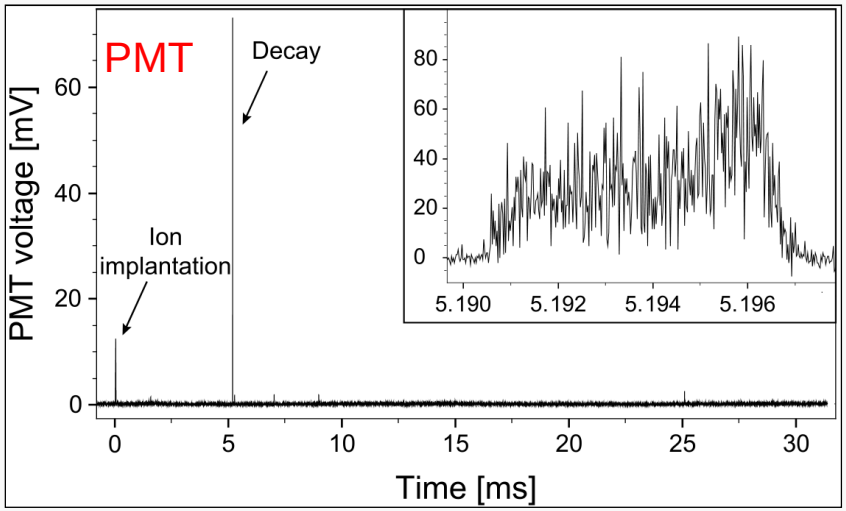


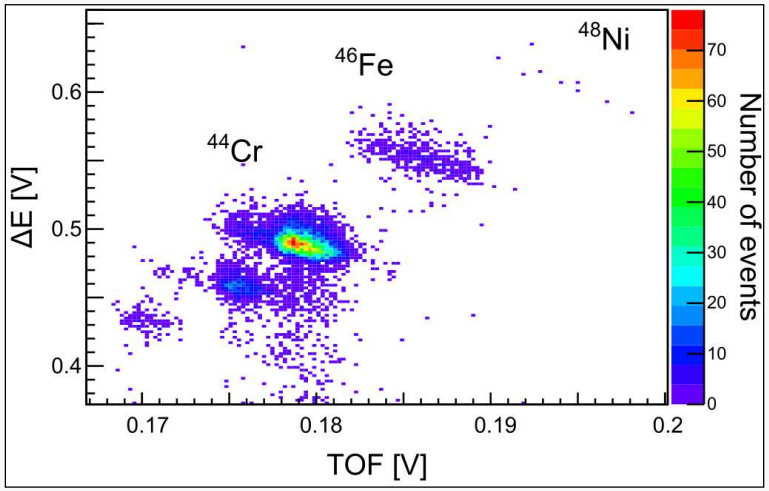
- Combination of the CCD image with the PMT waveform allows to fully reconstruct the track in three dimensions

