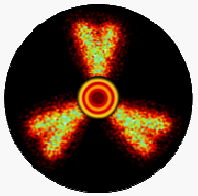
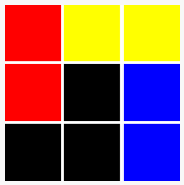
Two-Proton Radioactivity Status Report

Marek Pfützner





Nuclear Physics Division
University of Warsaw

PROCON 2019

20 years of PROCON

The two-proton emission was the PROCON topic from the first conference

- *Search for Two-Proton Emitters at FRS-GSI*
  M. Pfützner
- *Two-Proton Decay Experiments at MSU*
  M. Thoennessen, M. Chromik, P Thirolf
- *Two-Proton Emission in the Hyperharmonics Approach*
  I. Mukha
- *First Observation of Doubly-Magic ^{48}Ni*
  J. Giovinazzo et al.

The final transparency of my talk

Conclusion

Experimentally, the best candidate for 2p-decay is ^{45}Fe

- **cross section : ~ 2 pb**
- **rate : ~100 events/week**
- **implantation range : ~ 1 mm of silicon**
- **energy deposit in the last 150 μm : ~ 600 MeV**
- **half-life : 0.5 - 100 μs (?)**

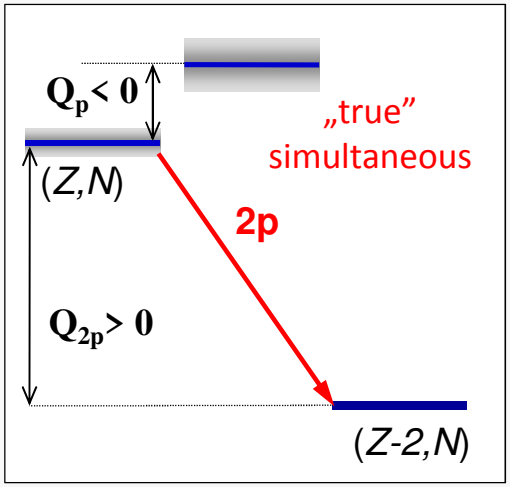
The problem : detect 1 MeV decay signal 1 μs after 600 MeV implantation signal

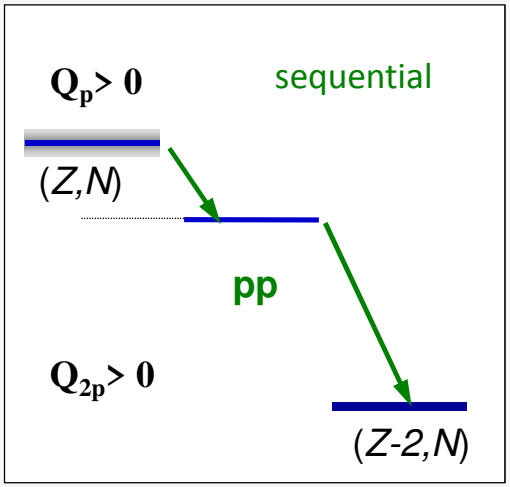
➔ **new approach to data acquisition**

For future : detect two protons separately

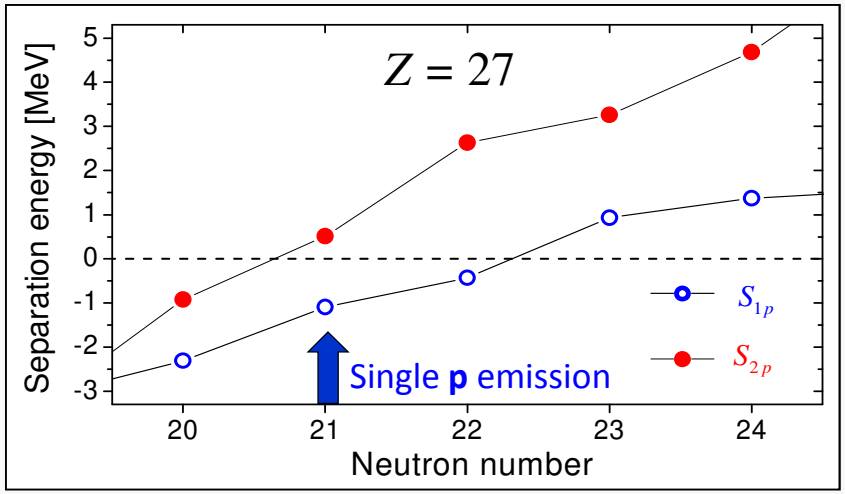
Introduction

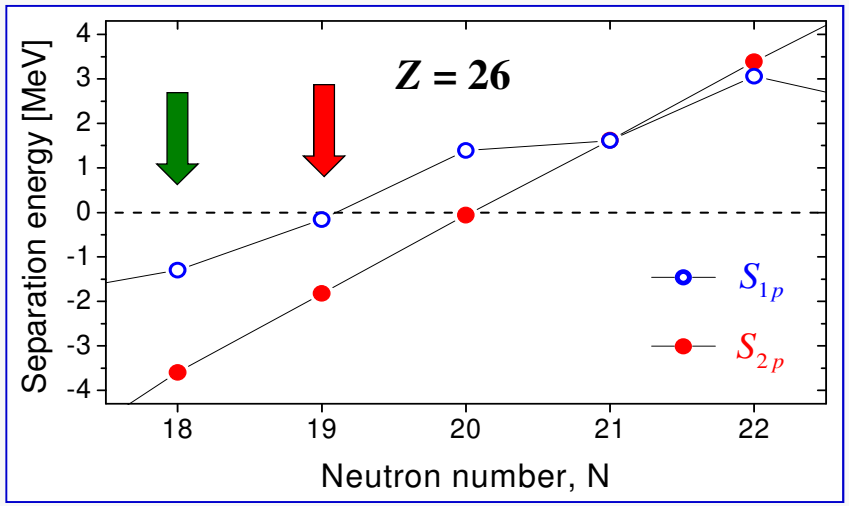
- Expected for even-Z nuclei beyond the proton drip-line





Goldanskii, Nucl. Phys. 19 (60) 482



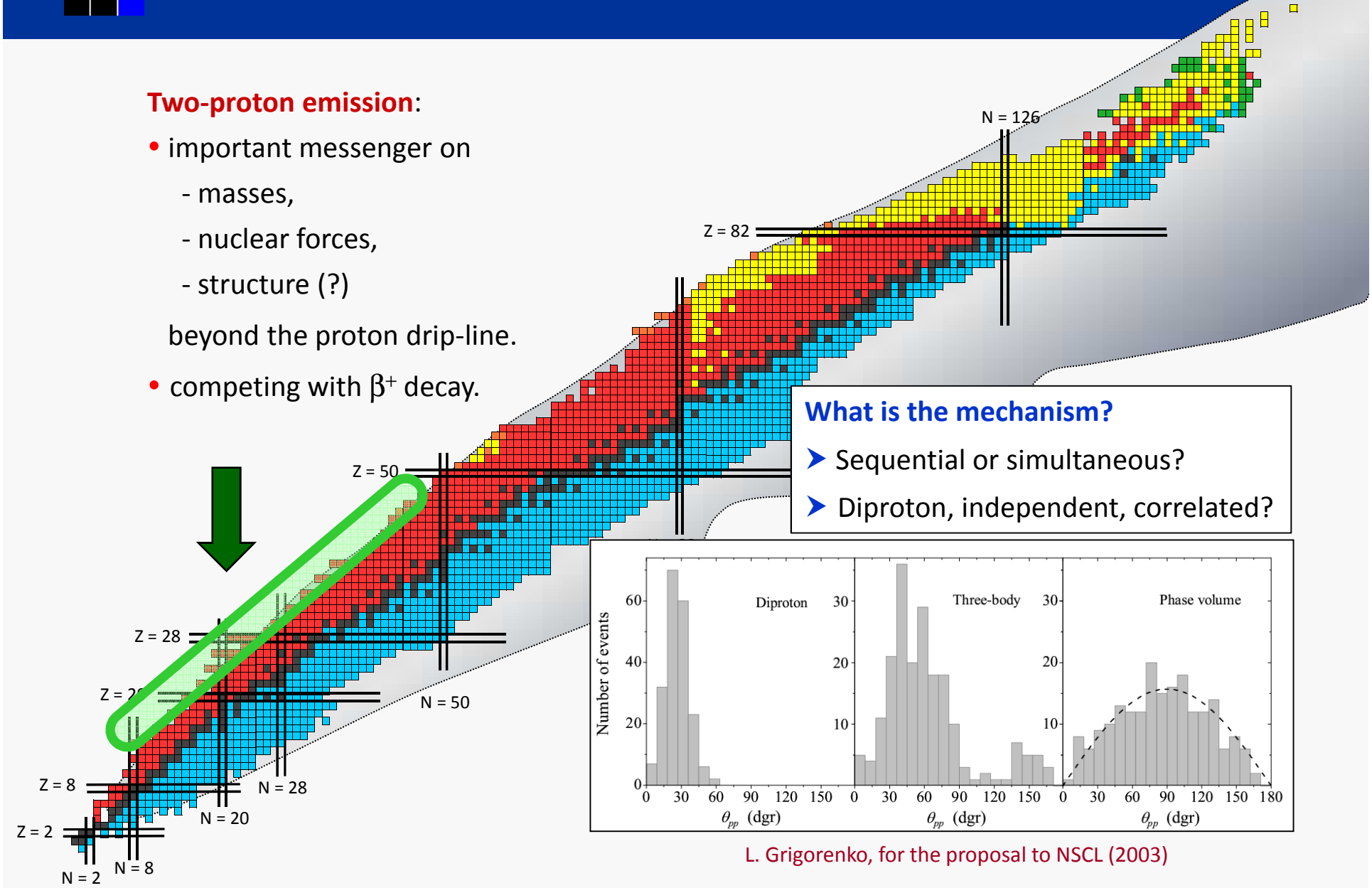


Introduction

Two-proton emission:

- important messenger on
  - masses,
  - nuclear forces,
  - structure (?)

  beyond the proton drip-line.
- competing with β^+ decay.



