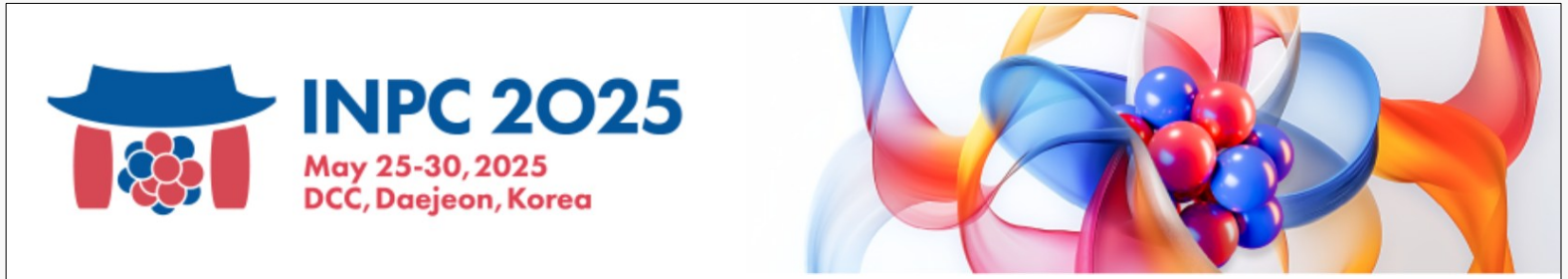
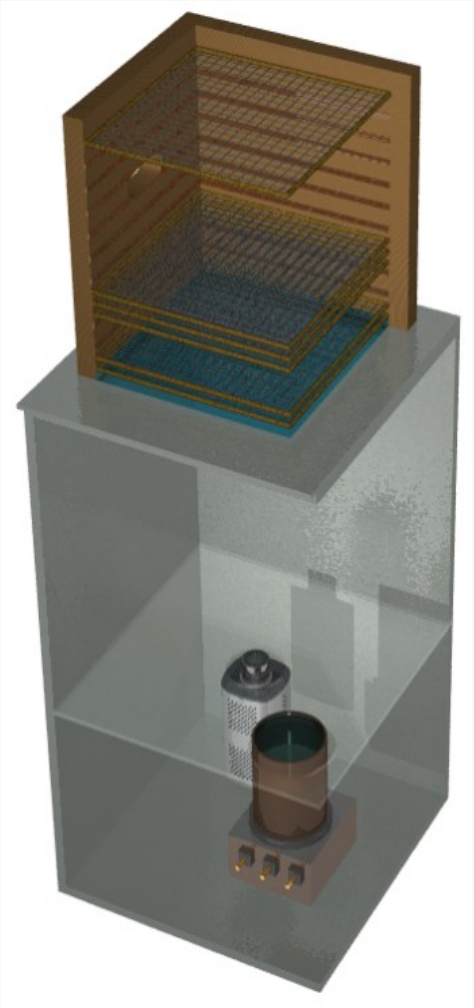
Charged particle spectroscopy with an optical time-projection chamber

Marek Pfützner

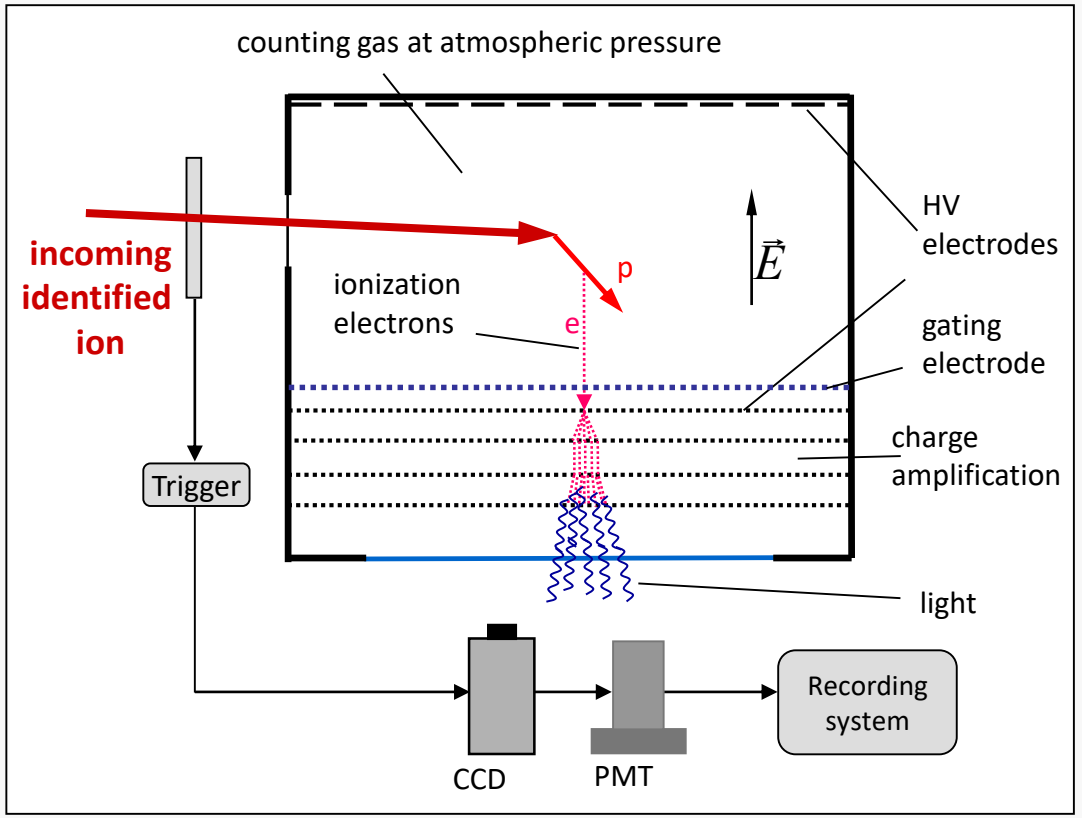
Nuclear Physics Division
University of Warsaw



The Warsaw Optical TPC

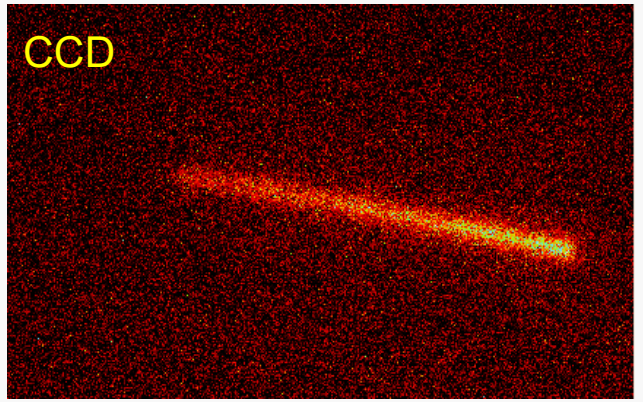


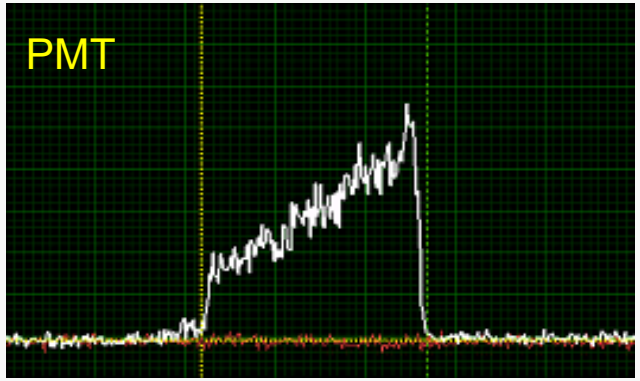
Time projection chamber with optical readout (OTPC)



Combination of the CCD image with the PMT waveform allows full reconstruction of one (two) tracks in 3-D

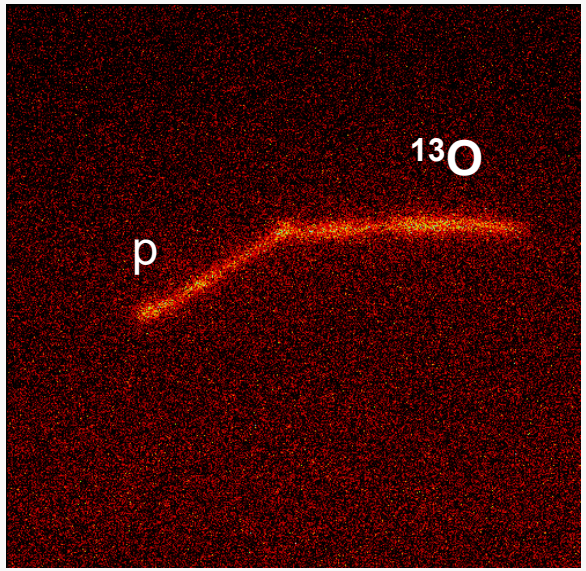
α particle

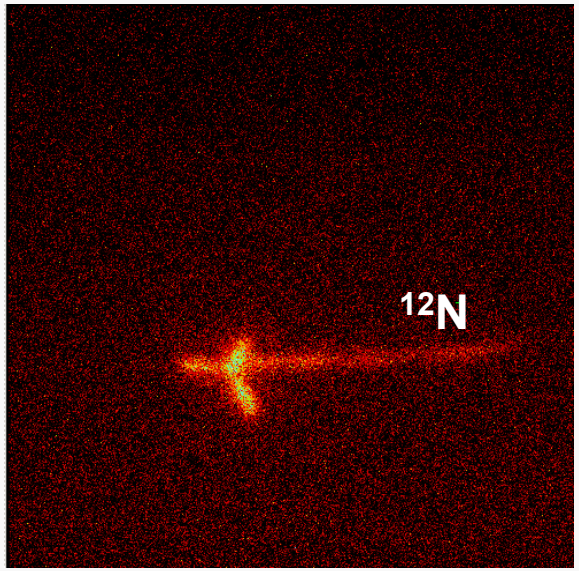


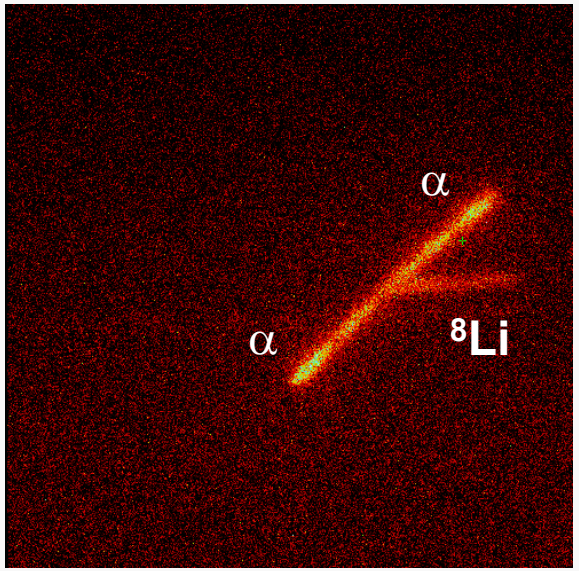


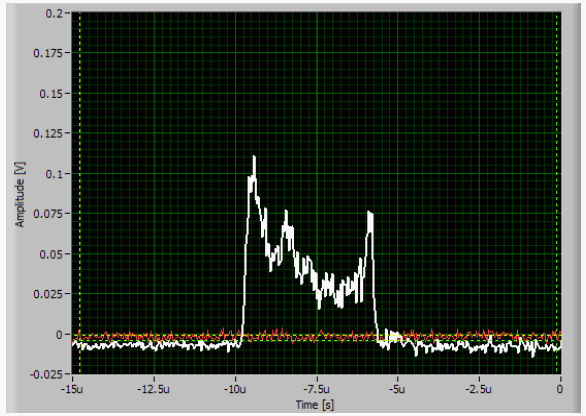
First results with a prototype

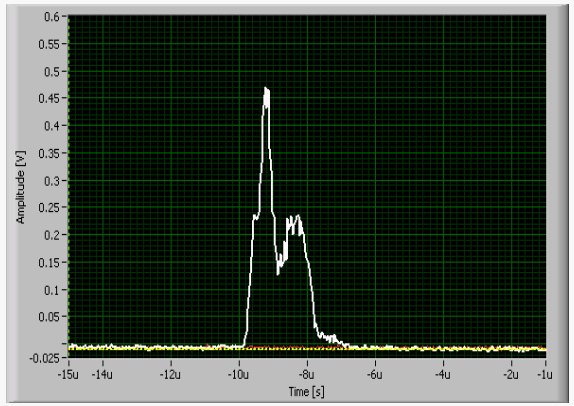
Dubna 2006: ^{20}Ne at 50 MeV/u + Be → ^{13}O, ^{12}N, ^{8}Li