Raw data and ion ID



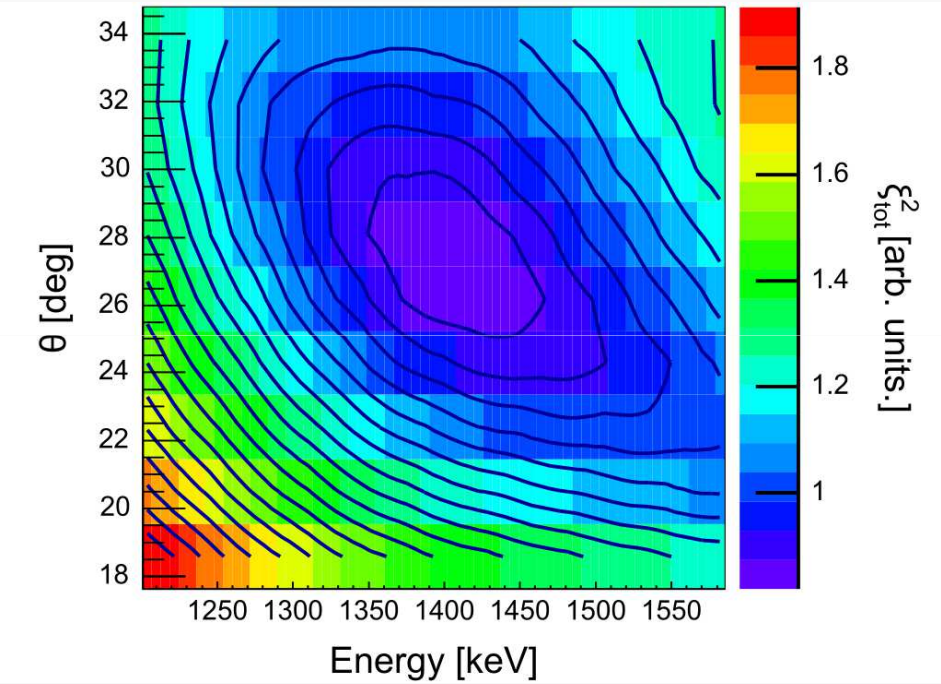


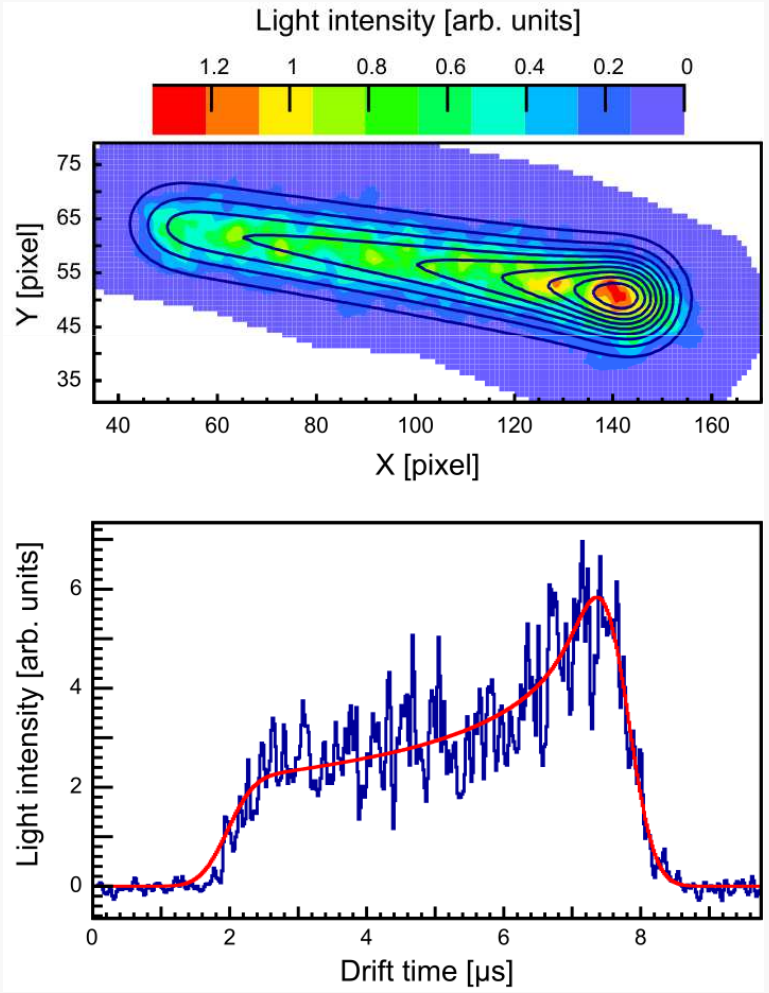




Track reconstruction

➤ A track is reconstructed by comparing the data with the SRIM simulation

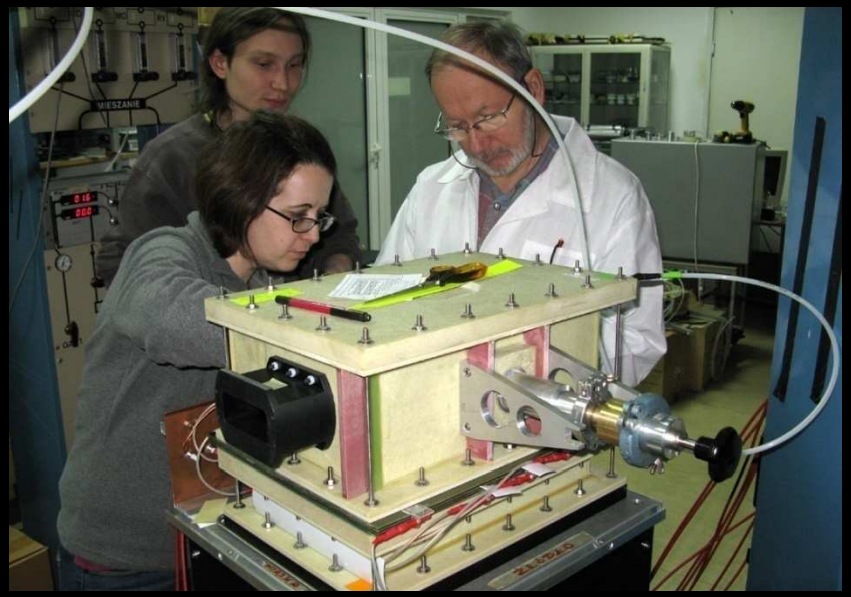


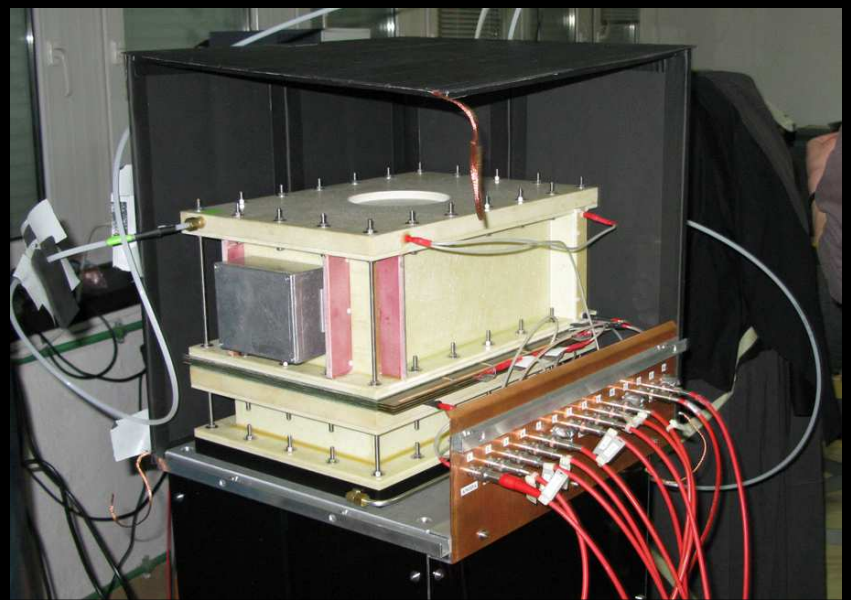


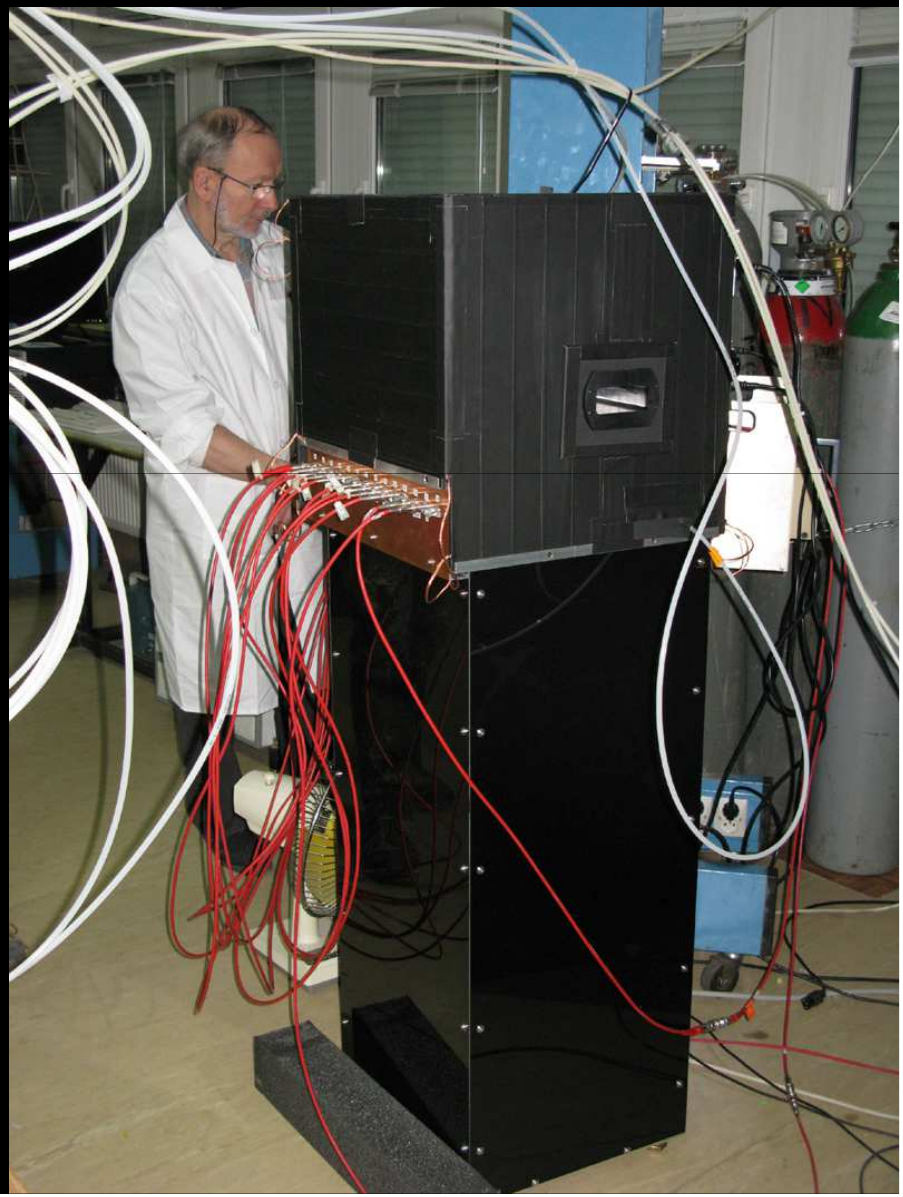
E_p = 1393 (50)(6) keV
Θ = 28 (4)(1)°

Pomorski et al., PRC 90 (14) 014311

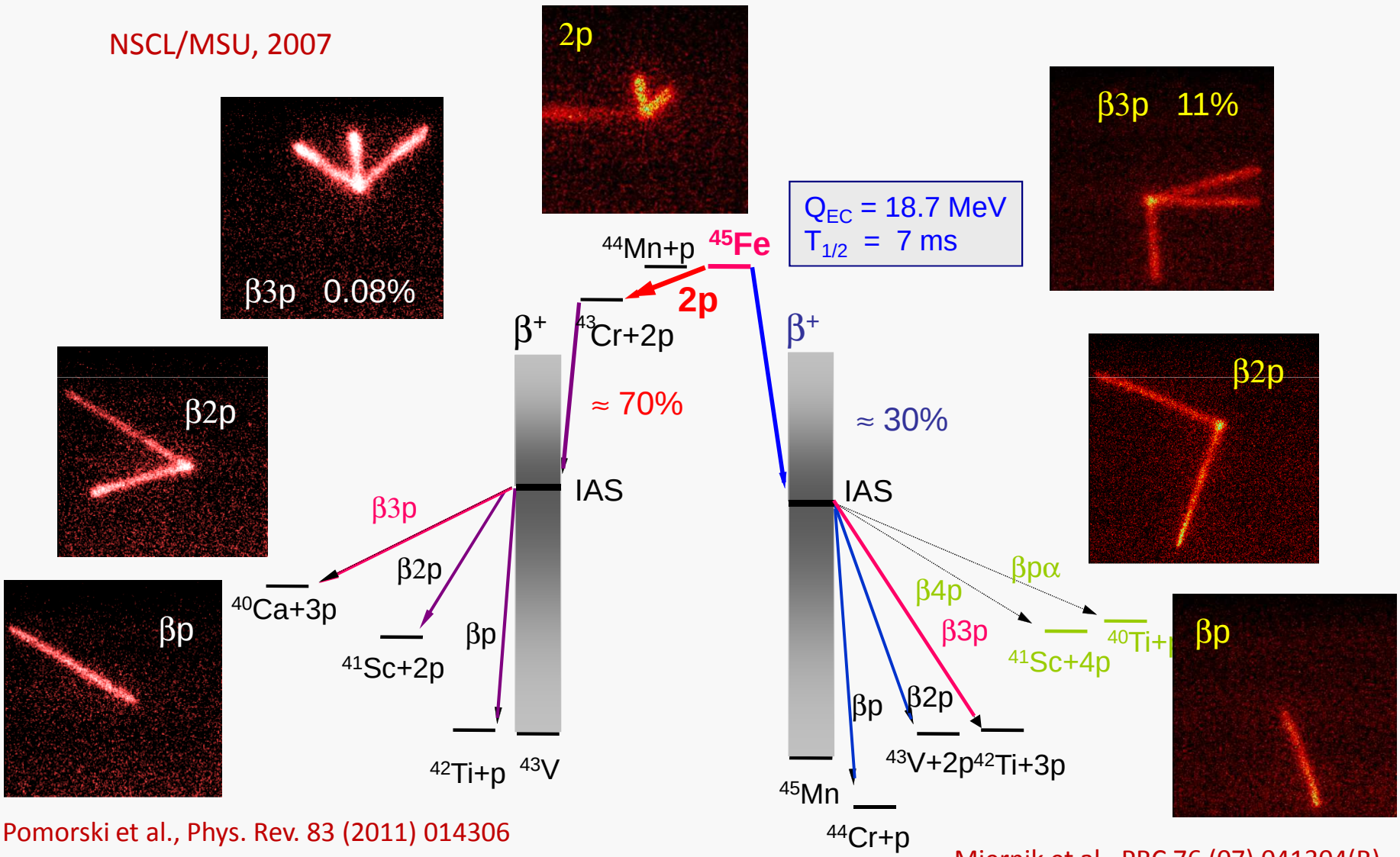
OTPC







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

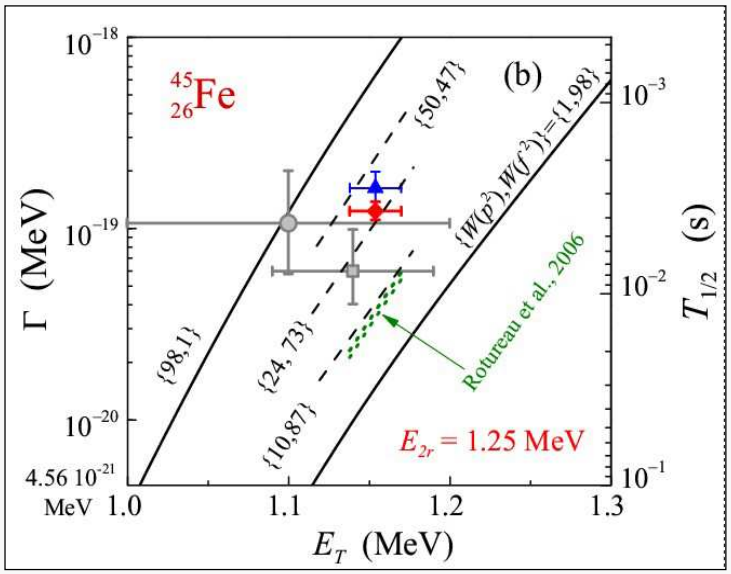


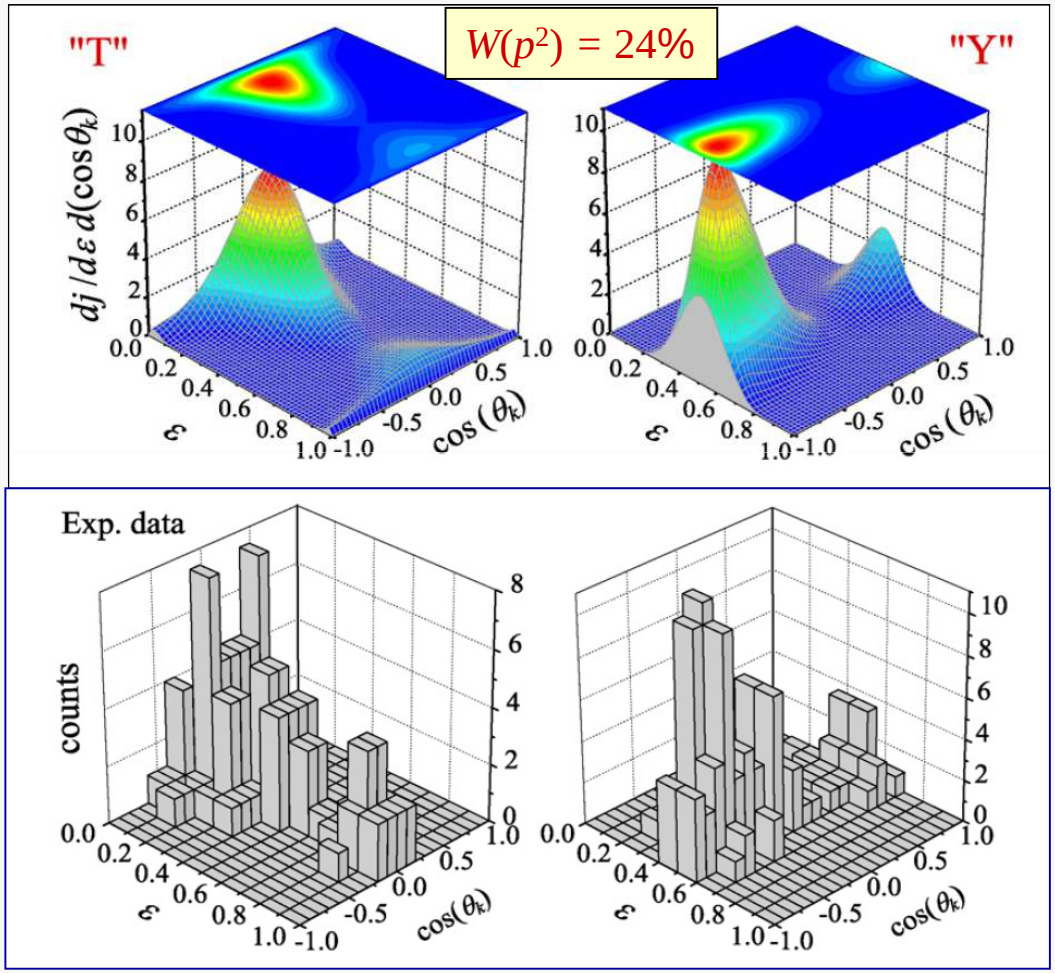
Pomorski et al., Phys. Rev. 83 (2011) 014306

Miernik et al., PRL 99 (07) 192501

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

p-p correlations from ^{45}Fe





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