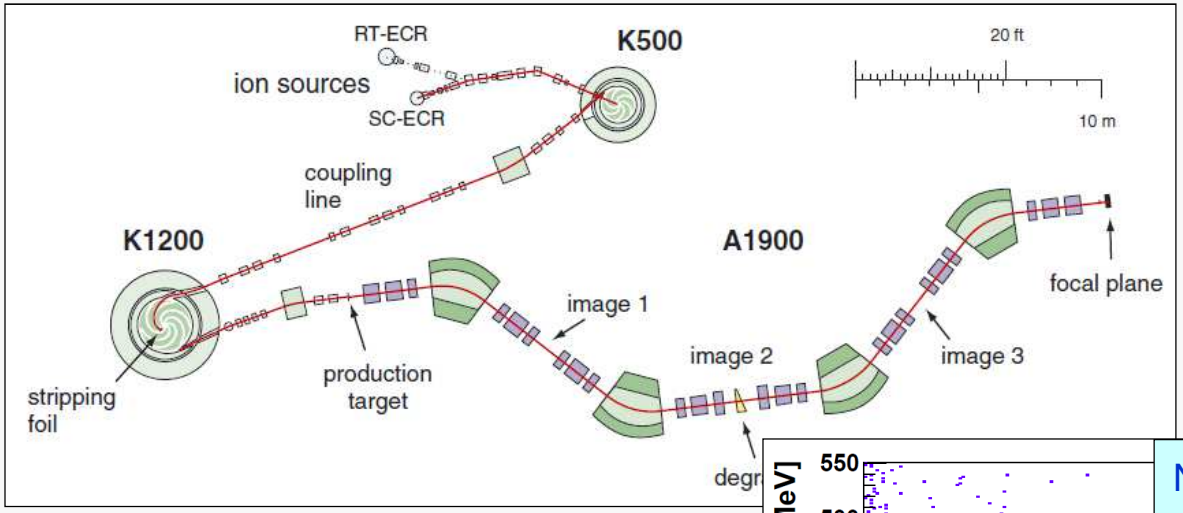
What is the mechanism?

- Sequential or simultaneous?
- Diproton, independent, correlated?

L. Grigorenko, for the proposal to NSCL (2003)

Production

Two-proton emission studies require in-flight fragmentation facilities



LISE @ GANIL

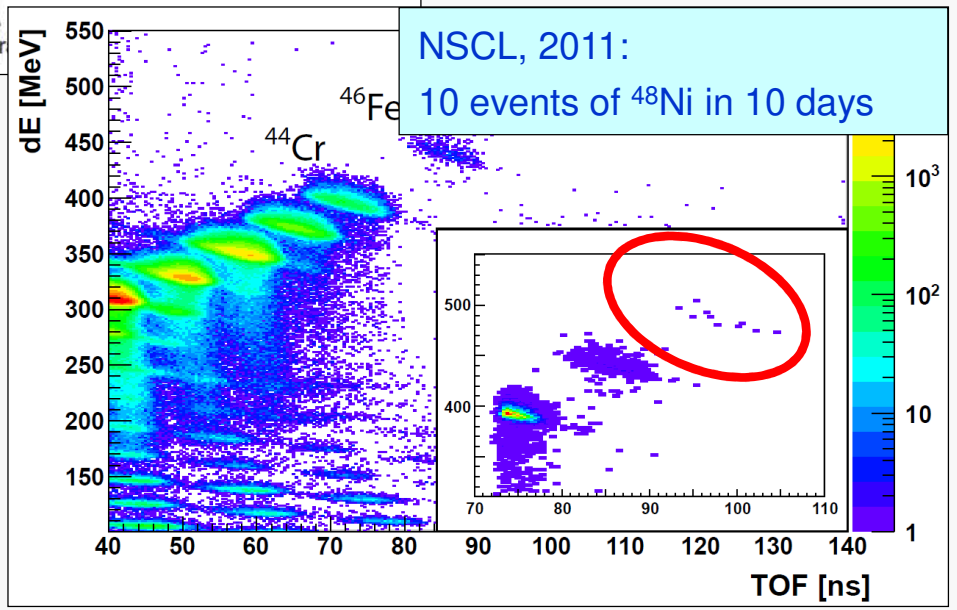
FRS @ GSI

A1900 @ NSCL

BigRIPS @ RIBF

Key features:

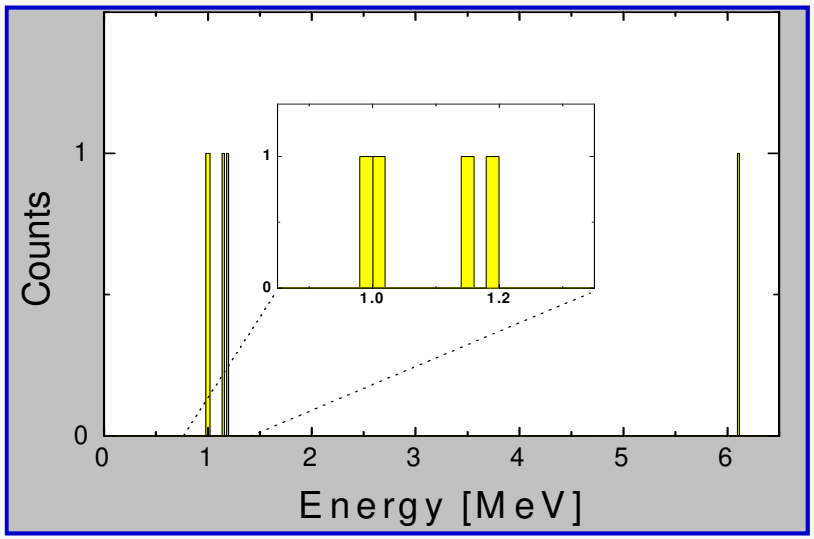
- full identification of single ions in-flight
- fast transport for short half-lives
- energy high enough to implant into detector arrays



Implantation into Si

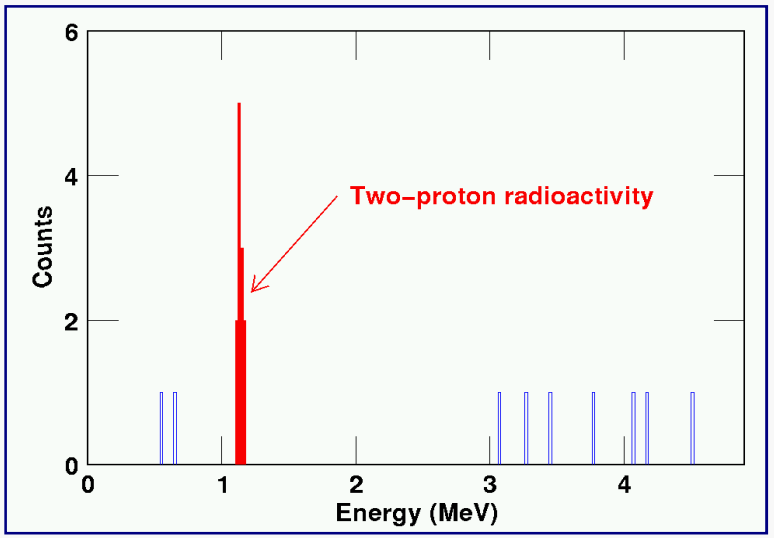
- Implantation into Si array – good measurement of energy, but protons not resolved!
  In addition, auxiliary detectors are necessary → one has to prove that observed peak is not β-delayed emission!

GSI: ^{58}Ni @ 650 MeV/A +Be → ^{45}Fe



MP et al., EPJ A 14 (2002) 279

GANIL: ^{58}Ni @ 75 MeV/A +Ni → ^{45}Fe

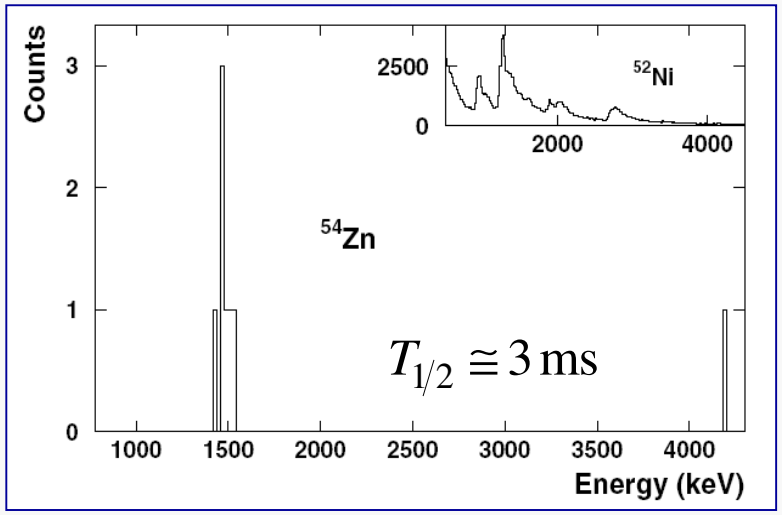


Giovinazzo et al., PRL 89 (2002) 102501

Discovery of 2p radioactivity in ^{45}Fe (2002), presented at 2nd PROCON 2003 (Legnaro)

