Two-proton radioactivity

status and perspectives

Marek Pfützner

Nuclear Physics Division
University of Warsaw

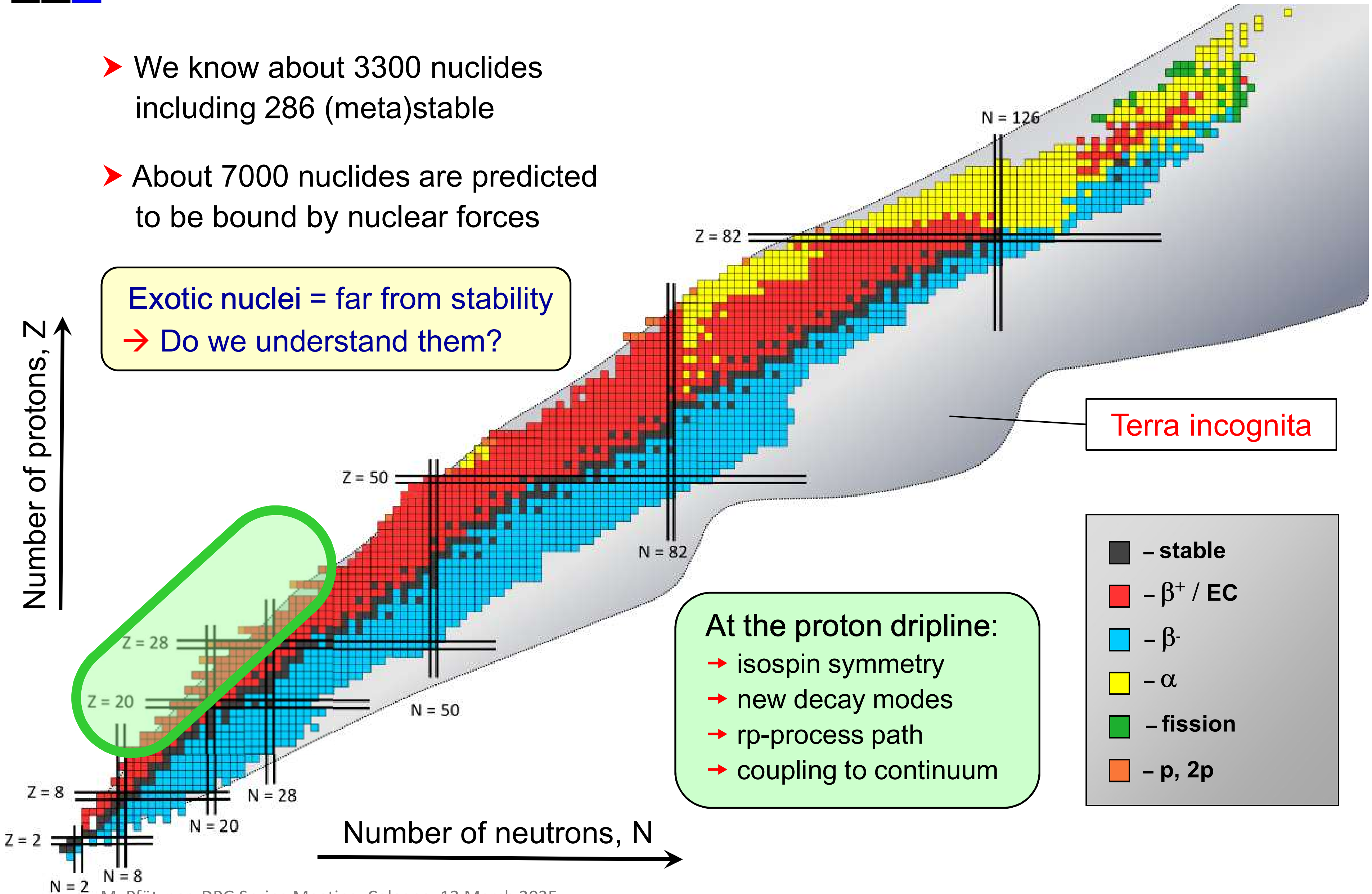
Dedication

Gottfried Münzenberg
1940 – 2024

Chart of nuclides

- We know about 3300 nuclides including 286 (meta)stable
- About 7000 nuclides are predicted to be bound by nuclear forces

Exotic nuclei = far from stability
→ Do we understand them?



At the proton dripline:
- isospin symmetry
- new decay modes
- rp-process path
- coupling to continuum

Beyond the proton drip-line

Competition between two decay modes

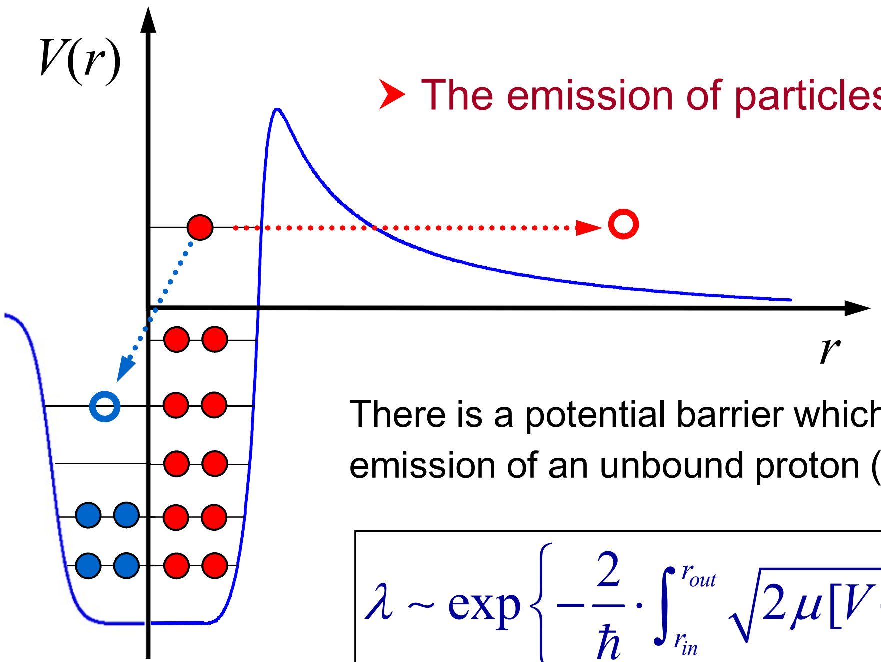
- The β^+ decay

  Probability of transition:

  $$\boxed{\lambda \sim Q^5}$$

  Decay energy is large,
  but the weak interaction
  is really weak

  → $\boxed{T_{1/2} > 1 \text{ ms}}$



- The emission of particles

  There is a potential barrier which hampers emission of an unbound proton (α, 2p, ^{14}C,..)

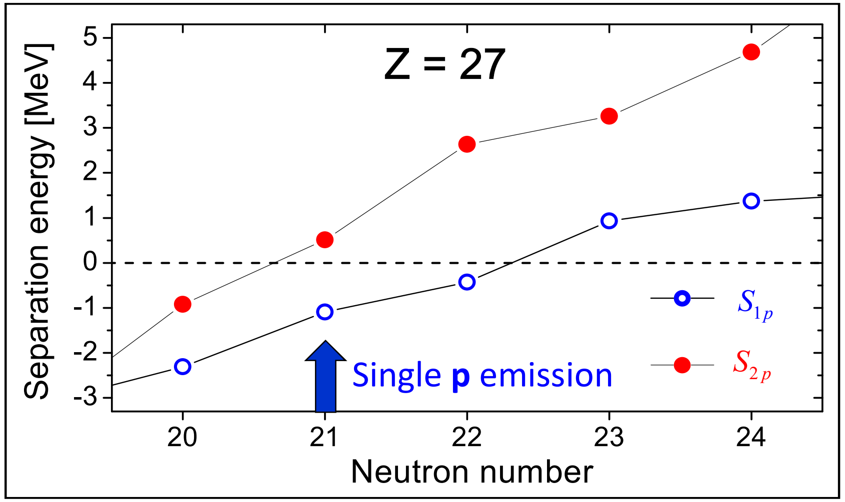
  $$\boxed{\lambda \sim \exp\left\{-\frac{2}{\hbar}\cdot\int_{r_{in}}^{r_{out}}\sqrt{2\mu[V(r)-Q_p]}\cdot dr\right\}}$$

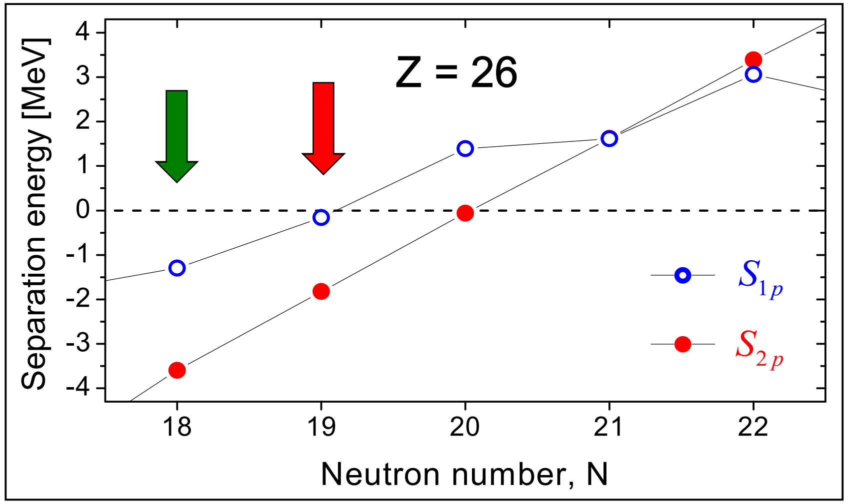
→ To study particle radioactivity fast techniques are necessary!