- 3-body model consistently reproduces all observables for a certain composition of the initial wave function

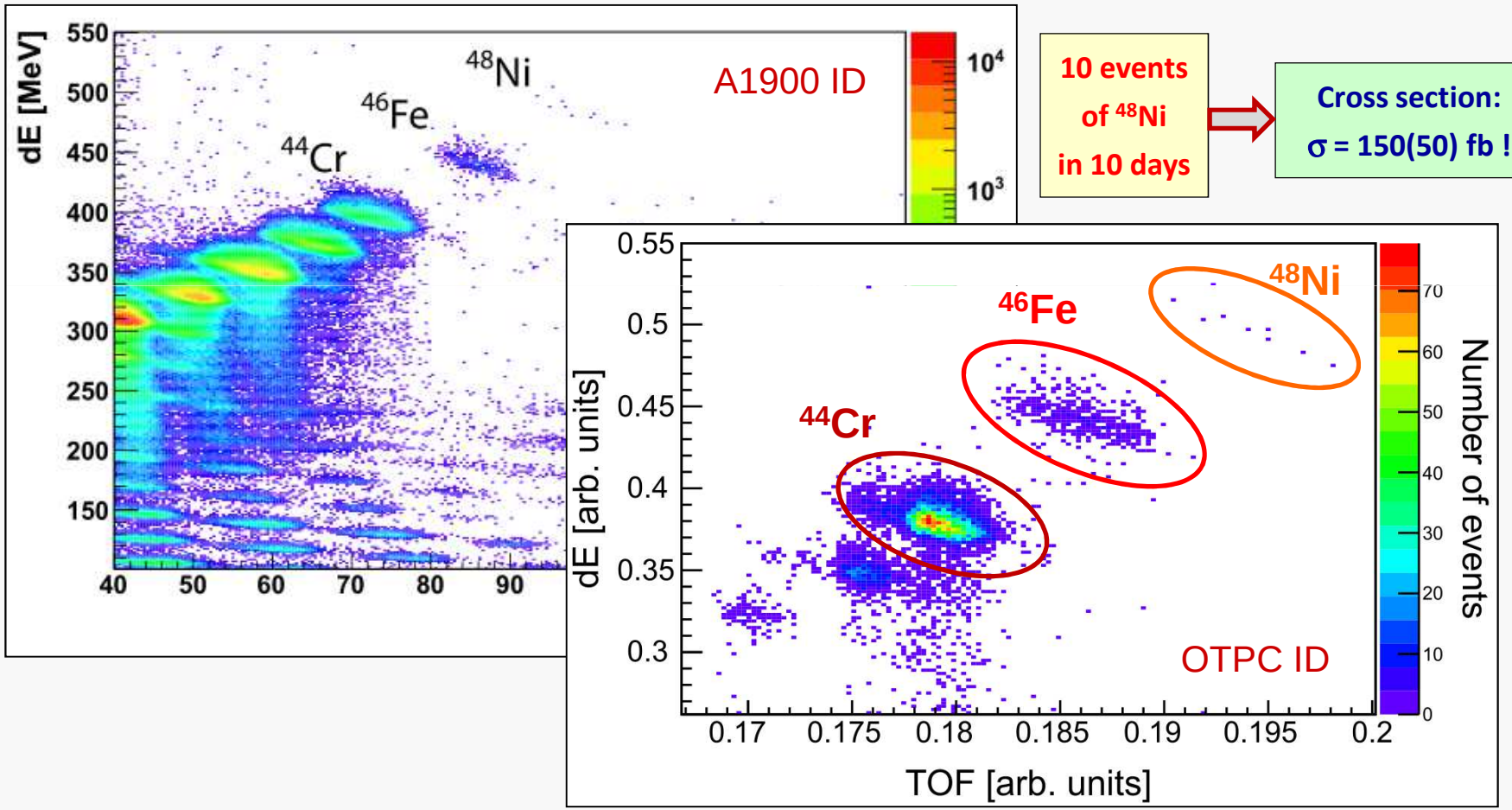
Miernik *et al.*, EPJA 42 (09) 431

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

M.P. et al., Rev. Mod. Phys. 84 (2012) 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

β-delayed protons from ^{44}Cr

5542 identified ions of ^{44}Cr

4098 properly stopped

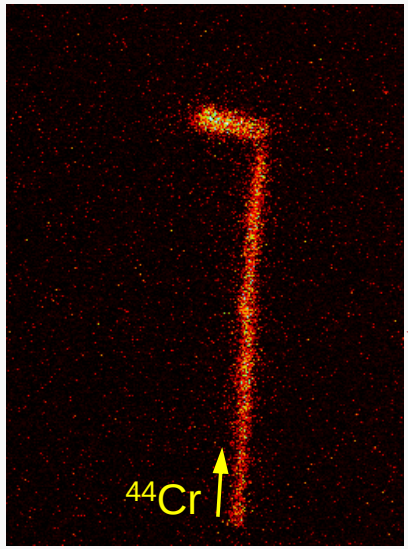
183 decays observed

→ $b_p = 10(1)\%$

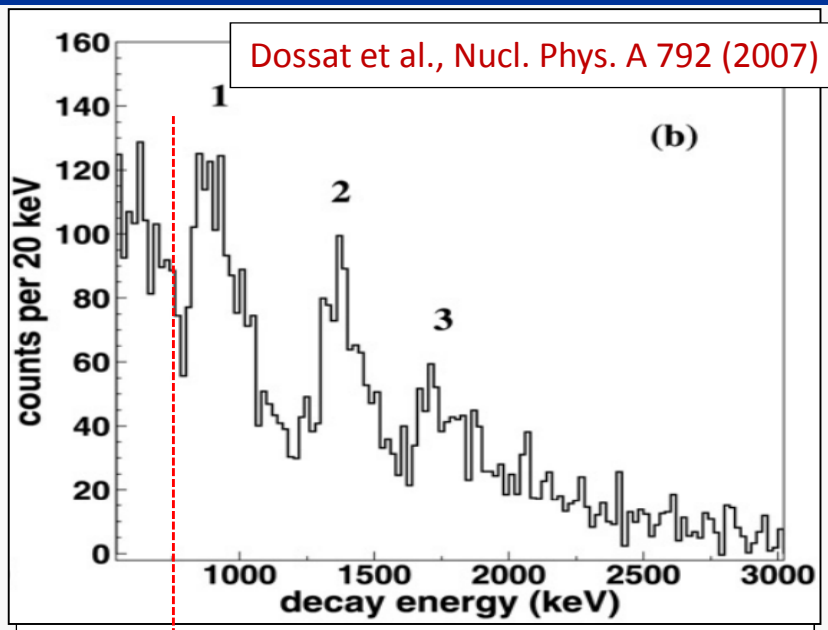
Dossat : $b_p = 14.0(9)\%$

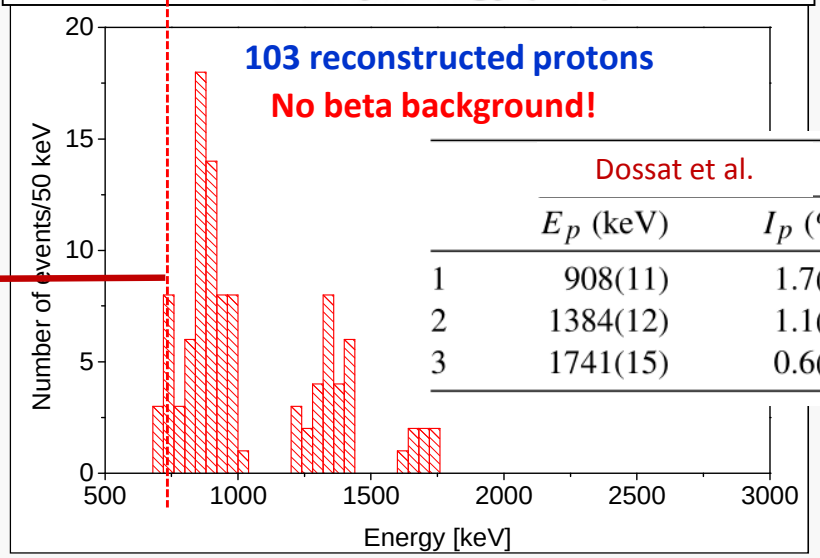
A clear new line at 740(20) keV

$I_p = 0.6(2)\%$



Dossat et al., Nucl. Phys. A 792 (2007) 18





	Dossat et al.		This work
	E_p (keV)	I_p (%)	
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