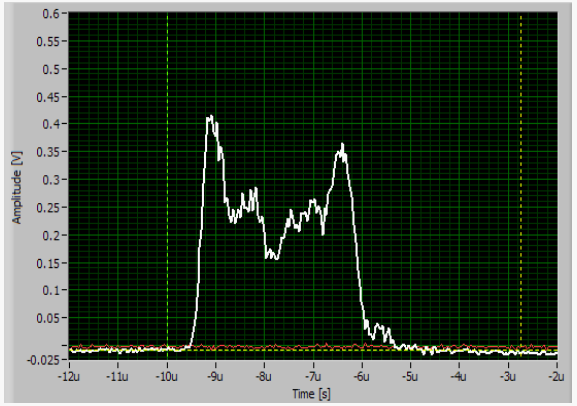






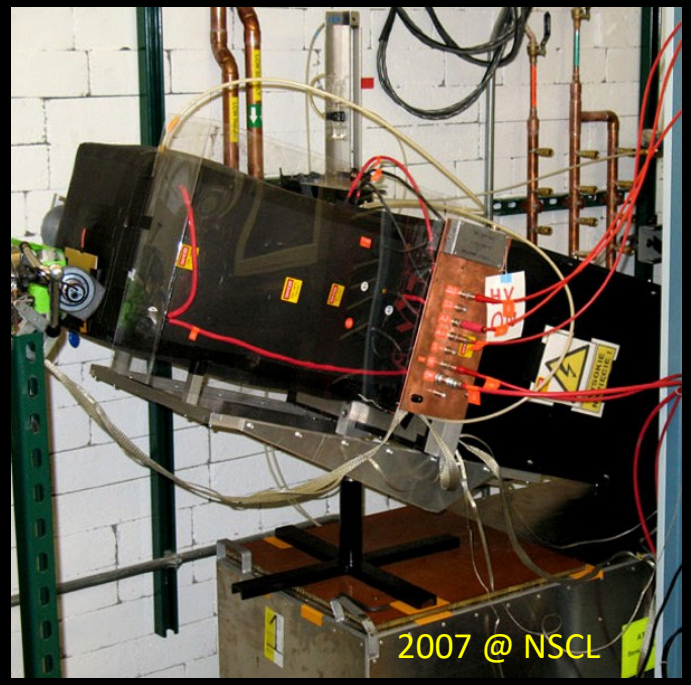






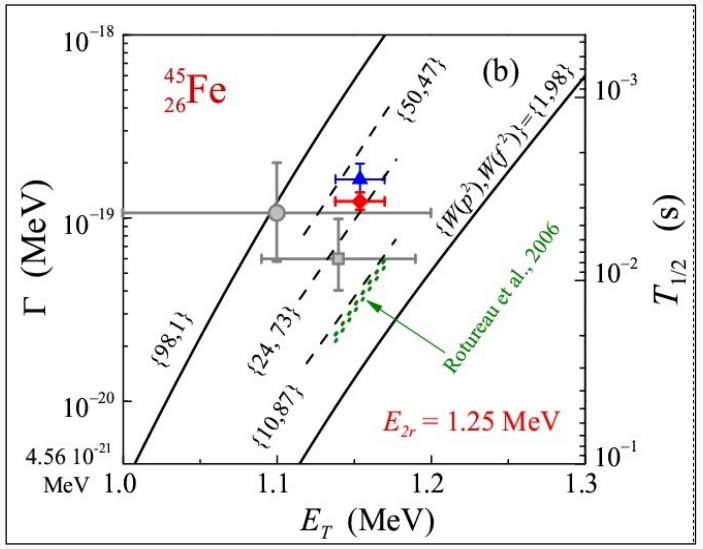
Miernik et al., NIM A581 (2007)

OTPC milestones



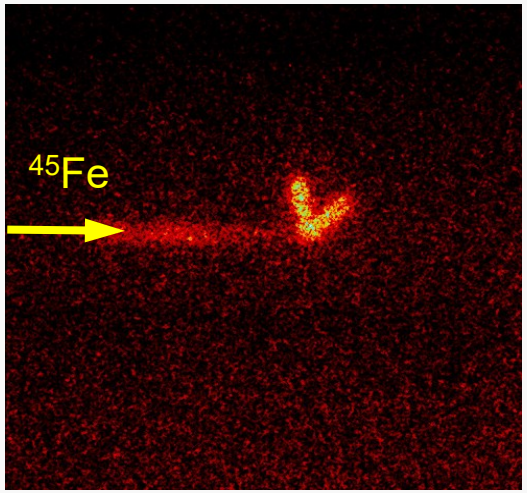
p-p momentum correlations for ^{45}Fe

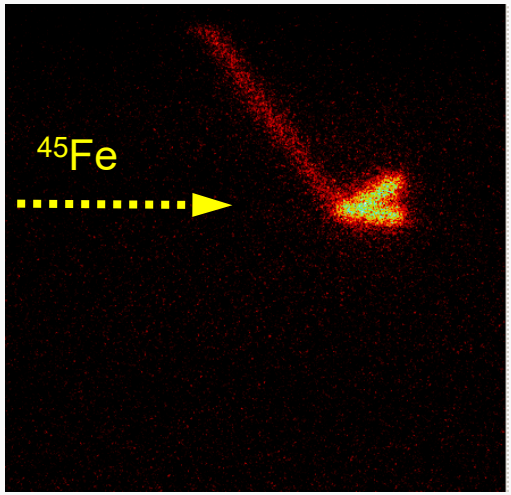
NSCL 2007: ^{58}Ni @ 161 MeV/u + Ni → ^{45}Fe

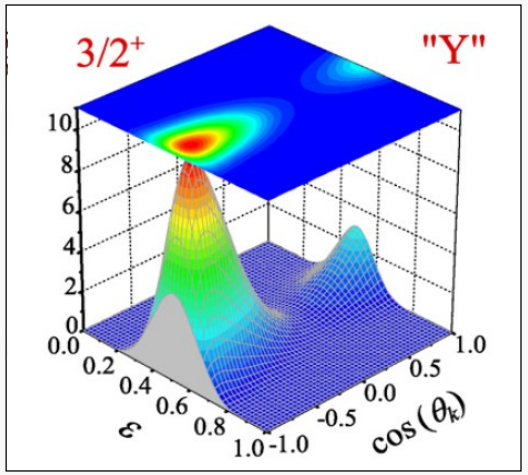


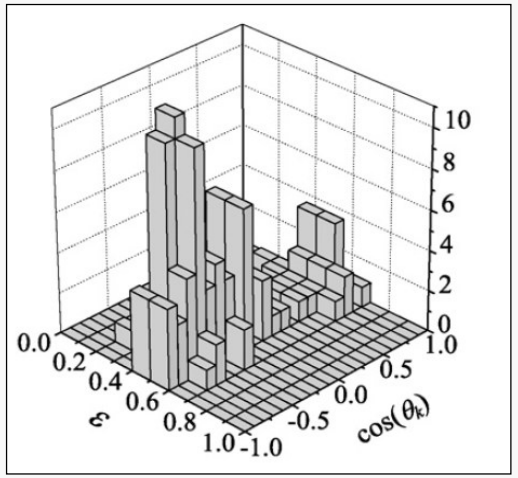
Result for ^{45}Fe: W(p^2) = 0.3±0.1

Miernik et al., PRL 99 (2007)









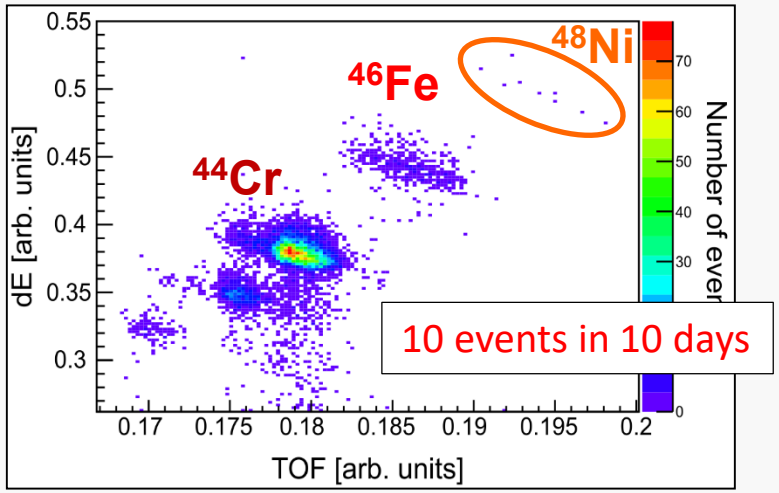
Grigorenko *et al.*, Phys. Lett. B 667 (2009)

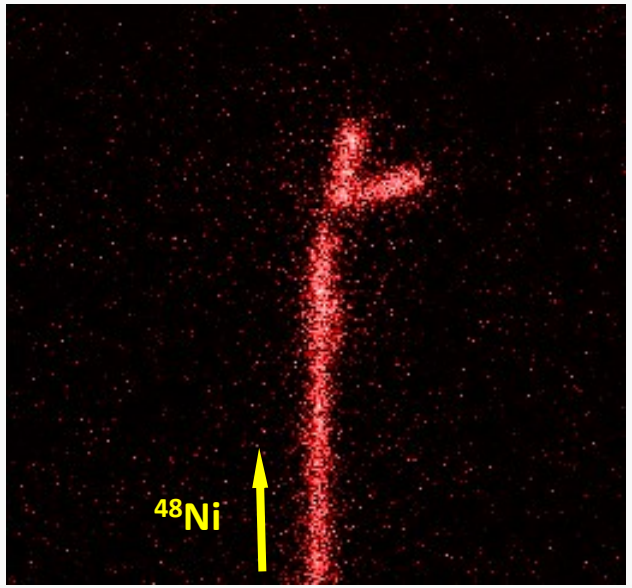
75 events reconstructed

- Proton-proton correlations are complex and indicate a genuine 3-body phenomenon
- Good agreement with the 3-body model of Grigorenko et al.
- The correlation picture depends on the initial wave function