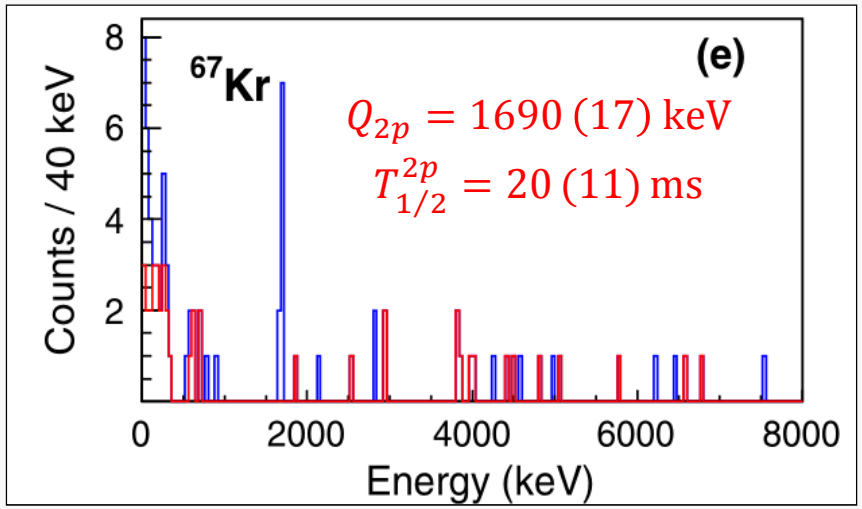
Implantation into Si

GANIL ^{58}Ni @ 75 MeV/A +Ni → ^{54}Zn



Blank et al., PRL 94 (2005) 232501

RIKEN: ^{78}Kr @ 345 MeV/A +Be → ^{67}Kr



Goigoux et al., PRL 117 (2016) 162501

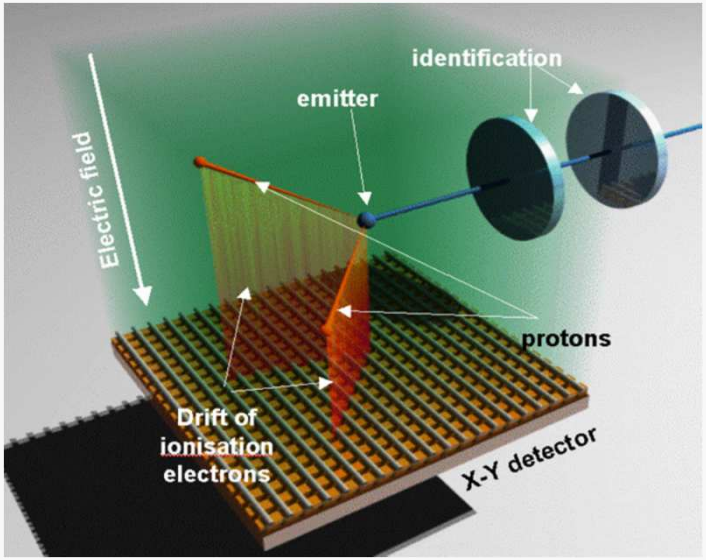
Presented at 3rd PROCON 2007 (Lisbon)

A puzzle:
the 2p emission 20 × faster than expected

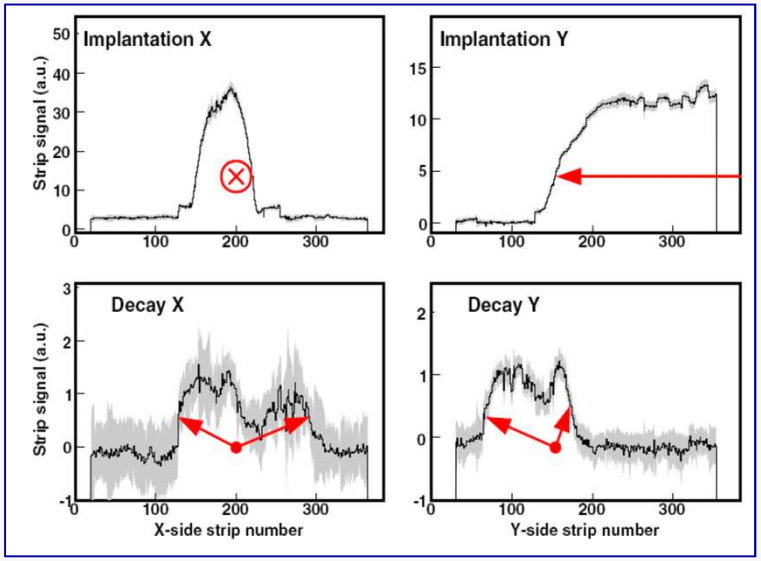
See the talk of B. Blank later today

TPC for 2p decays

- To measure momenta of both protons gaseous TPC detectors were developed
- CEN Bordeaux – the „classical" TPC with electronic readout
  the first direct observation of two protons emitted by ^{45}Fe



A decay event of ^{45}Fe



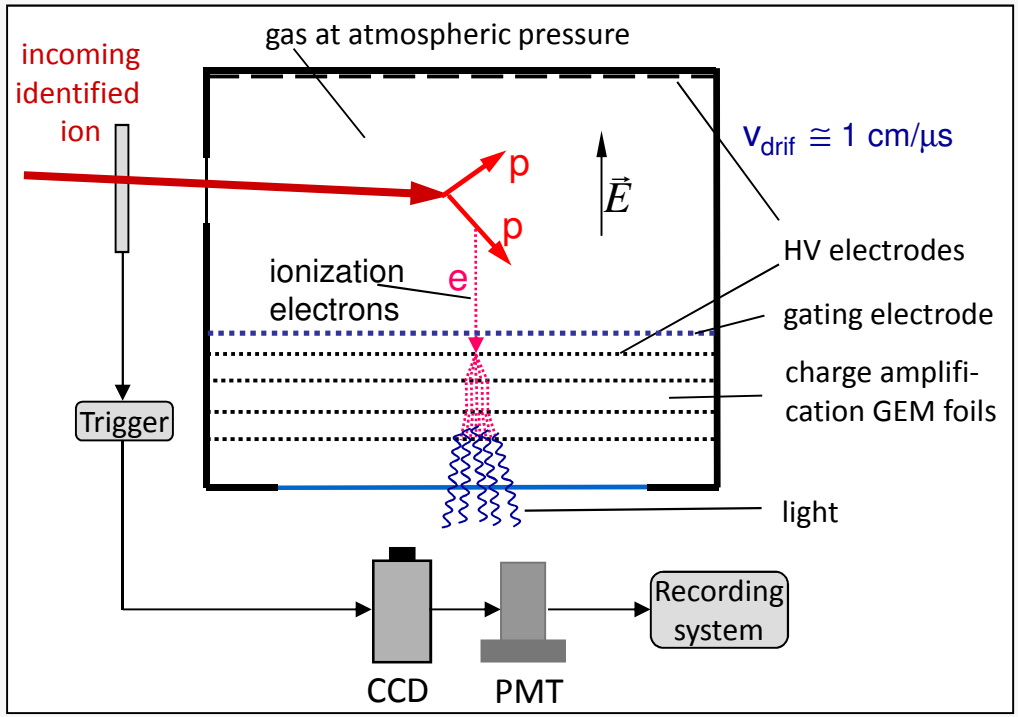
Giovinazzo et al., PRL 99 (2007) 102501

Presented at 3rd PROCON 2007 (Lisbon)

TPC for 2p decays

➤ University of Warsaw – a novel type of TPC with optical readout

OTPC – Optical Time Projection Chamber

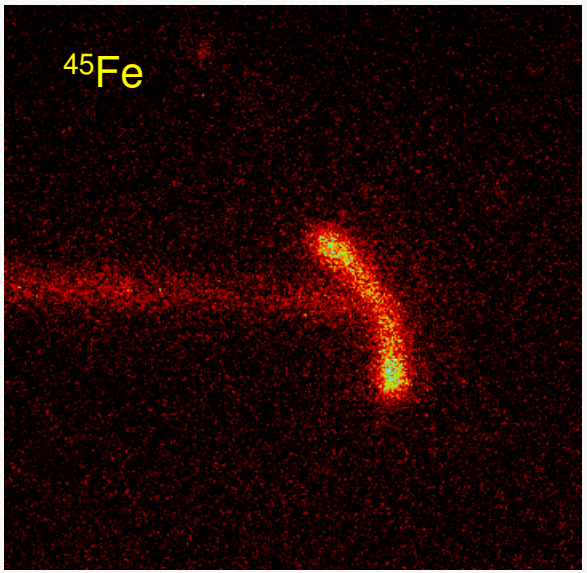


More on the OTPC and its applications to other decays see talks of A.A. Ciemny (today afternoon) and N. Sokołowska (tomorrow morning)