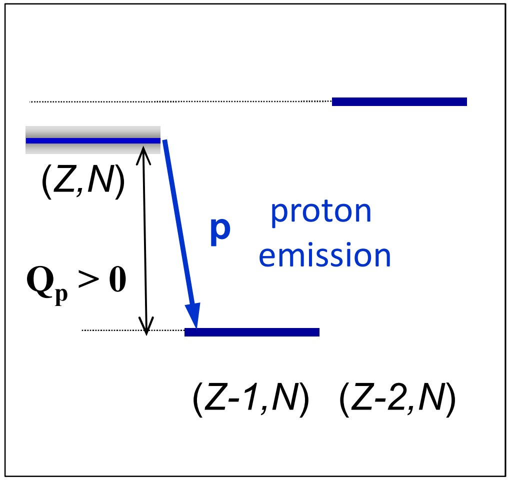
→ To find where the drip-line actually is and to predict which decay will happen, precise **mass values** are needed!

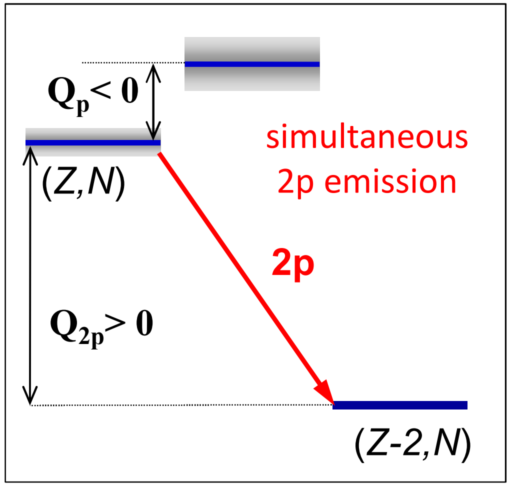
Proton emission

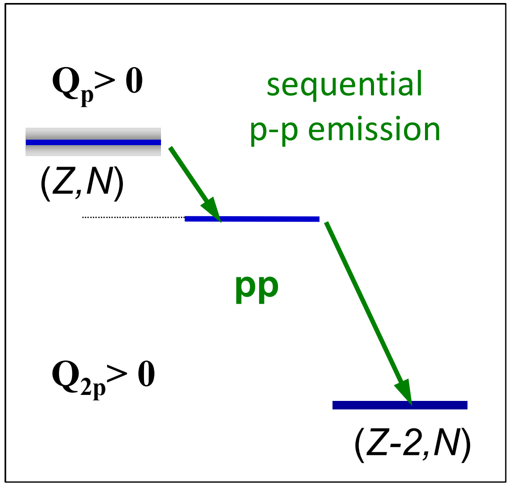
Proton and two-proton separation energies at the proton drip-line











Goldansky

Vitaly Iosifovich Goldansky
1923 – 2001

ON NEUTRON-DEFICIENT ISOTOPES OF LIGHT NUCLEI AND THE PHENOMENA OF PROTON AND TWO-PROTON RADIOACTIVITY

V. I. GOLDANSKY
P. N. Lebedev Physical Institute, USSR Academy of Sciences, Moscow

Received 14 March 1960

Abstract: Application of isobaric invariance principles to light nuclei leads to a very simple relation between the Z-th proton binding energy E_p in nucleus 1 ($_Z M_N{}^A$) and the Z-th neutron binding energy E_n in the miror nucleus 2 ($_N M_Z{}^A$). With an accuracy of the order of a few per cent their difference $E_{n2} - E_{p1} = \Delta E_{np}$ is independent of N for a given Z and is given by

$$\Delta E_{np} \approx E_n(_Z M_Z^{2Z}) - E_p(_Z M_Z^{2Z}) \approx 1.2 \frac{Z-1}{(2Z-1)^{\frac{1}{3}}},$$

which is more correct than the usual expression $1.2\,(Z-1)/(Z+N-1)^{\frac{1}{3}}$. By exploiting this fact one can predict the existence and properties of almost ninety new neutron-deficient isotopes of light nuclei (up to $Z = 34$) and establish the limits of stability of the isotopes with respect to decay with proton emission. Among the specific properties of neutron-deficient isotopes, proton and two-proton radioactivity effects which may occur are of special interest. Some nuclei are indicated in which these effects may be observed. The main features of a very curious phenomenon of two-proton radioactivity are discussed.

Baz, Goldansky, Goldberg, Zeldovich, „Light and medium nuclei at the limits of stability", Moscov 1972 →

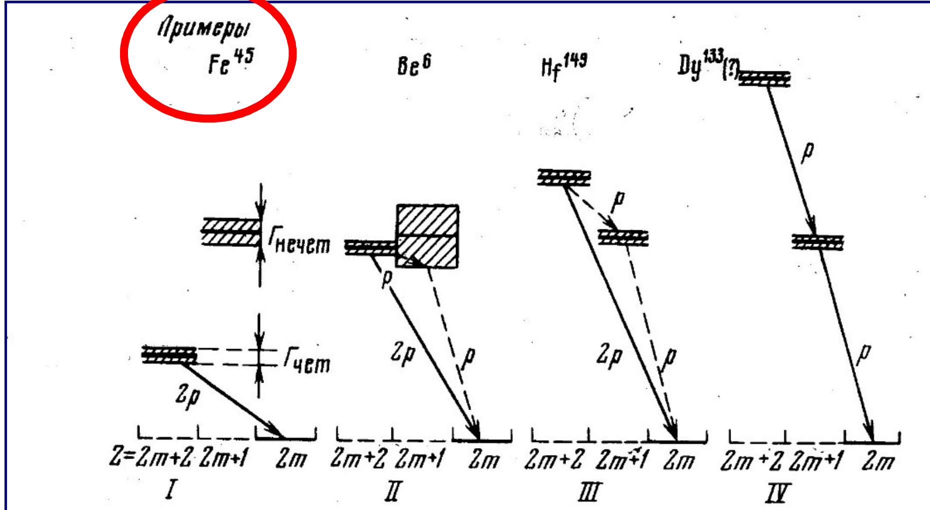
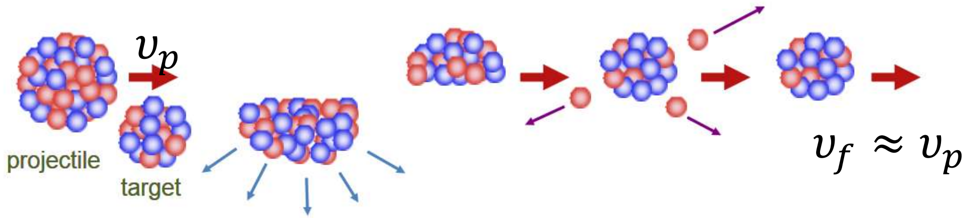


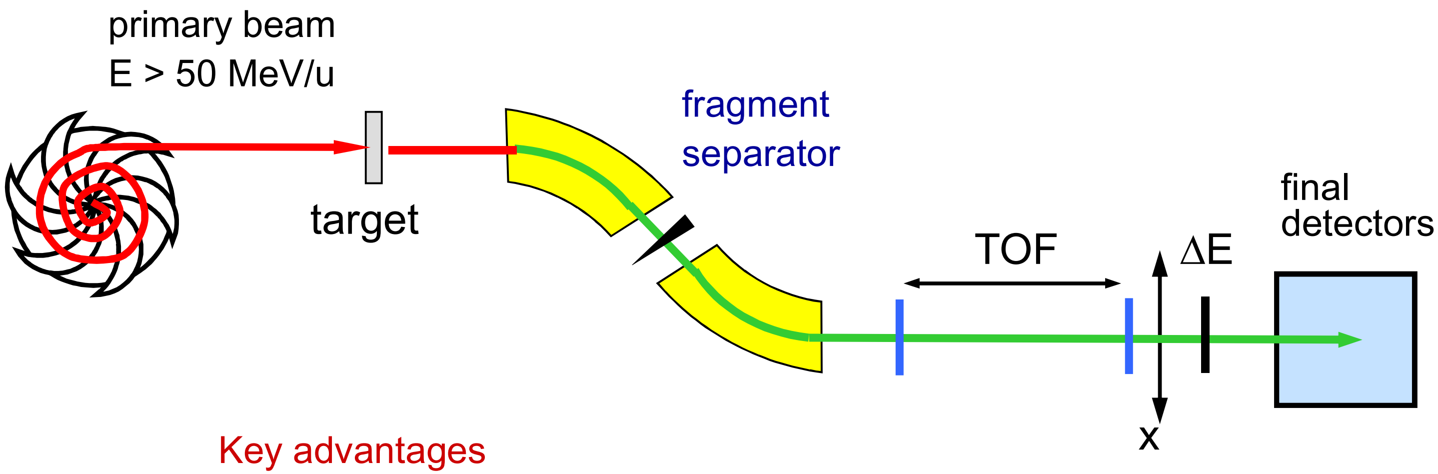
Рис. 48. Различные варианты испускания ядрами пар протонов

^{45}Fe as a 2p candidate was confirmed later by more refined model calculations

Projectile Fragmentation

Projectile energy/nucleon larger than Fermi energy (> 50 MeV/u)