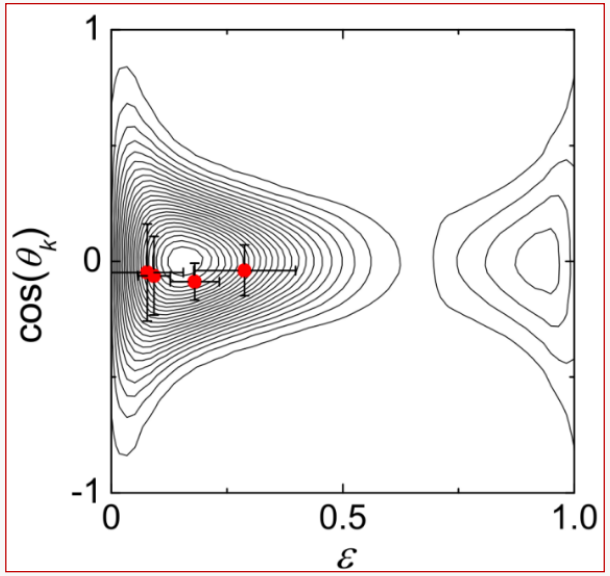
2p radioactivity of ^{48}Ni

NSCL 2011: ^{58}Ni @ 161 MeV/u + Ni → ^{48}Ni



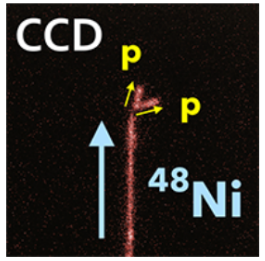


Pomorski et al., PRC 83 (2011)



Physical Review C 50th Anniversary Milestones

PHYSICAL REVIEW C



First observation of two-proton radioactivity in ^{48}Ni

A rare form of radioactivity, in which a proton-laden nucleus decays toward stability via the simultaneous emission of two protons, was observed for ^{48}Ni. Using an optical time-projection chamber, the two-proton emission of four ^{48}Ni nuclei produced at the National Superconducting Cyclotron Laboratory was captured for the first time on CCD camera, marking a new era of optical detection of sub-atomic charged-particle processes in nuclear physics.

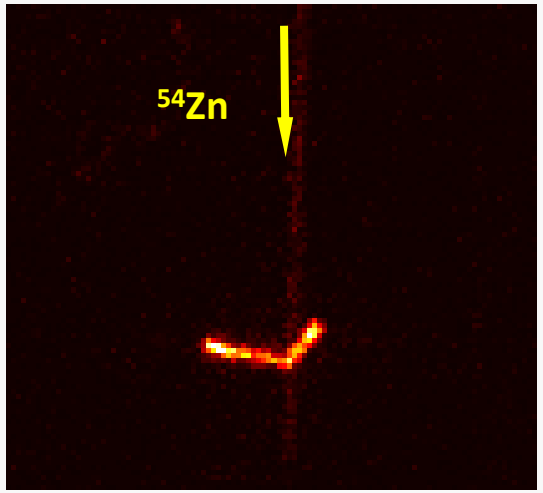
First observation of two-proton radioactivity in ^{48}Ni

M. Pomorski, M. Pfützner, W. Dominik, R. Grzywacz, T. Baumann, J. S. Berryman, H. Czyrkowski, R. Dąbrowski, T. Ginter, J. Johnson, G. Kamiński, A. Kuźniak, N. Larson, S. N. Liddick, M. Madurga, C. Mazzocchi, S. Mianowski, K. Miernik, D. Miller, S. Paulauskas, J. Pereira, K. P. Rykaczewski, A. Stolz, and S. Suchyta

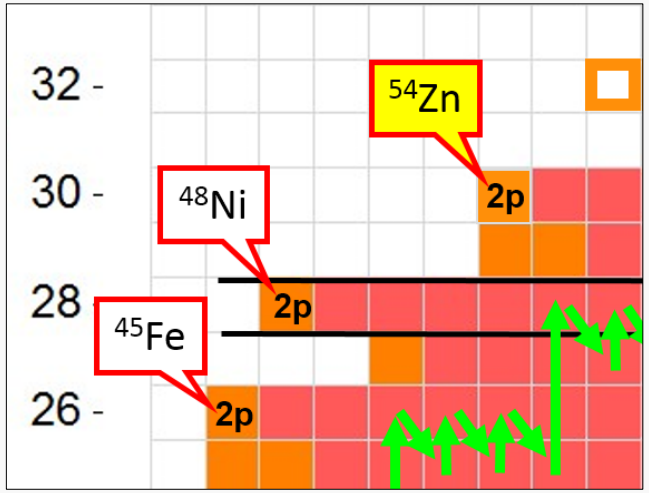
2p decay of ^{54}Zn

RIKEN, 2019: ^{78}Kr @ 350 MeV/u + ^{9}Be → ^{54}Zn

The production X-section: σ = 3.5 ± 0.8 ± 0.7 fb

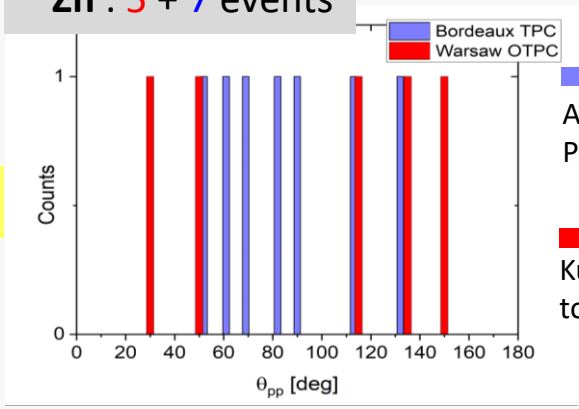


Can 2p emission tell us something on Z=28 shell closure?



Z=30

^{54}Zn : 5 + 7 events

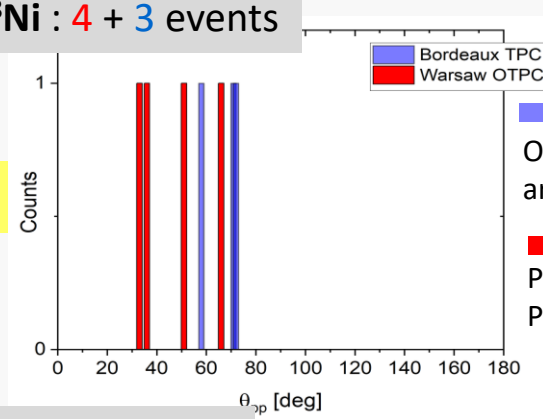


Ascher et al
PRL 107 (2011)

Kubiela et al.,
to be published

Z=28

^{48}Ni : 4 + 3 events

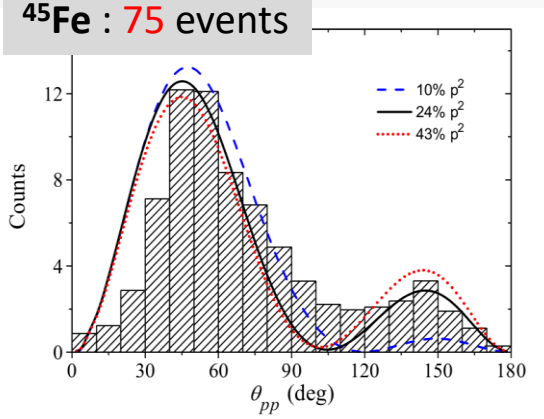


Ortega Moral et al.,
arXiv:2504.14607

Pomorski et al
PRC 90 (2014)

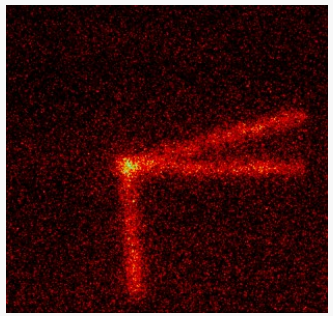
Z=26

^{45}Fe : 75 events



Miernik et al
PRL 99 (2007)

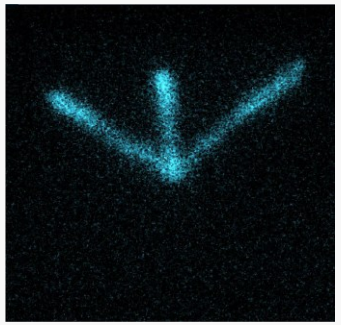
β-delayed 3p emission



^{45}Fe

NSCL 2007

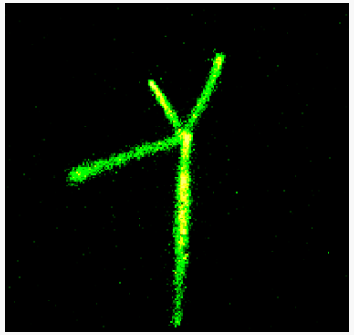
Miernik et al., PRC 76 (2007)



^{43}Cr

NSCL 2007

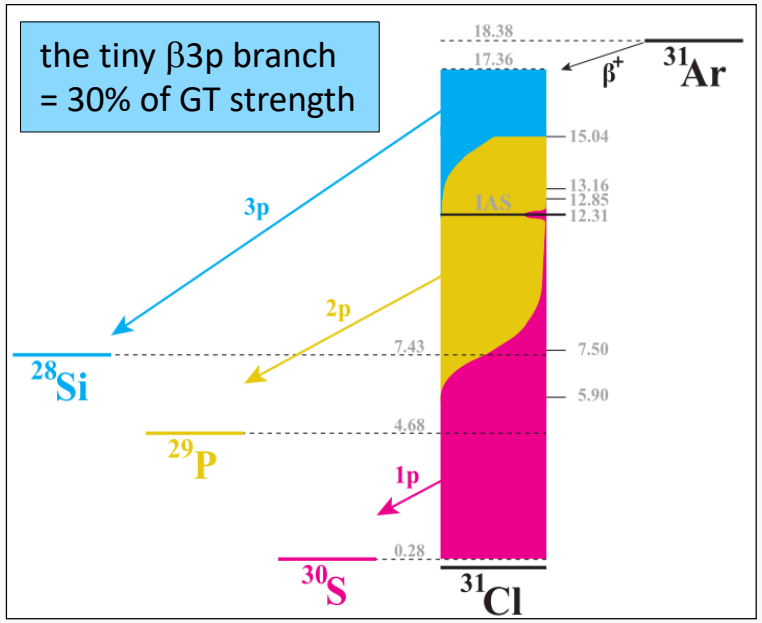
Pomorski et al., PRC 83 (2011)



^{31}Ar

GSI 2012

Lis et al., PRC 91 (2015)

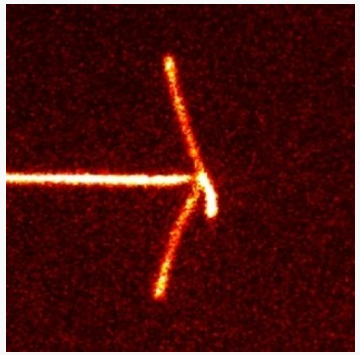


Koldste et al., PRC 89 (2014)

With the OTPC we observed for the first time this decay mode in four cases

New!

