Proton-proton correlations in ground-state two-proton radioactivity

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WPCF 2023 - XVI Workshop on Particle Correlations and Femtoscopy & IV Resonance Workshop 2023

November 8^{th}, 2023

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Uniwersytet Warszawski

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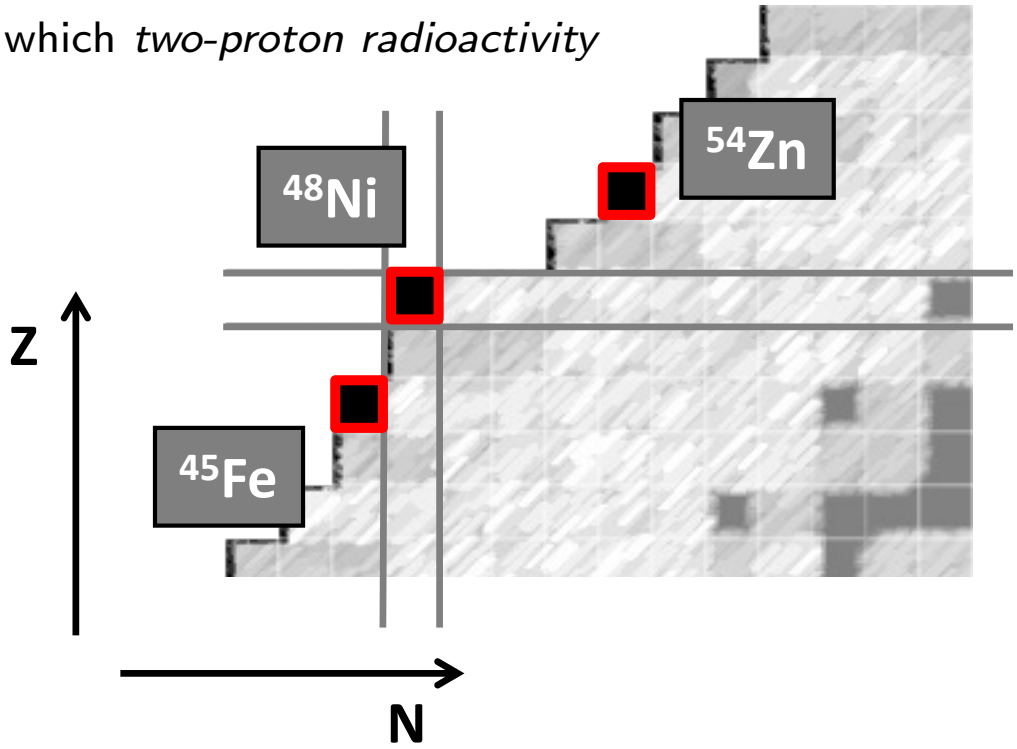
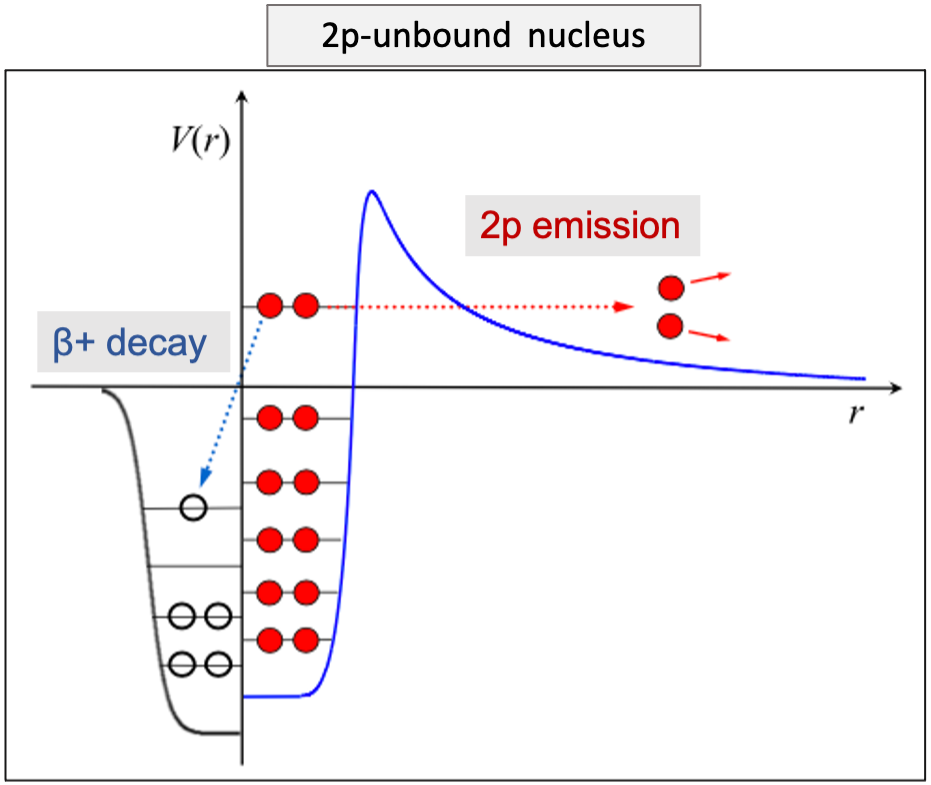
Exotic nuclei

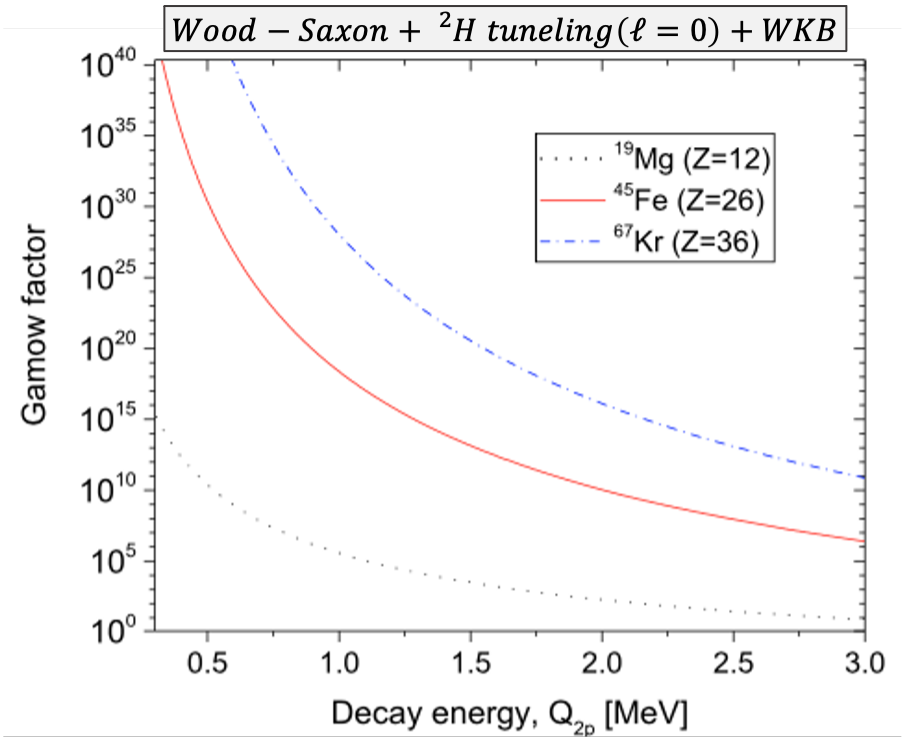
Medium-mass proton drip-line region

- Nuclear structure at the limits of nuclear stability
- Unique phenomena that result from the interplay between nuclear forces (pairing and Coulomb)
- New decay modes, among which *two-proton radioactivity*
- Data for the rp-process