^{45}Fe and ^{48}Ni with OTPC

- Experiments at the NSCL/MSU: ^{58}Ni @ 161 MeV/u + ^{nat}Ni

2007

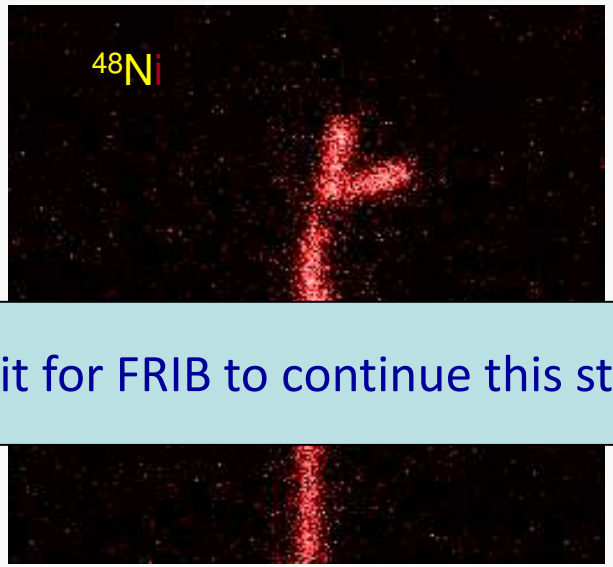


Miernik et al., PRL 99 (07) 192501

≈ 80 events → p-p correlations

Presented at 3rd PROCON 2007 (Lisbon)

2011



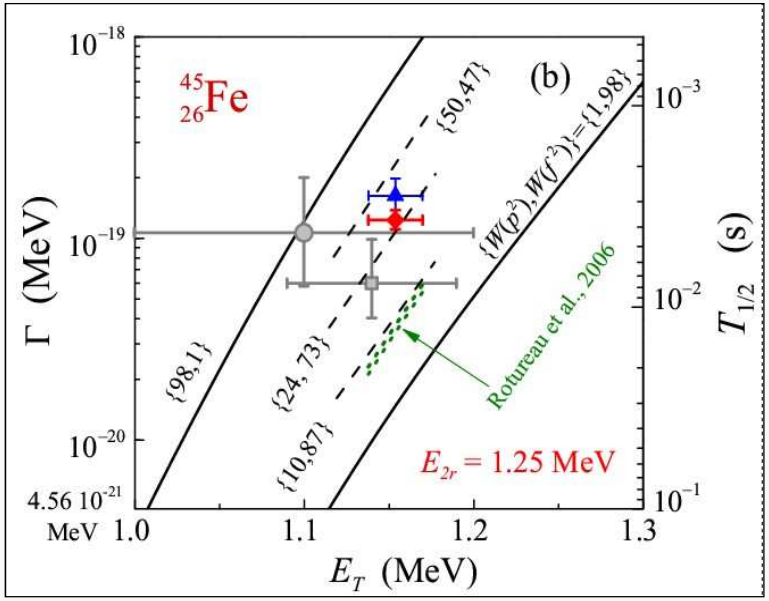
We wait for FRIB to continue this study!

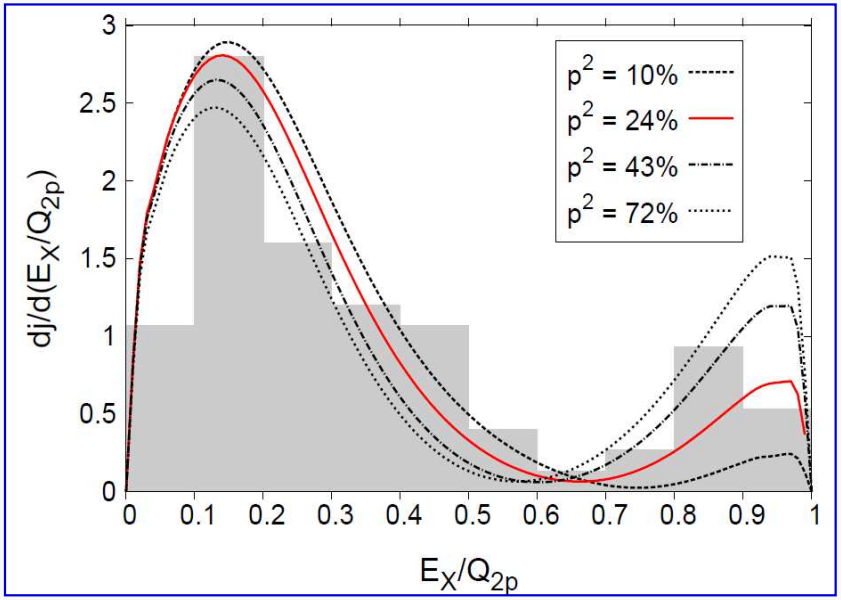
Pomorski et al., PRC 83 (2011) 061303(R)

4 events → the first observation of 2p decay in this nucleus

Presented at 4th PROCON 2011 (Bordeaux)

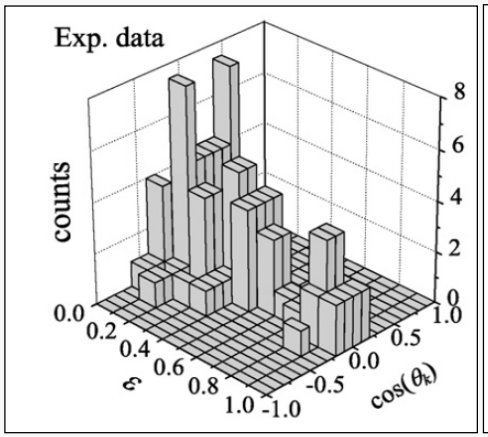
p-p correlations in ^{45}Fe

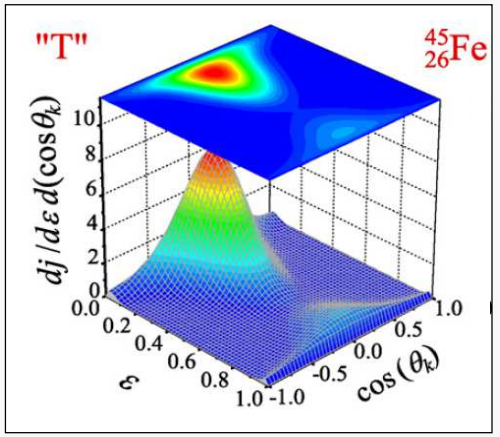




Result for ^{45}Fe: $W(p^2) = 0.3 \pm 0.1$

- 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





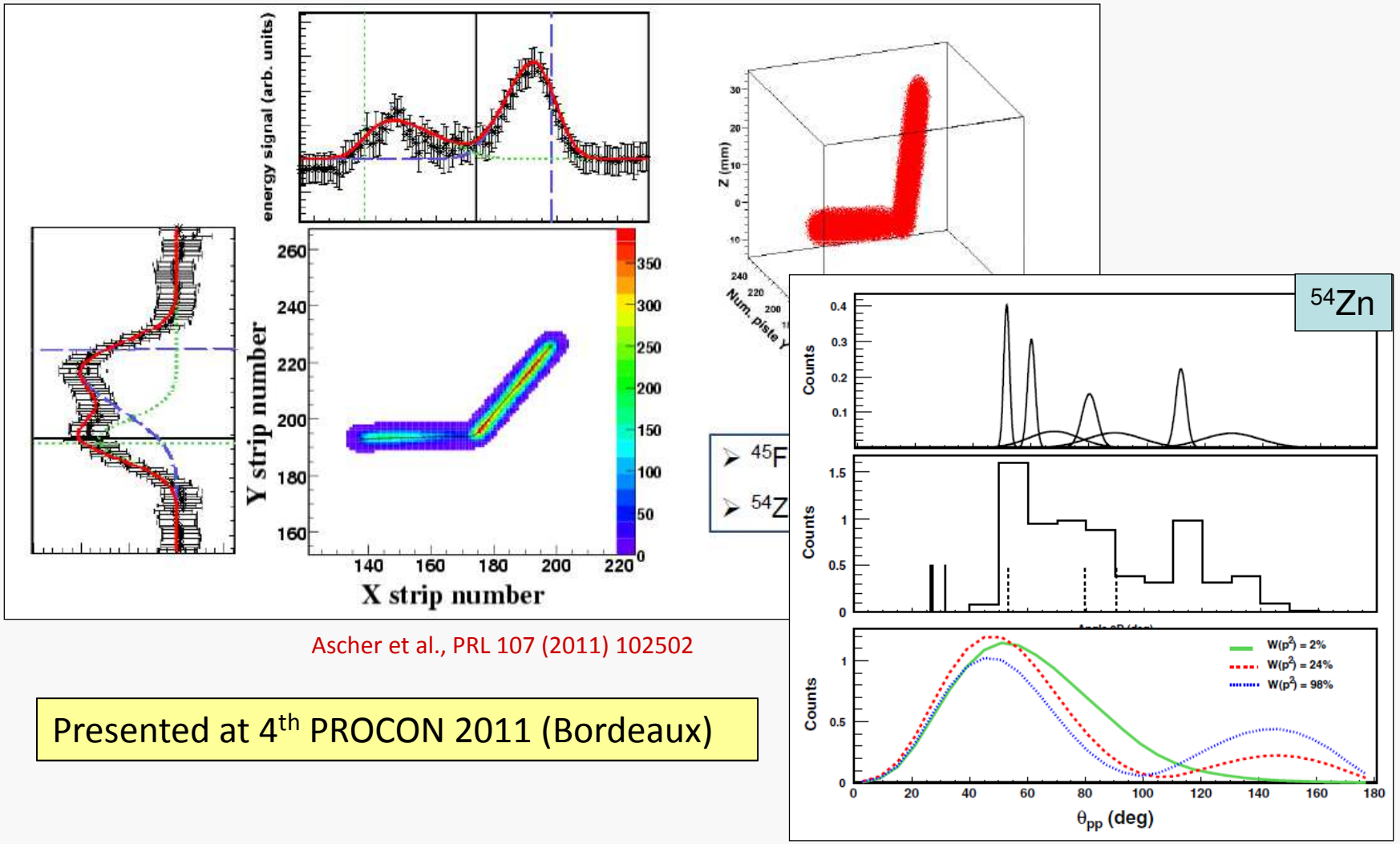
Miernik *et al.*, EPJA 42 (2009) 431

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

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

p-p correlations in ^{54}Zn

- Bordeaux TPC @ LISE (GANIL). Seven 2p events from ^{54}Zn reconstructed in 3D



Ascher et al., PRL 107 (2011) 102502

Presented at 4th PROCON 2011 (Bordeaux)