β-delayed protons from ^{46}Fe

471 identified ions of ^{46}Fe

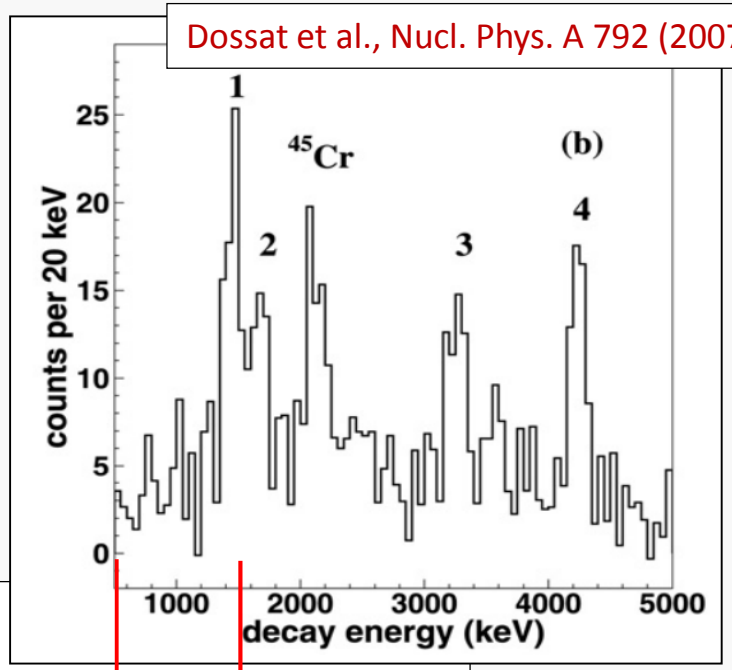
269 properly stopped

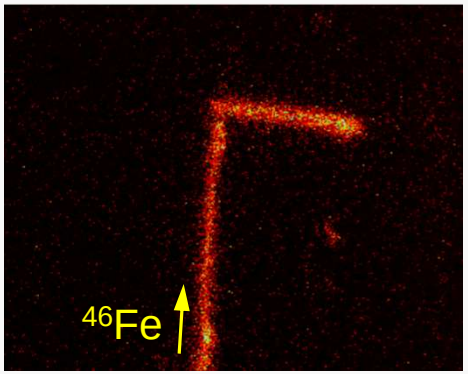
148 decays observed

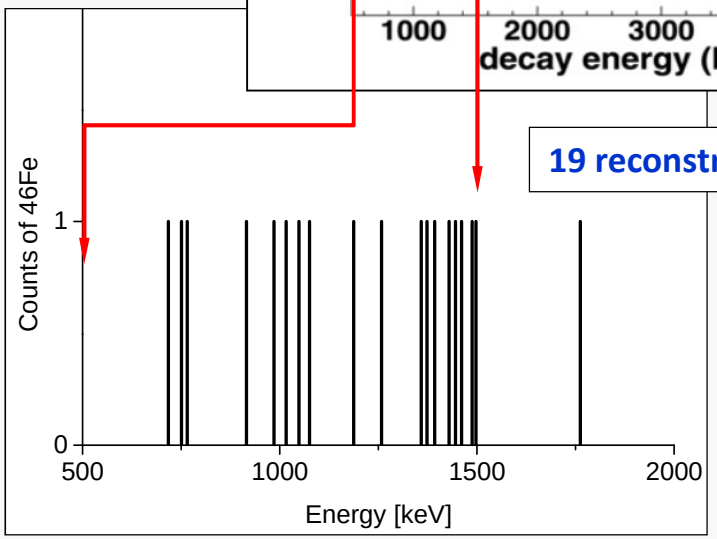
→ $b_p = 66(4)\%$

Dossat : $b_p = 79(4)\%$

Dossat et al., Nucl. Phys. A 792 (2007) 18





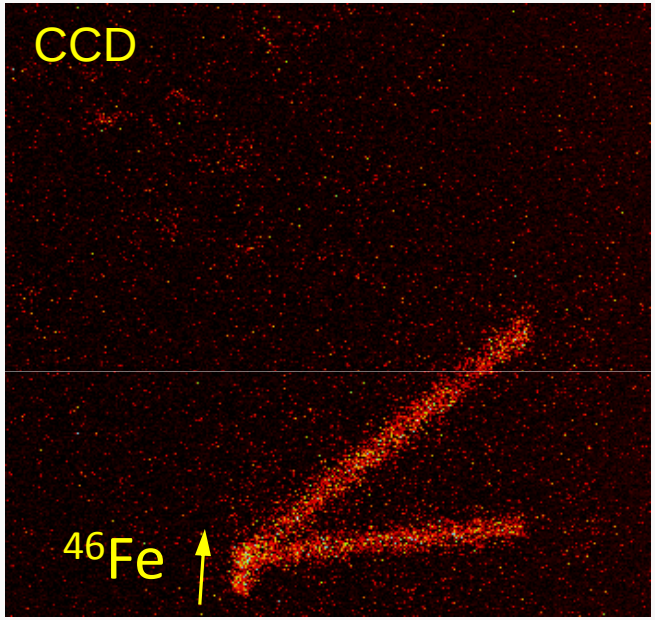


19 reconstructed protons

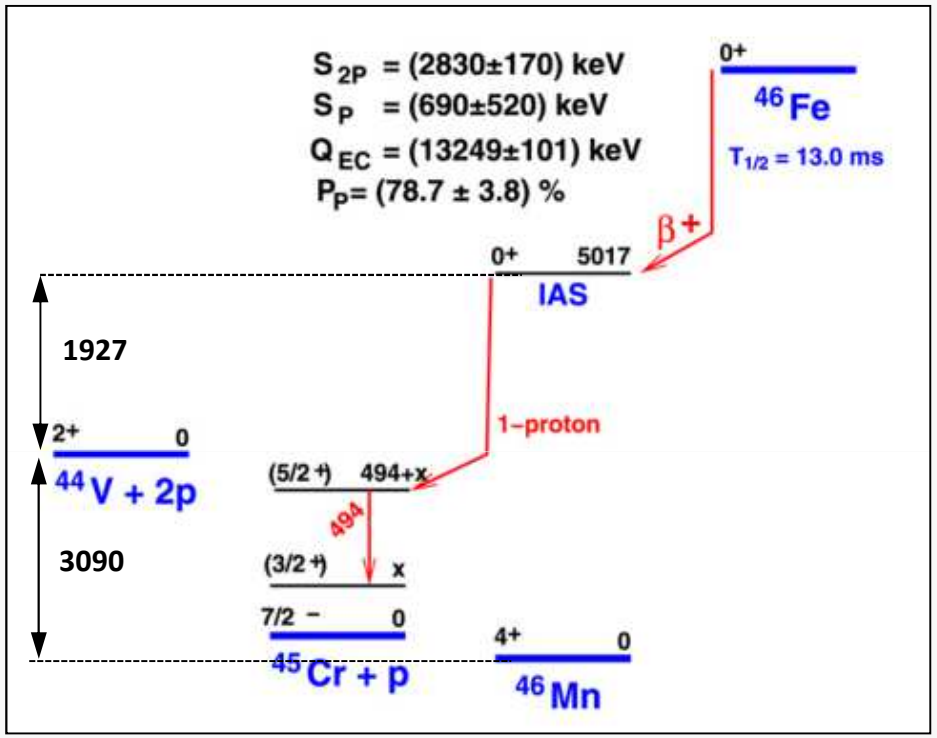
Pomorski et al., PRC 90 (14) 014311

β2p channel in ^{46}Fe

- One good event!



Pomorski et al., PRC 90 (14) 014311



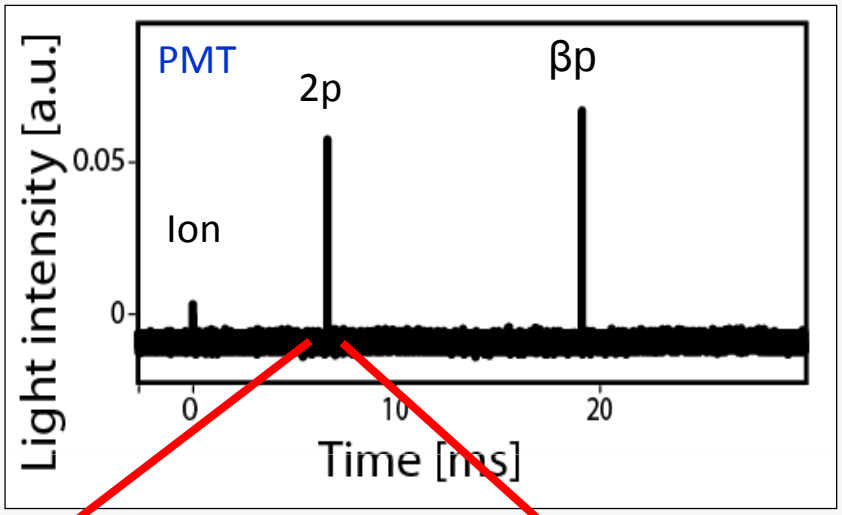
Dossat et al., Nucl. Phys. A 792 (2007) 18

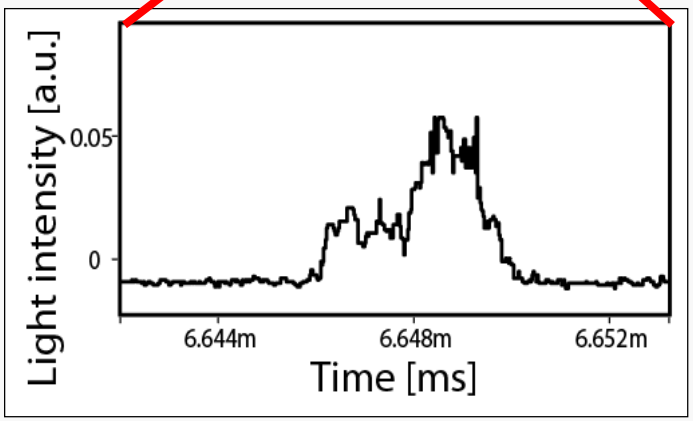
- Both protons escaped the detector.
  From the length of tracks
  we know only that:

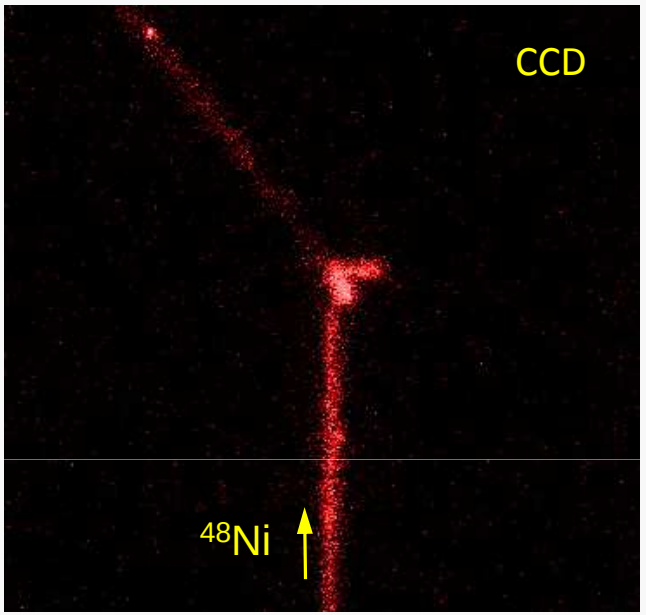
$$E_1 > 1.96 \text{ MeV}$$
$$E_2 > 1.67 \text{ MeV}$$
$$E_1 + E_2 > 3.63 \text{ MeV}$$

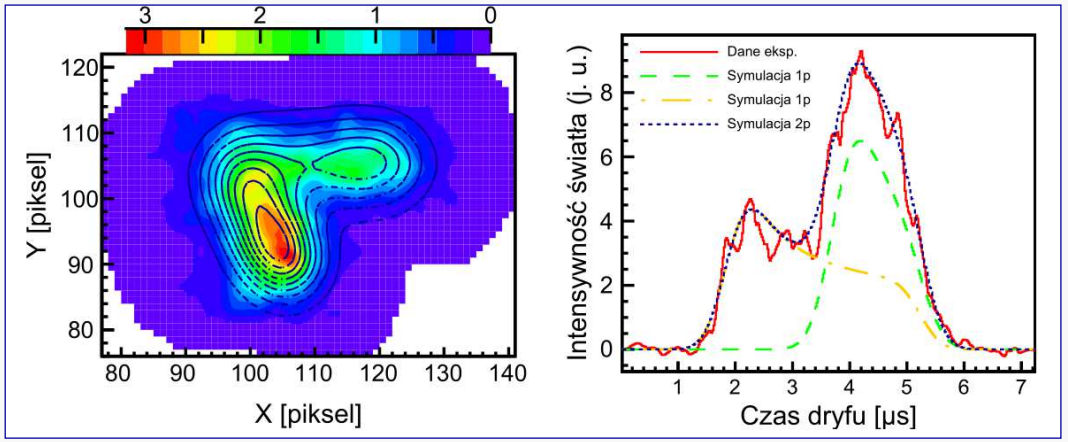
} The decay goes above the IAS!

2p decay of ^{48}Ni



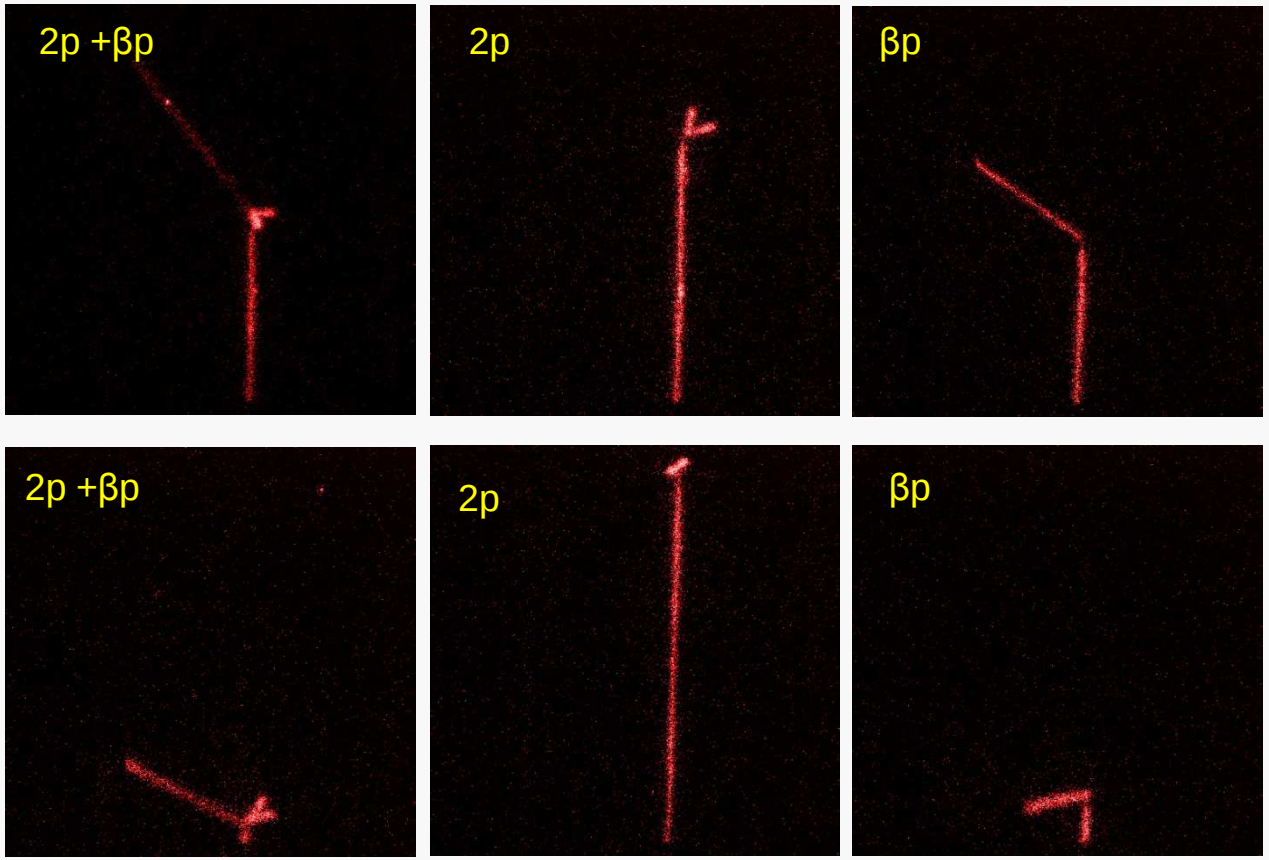






Pomorski et al., PRC 90 (14) 014311

All decays of ^{48}Ni



- Results of the full analysis:

$$Q_{2p} = 1.29(4)\ \text{MeV}$$

Brown [38]	Ormand [39]	Cole [40]
1.36(13)	1.29(33)	1.35(6)

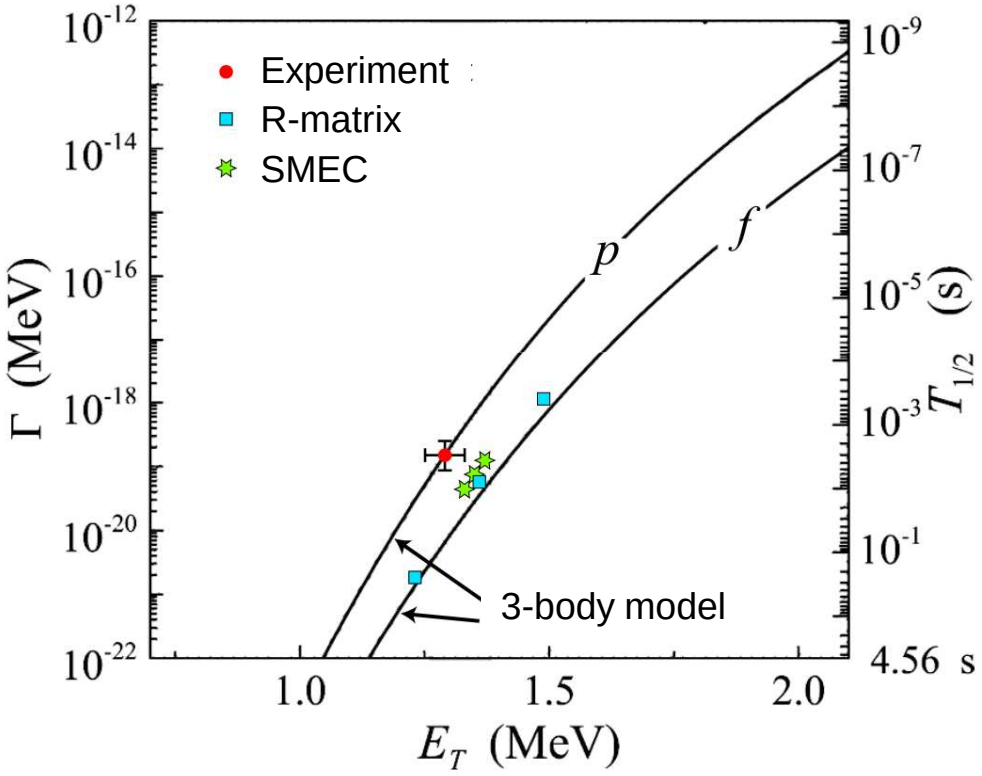
$$T_{1/2} = 2.1^{+1.4}_{-0.6}\ \text{ms}$$

$$b_{2p} = 0.7(2) \qquad b_{\beta} = 0.3(2)$$

$$\Rightarrow \quad T_{1/2}^{2p} = 3^{+2}_{-1}\ \text{ms} \qquad T_{1/2}^{\beta} = 7^{+7}_{-5}\ \text{ms}$$