Ground-state two-proton radioactivity





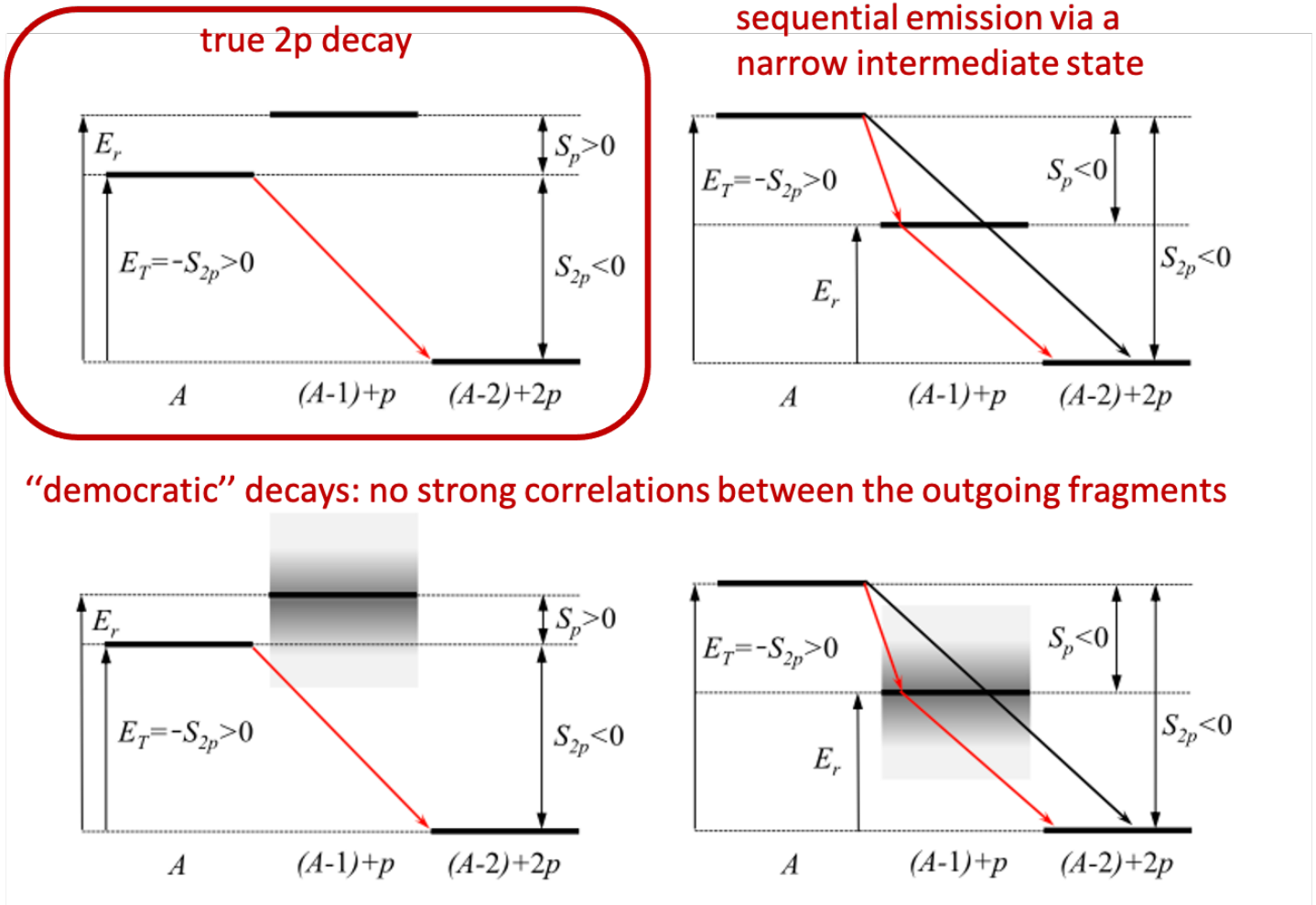
$$S_{2p} = B(N,Z) - B(N,Z-2)$$

→ limits of nuclear stability
→ exact 2p-dripline location requires precise knowledge of the masses in the region

$$T_{1/2}^{2p} \approx G = exp\left[2\int_{r_{in}}^{r_{out}} \sqrt{\frac{2\mu}{\hbar^2}|Q - V(r)|}dr\right]$$

$$Q_{2p} = -S_{2p}$$

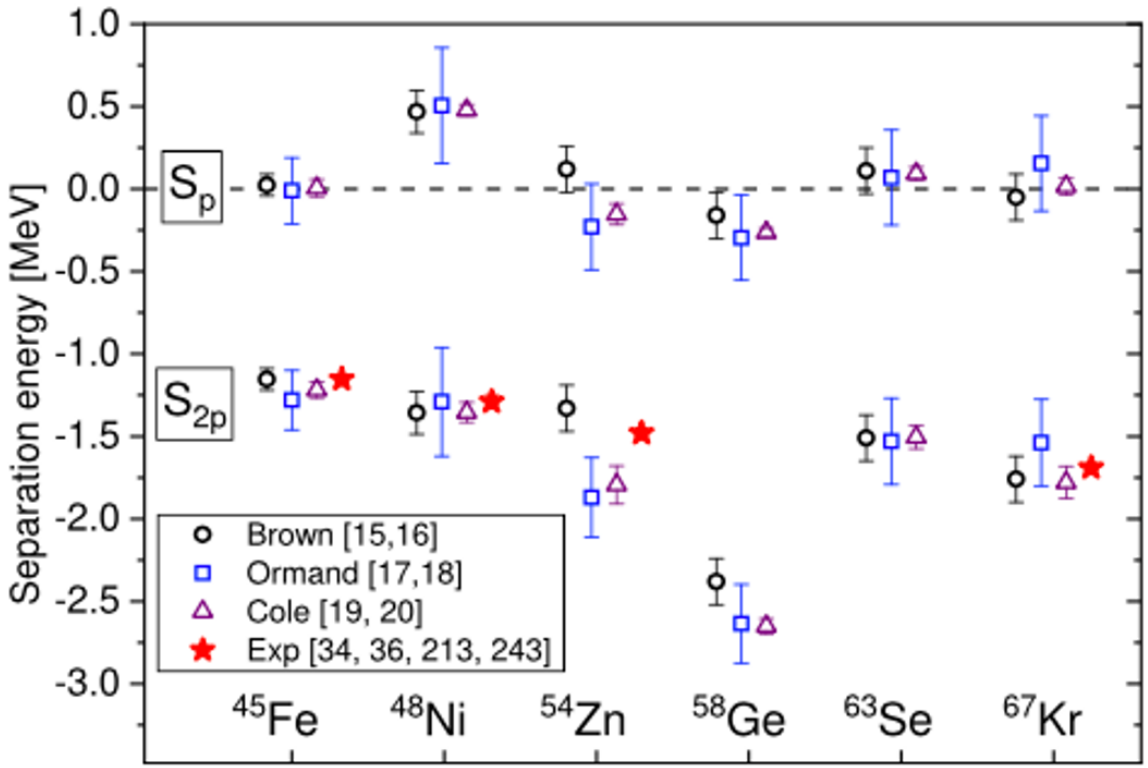
Ground-state two-proton radioactivity



Pfützner et al., Prog. Part. Nucl. Phys. 132 (2023)

Ground-state two-proton radioactivity

Expected for even-Z nuclei beyond the proton drip-line



Pfützner et al., Prog. Part. Nucl. Phys. 132 (2023)

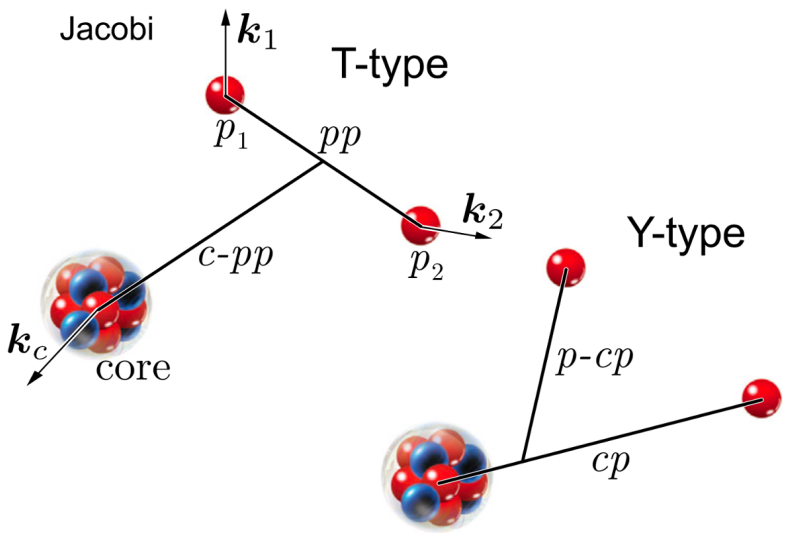
Two-proton emission

Important messenger on

- masses
- nuclear forces
- structure (?)

beyond the proton drip-line.