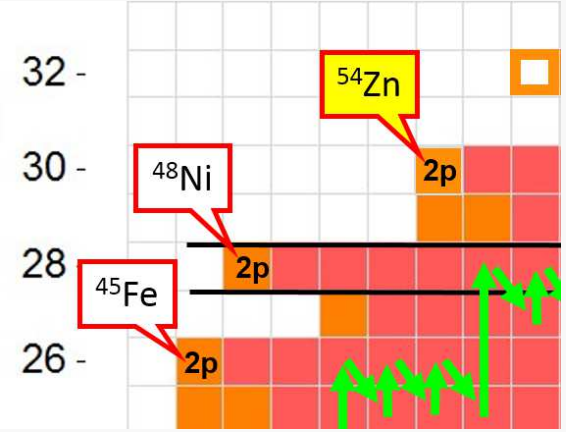
OTPC attempt at ^{54}Zn

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

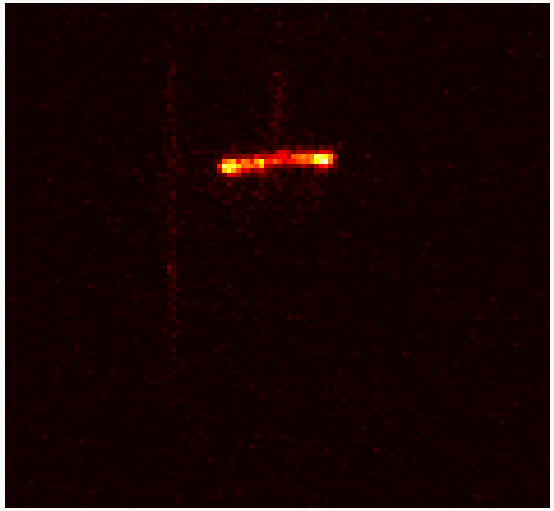
Experiment at BigRIPS, RIKEN, April 2019

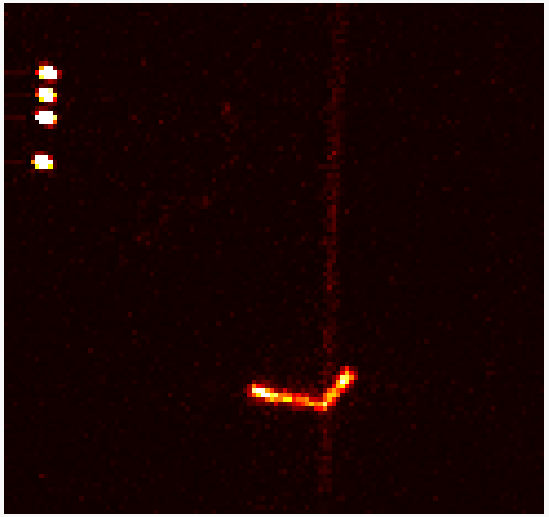
^{78}Kr @ 350 MeV/u + ^{9}Be → ^{54}Zn

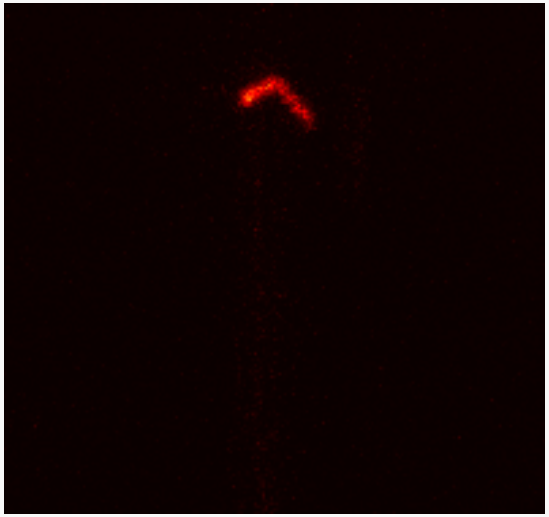
The beam intensity was great: 300 pnA
but the cross section was found
more than 100 x smaller than EPAX 3.01



➔ Only a few 2p decay events observed ☹





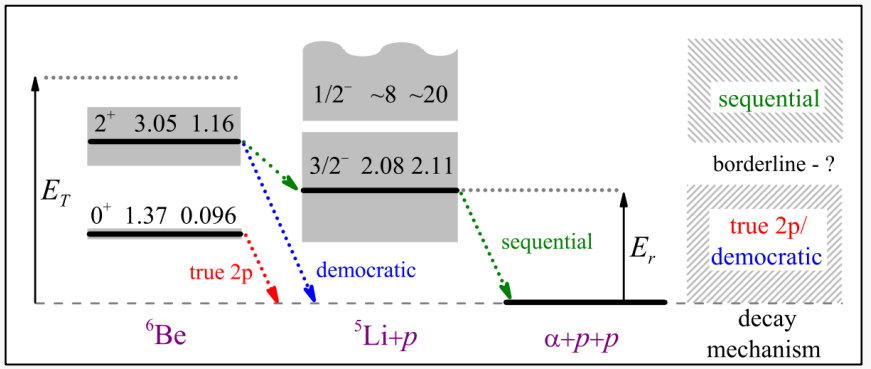


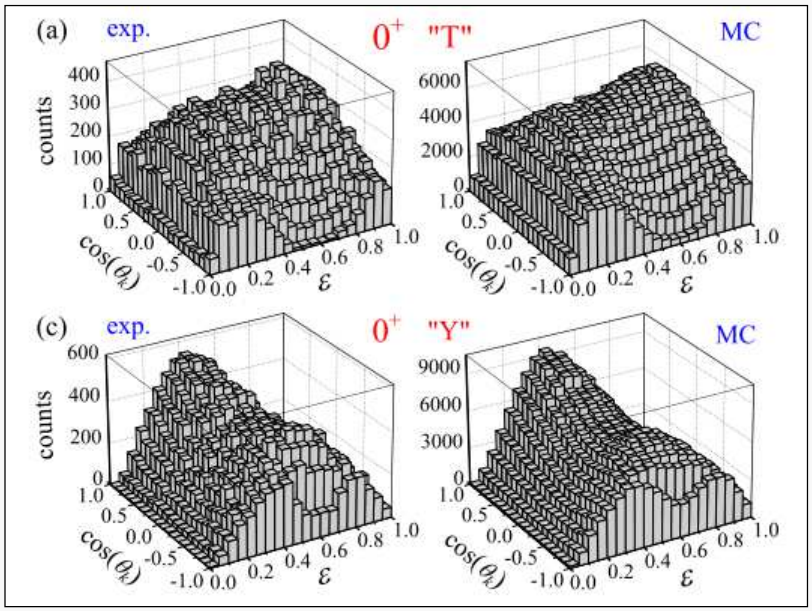
Democratic decay of ^{6}Be

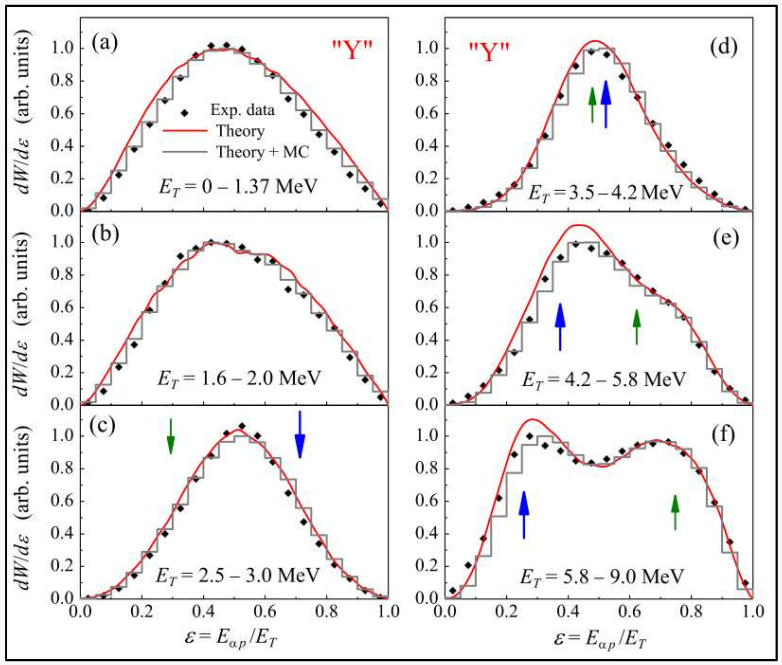
- The earliest known and the best studied 2p emiter. The most recent, high statistics study @ NSCL (2012)

^{16}O @ 150 MeV/A + ^{9}Be → ^{7}Be (A1900)

^{7}Be + ^{9}Be → ^{6}Be → α + p + p (HiRA)