2p decay of ^{48}Ni

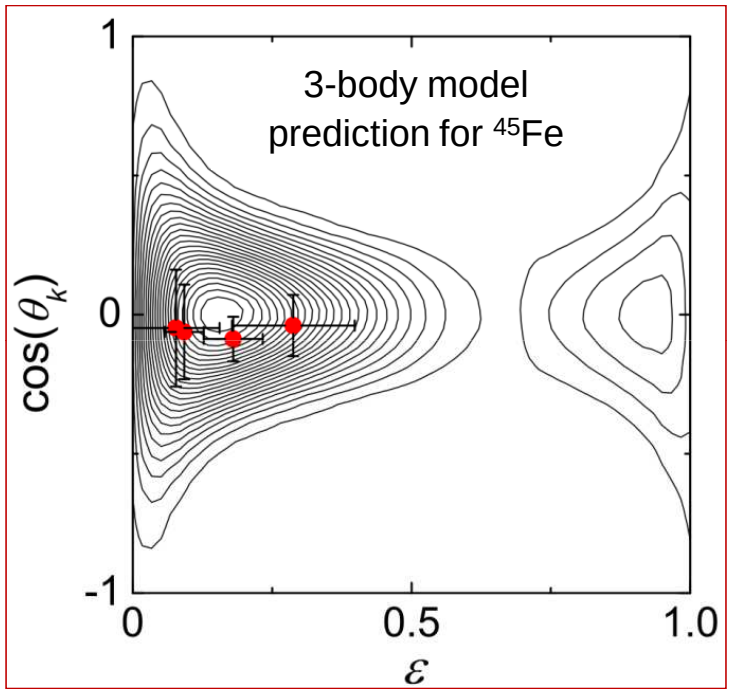
➤ Comparison with predictions



Grigorenko and Zhukov, PRC 68 (2003) 054005

Brown and Barker, PRC 67 (2003) 041304

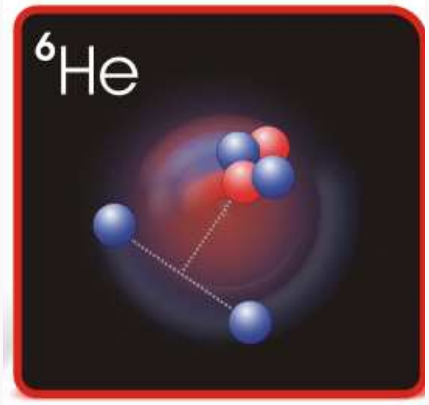
Rotureau, Okołowicz, Płoszajczak, NPA 767 (2006) 13

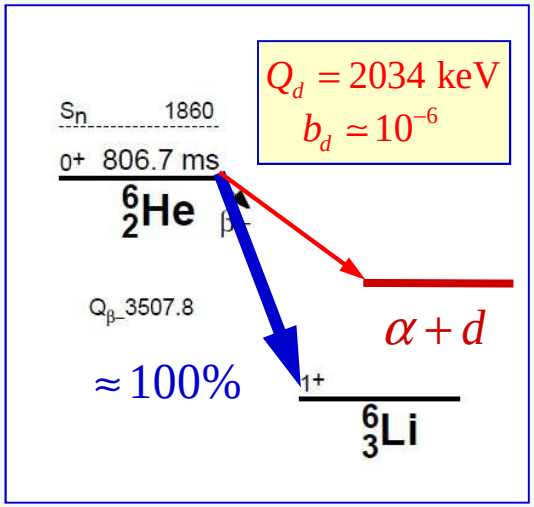


Pomorski et al., PRC 90 (14) 014311

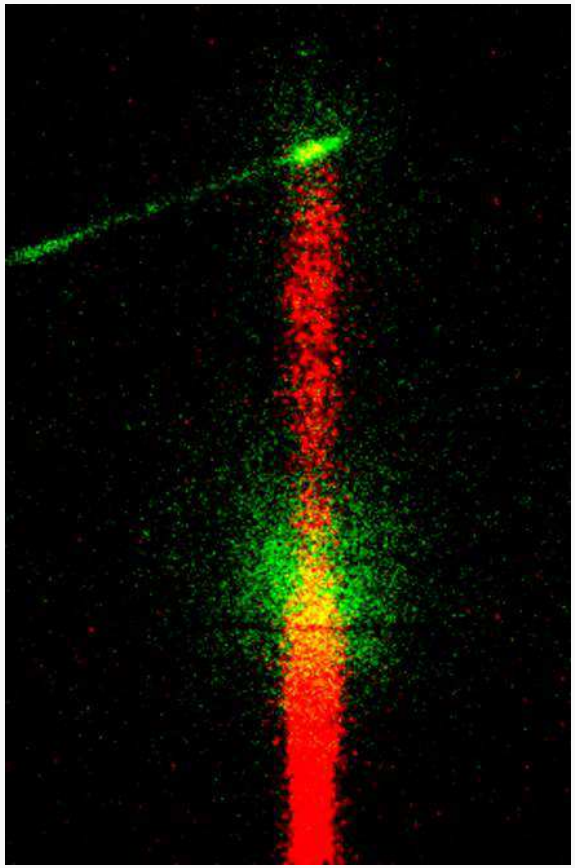
➔ Unfortunately, there are no predictions for the *p*-*p* correlations in ^{48}Ni ☹

A digression: decay of ^{6}He



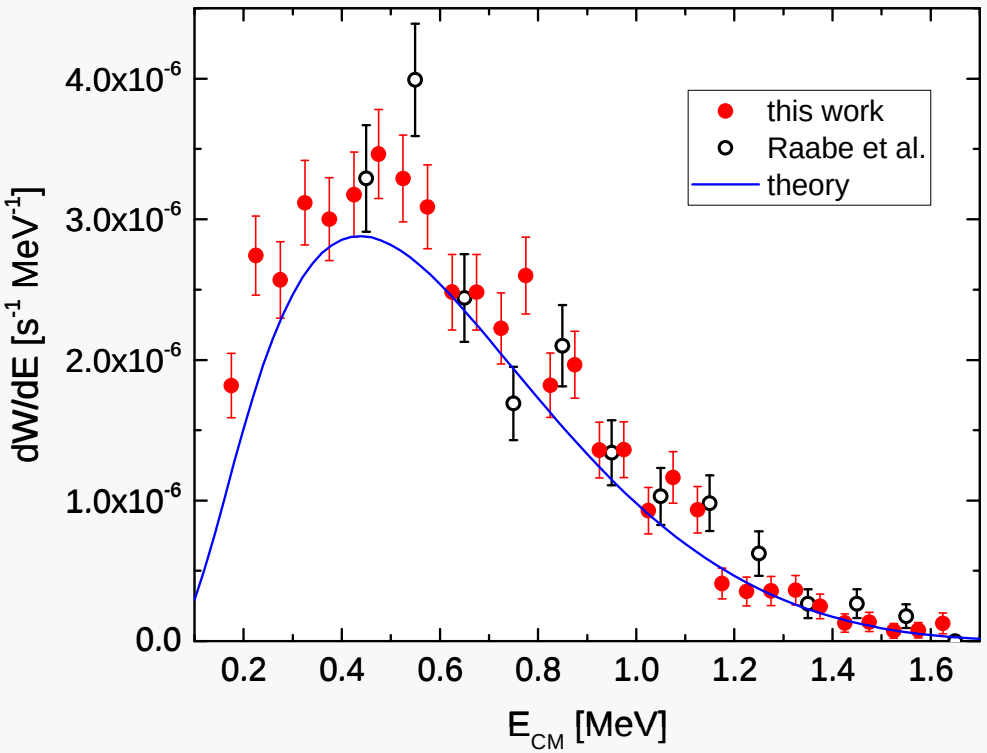


- A tiny decay branch into α + d (≈10^{-6}) provides insight into the halo of ^{6}He
- Bunches of ^{6}He ions were delivered by **REX-ISOLDE** and implanted into the OTPC
- Clear images of decay events with tracks of an α particle and a deuteron were recorded

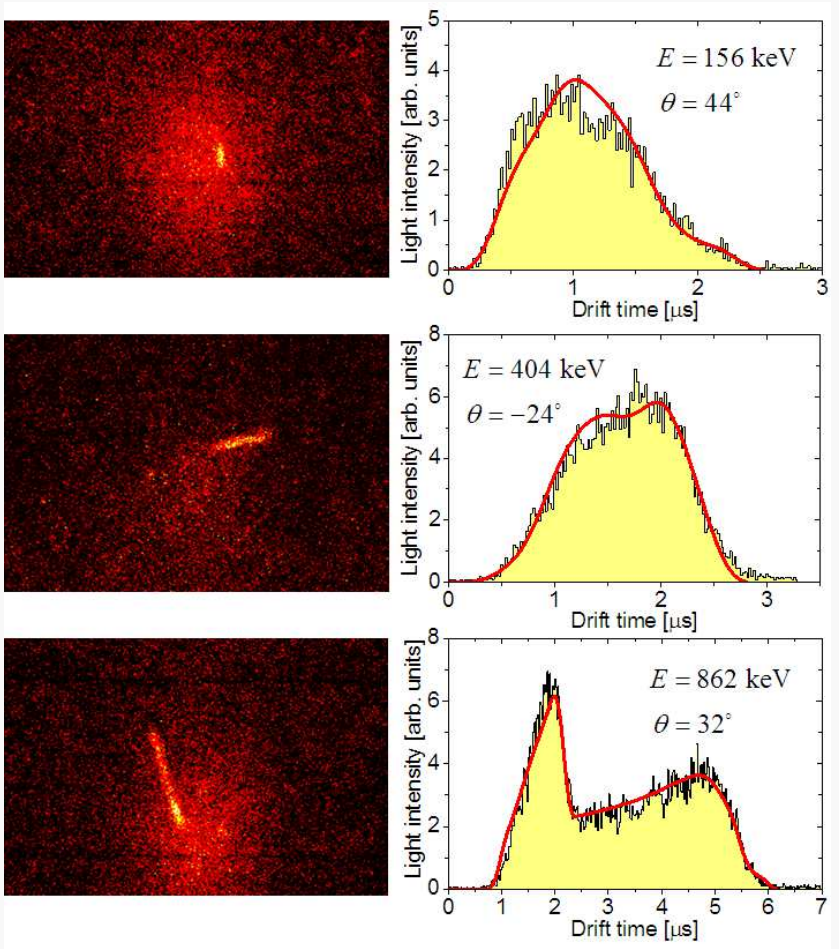


A bunch of implanted ^{6}He ions (red) and a ^{6}He → α + d decay plus background from thousands β electrons (green)

The spectrum of $\alpha + d$



Raabe et al., PRC 80 (09) 054307
theory: Tursunov, Baye, Descouvemont, PRC73 (06) 014303