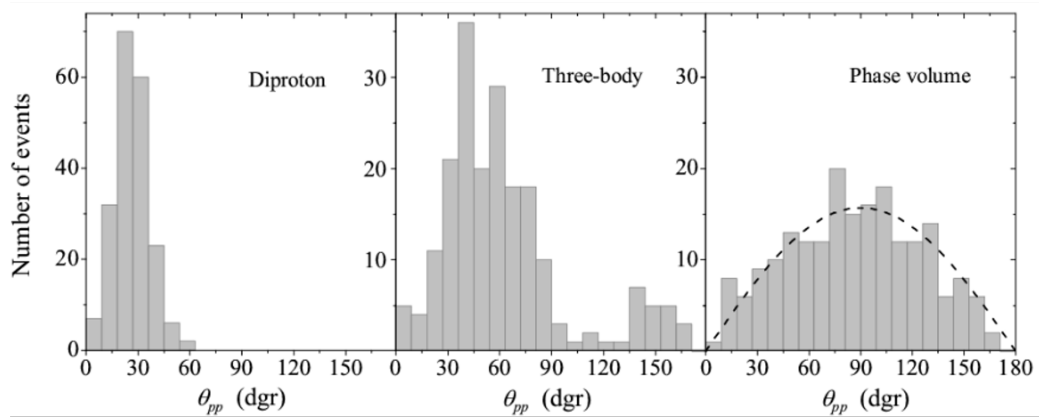
It competes with β^+ decay



What is the mechanism?

- sequential or simultaneous?
- di-proton, independent, correlated?

$\rightarrow$ measurement of the angular distribution of the two protons

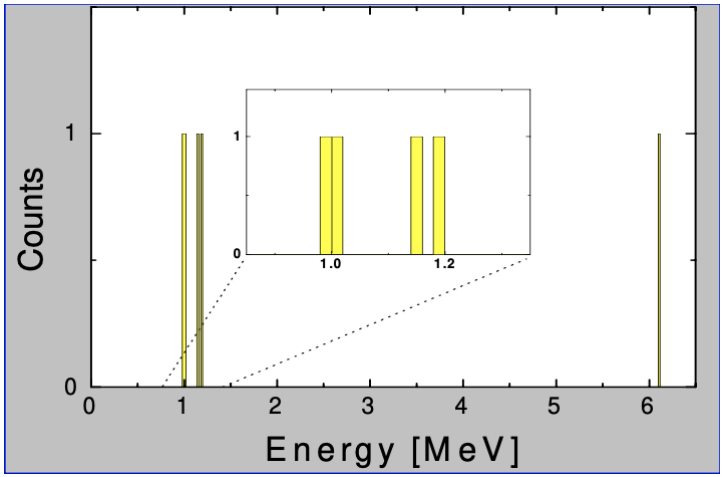


L. Grigorenko, two-proton decay mechanisms of ^{45}Fe

The beginning of an adventure: discovery of 2p radioactivity (2002)

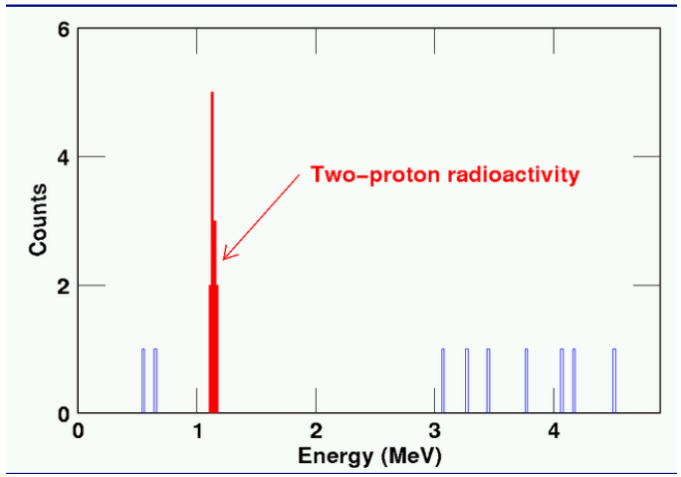
Implantation into Si-det. array
$\rightarrow$ good measurement of total energy but protons not resolved!
$\Rightarrow$ auxiliary detectors needed to prove peak is not βp emission!

GSI: ^{58}Ni *at* 650 @ A·MeV + ^{nat}Be $\rightarrow$ ^{45}Fe



M. Pfützner et al., Eur. Phys. J. A14 (2002) 279

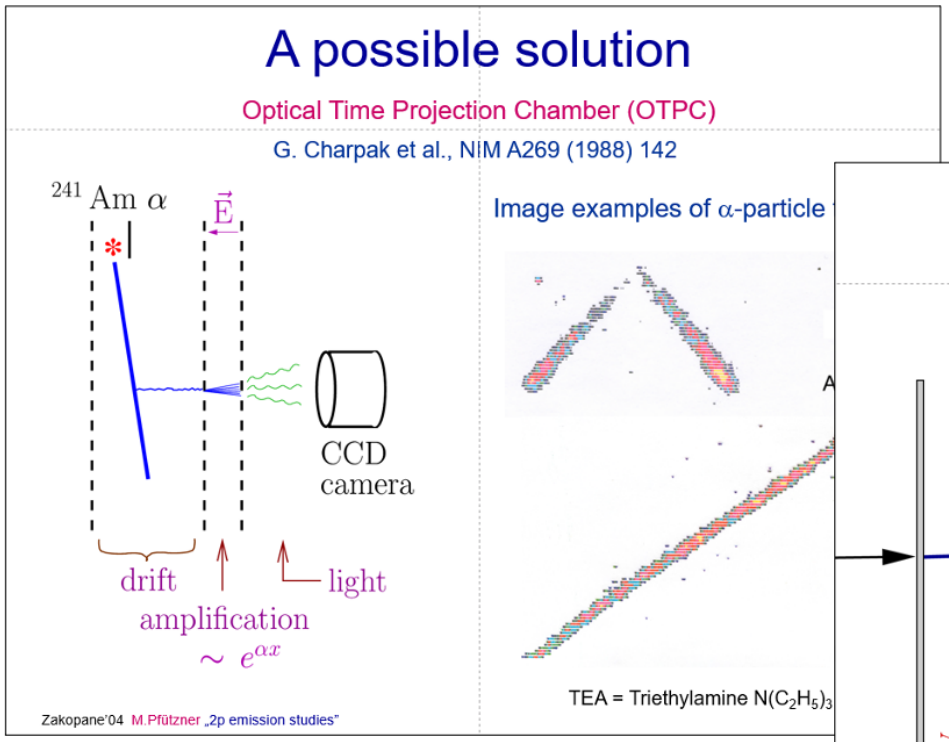
GANIL: ^{58}Ni @ 75 A·MeV + ^{nat}Ni $\rightarrow$ ^{45}Fe