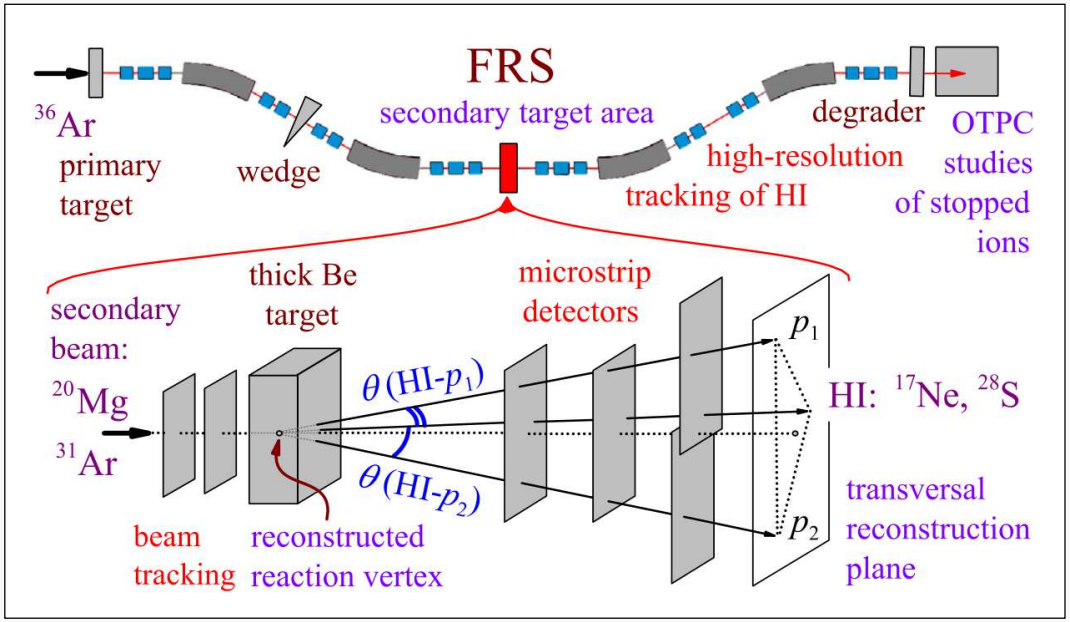


Egorova *et al.*, PRL 109 (2012) 202502

Complex 3-body decay!

In-flight method

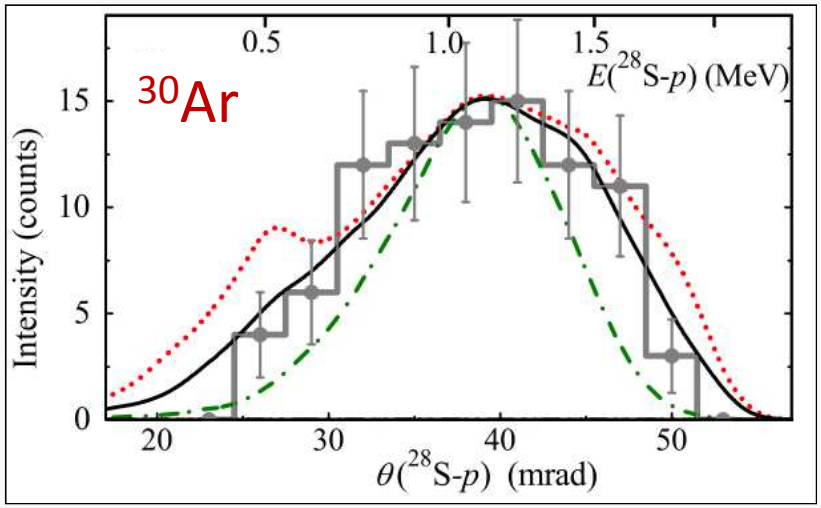
- In-flight approach applied @ GSI to study decays of ^{16}Ne, ^{19}Mg, ^{30}Ar

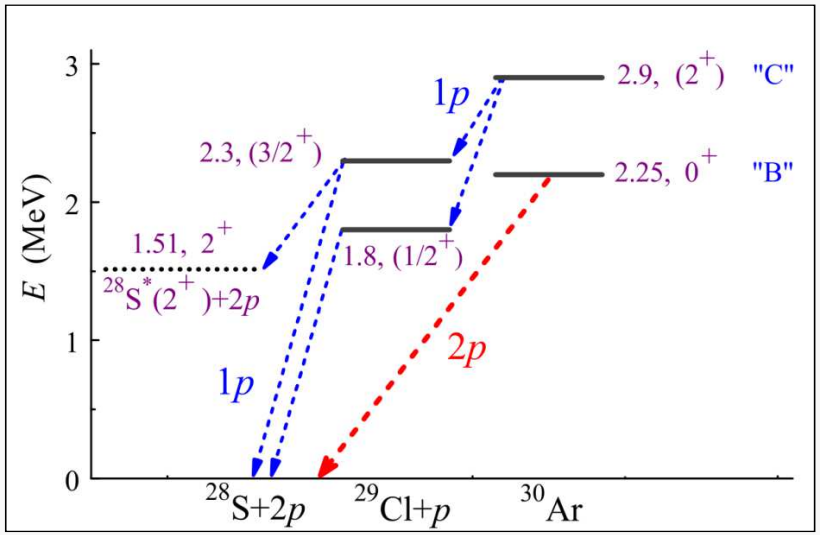


Mukha et al., PRL 99 (2007) 182501
Mukha et al., PRC 82 (2010) 054315

Presented at 5th PROCON 2015 (Lanzhou)

See the talk of I. Mukha today afternoon





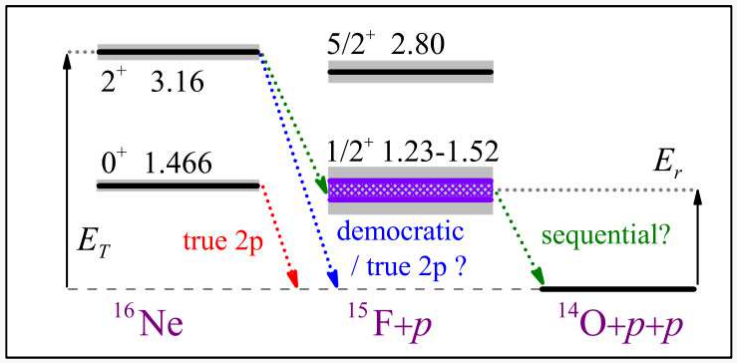
Mukha et al., PRL 115 (2015) 202501

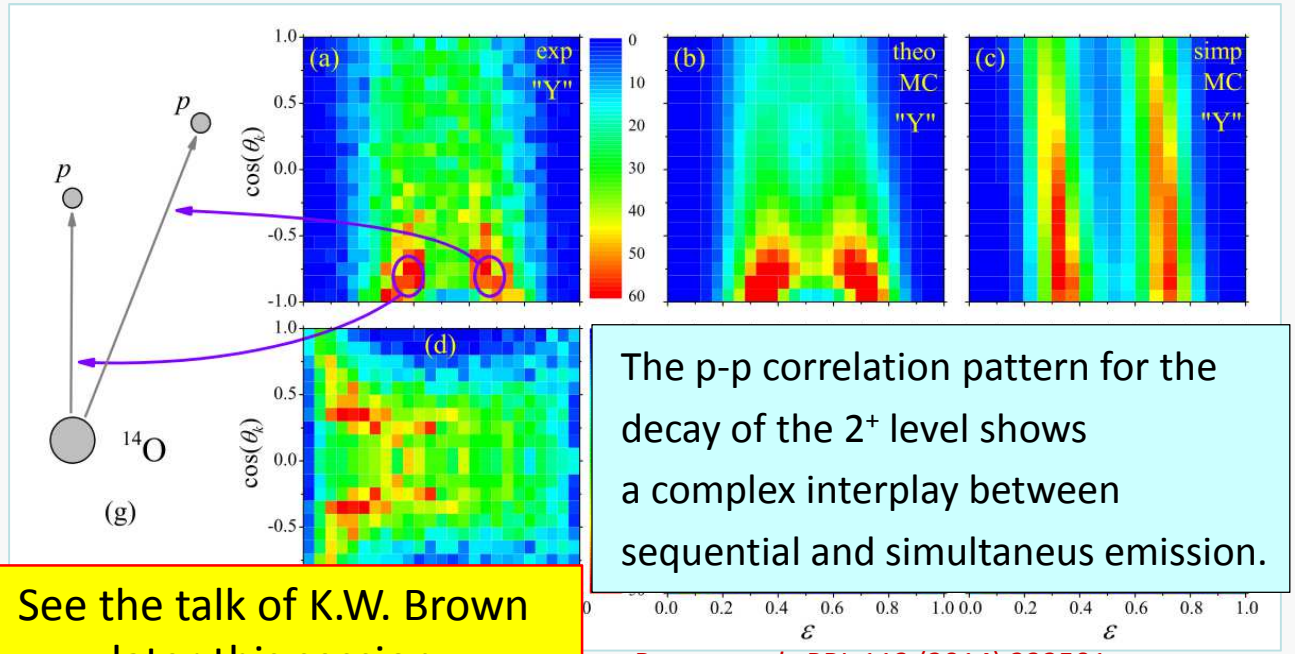
A ”tethered” 2p decay of ^{16}Ne*

- 2p decay of the first excited state of ^{16}Ne can be expected to be sequential. But it seems to be more complicated…

^{20}Ne @ 170 MeV/A + ^{9}Be → ^{17}Ne (A1900)

^{17}Ne + ^{9}Be → ^{16}Ne → ^{14}O + p + p (HiRA)





The p-p correlation pattern for the decay of the 2+ level shows a complex interplay between sequential and simultaneus emission.