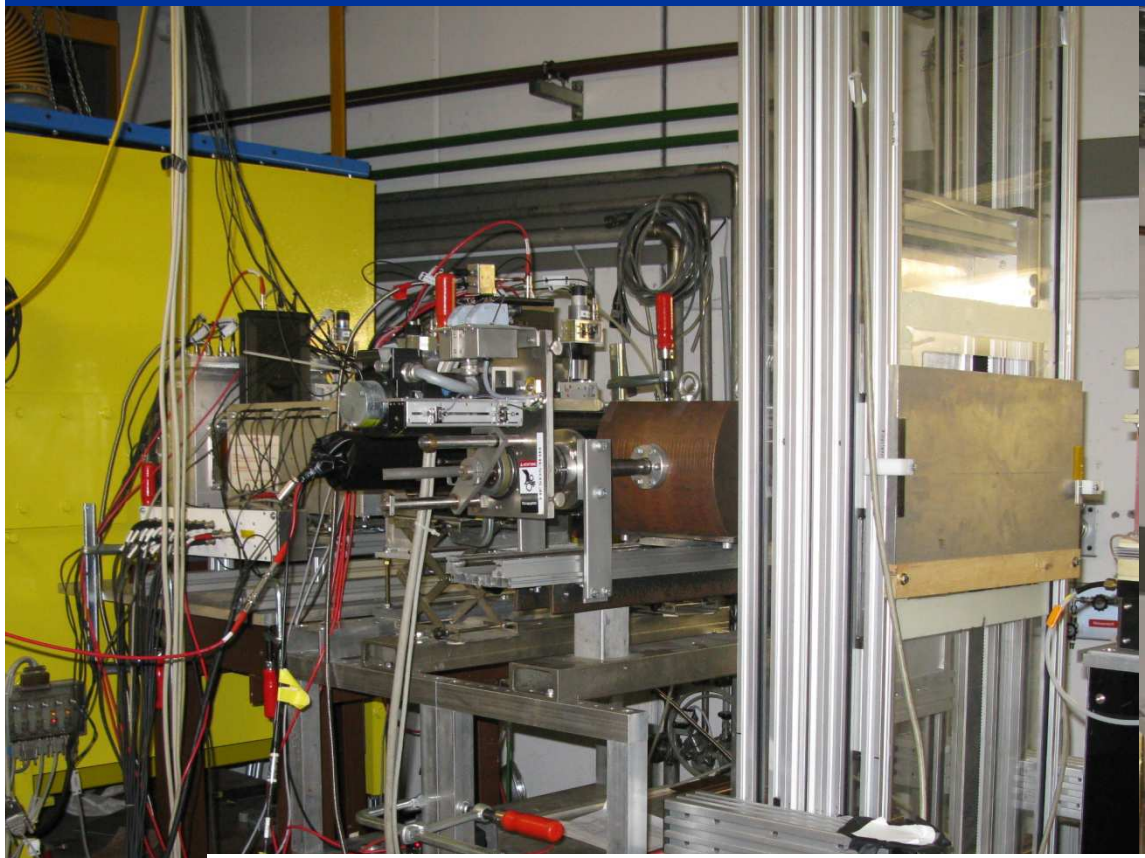


1650 decay events reconstructed

➔ By extending the spectrum to lower energy, we see 70% more intensity

M.P. et al., accepted by PRC

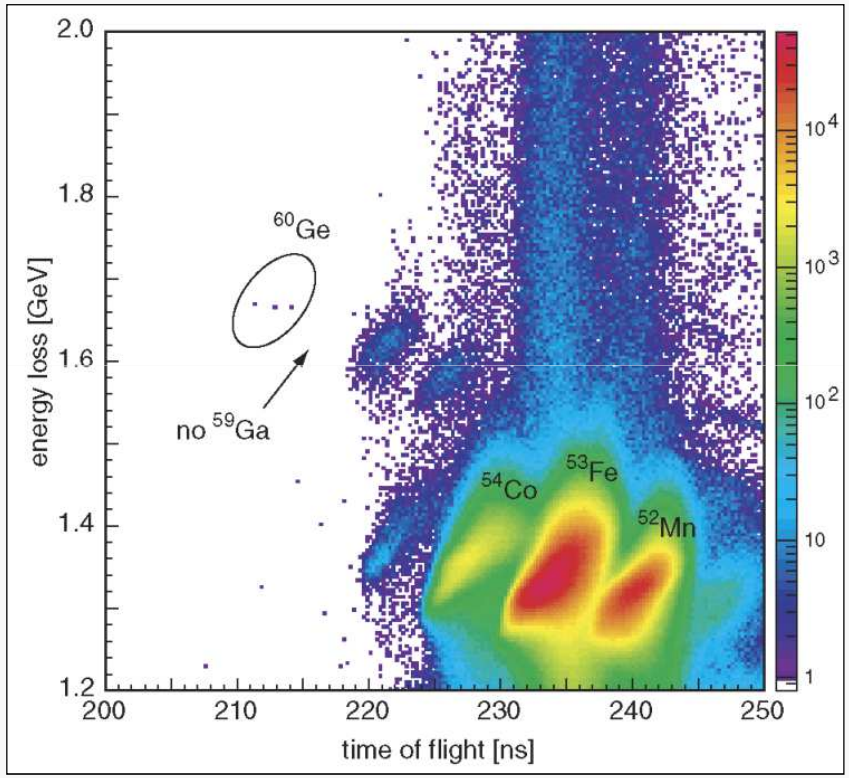
An advertisement



- We used the OTPC also at the FRS @ GSI Darmstadt
  We took along a young student, and she will tell you the story later this session