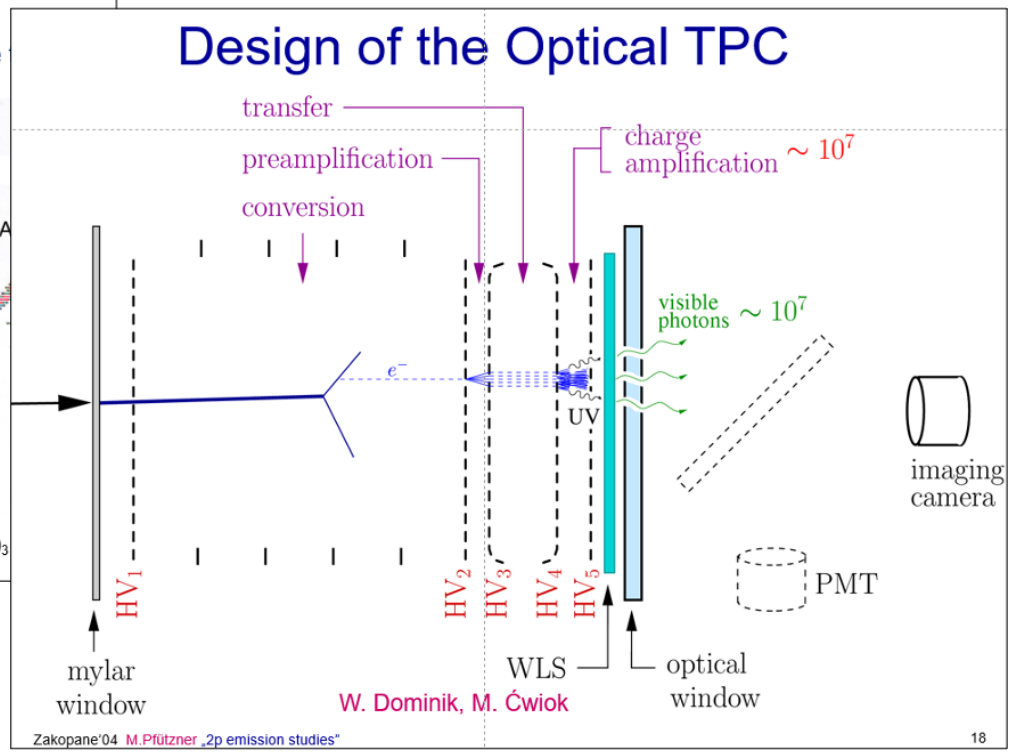


J. Giovinazzo et al., Phys. Rev. Lett. 89 (2002) 102501

The beginning of an adventure: momenta of the 2 protons (2007)

A possible solution: Optical readout Time Projection Chamber (OTPC)

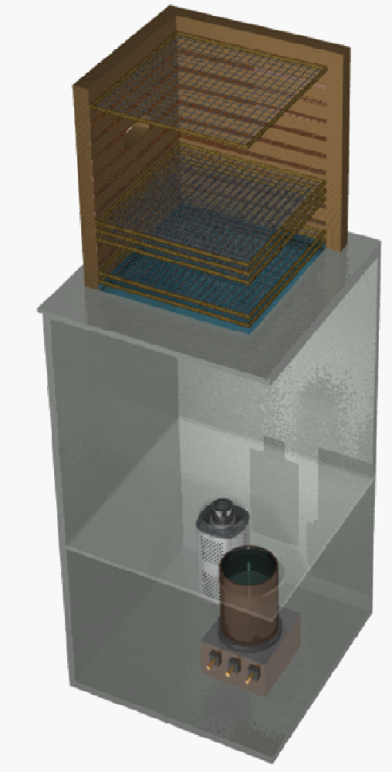


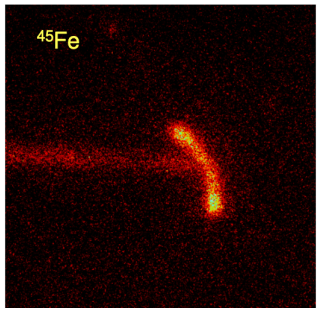


The beginning of an adventure: momenta of the 2 protons (2007)

Time-projection chambers developed to measure the momenta of the 2 protons

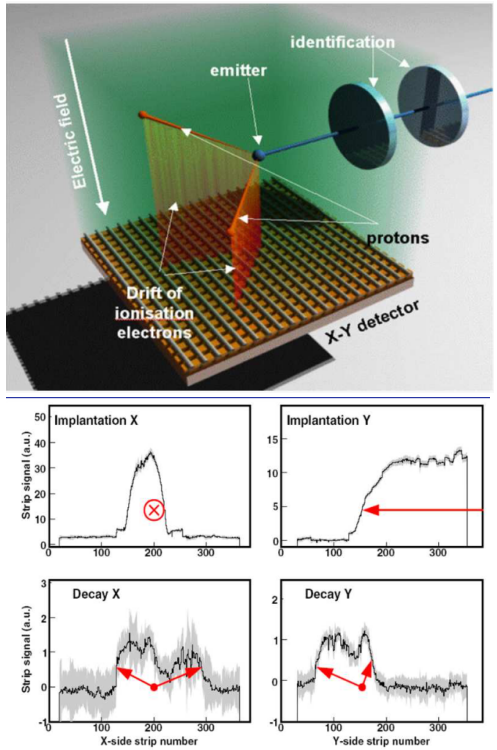
University of Warsaw:: "optical" TPC





K. Miernik et al., Phys. Rev. Lett. 99 (2007) 192501

CENBG-Bordeaux:: "classical" TPC (electronic readout)



J. Giovinazzo et al., Phys. Rev. Lett. 99 (2007) 102501

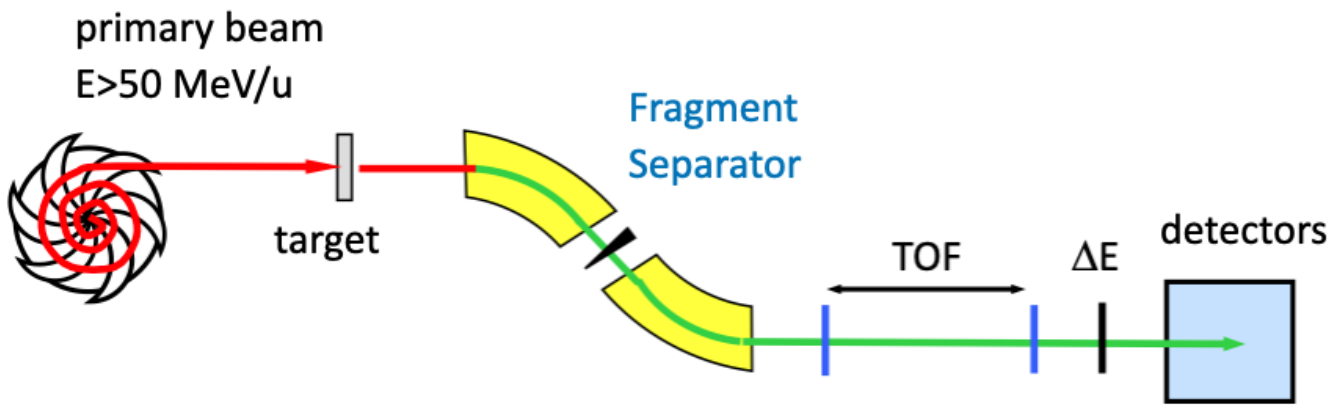
Challenges for experimenters

- exotic nuclei $\rightarrow$ low production rates
- rare decay modes $\rightarrow$ small branching ratios
- high background levels
- physics requirements
  - low-energy particle detection
  - particle correlation measurements

Experimental solution(s)

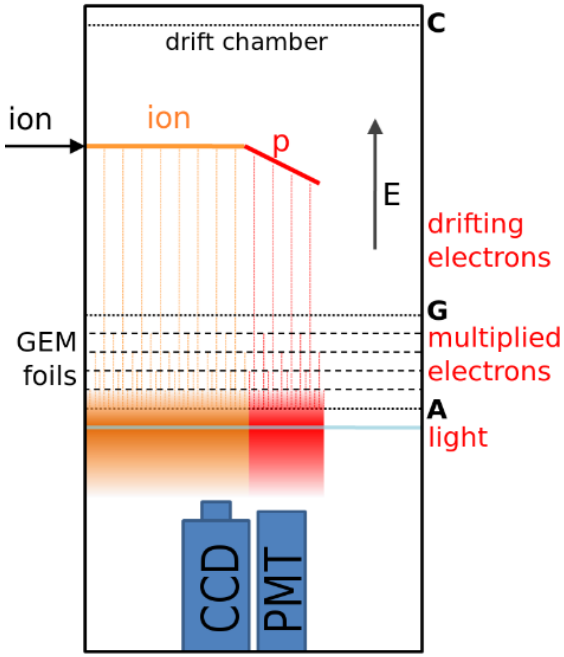
Production of the isotopes of interest

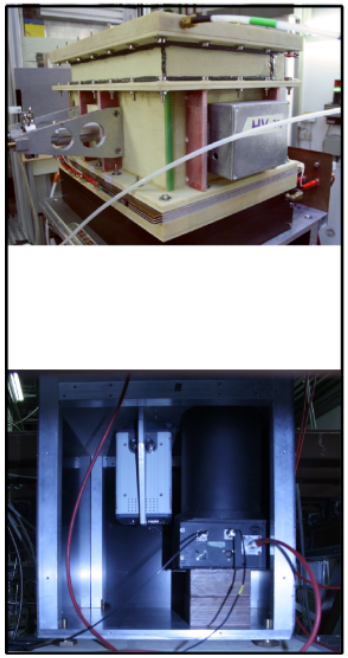
- projectile fragmentation + in-flight separation
  → A1900@NSCL, BIGRIPS@RIKEN, FRS@GSI