LISE @ GANIL

FRS @ GSI

A1900 @ NSCL

BigRIPS @ RIKEN

Key advantages

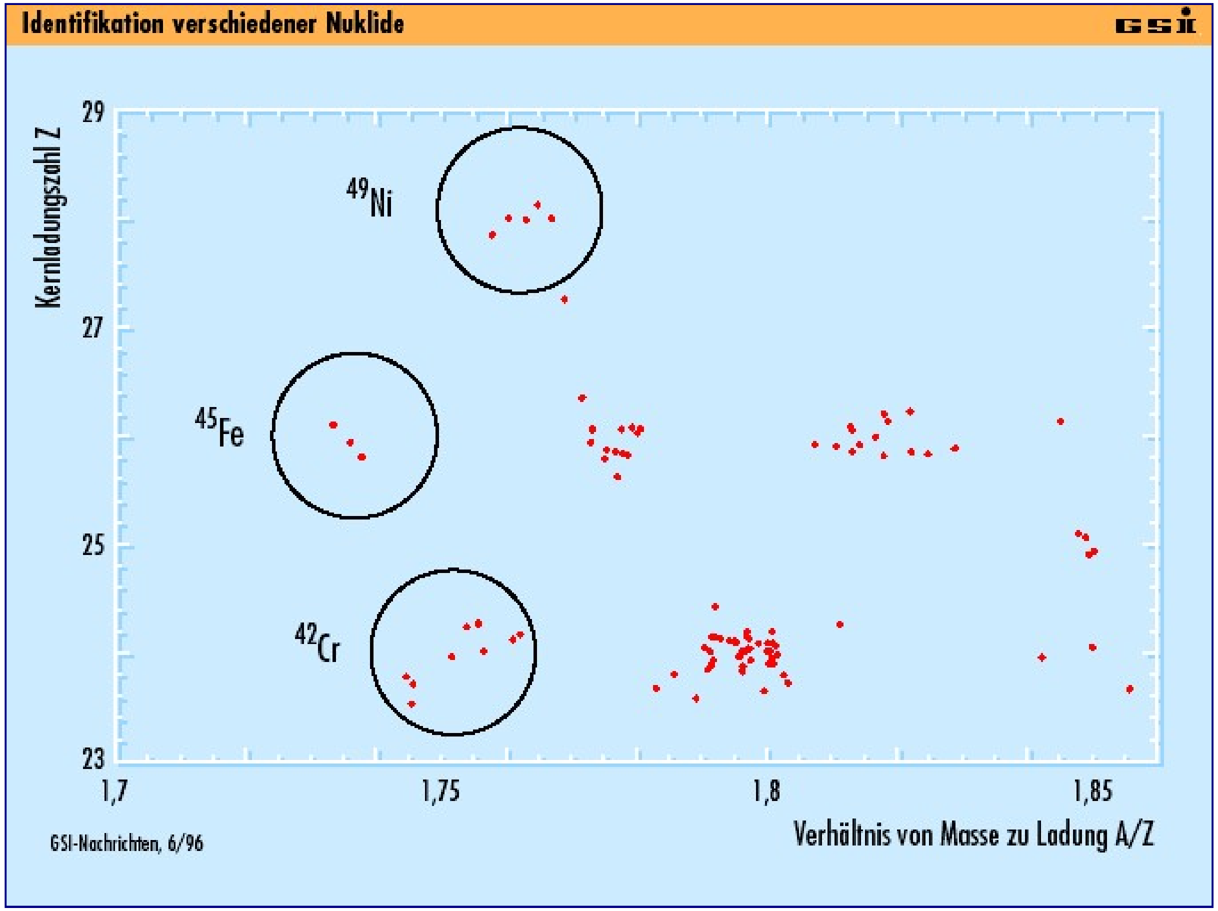
- thick targets (large yields)
- chemical independence
- full identification of single ions in-flight
- fast transport (ms)
- implantation into thick detectors
- ready for secondary reactions
- cocktail beams

However

- large and expensive facility
- low intensity of heavy projectiles
- large range straggling
- bad ion-optical properties of secondary beams
- products are lighter than projectiles

Example of identification

- First observation of three new nuclides : ^{42}Cr, ^{45}Fe i ^{49}Ni
  FRS, GSI, 1996

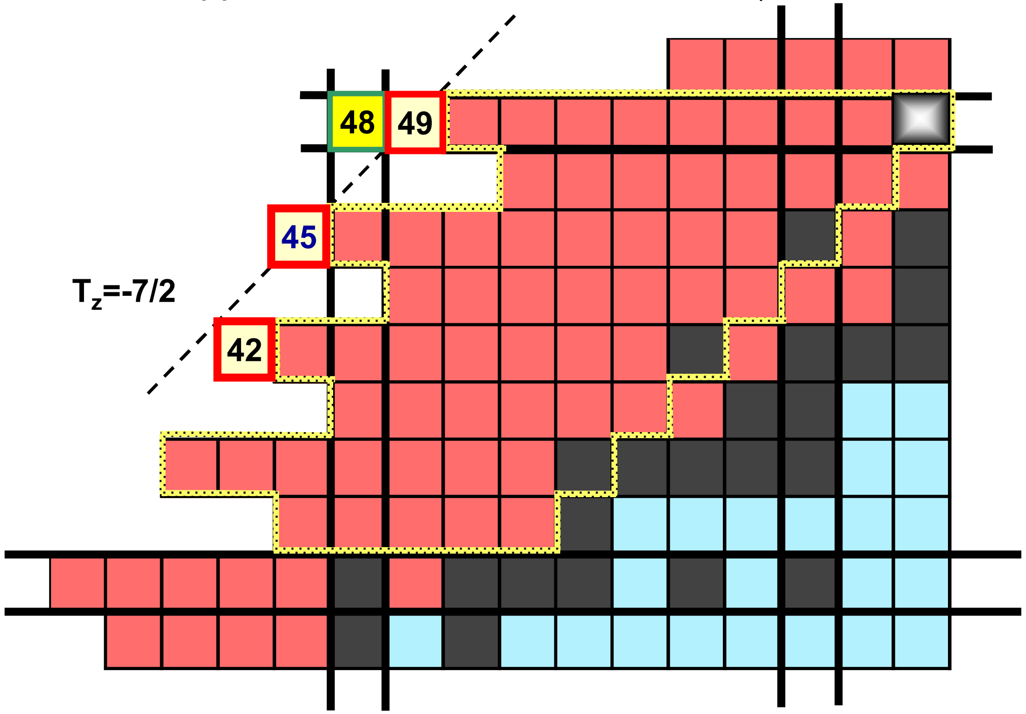


Blank et al., PRL 77 (1996)

A long way to discovery

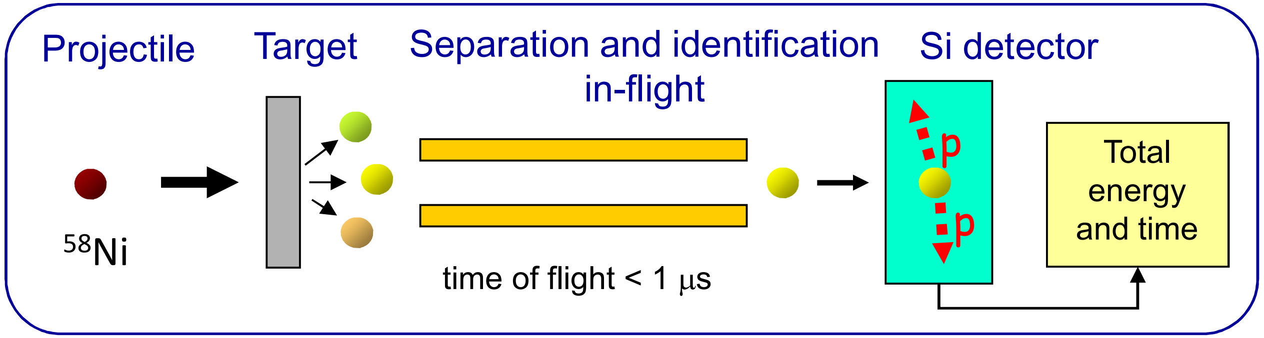
by Bordeaux-GANIL-GSI-Warsaw collaboration

- GSI 1992 : first experiment, determination of x-sections, ^{50}Ni
- GSI 1996 : first observation of ^{45}Fe (3 ions!), ^{49}Ni and ^{42}Cr
- GANIL 1999 : discovery of ^{48}Ni, 53 ions of ^{45}Fe
- GANIL VII 2000: next attempt of ^{45}Fe spectroscopy: 22 ions of ^{45}Fe
- GSI VII 2001: new approach to ^{45}Fe studies: focus on μs lifetimes

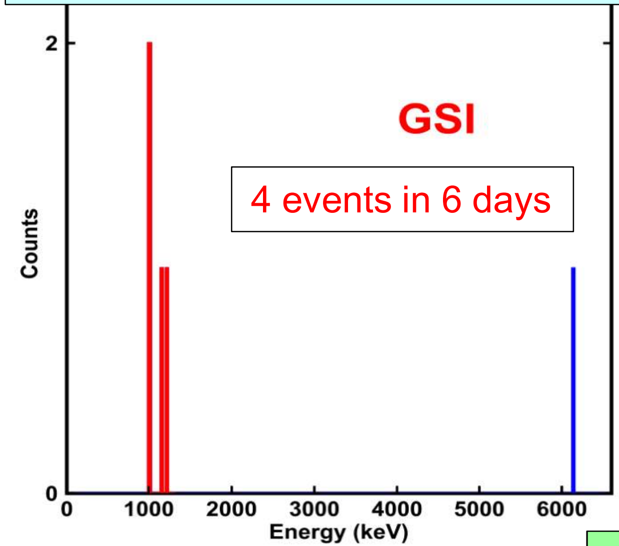


2p radioactivity

- Implantation into Si – good measurement of energy and time, but **protons not resolved!**

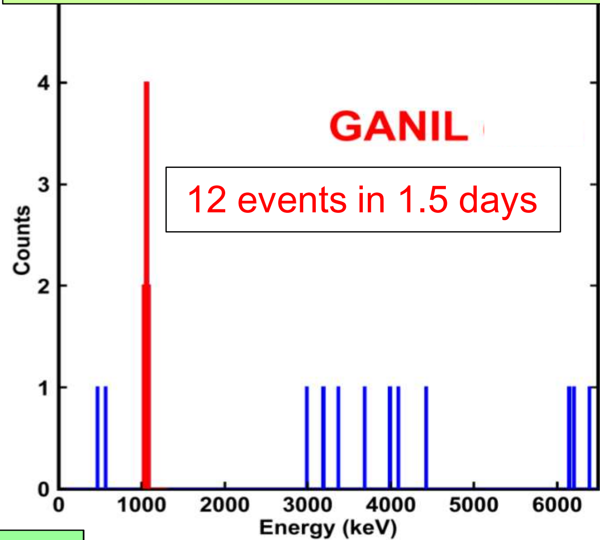


GSI: ^{58}Ni @ 650 MeV/A +Be → ^{45}Fe



MP et al., EPJ A 14 (2002)