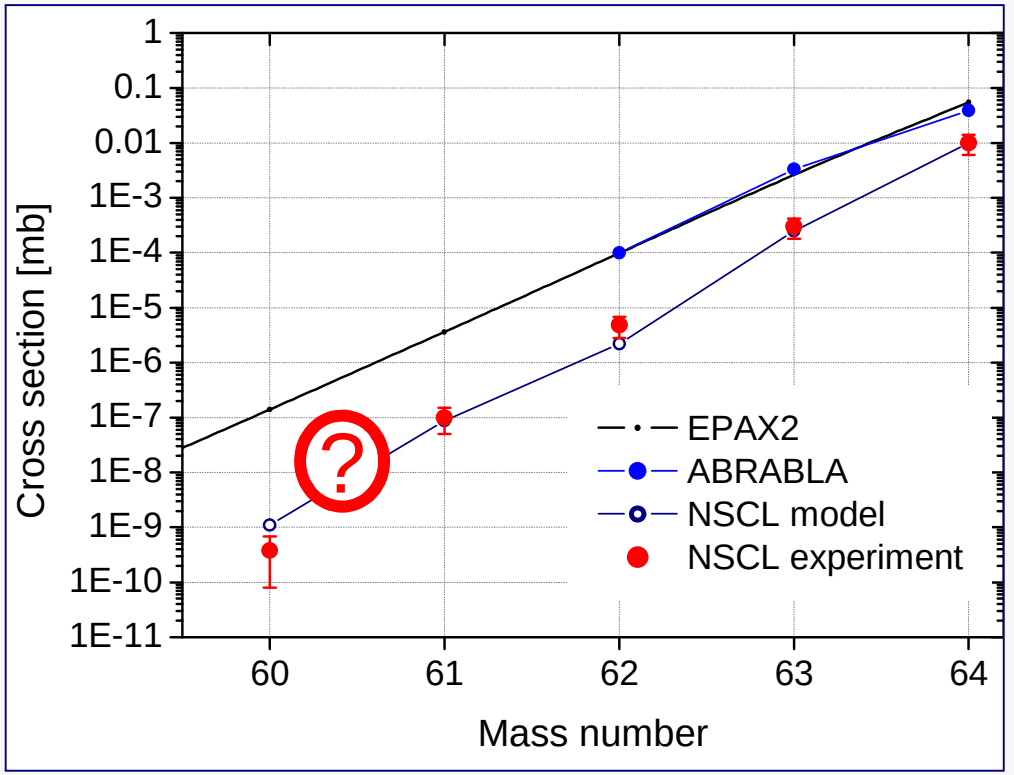
Ge isotopes at the proton drip-line

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



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

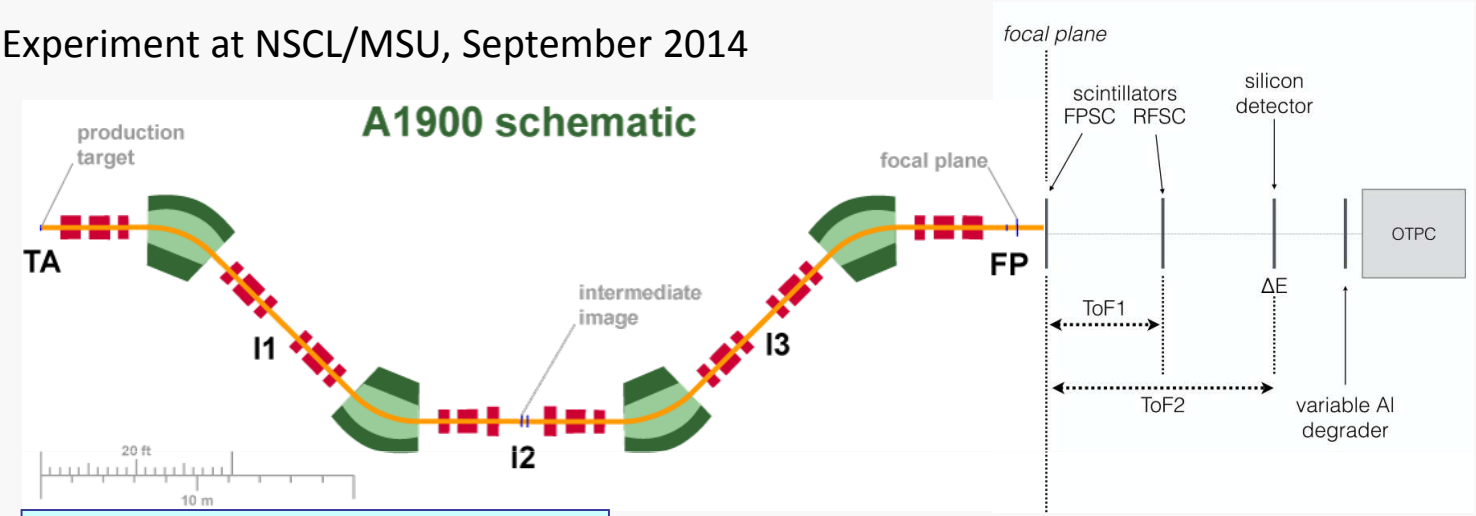
A1900: ^{78}Kr @ 140 MeV/u + Be



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

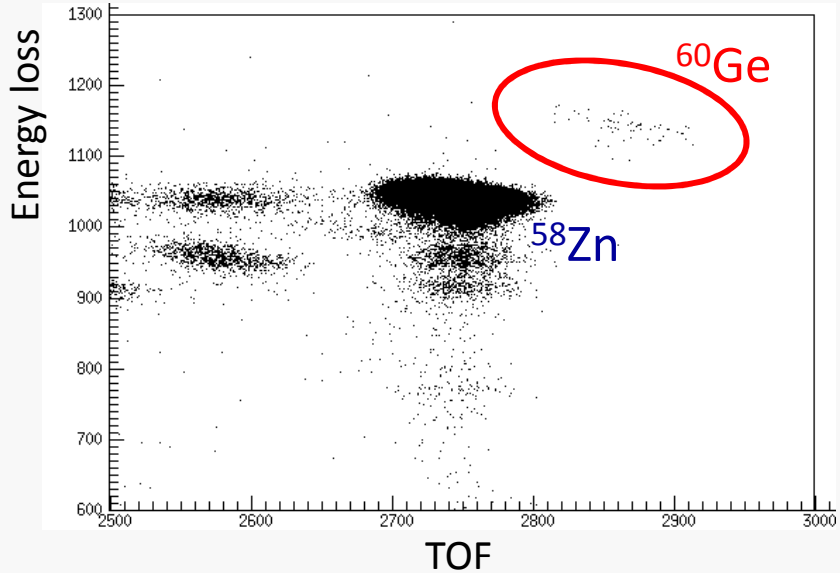


A1900: ^{78}Kr @ 150 MeV/u + Be

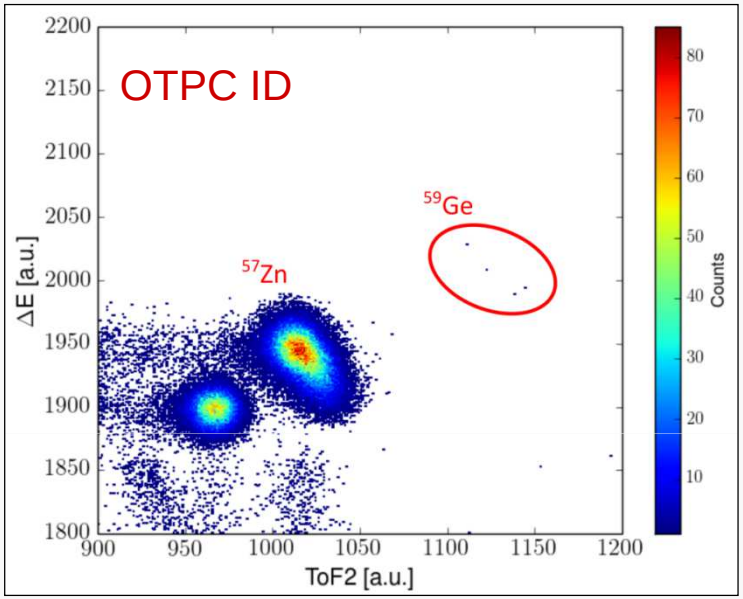
→ 73 atoms of ^{60}Ge identified!
Delayed protons observed, analysis in progress

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

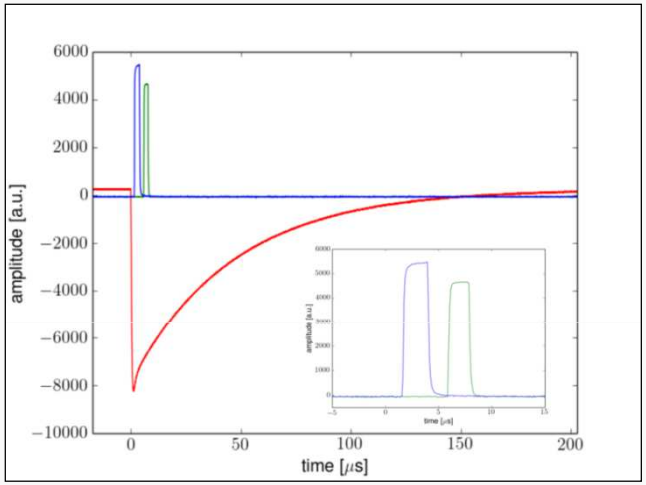
→ Search for ^{59}Ge

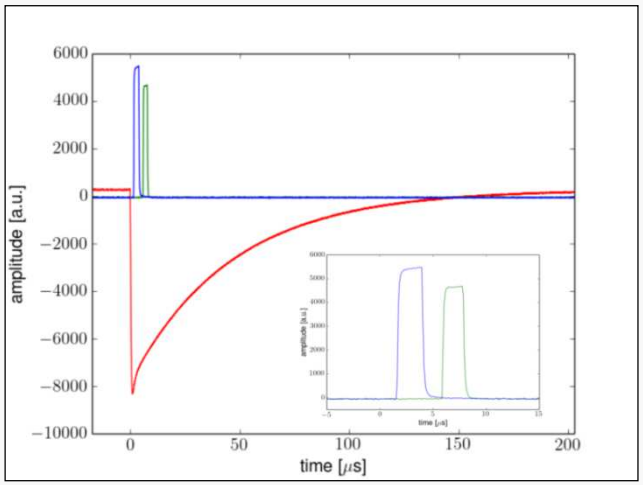


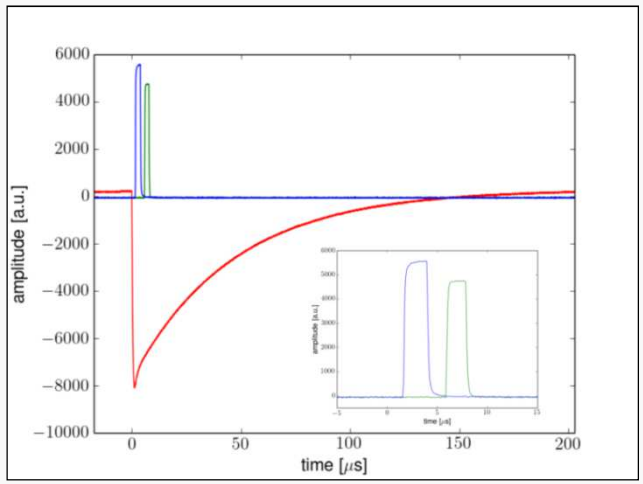
First observation of ^{59}Ge



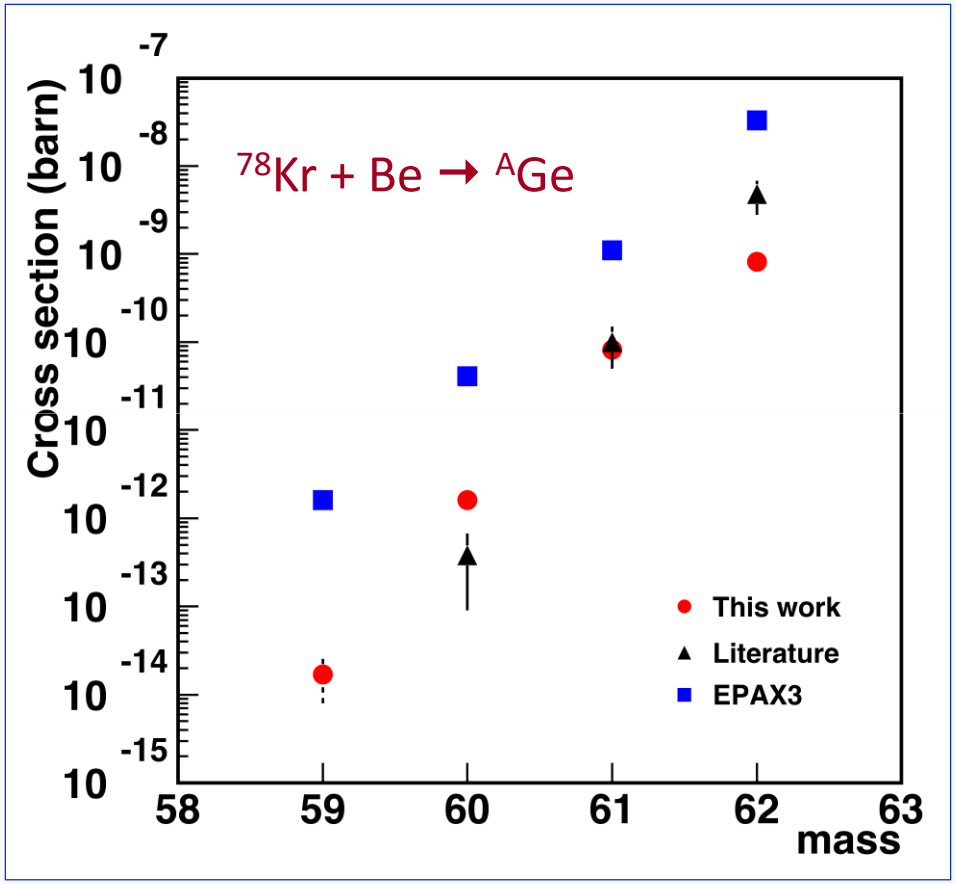
A. Ciemny et al., accepted by PRC

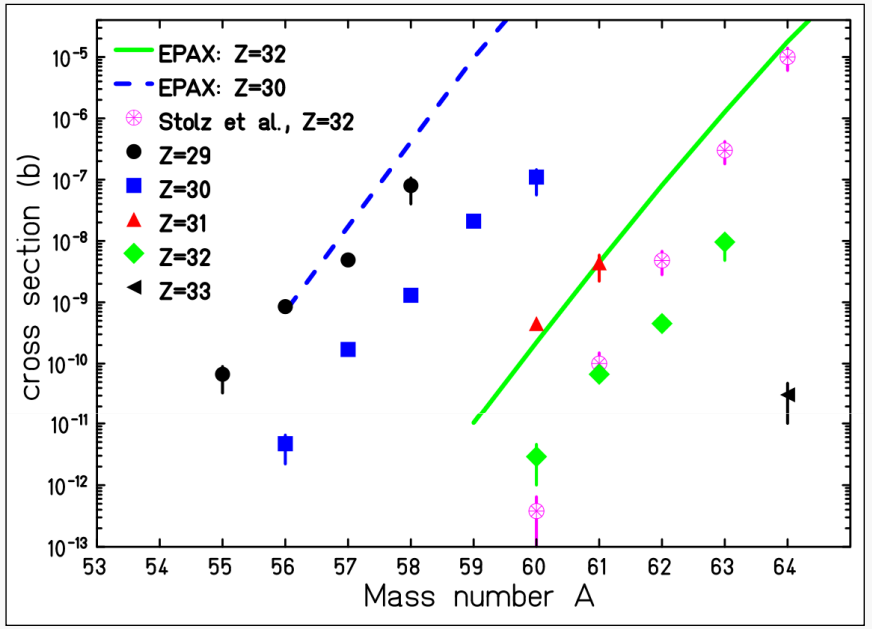






Cross section for Ge isotopes





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. But at RIKEN one can go even further…

Summary

- 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,…), observed for the first time.
  β2p emission identified in ^{46}Fe based on one atom decay!
- New neutron-deficient isotope ^{59}Ge identified, first decay data for ^{60}Ge collected.
- Perhaps, one day we could use the OTPC at Lanzhou?

Thank you!