^{49}Ni and ^{48}Ni (?) β3p observed @GANIL in 2022 with ACTAR TPC



^{23}Si

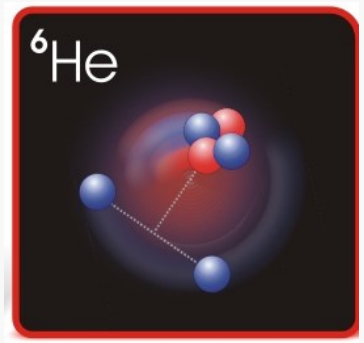
Texas A&M 2017

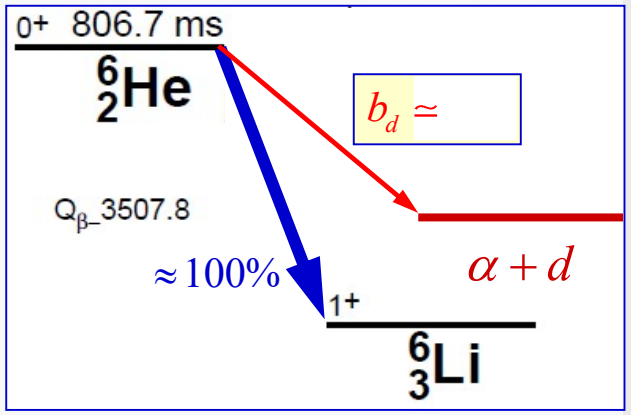
Ciemny et al., PRC 106 (2022)

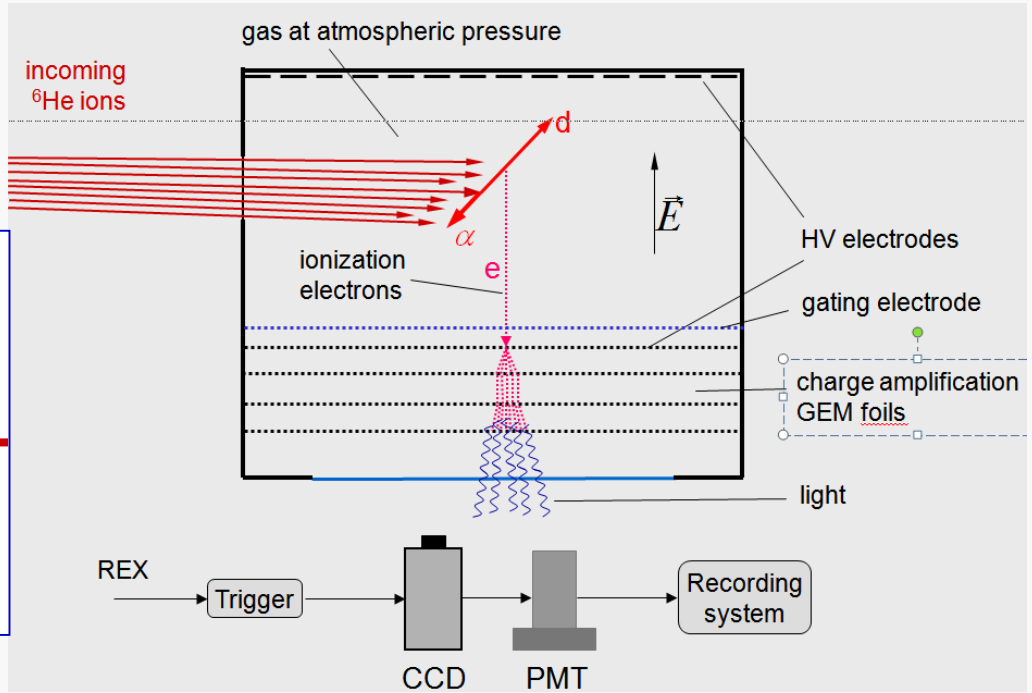
Decay study of ^{6}He @ISOLDE

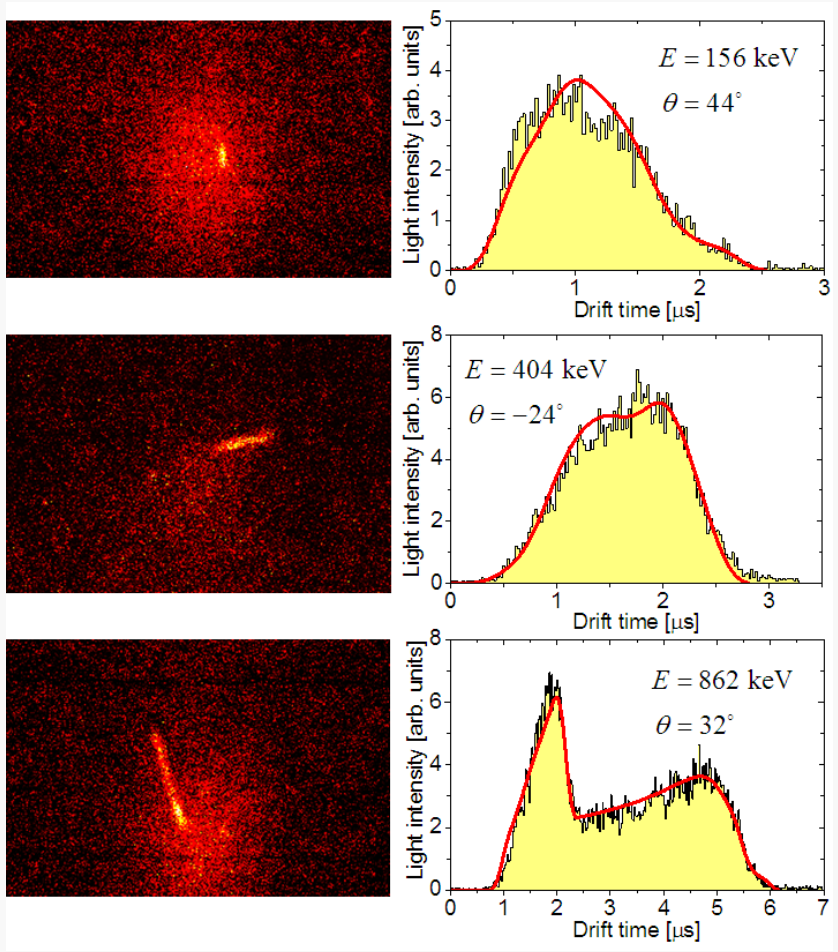
ISOLDE, 2012: p @ 1.4 GeV + UC_x → ^{6}He

- **Bunches** of about 10^4 ions of ^{6}He accelerated by **REX-ISOLDE** to 3 MeV/u were implanted into the OTPC.
- After implantation, an exposure of 650 ms was started to see the decays.





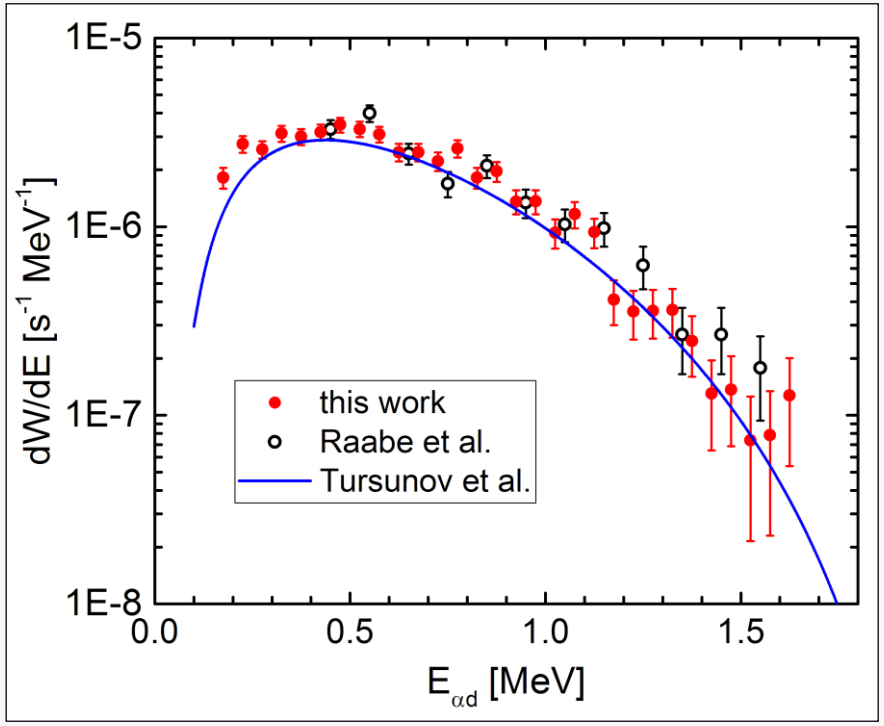




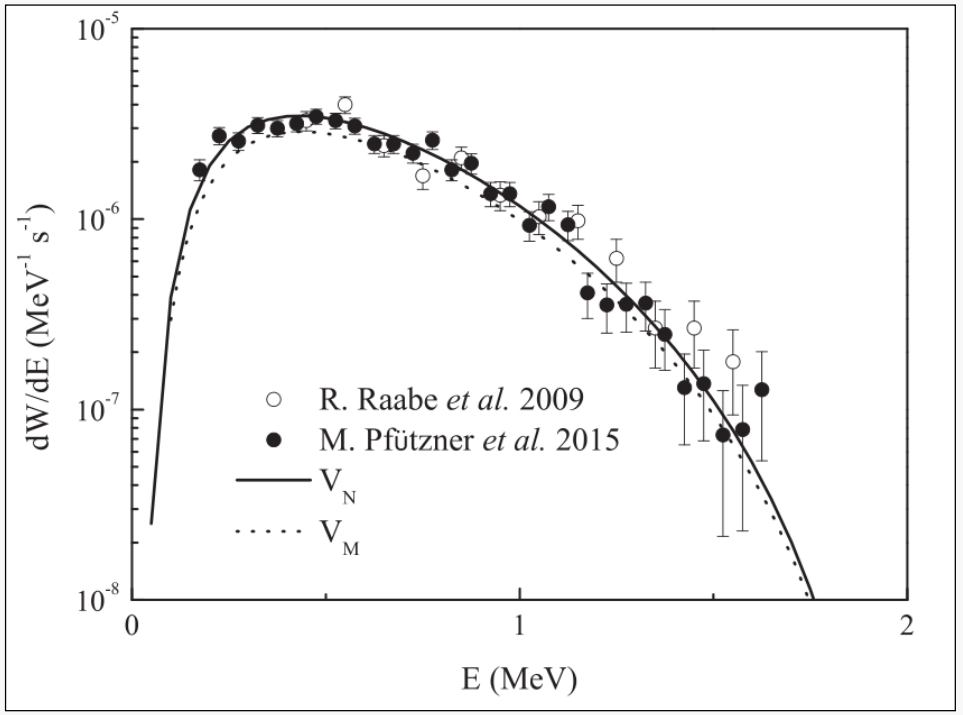
1650 decay events reconstructed

M.P. et al., PRC 92 (2015)