- ion identification: energy loss (ΔE) vs time-of-flight (ToF) matrices
- implantation of the ions into the Optical Time-Projection Chamber (OTPC)

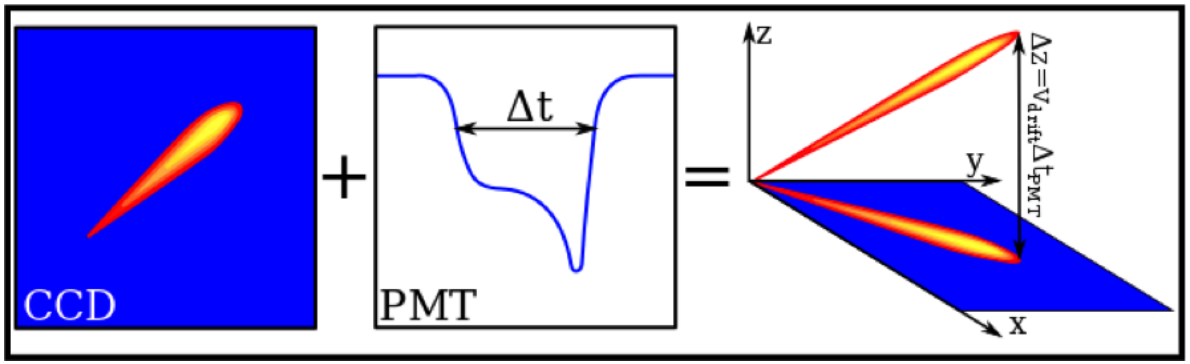
Optical-readout Time-Projection Chamber (OTPC)





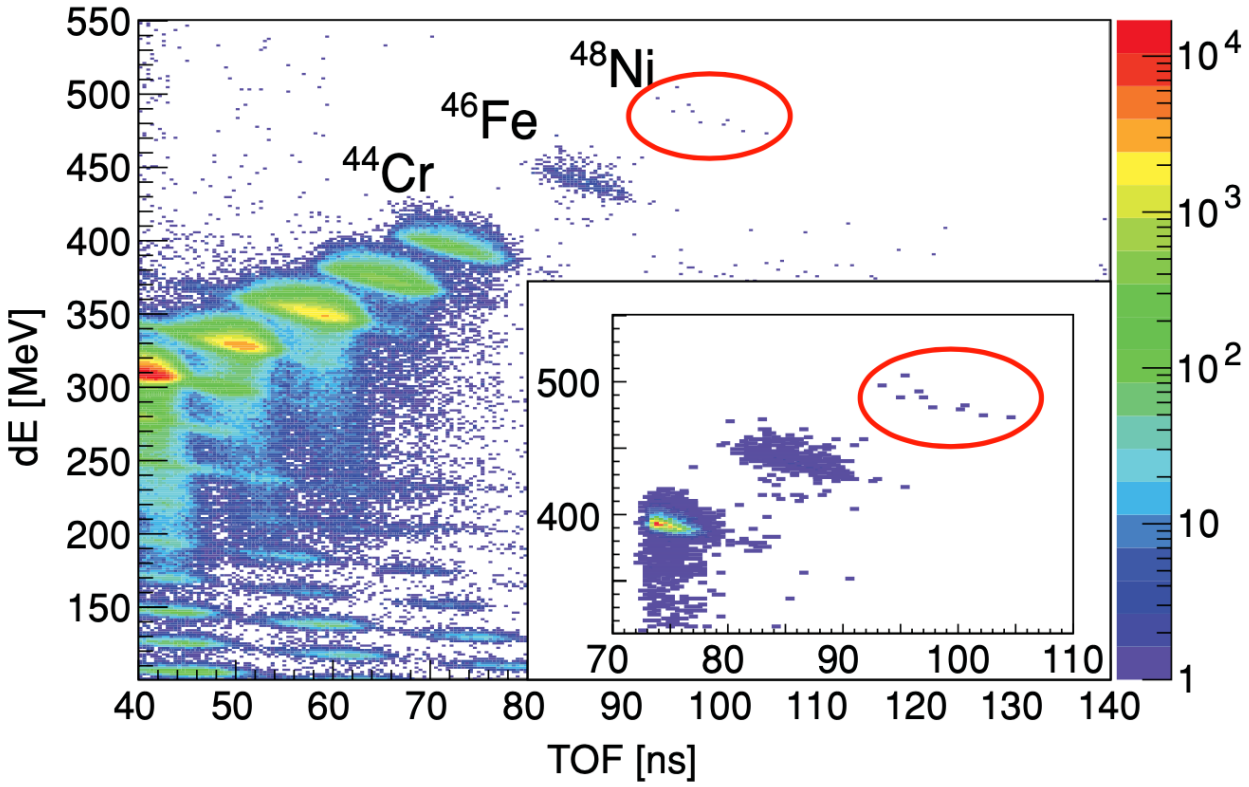
Identified ions implanted in the OTPC

Combination of CCD image and PMT waveform
$\rightarrow$ 3D reconstruction of particle tracks



Two-proton decay experiments

rates from 1 event/2 hours (^{45}Fe) to 1 event/day (^{48}Ni)

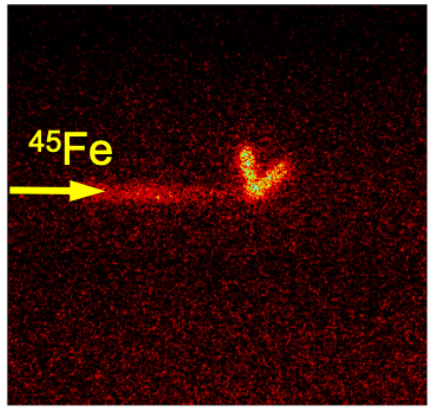


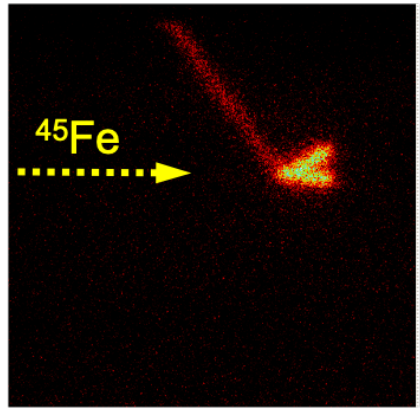
M. Pomorski et al., Phys. Rev. C 83 (2011) 061303(R)

p-p momentum correlations in ^{45}Fe decay

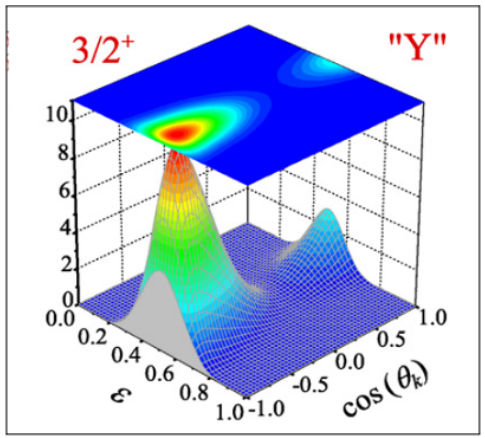
NSCL: ^{58}Ni @ 161 MeV/u + Ni $\rightarrow$ ^{45}Fe