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



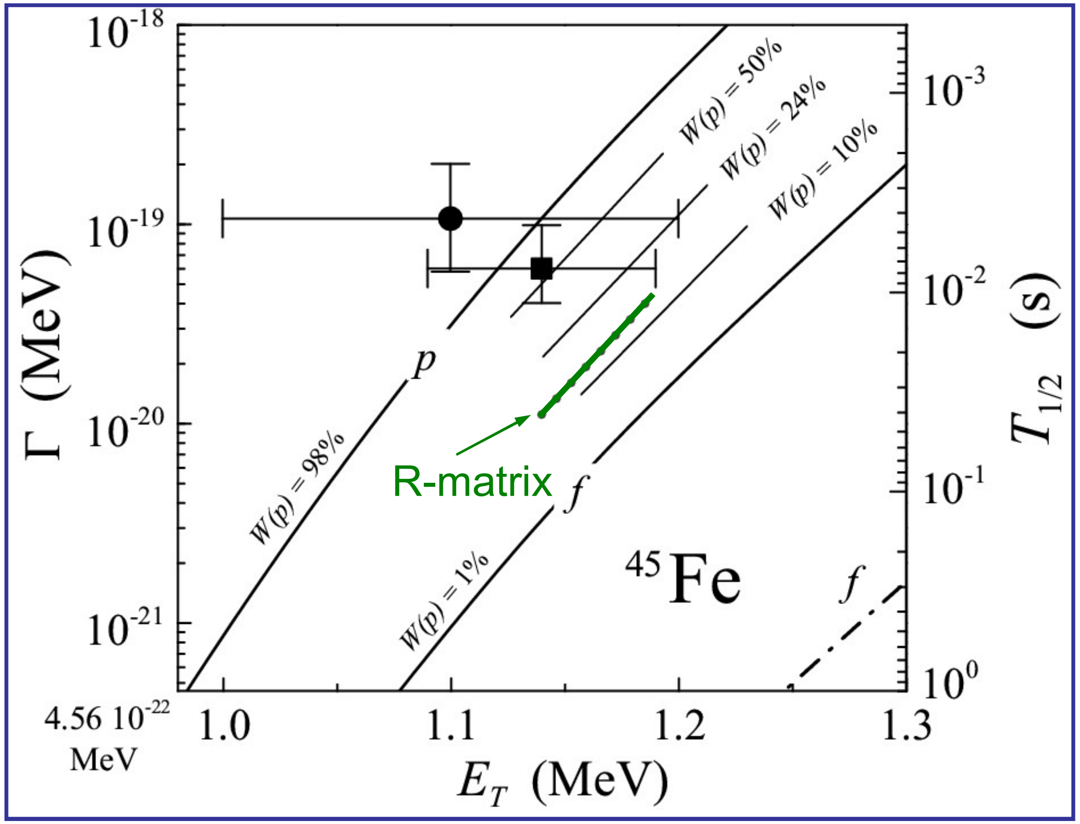
Giovinazzo et al., PRL 89 (2002)

$T_{1/2}$ = 2.6 ms

$T_{1/2}$ predictions for ^{45}Fe

3-body : L.V. Grigorenko and M.V. Zhukov, PRC68 (2003)

R-matrix : : B.A. Brown, F.C. Barker, Proc. PROCON'03

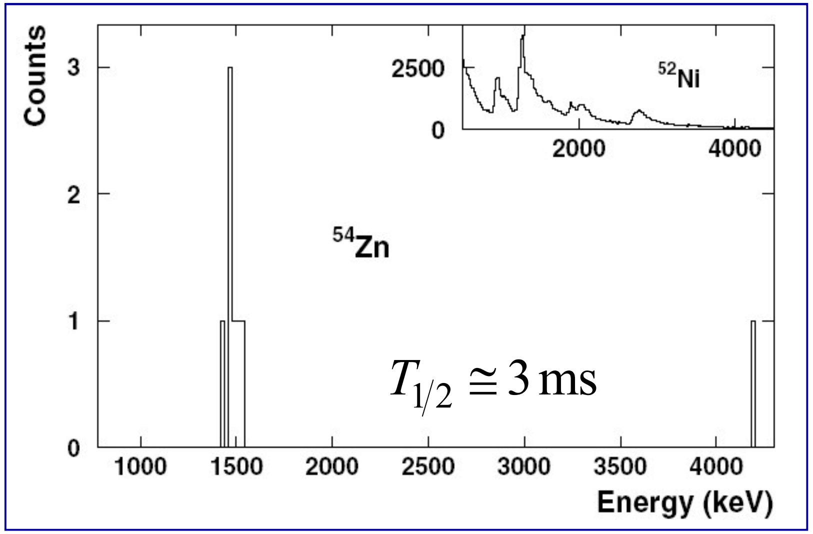


No other decay scenario could explain the measured decay energy and lifetime

Further cases

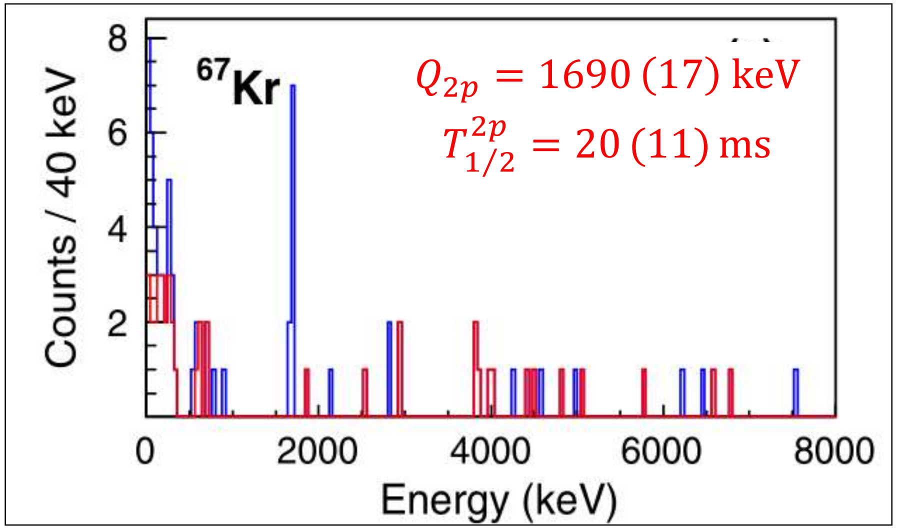
- Two more cases of 2p emission discovered by implantation into Si detetctors

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



Blank et al., PRL 94 (2005)

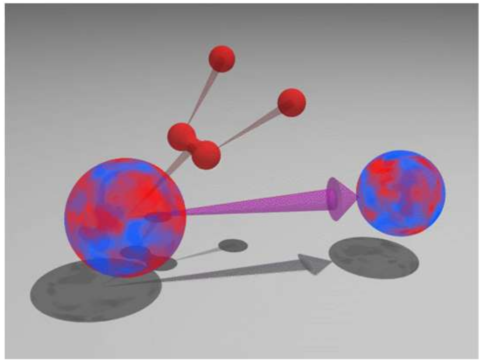
RIKEN: ^{78}Kr @ 345 MeV/A +Be → ^{67}Kr

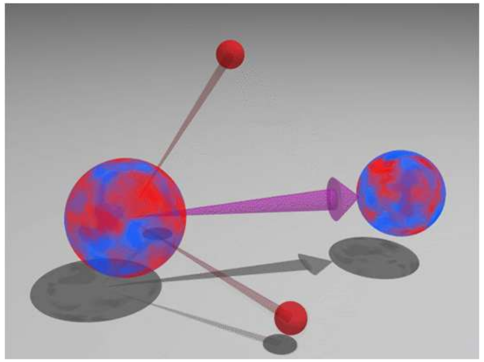


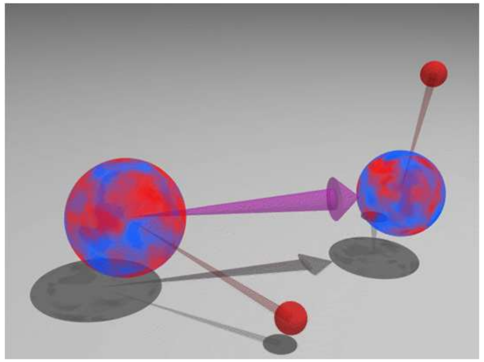
Goigoux et al., PRL 117 (2016)

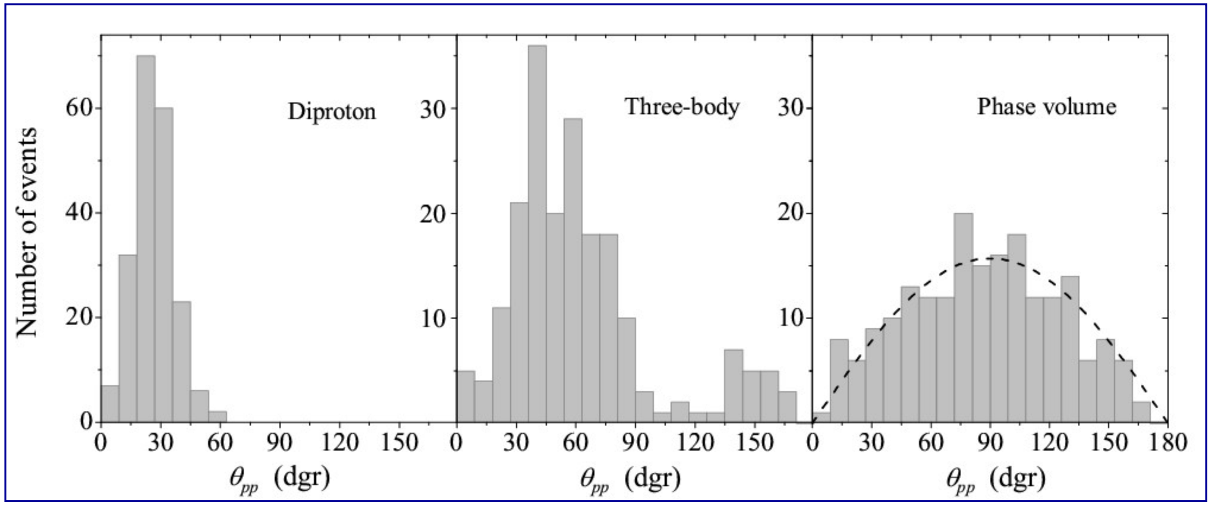
→ Need to record two protons separately!