The spectrum of $\alpha + d$



Raabe et al., PRC 80 (2009)
theory: Tursunov, Baye, Descouvemont, PRC73 (2006)



update: Tursunov, Baye, Descouvemont, PRC97 (2018)

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

$B_{\alpha d} = (2.78 \pm 0.07(stat) \pm 0.17(sys)) \times 10^{-6}$

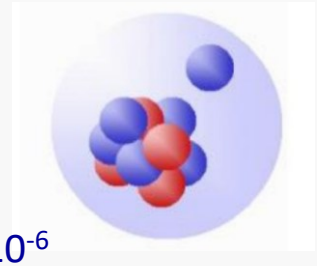
= 20% more than the theoretical prediction

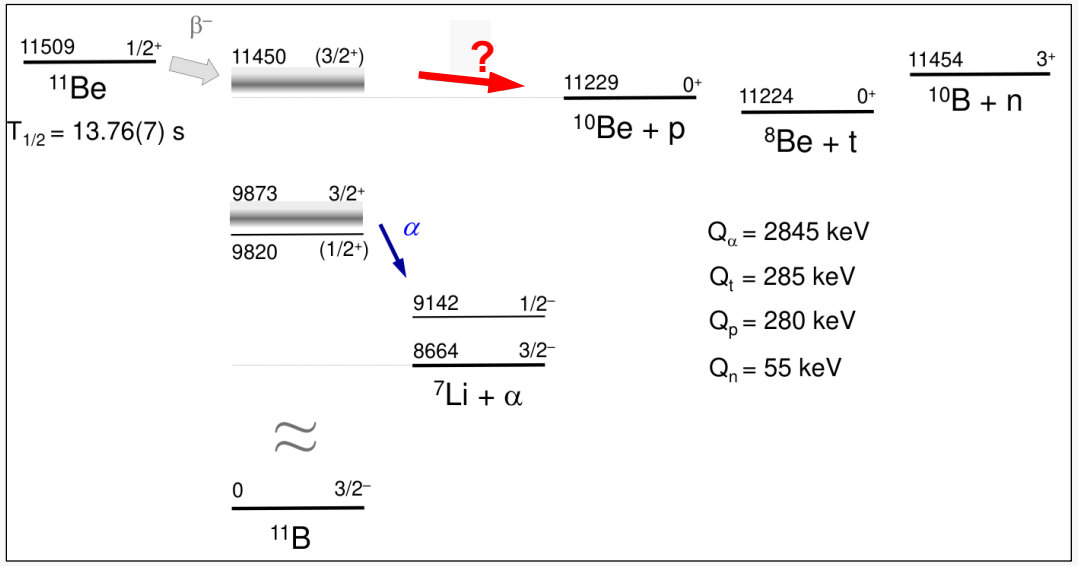
➤ Three-body model of ^{6}He decay: modification of $\alpha + d$ potential in the s-wave.

βα decay of ^{11}Be

- 1n halo nucleus
- The $\beta^-\alpha$ known, b_α = 3.3 %
- The β^-p decay possible

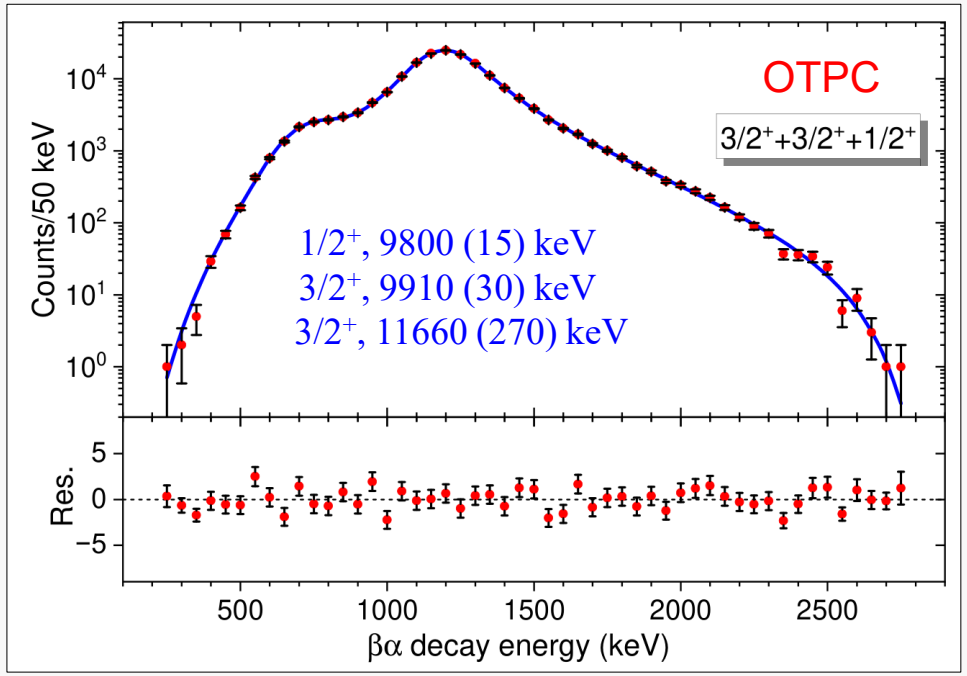
Q_p = 280 keV, predicted branching: $b_p < 10^{-6}$

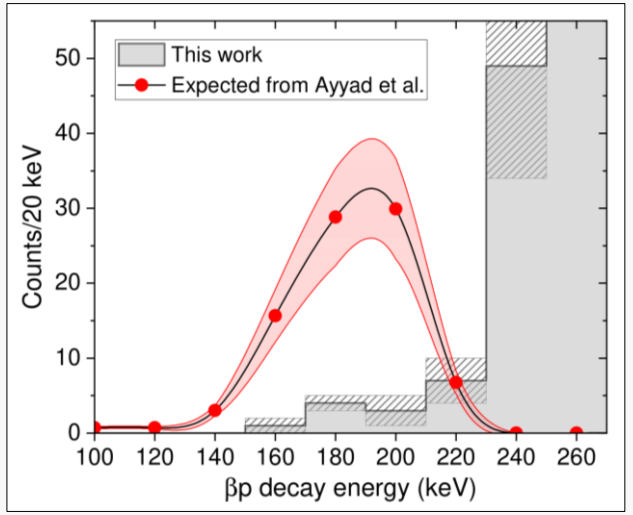




ISOLDE, 2018: p @ 1.4 GeV + UC_x → ^{11}Be

- Bunches of ≈ 10^4 ions of ^{11}Be of 7.5 MeV/u from **HIE-ISOLDE**
- about 1.4M frames recorded → ≈200k clean βα events





Sokołowska et al., PRC (2024)

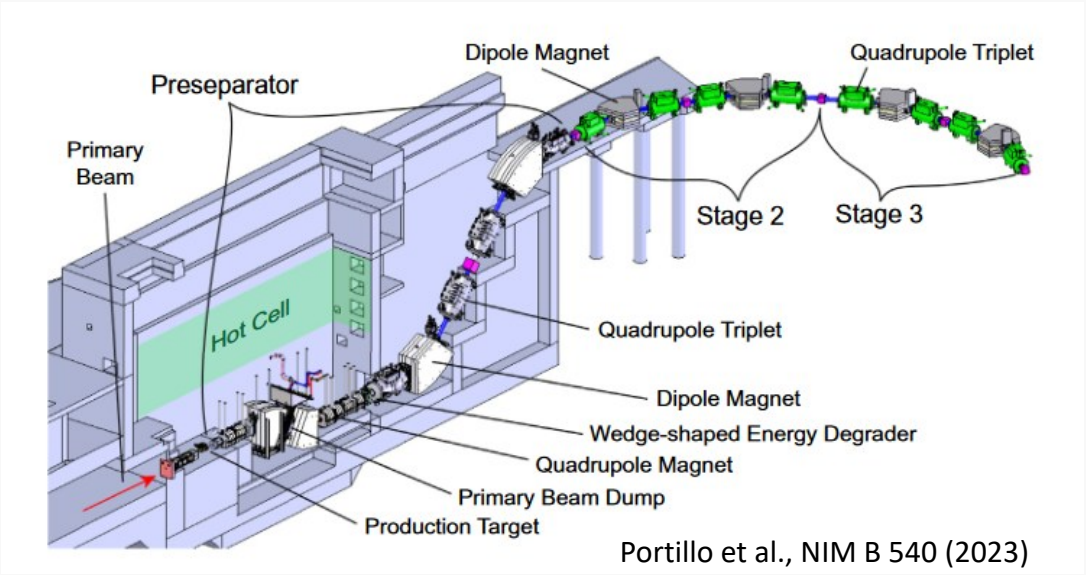
Ayyad at al., PRL 123 (2019)

→ Branching limit: $b_{\beta p} < 2 \cdot 10^{-6}$

Further measuremens needed!

Latest news from FRIB

Advanced Rare Isotope Separator (ARIS) @ FRIB, MSU



Portillo et al., NIM B 540 (2023)

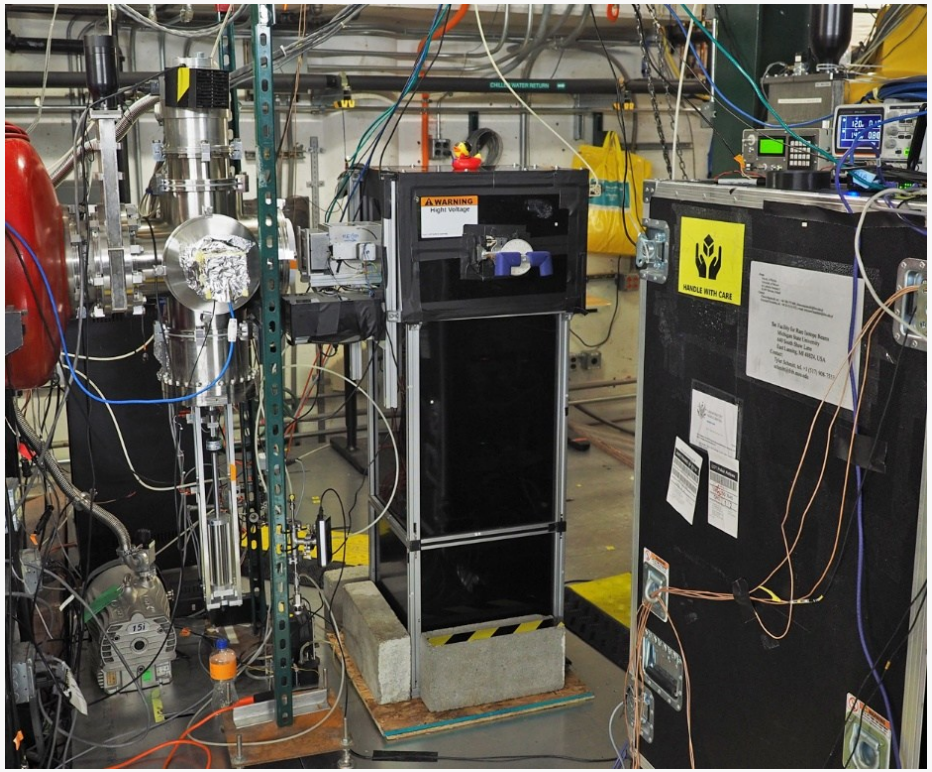
- ARIS at MSU started in 2021

  Ions up to 200 MeV/u for U accelerated by linac

Currently running at 16 kW

Designed to 400 kW !