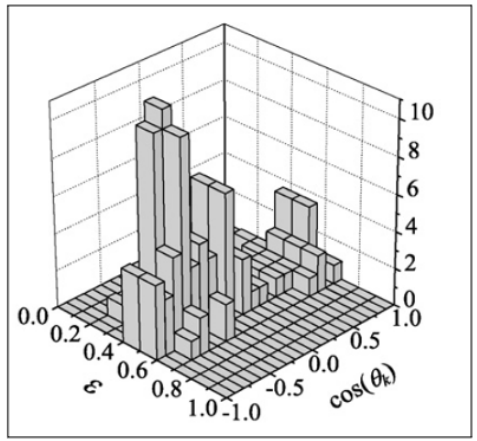
- 75 events reconstructed
- Proton-proton correlations are complex and indicate a genuine 3-body phenomenon
- good agreement with the 3-body model (Grigorenko et al.)
- correlation picture depends on the initial wave function





Miernik et al., PRL 99 (2007) 192501



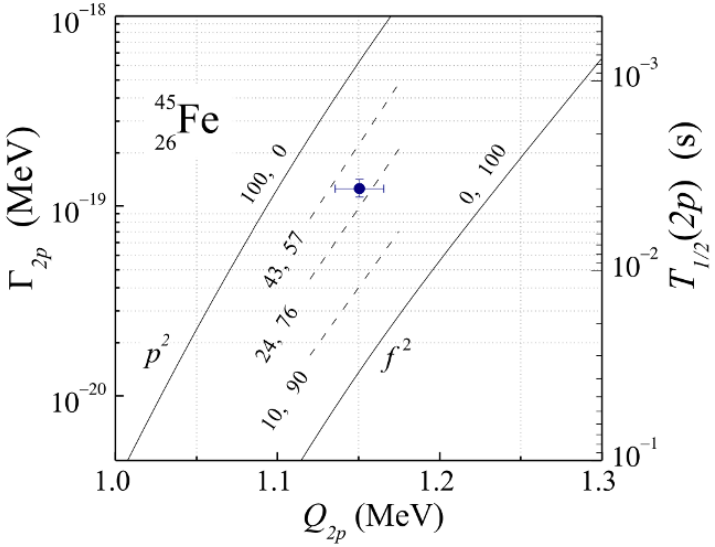


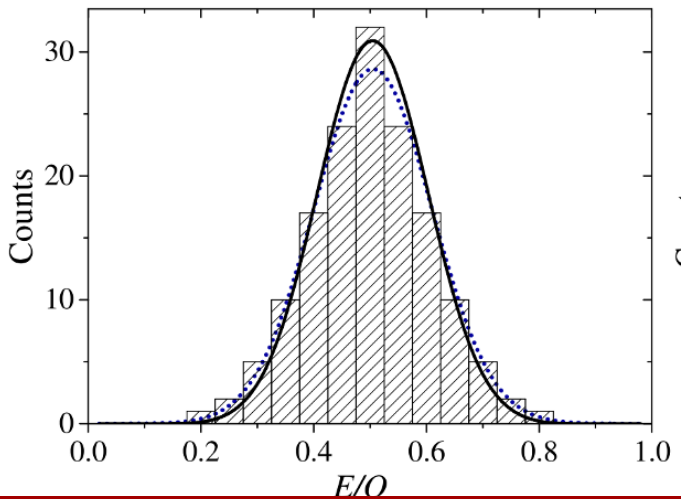
Grigorenko *et al.*, Phys. Lett. B 667 (2009) 30

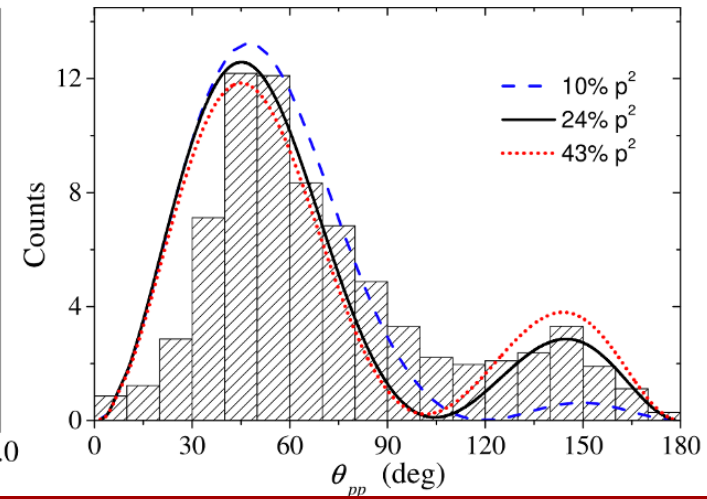
p-p momentum correlations in ^{45}Fe decay

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

- All observables are well reproduced by the 3-body model and contradict two-body/diproton-type models
- Detailed shape of the correlation depends on the composition of the initial wave function of the protons





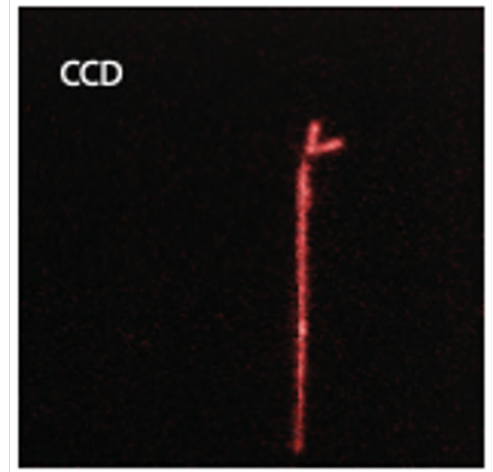


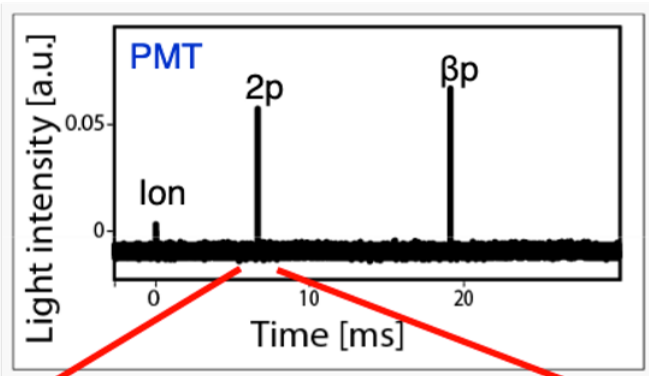
Two-proton decay of ^{48}Ni

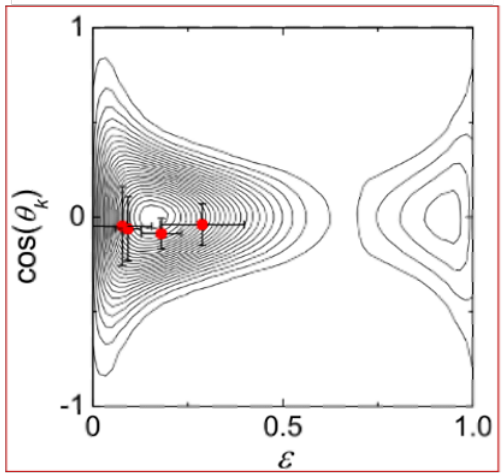
NSCL: ^{58}Ni @ 161 MeV/u + Ni $\rightarrow$ ^{48}Ni

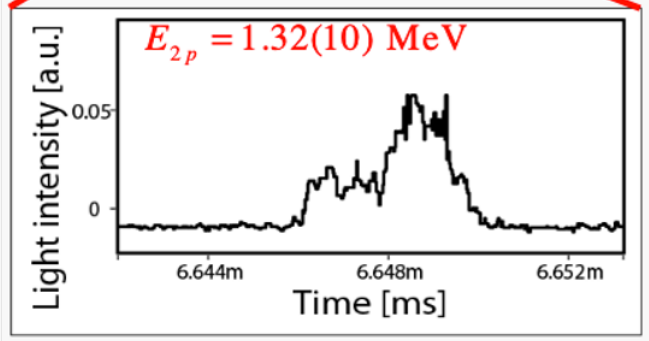
- The first direct observation of 2p radioactivity of ^{48}Ni
- 10 events in 10 days

... to be continued @ FRIB ...