See the talk of K.W. Brown later this session

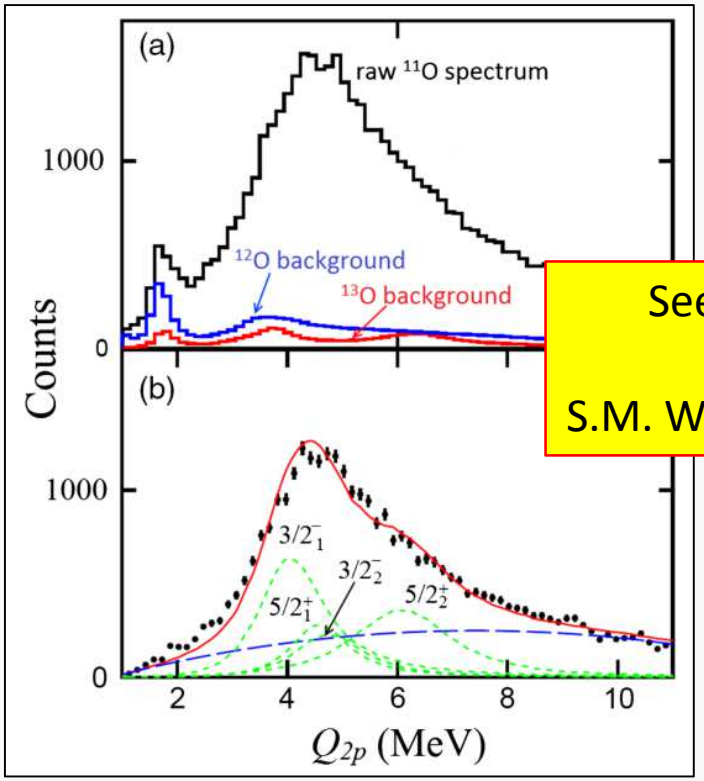
Brown *et al.*, PRL 113 (2014) 232501
Brown *et al.*, PRC 92 (2015) 034329

^{11}O vs. ^{11}Li

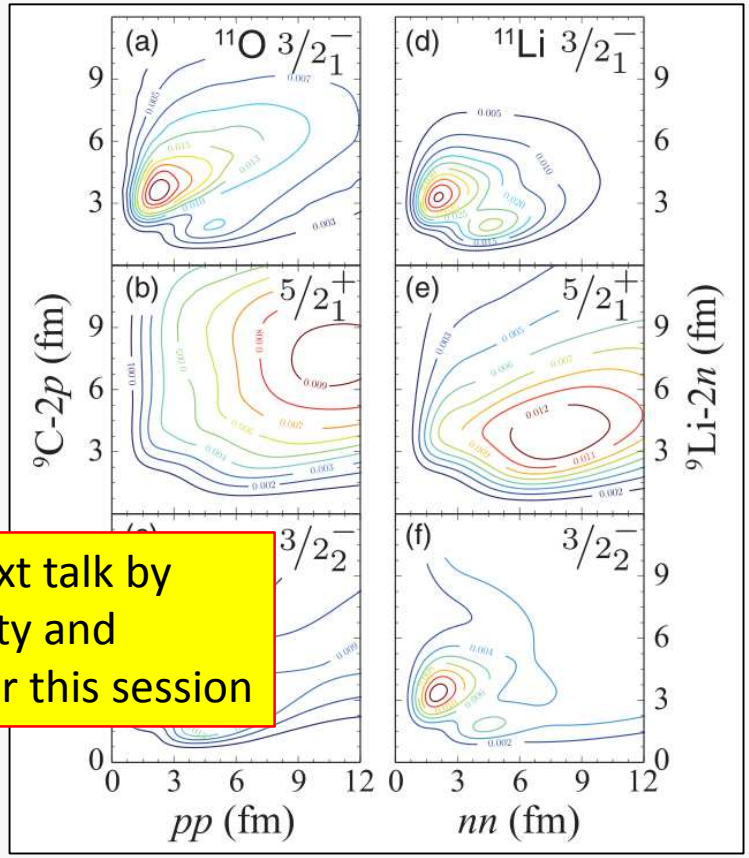
- The second 2p emiter in one element, after ^{12}O
  The large mirror asymmetry expected

^{16}O @ 150 MeV/A + ^{9}Be → ^{13}O (A1900+RFFS)

^{13}O + ^{9}Be → ^{11}O → ^{9}O + p + p (HiRA)



Webb *et al.*, PRL 122 (2019) 122501



See the next talk by
R. Charity and
S.M. Wang later this session

Data analyzed with the Gamow Coupled-Channel (GCC) model, newly developed for 2p decays. Moderate isospin asymmetry between ^{11}O and ^{11}Li found.

Theoretical models

„Classical" era, search for candidates

prediction of masses, schematic di-proton models for half-lives

Brown, PRC 43 (91) R1513,
Brown et al., PRC 65 (2002) 045802
Ormand, PRC 55 (97) 2407,
Cole, PRC 54 (96) 1240

More advanced half-lives

R-matrix Brown, Barker, PRC 67 (2003) 041304(R)

SMEC Rotureau, Okołowicz, Płoszajczak, Nucl. Phys. A767 (2006) 13

See the talk of A. Brown later this session

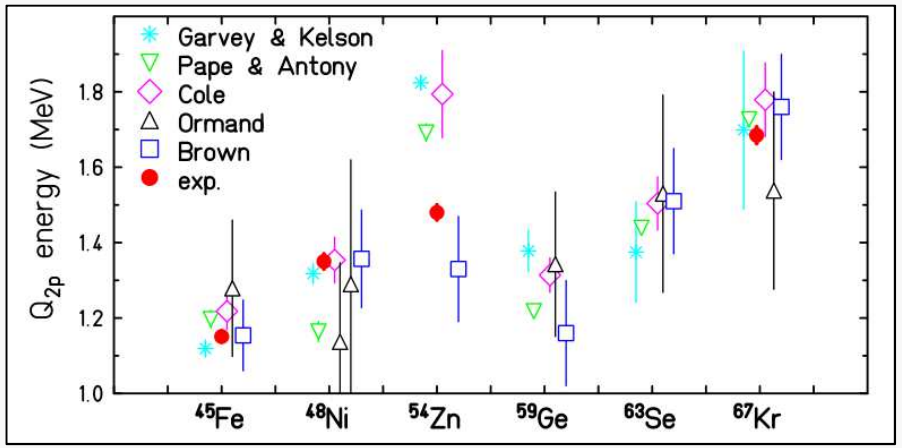
Various recent initiatives

Emission from a BCS state
Delion, Liotta, Wyss PRC 87 (2013) 034328

Effective liquid drop
Tavares Medeiros, EPJ. A 54 (2018) 65

Empirical formula
Sreeja, Balasubramaniam EPJ. A 55 (2019) 33

Goigoux et al., PRL 117 (2016) 162501



3-body models

Hypershperical harmonics, proper Coulomb asymptotics
Grigorenko and Zhukov, PRC 68 (2003) 054005

Time Dependent Method (TDM)
Oishi, Hagino, Sagawa, PRC 90 (2014) 034303

Oishi, Kortelainenm Pastore, PRC 96 (2017) 044327

Gamow Coupled-Channel (GCC)

Wang, Michel, Nazarewicz, Xu, RC 96 (20017) 044307
Wang, Nazarewicz, PRL 120 (2018) 212502

A new 3-body model

- New theoretical model on the market!

  Gamow coupled-channel (GCC) method in Jacobi coordinates

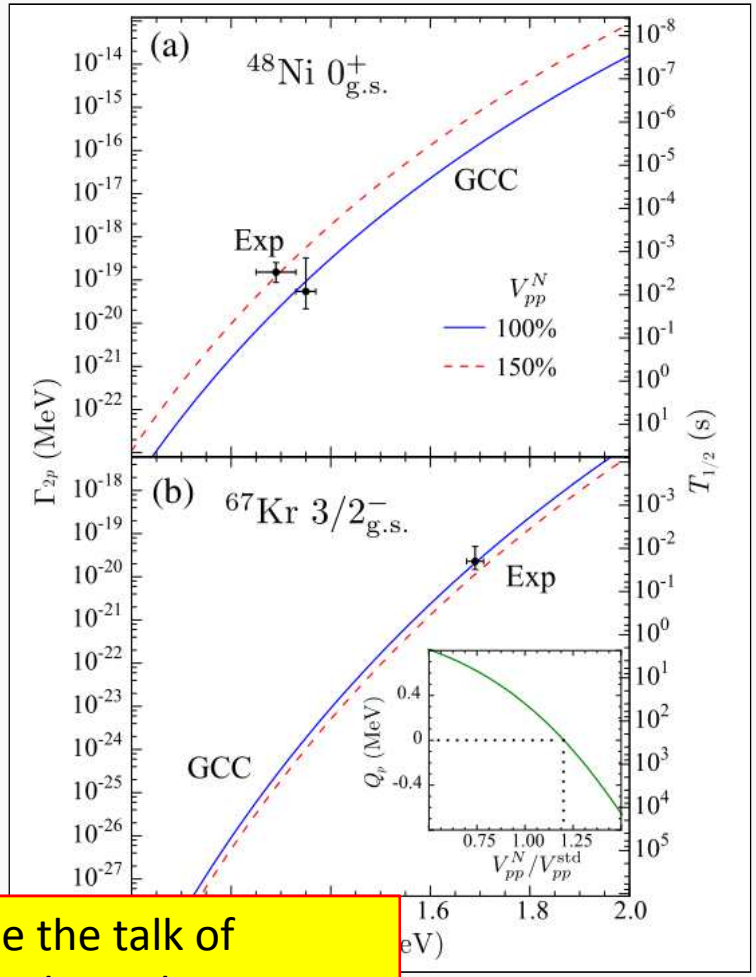
- Bound, scattering, and Gamow outgoing states on the same footing → nuclear and asymptotic regions treated coherently.