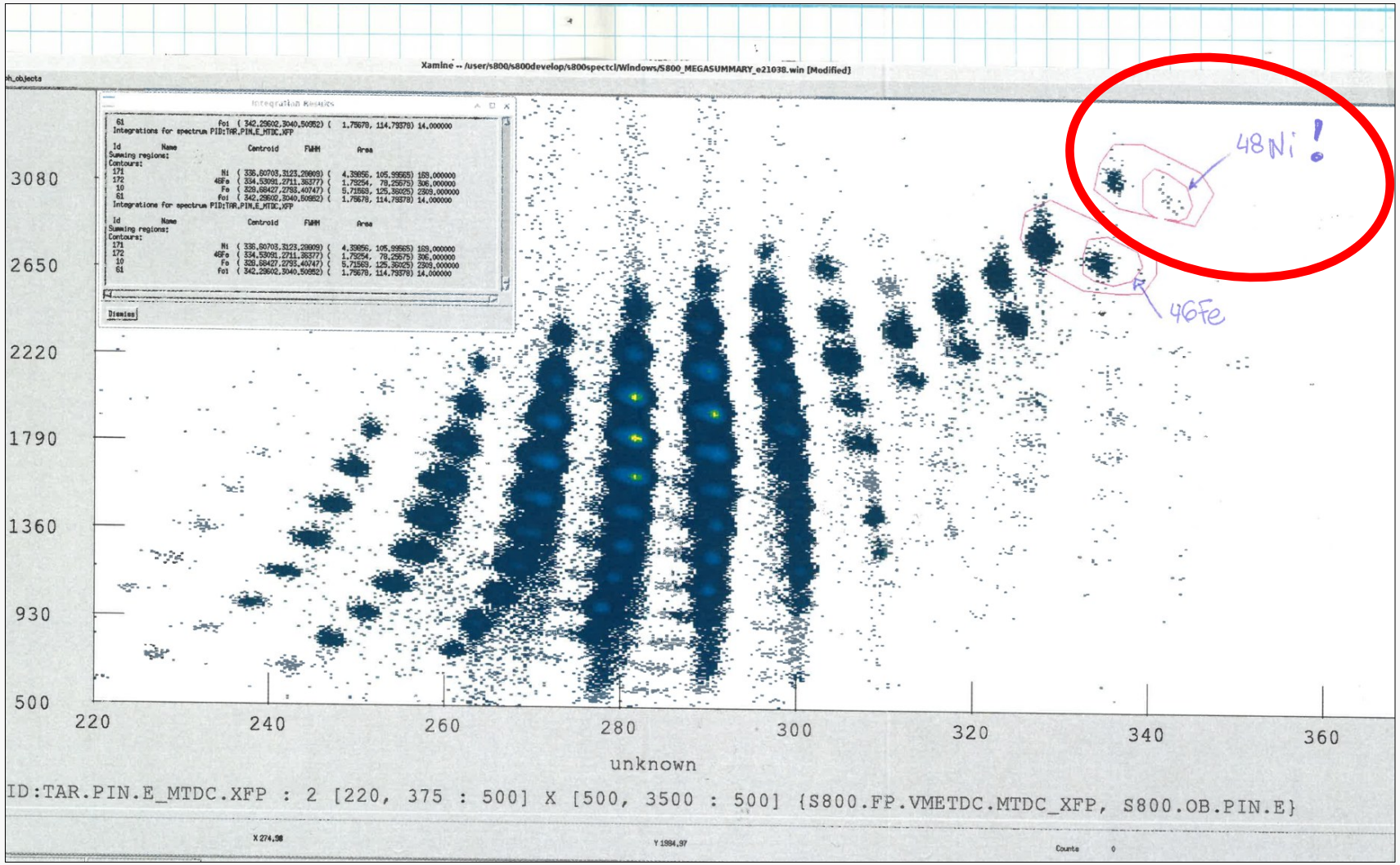
FRIB: ^{58}Ni @ 250 MeV/u + C→ ^{48}Ni, ^{54}Zn, ^{45}Fe



Experiment conducted in January/February 2025

On-line ID plot

We have seen about 6 ions of ^{48}Ni/h ➔ about 2 *2p* decays/h observed!



Luminosity

$$I = L\,\sigma$$

$$L = I_0\,n\,d$$

➤ **NSCL, 2011**:

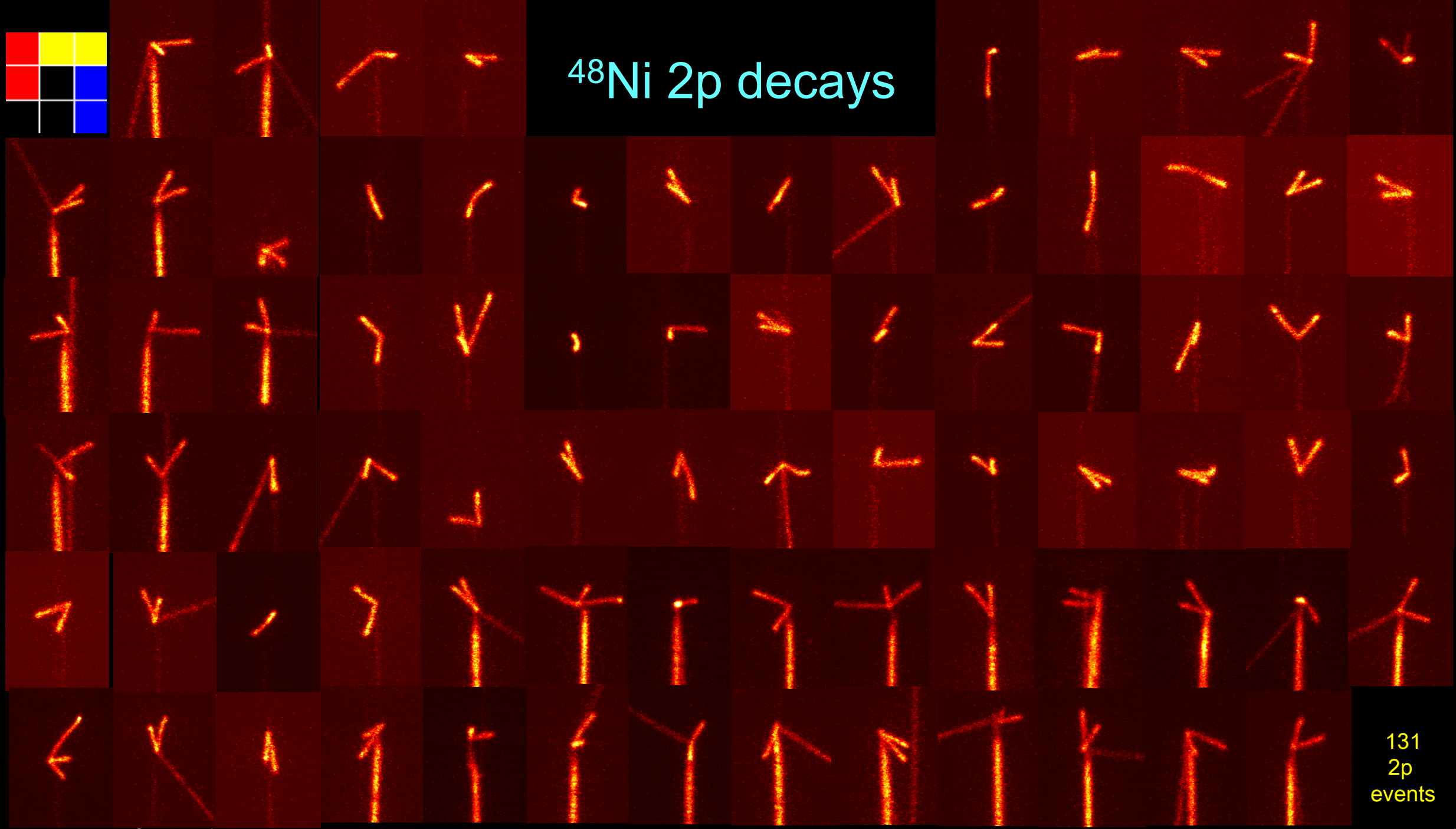
$L_1 = 1.5 \times 10^{33}$ 1/(s cm²)

➤ **FRIB, 2025**:

$L_2 = 5.7 \times 10^{35}$ 1/(s cm²)

$= 380 \times L_1$

^{48}Ni 2p decays



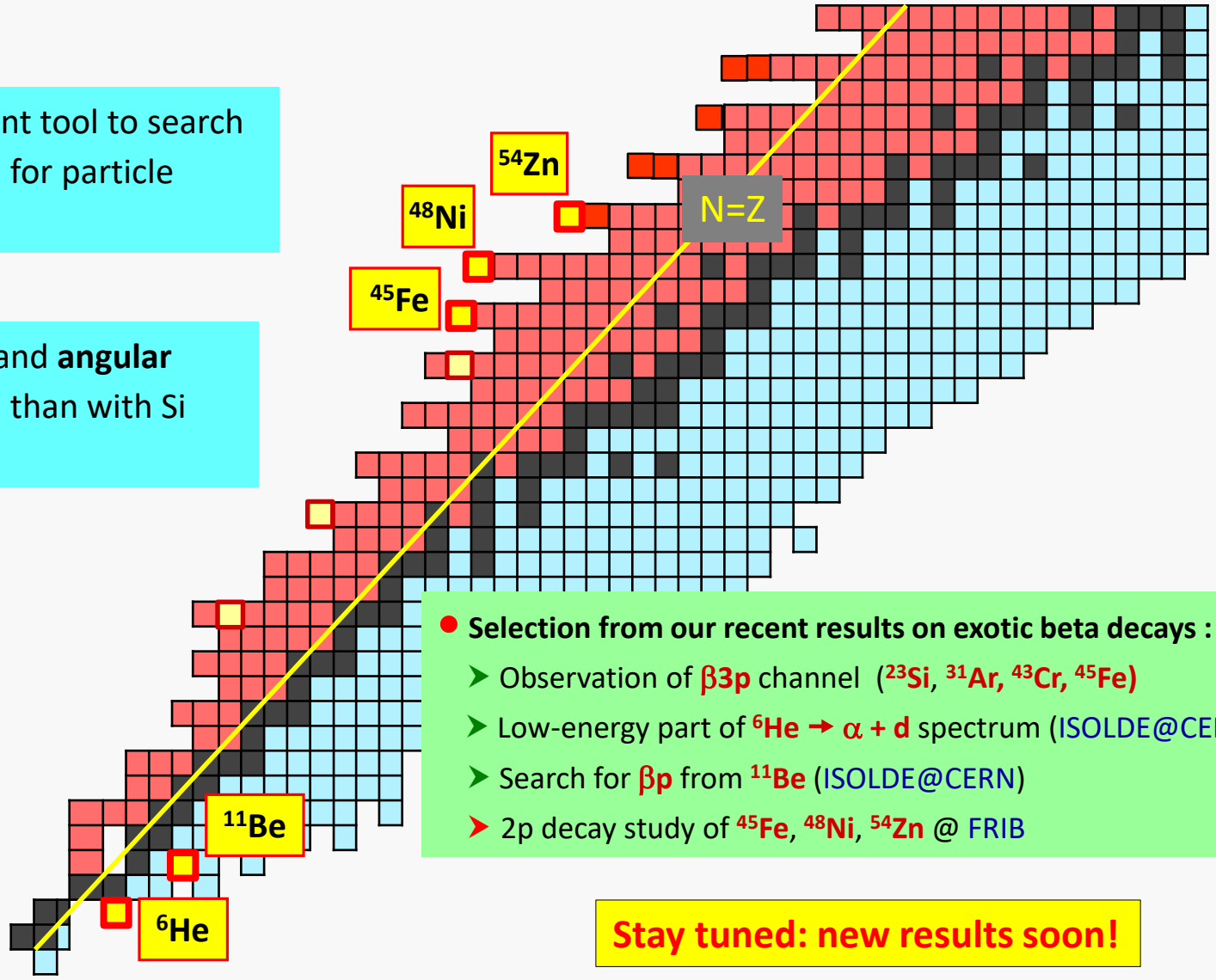
131
2p
events

Summary

- The **OTPC** detector: simple and efficient tool to search for rare decays (like multiparticle) and for particle decays obscured by beta background.