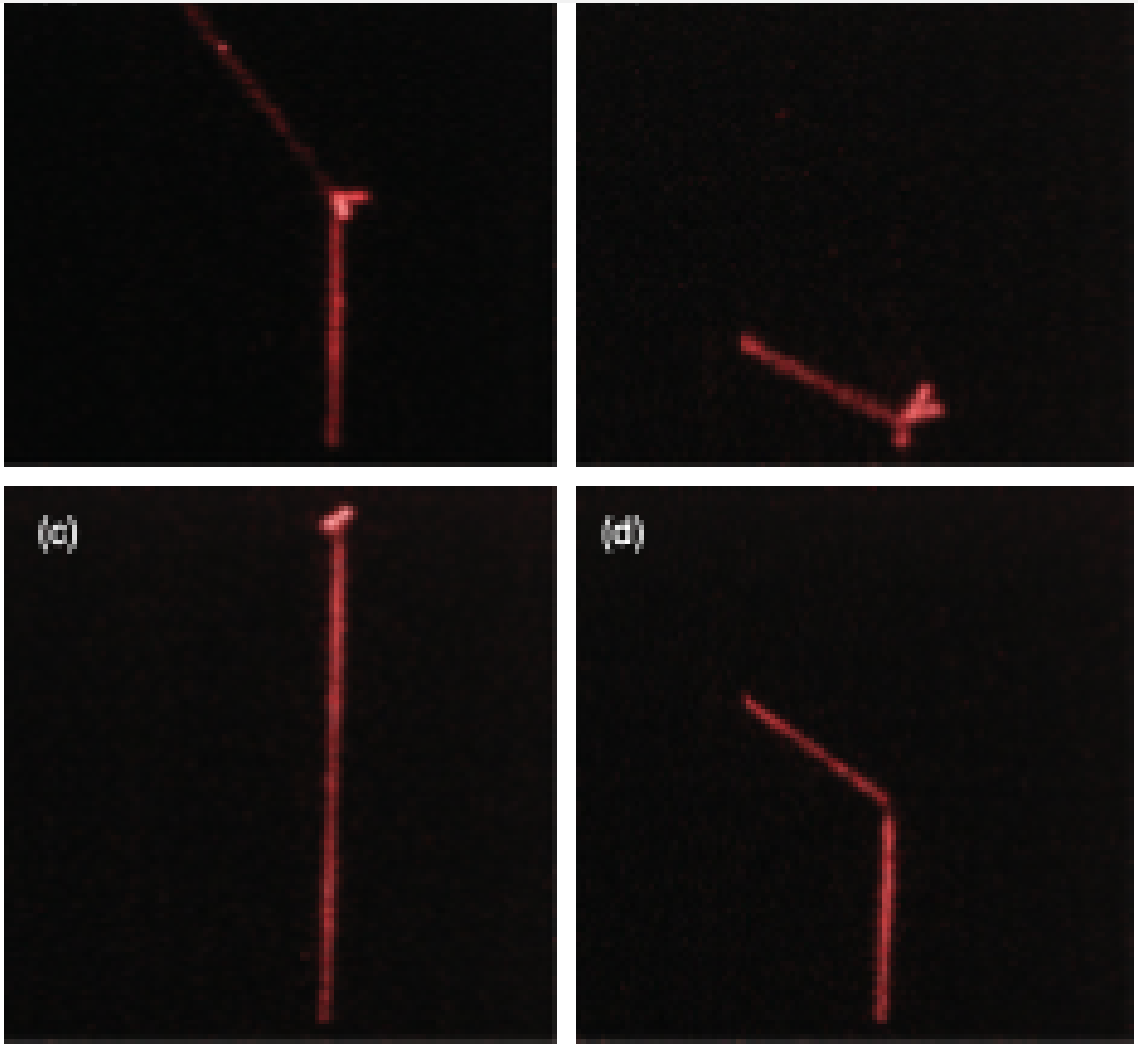






M. Pomorski et al., Phys. Rev. C 83 (2011) 061303(R)

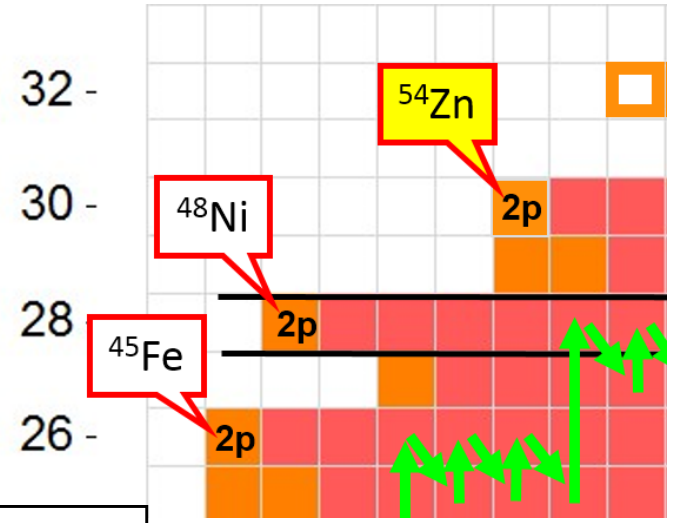
Two-proton decay of ^{48}Ni



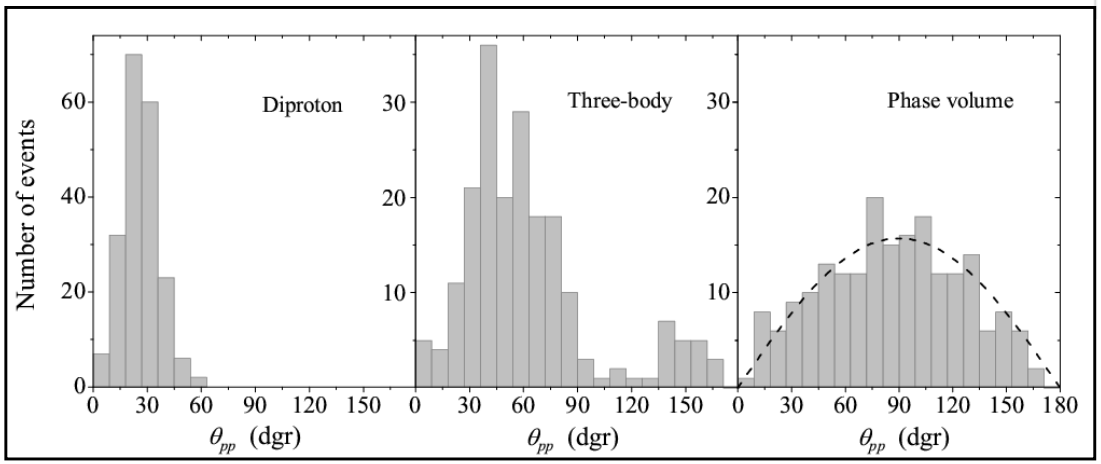
M. Pomorski et al., Phys. Rev. C 83 (2011) 061303(R)

Two-proton decay of ^{54}Zn

Can we see the Z=28 shell closure in the p-p correlations?