- Protons may couple to collective states of the core

- Oblate deformation of ^{67}Kr $\beta_2 \approx -0.3$ provides $l = 2$ amplitude to valence protons which speeds-up the 2p decay!

- The GCC predictions indicate sensitivity to:
  a) the strength of *pp* interaction, and
  b) the valence proton structure

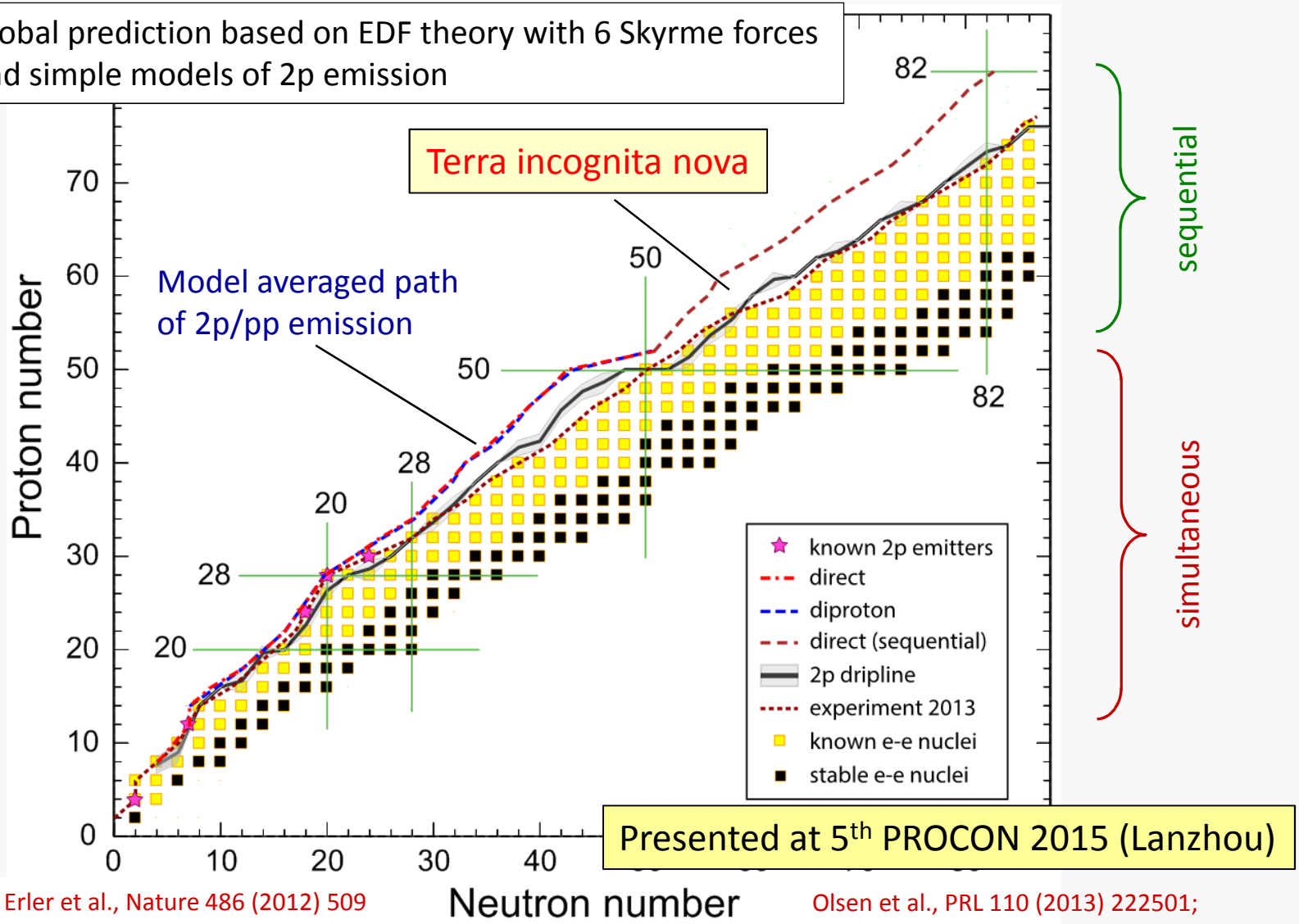
Wang, Nazarewicz, PRL 120 (2018) 212502



See the talk of S.M. Wang later this session

Full 2p landscape

Global prediction based on EDF theory with 6 Skyrme forces and simple models of 2p emission



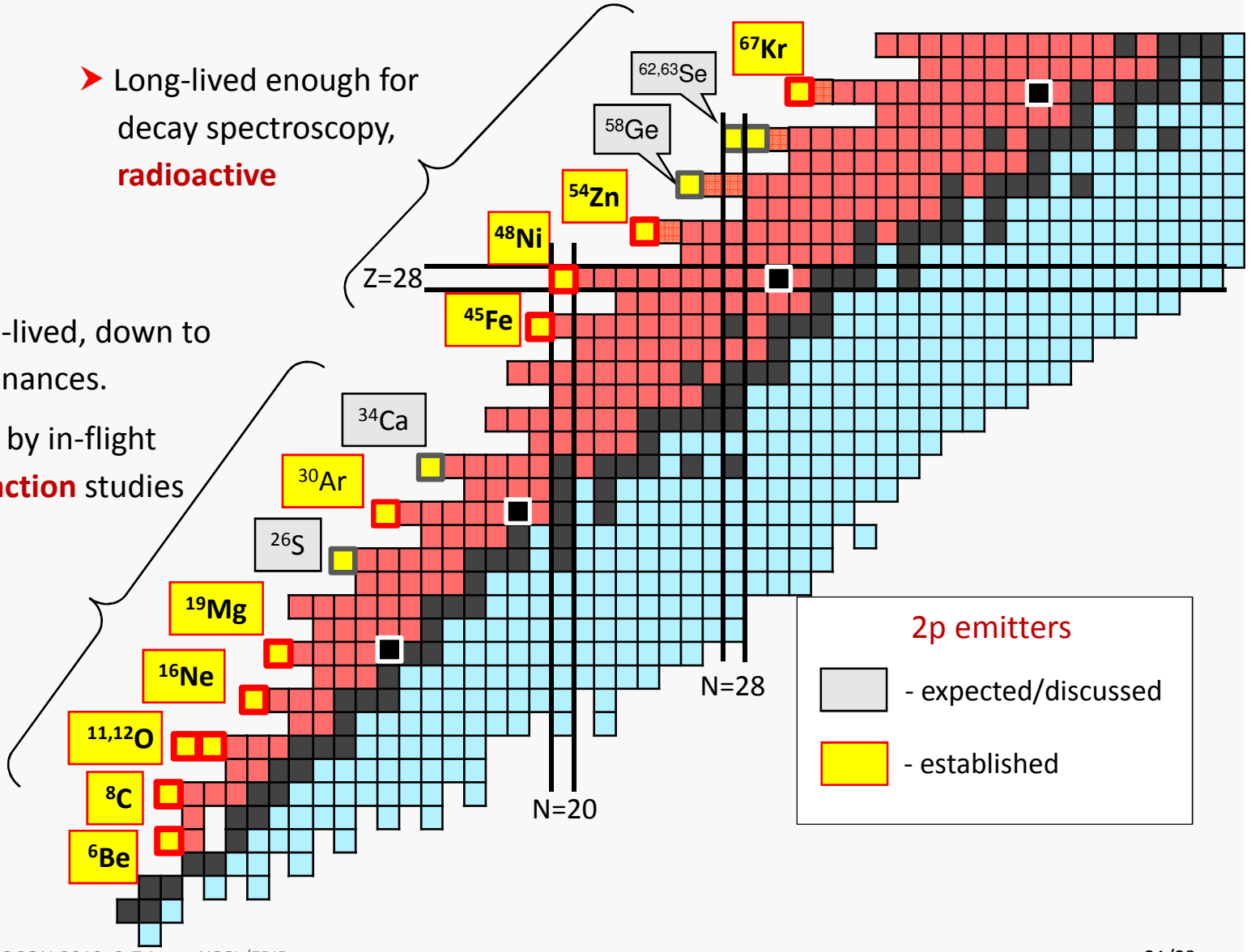
Presented at 5th PROCON 2015 (Lanzhou)

Erler et al., Nature 486 (2012) 509

Olsen et al., PRL 110 (2013) 222501; PRL 111 (2013) 139903 (E)

The current status of *2p* emission

- Long-lived enough for decay spectroscopy, **radioactive**
- Very short-lived, down to broad resonances.
- Measured by in-flight decays/**reaction** studies



Summary

- The ground-state *2p* emission observed for 11 nuclei.
  The heaviest is the newly discovered ^{67}Kr .

- Many other cases wait for discovery.
  Above tellurium a *sequential* emission is predicted.

- *2p* correlations measured for ^{45}Fe indicate non trivial 3-body character.
  Still needed correlations for ^{48}Ni and ^{54}Zn – **we wait for FRIB!**
  Can we see the Z=28 shell closure in the *2p* decay data?

- In a few light cases a complex interplay between prompt and sequential
  2p emission is observed.

- Progress in theory → a new 3-body GCC model!
  Fast *2p* emission from ^{67}Kr explained by strong oblate deformation.

Thank you!