- Can provide precise **branching ratios** and **angular correlations**. Worse energy resolution than with Si detectors → complementarity!

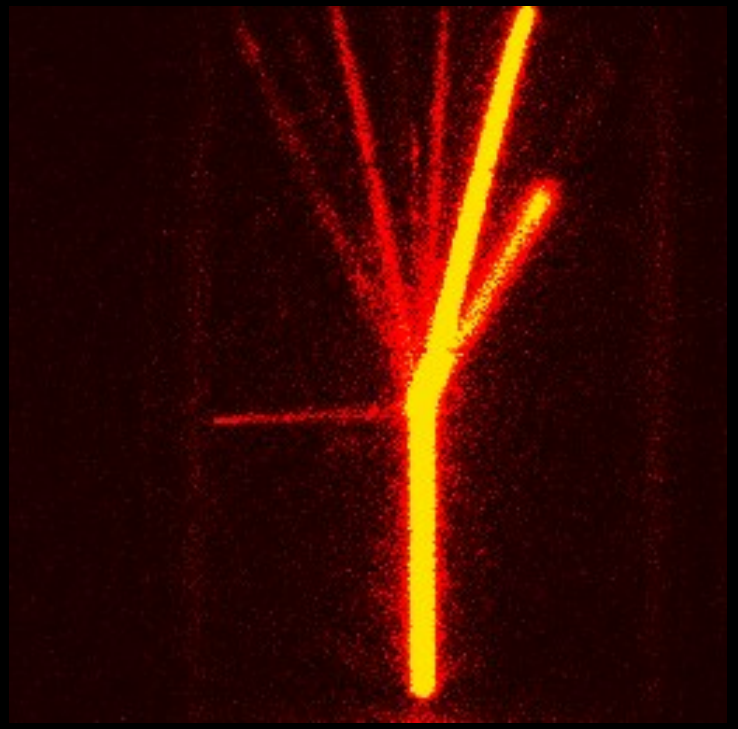
- *2p* correlations measured for **^{45}Fe**
  Needed for **^{48}Ni** and **^{54}Zn** !
  Can we see the Z=28 shell closure in the *2p* decay data?



- **Selection from our recent results on exotic beta decays :**
  - Observation of **β3p** channel (**^{23}Si**, **^{31}Ar**, **^{43}Cr**, **^{45}Fe**)
  - Low-energy part of **^{6}He → α + d** spectrum (ISOLDE@CERN)
  - Search for **βp** from **^{11}Be** (ISOLDE@CERN)
  - 2p decay study of **^{45}Fe**, **^{48}Ni**, **^{54}Zn** @ FRIB

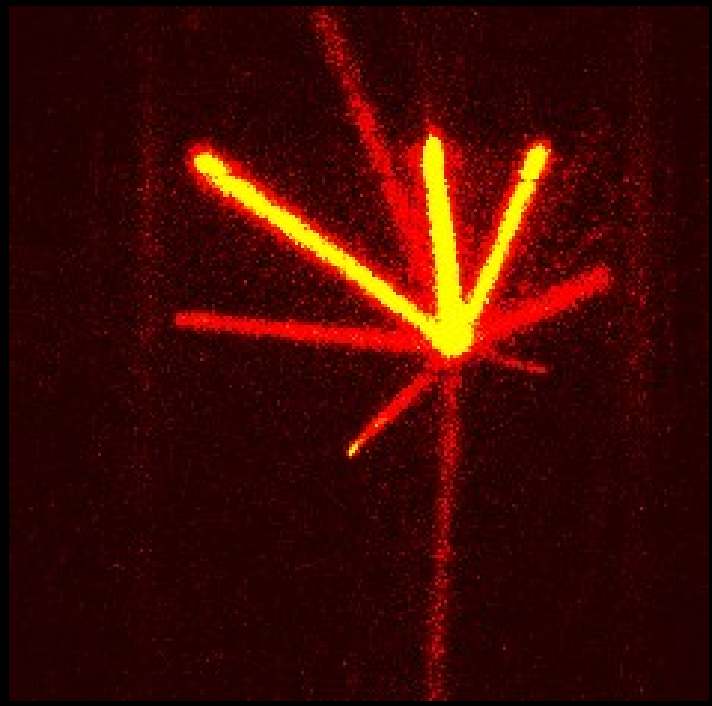
Stay tuned: new results soon!

Thank you!

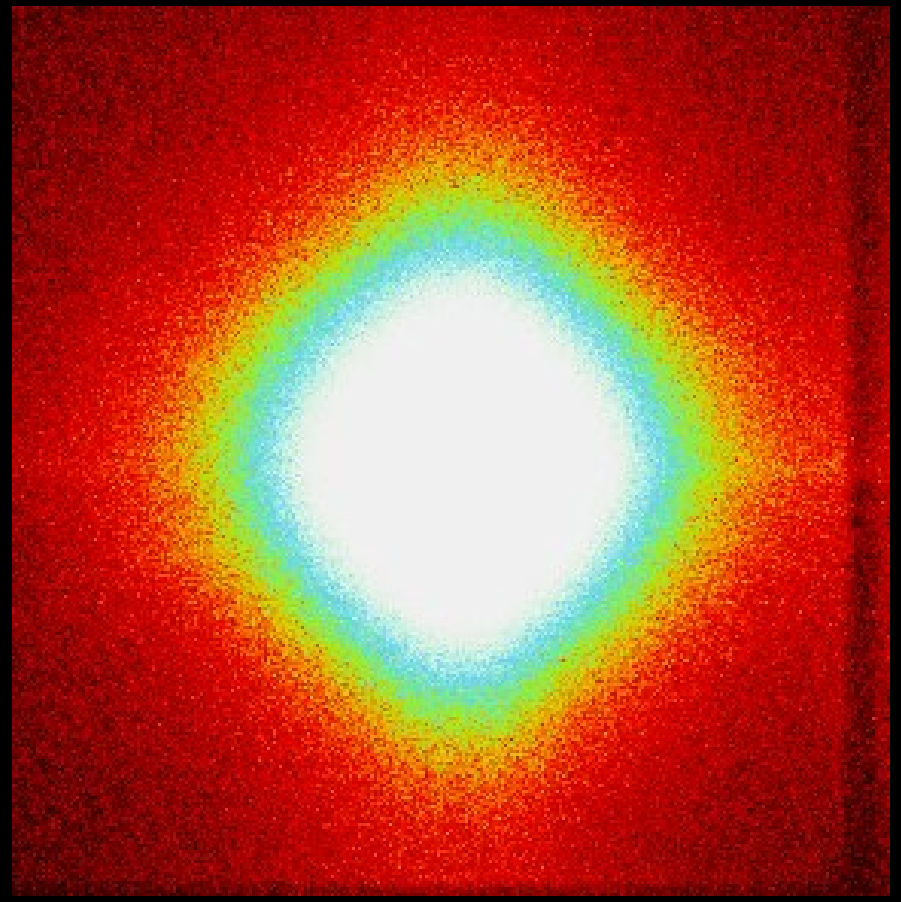


The real work was mainly done by:

- Wojciech Dominik
- Henryk Czyrkowski
- Zenon Janas
- Chiara Mazzocchi
- Víctor Guadilla
- Students:
  - Krzysztof Miernik
  - Marcin Pomorski
  - Aleksandra Lis/Ciemny
  - Adam Kubiela
  - Natalia Sokołowska
  - Aleksandra Skruch