^{45}Fe case (Z=28-2)



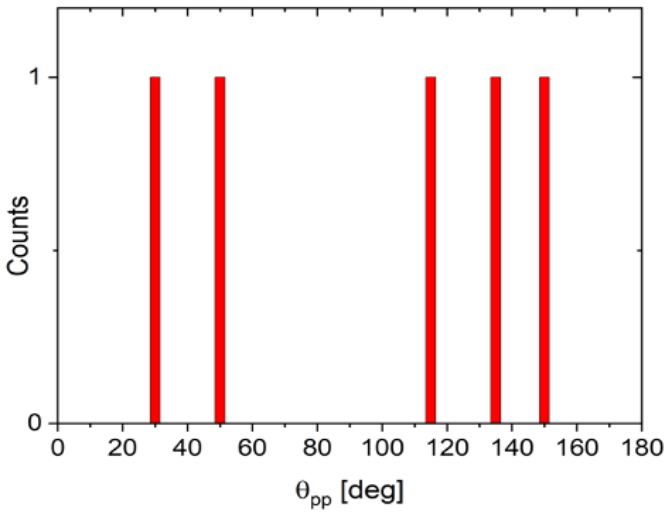
Two-proton decay of ^{54}Zn

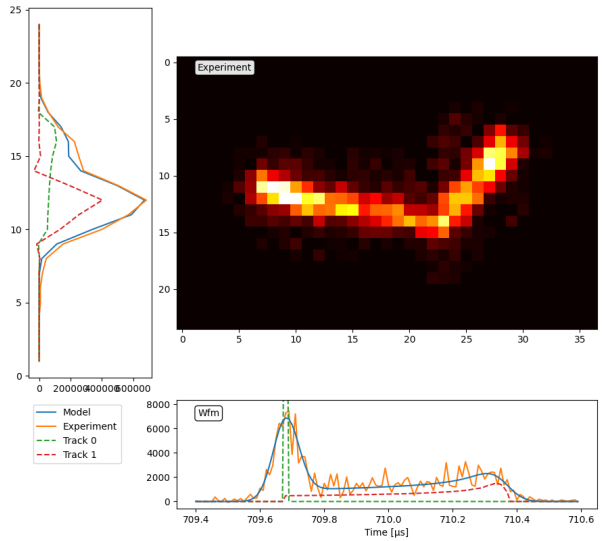
RIKEN: ^{78}Kr @ 350 MeV/u + ^{9}Be $\rightarrow$ ^{54}Zn

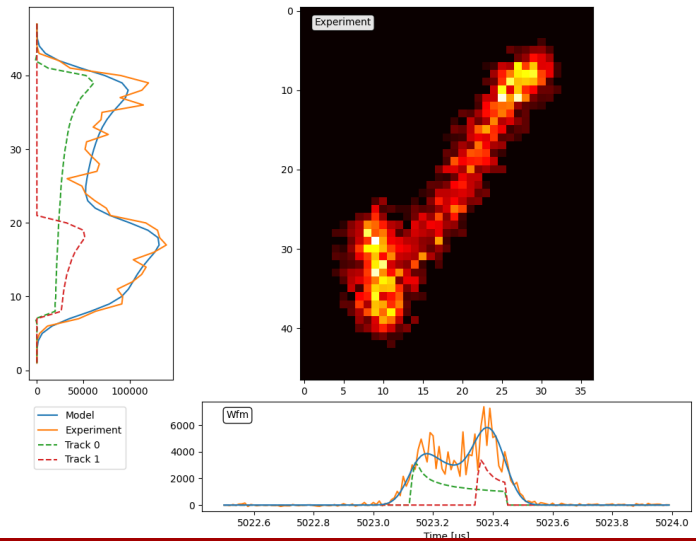
- production cross section: 3.5±0.8±0.7 fb
- 5 events observed

- opening angle reconstructed for 5 events

  ... to be continued FRIB ...







A. Kubiela et al., Phys. Rev. C 104, 064610 (2021)
A. Kubiela, PhD thesis, University of Warsaw, in preparation

p-p correlations around Z=28

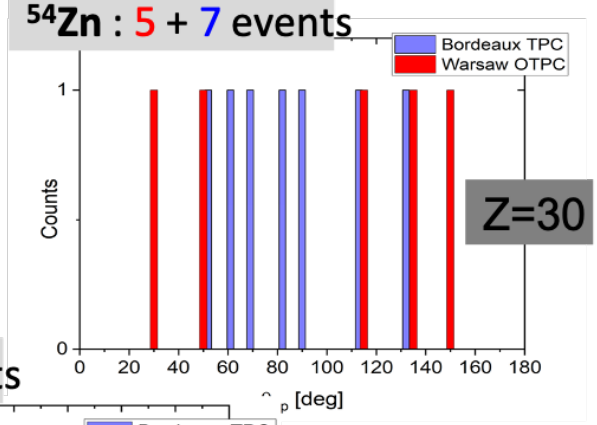
$$R_{>90^\circ} = \frac{N(\theta > 90^\circ)}{N_{tot}}$$

$^{54}Zn : R_{>90^\circ} = 0.5(2)$

$^{48}Ni : R_{>90^\circ} = 0.0(1)$

$^{45}Fe : R_{>90^\circ} = 0.20(5)$

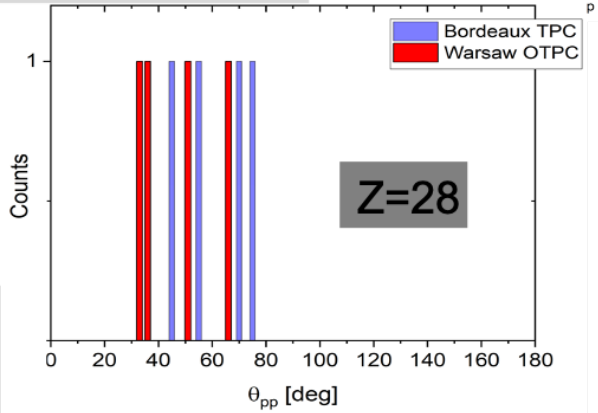
^{54}Zn : 5 + 7 events



Ascher et al
PRL 107 (2011)

Kubiela et al.,
to be published

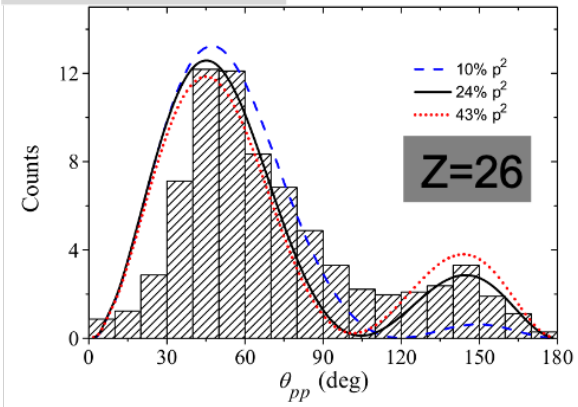
^{48}Ni : 4 + 4 events



Ortega-Moral, Acta Phys. Pol. B Proc. Supp. 16 (2023)

Pomorski et al., PRC 90 (2014)

^{45}Fe : 75 events

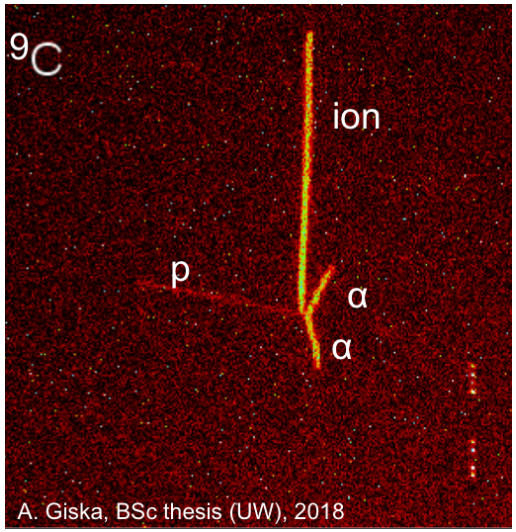


Miernik et al
PRL 99 (2007)

Summary and outlook

OTPC used in connection with different ion-delivery systems:

- simple and very efficient tool to search for very rare decays and to investigate charged-particle decays obscured by β background
- it can provide precise branching ratios and angular correlations
- low energies can be reconstructed (worse energy resolution than with Si detectors - complementarity!)
- 2p correlations measured for ^{45}Fe indicate non trivial 3-body character
- correlations needed for ^{48}Ni and ^{54}Zn
- can we see the Z=28 shell closure in the 2p decay data?



- experiments approved at FRIB to measure p-p angular correlations in the decay of ^{48}Ni and ^{54}Zn

thank you!

The OTPC core team

- Wojciech Dominik
- Henryk Czyrkowski
- Zenon Janas
- C.M.
- Marek Pfützner
- PhD Students
  - Krzysztof Miernik
  - Marcin Pomorski
  - Sławomir Mianowski
  - Aleksandra Ciemny
  - Natalia Sokołowska
  - Adam Kubiela