What is the mechanism?





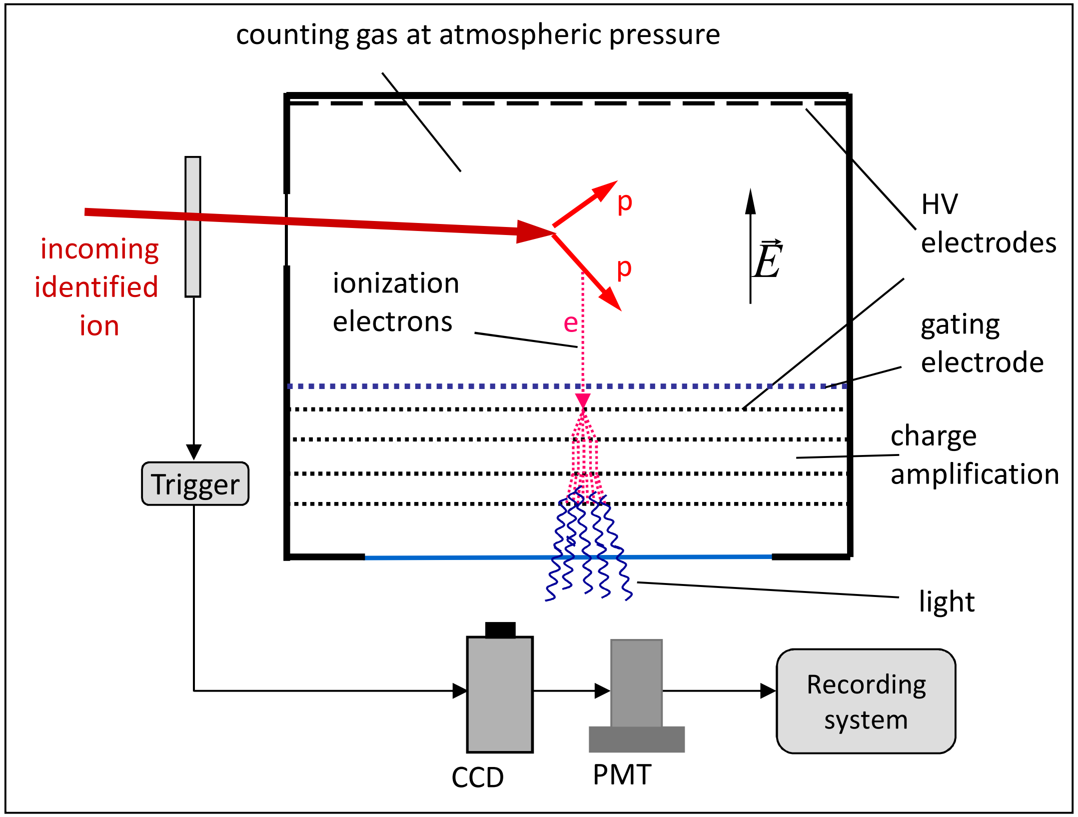


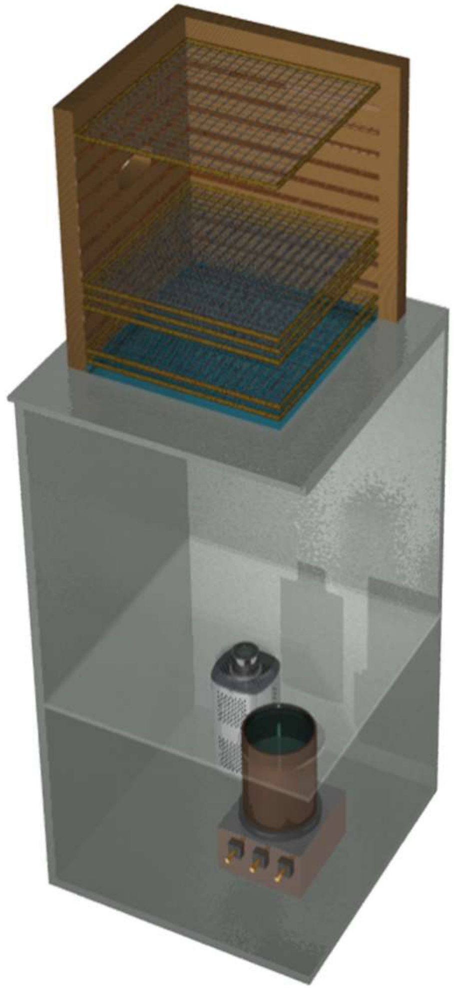


Predicted angle between two proton momenta (L. Grigorenko)

The Warsaw OTPC

Time projection chamber with optical readout (OTPC) (W. Dominik)



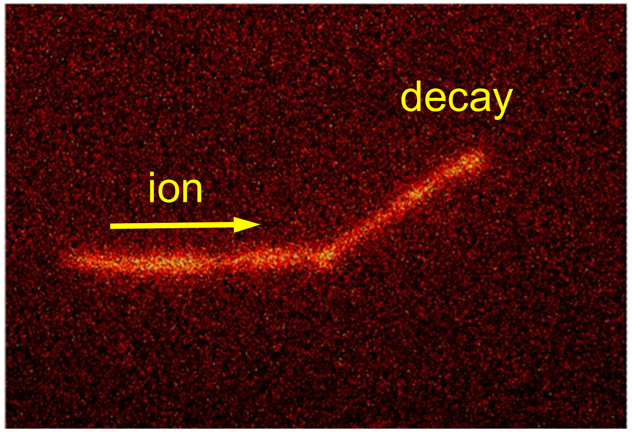


Combination of the CCD image with the PMT waveform allows full reconstruction of two tracks in 3-D

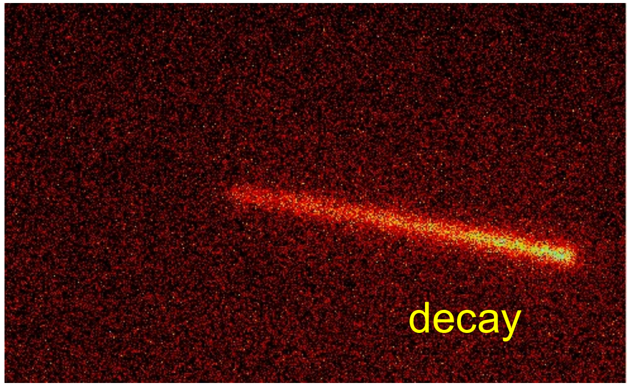
Event data

CCD image

tracks of the ion and emitted particle(s)

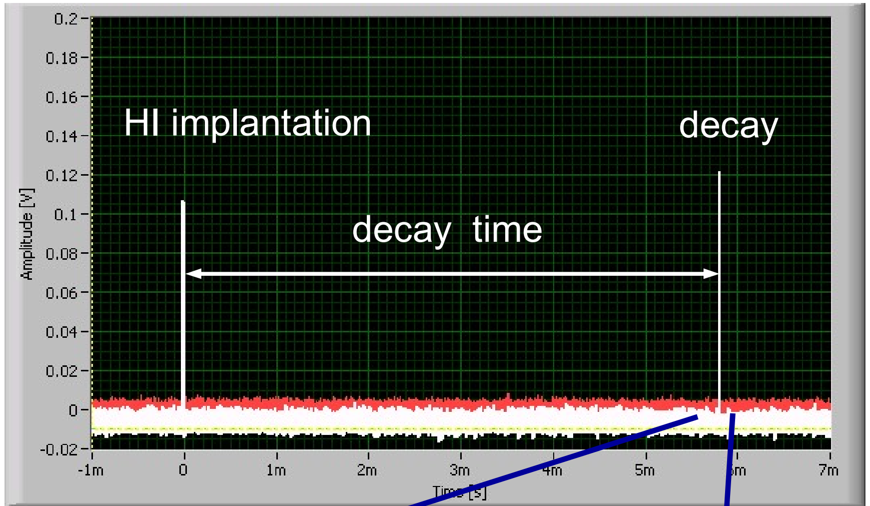


or only emitted particle(s)