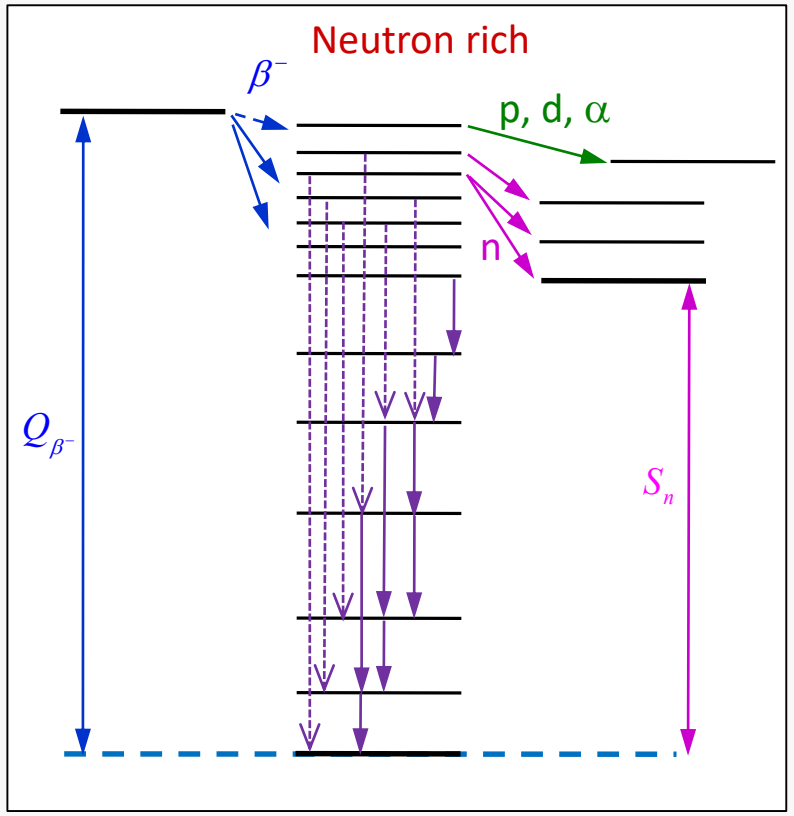


Backup slides



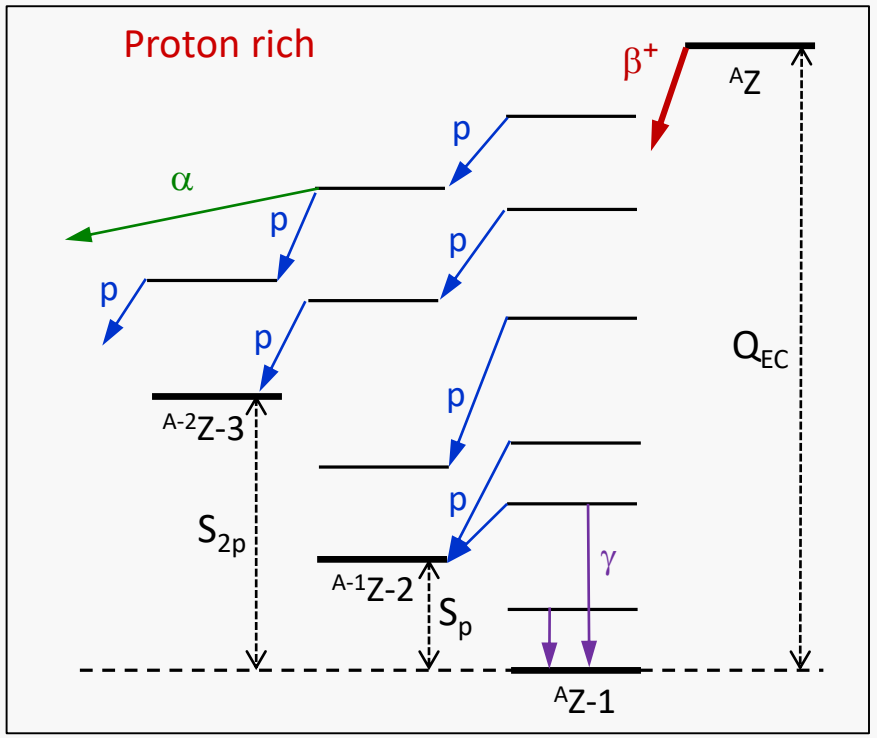
β-delayed particle emission

- Far from stability Q-values are large → many delayed-particle emissions are open



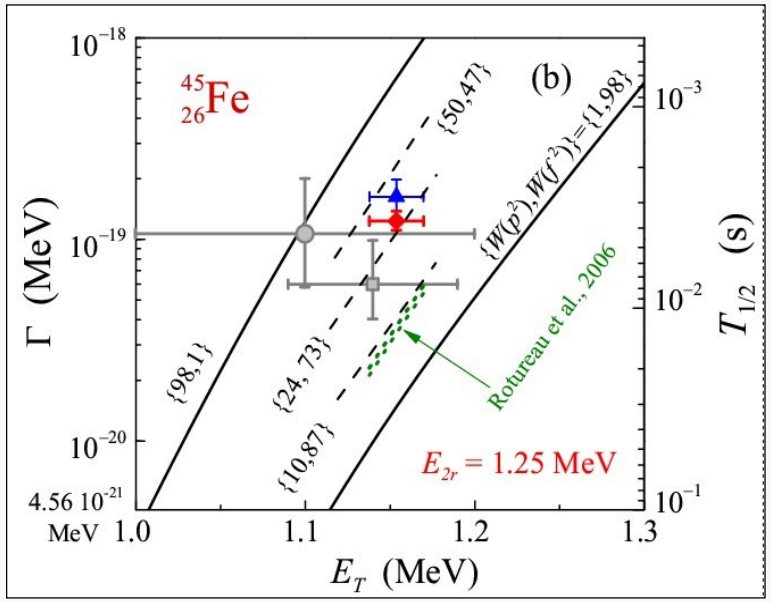
Neutron halos → charged particles

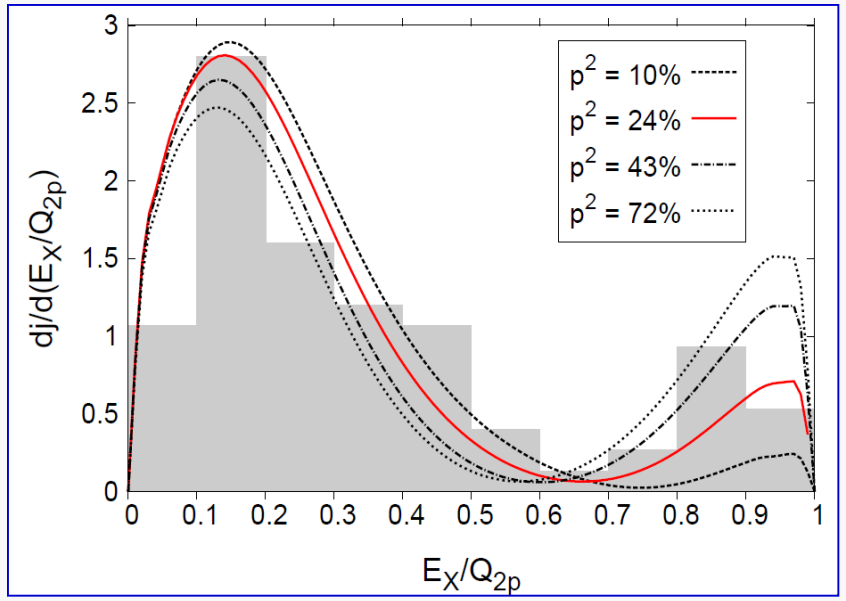
Gamma spectroscopy → *Pandemonium* effect!



- Strong beta transitions to highly excited states are suppressed by kinematics and appear as weak radiation channels
- Low-energy delayed protons may be of interest to astrophysics

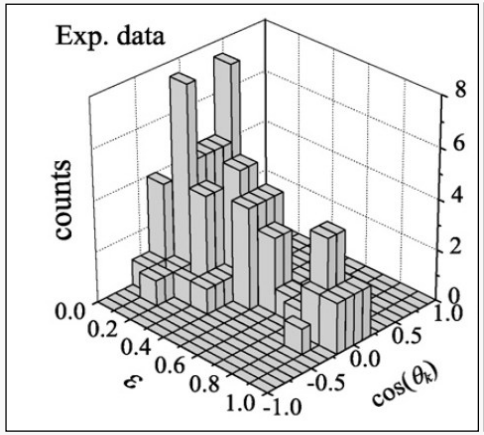
p-p correlations in ^{45}Fe

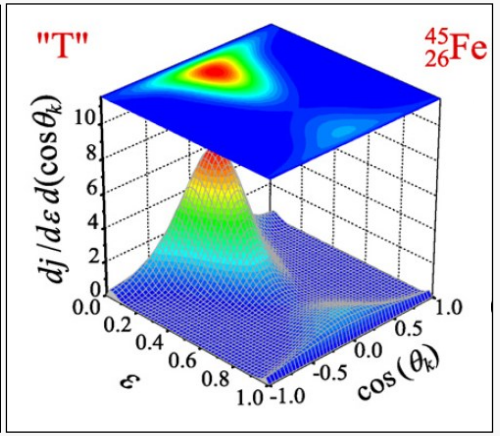




Result for ^{45}Fe: $W(p^2) = 0.3 \pm 0.1$

- All observables are well reproduced by the 3-body model of Grigorenko
- The picture seems to depend on the composition of the initial wave function





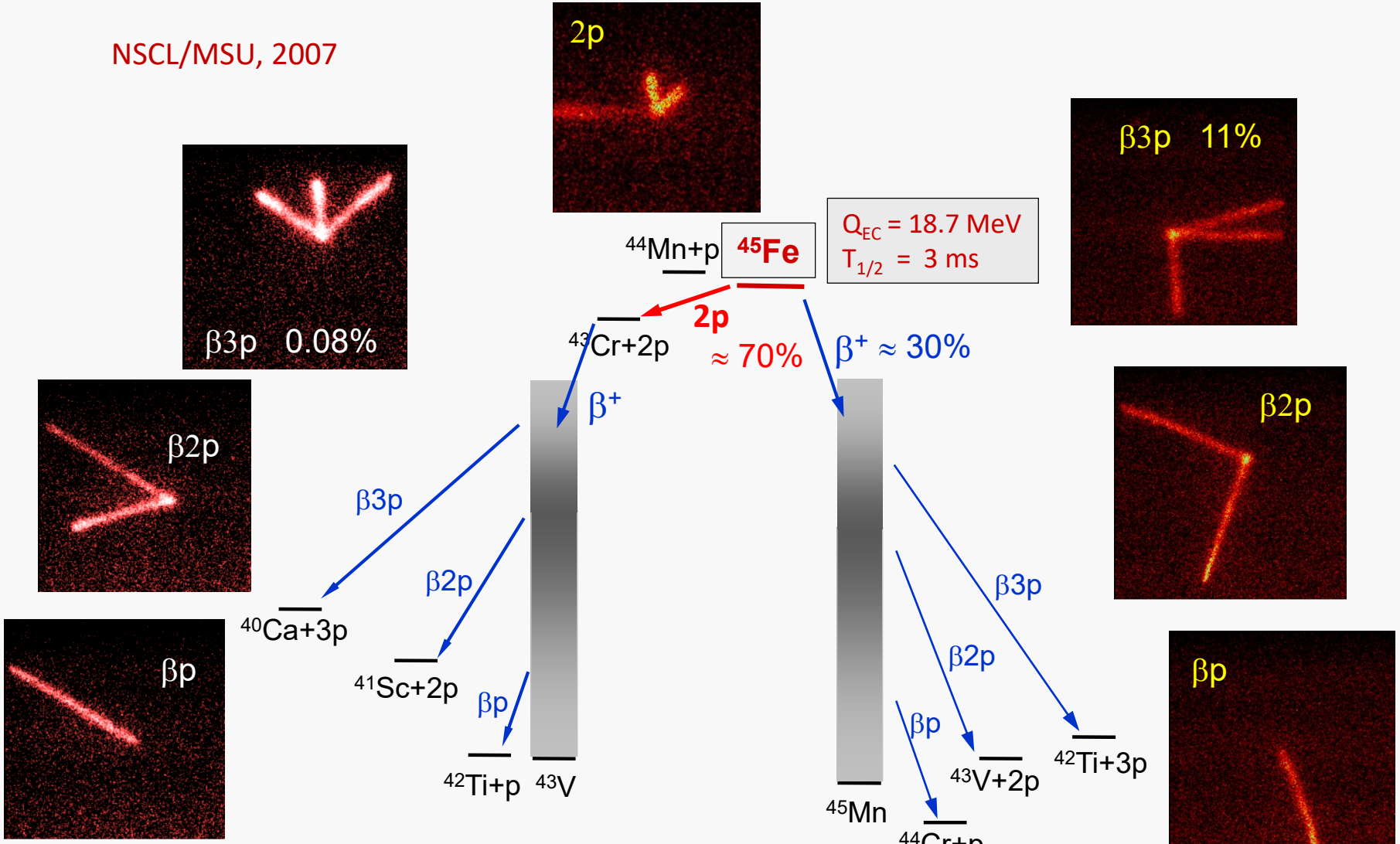
Miernik *et al.*, EPJA 42 (2009) 431

M.P. et al., Rev. Mod. Phys. 84 (2012) 567

Grigorenko *et al.*, PLB 677 (2009) 30

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

NSCL/MSU, 2007



Pomorski et al., PRC 83 (2011) 014306

Miernik et al., PRL 99 (07) 192501