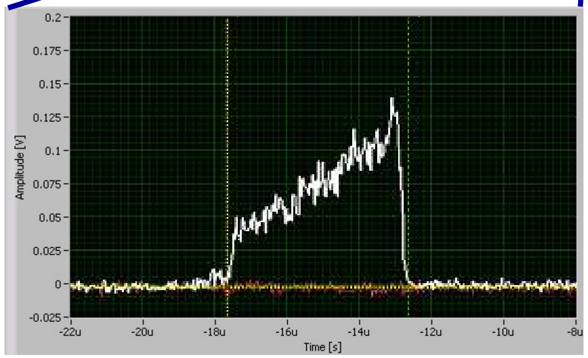


PMT signal sampled

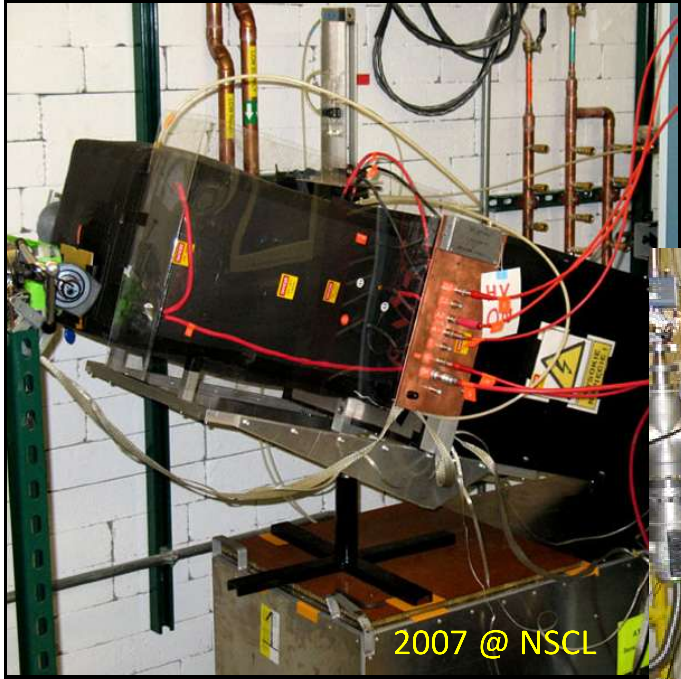
time sequence of events

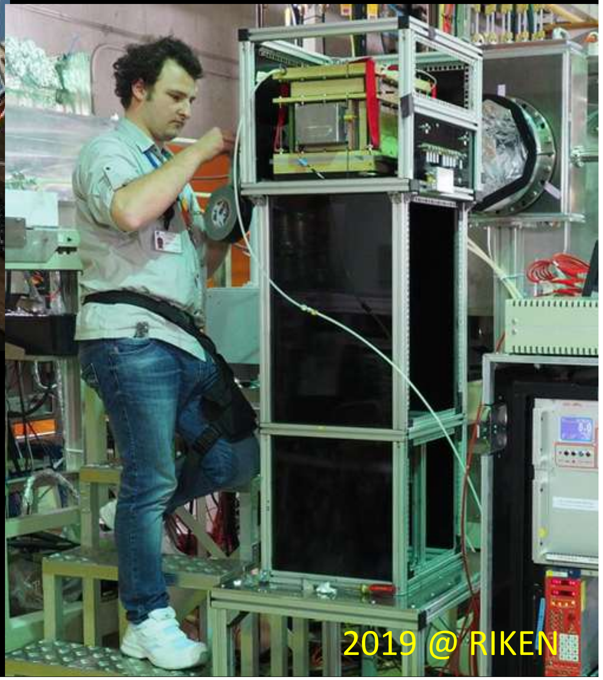


decay details



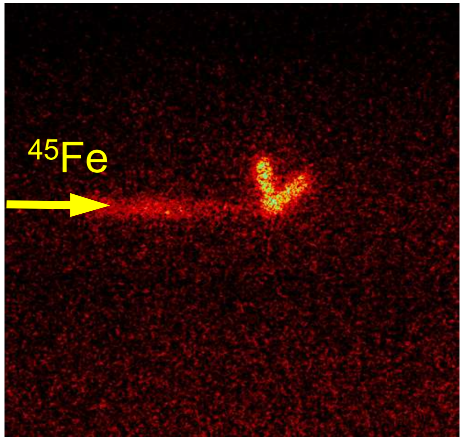
OTPC develops

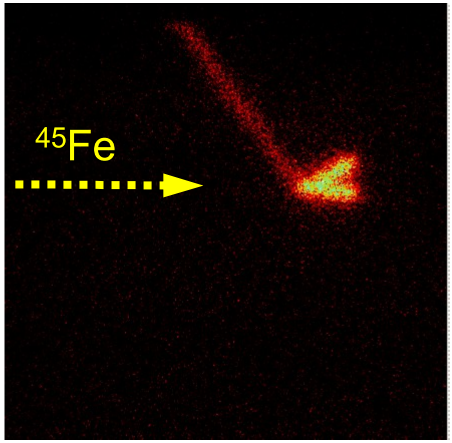




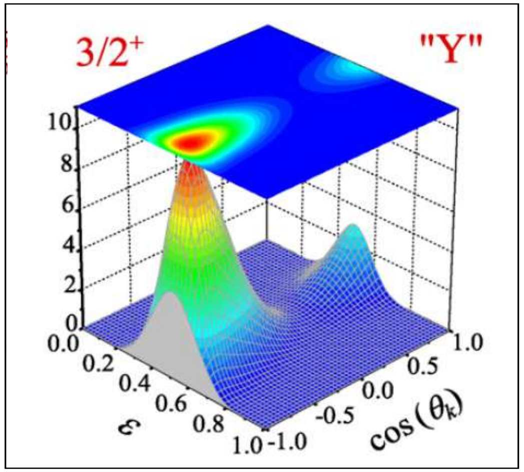
p-p momentum correlations for ^{45}Fe

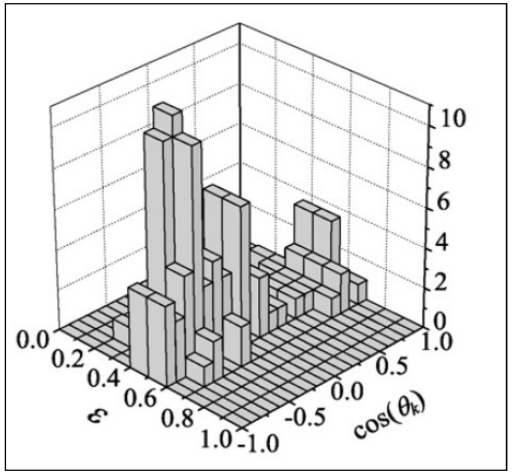
NSCL: ^{58}Ni @ 161 MeV/u + Ni → ^{45}Fe





Miernik et al., PRL 99 (2007)





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

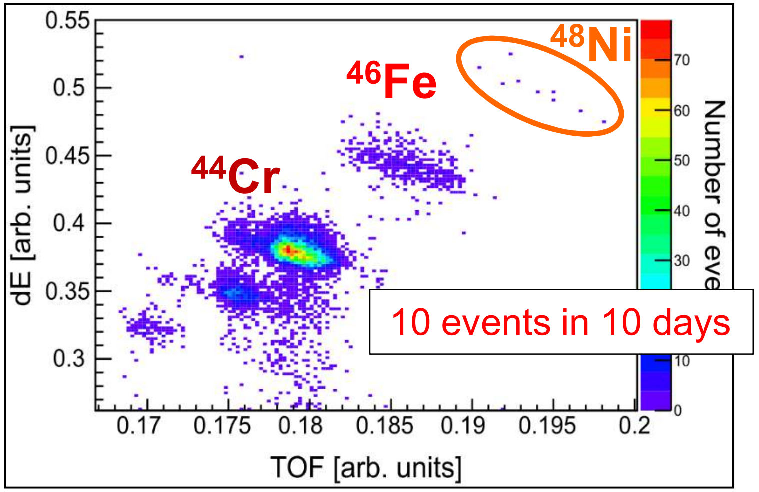
87 events reconstructed

- 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

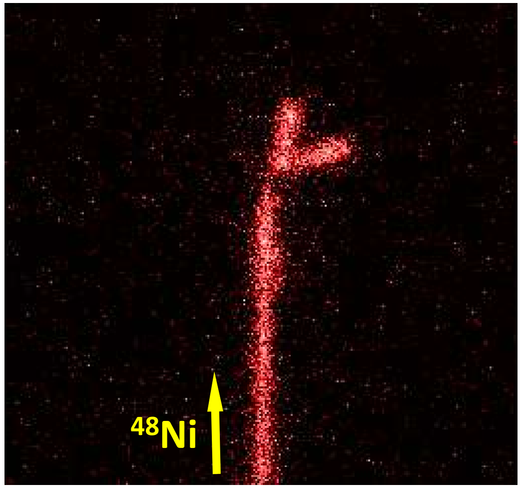
2p radioactivity of ^{48}Ni

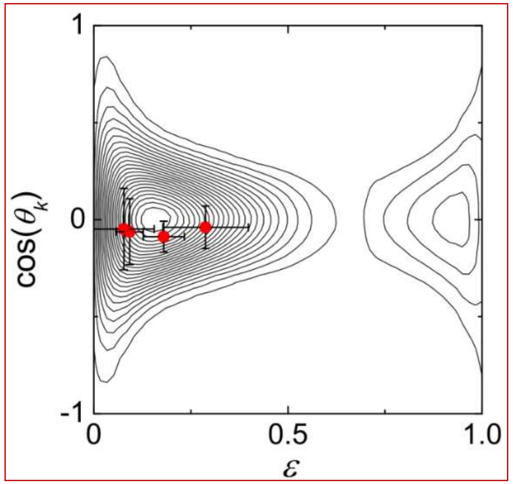
NSCL: ^{58}Ni @ 161 MeV/u + Ni → ^{48}Ni

Only 4 2p decays observed



10 events in 10 days

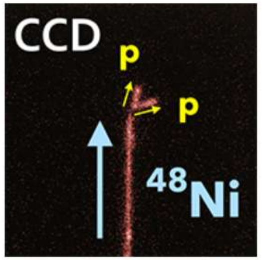




Pomorski et al., PRC 83 (2011)

Physical Review C 50th Anniversary Milestones

50 YEARS 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.

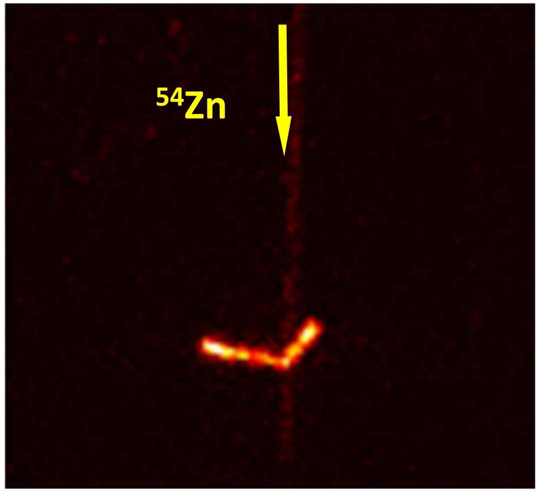
First observation of two-proton radioactivity in ^{48}Ni

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

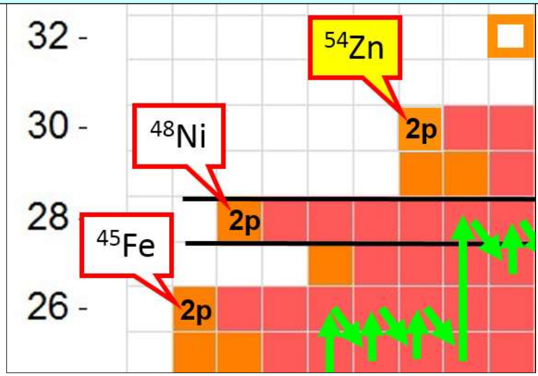
2p decay of ^{54}Zn

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

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

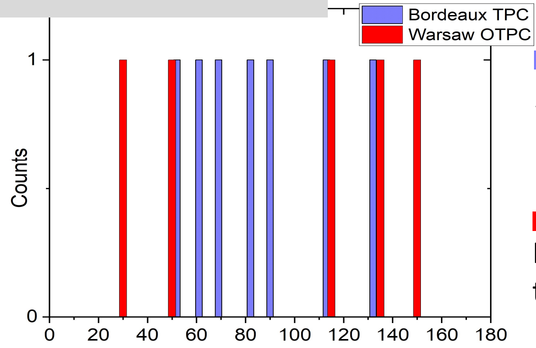


Can 2p emission tell us something on Z=28 shell closure?



Z=30

^{54}**Zn** : 5 + 7 events

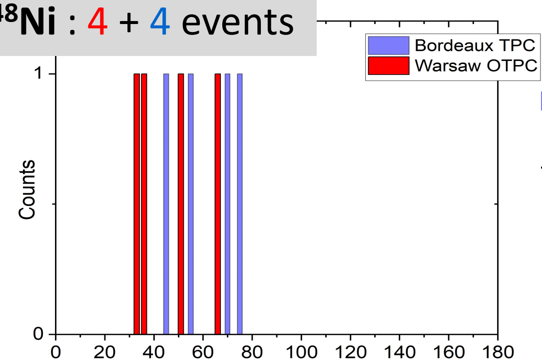


Ascher et al PRL 107 (2011)

Kubiela et al., to be published

Z=28

^{48}**Ni** : 4 + 4 events

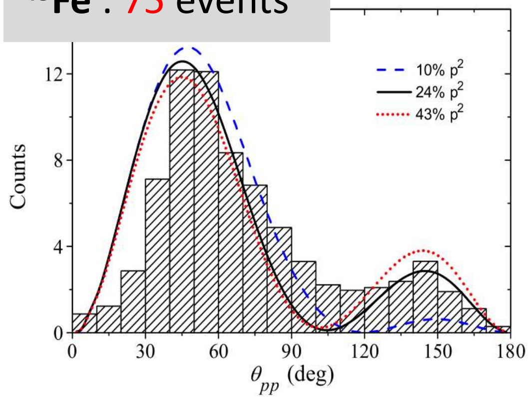


Ortega-Moral et al., to be published

Pomorski et al PRC 90 (2014)

Z=26

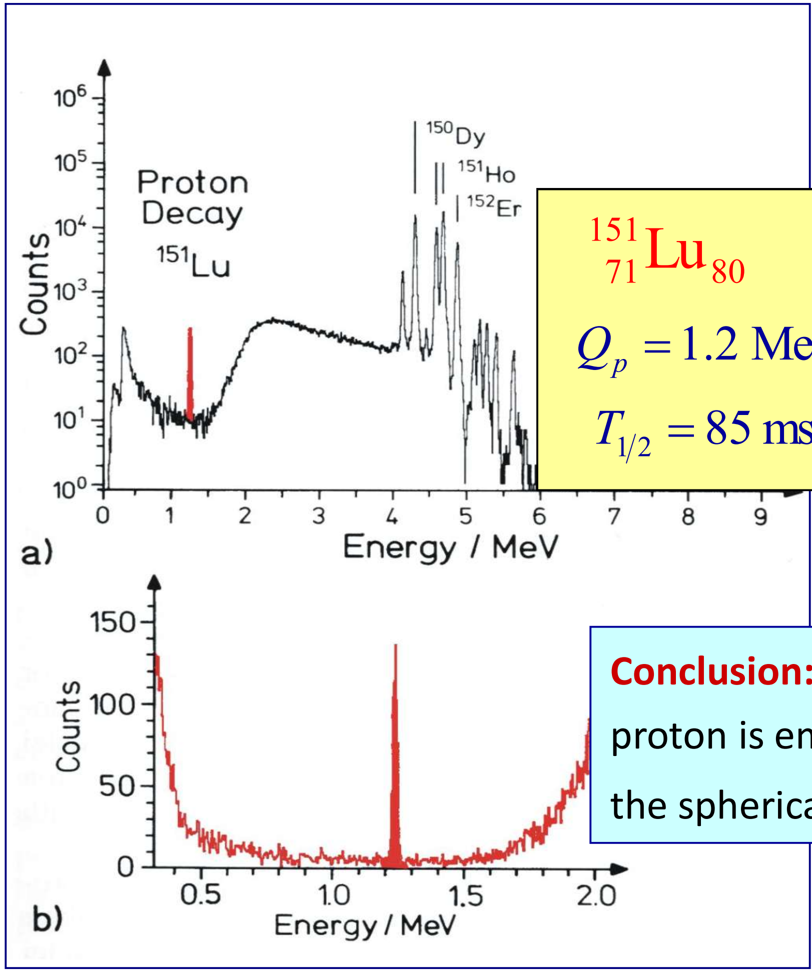
^{45}**Fe** : 75 events



Miernik et al PRL 99 (2007)

Physics of single p emission

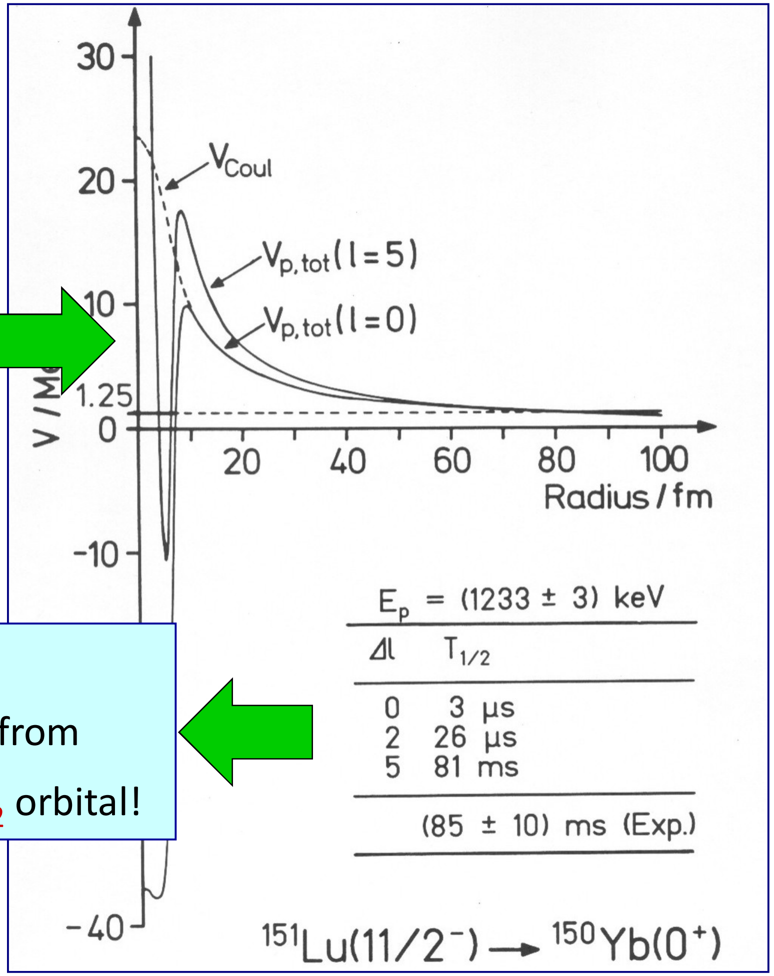
The first case of proton radioactivity – GSI Darmstadt 1982



$^{151}_{71}\mathrm{Lu}_{80}$

$Q_p = 1.2$ MeV

$T_{1/2} = 85$ ms



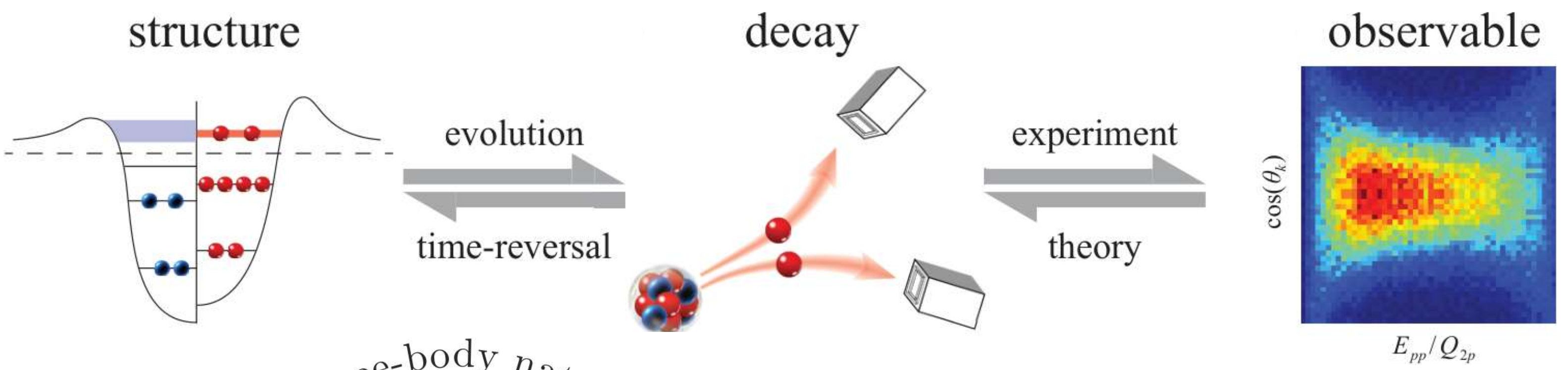
Conclusion:

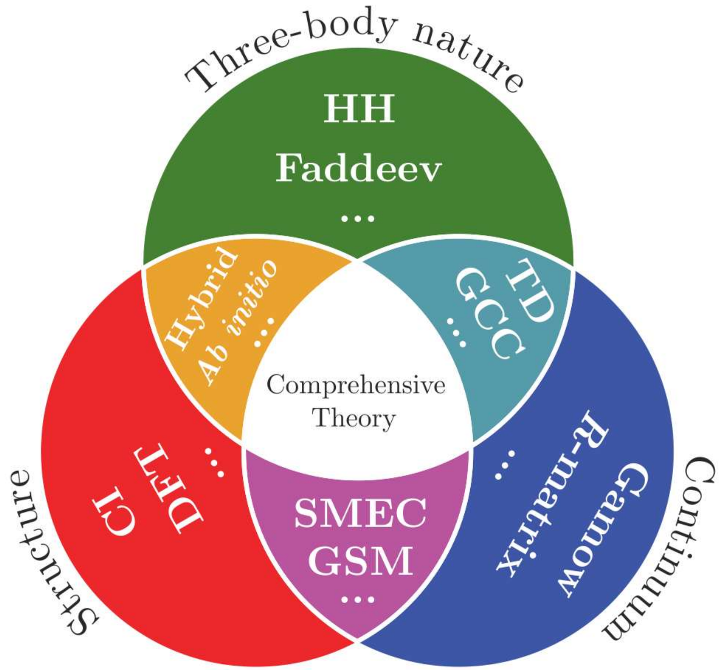
proton is emitted from

the spherical $h_{11/2}$ orbital!

Hofmann et al., Z. Phys. A 305 (1982)

Theory of 2p emission





MP, Mukha, Wang, PPNP 132 (2023)

HH: Hyperspherical harmonics

CI: Configuration interaction (shell model)

DFT: Density functional theory

SMEC: Shell model embedded with continuum

GSM: Gamow shell model

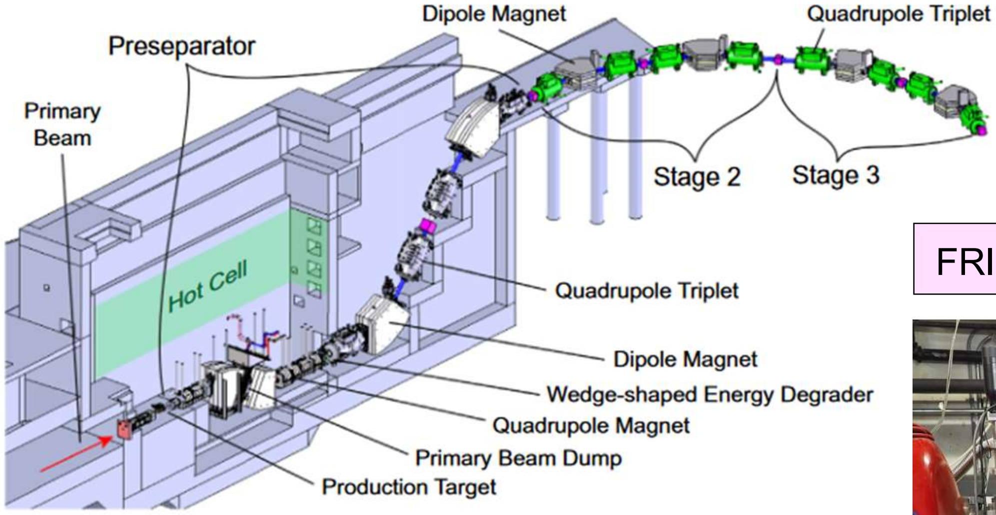
GCC: Gamow coupled channel

TD: Time dependent approach

A comprehensive theory is still missing

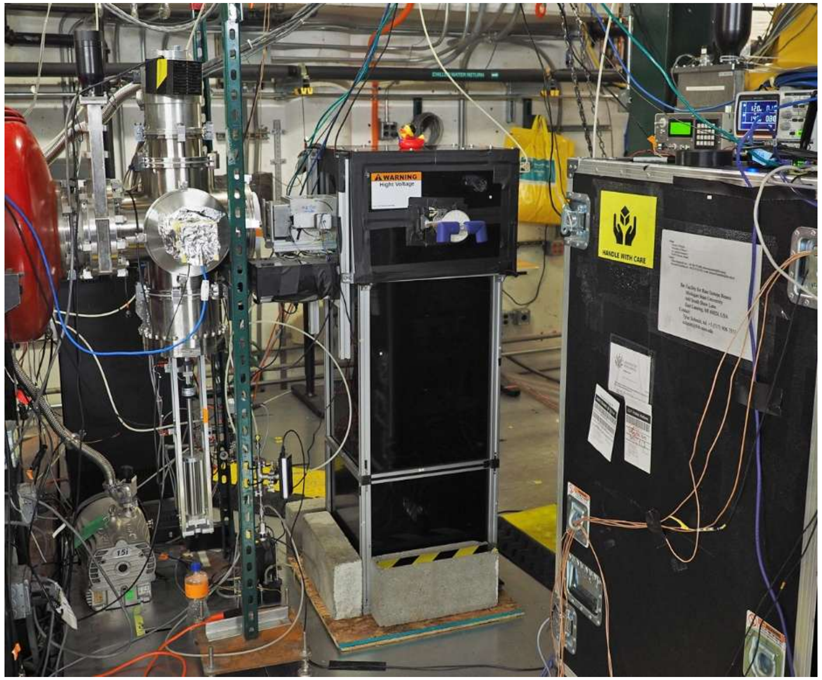
Next step: FRIB

Advanced Rare Isotope Separator (ARIS) @ FRIB, MSU



Portillo et al., NIM B 540 (2023)

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

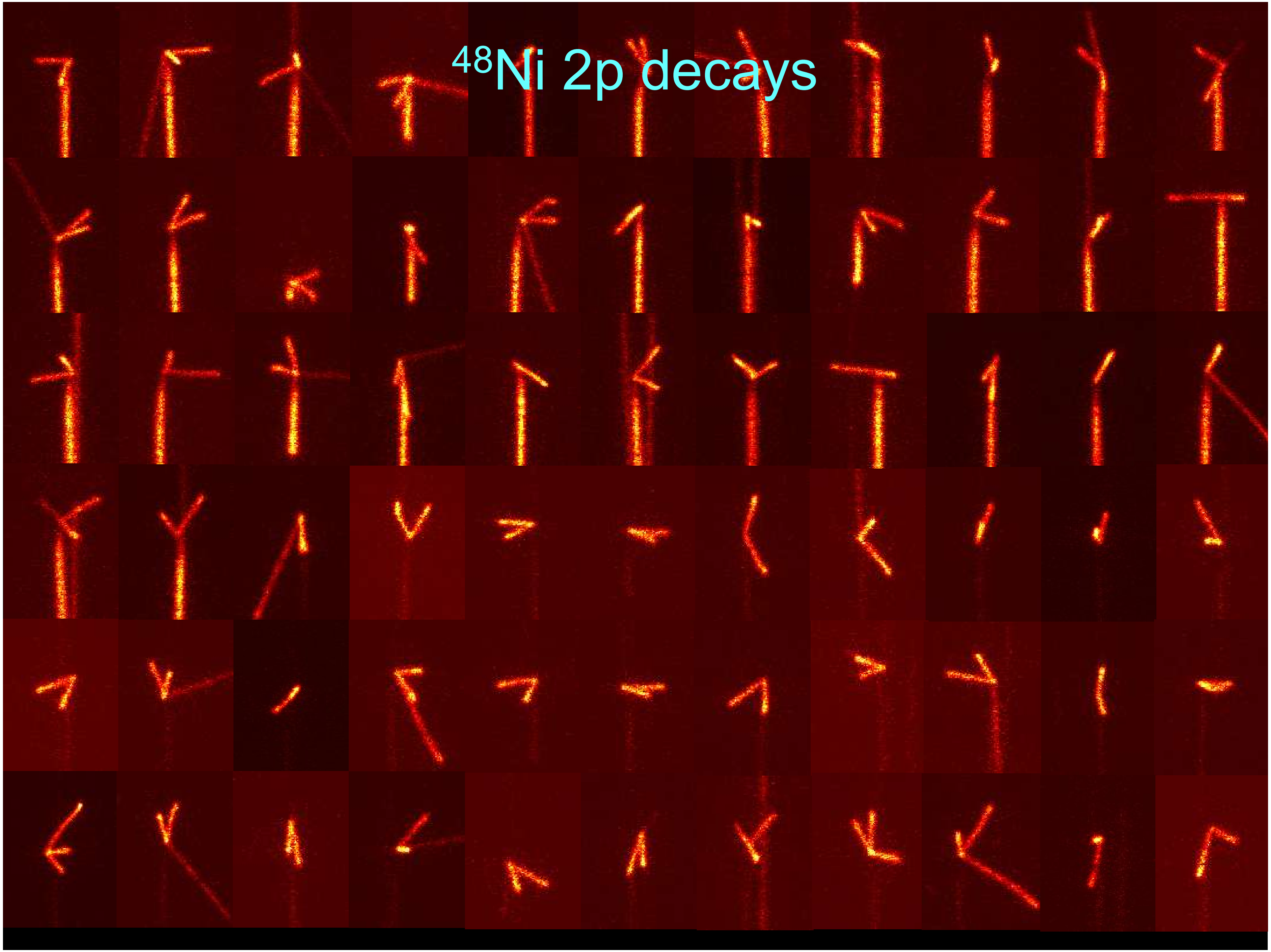


Experiment conducted in January/February 2025

- ARIS at MSU started in 2021

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

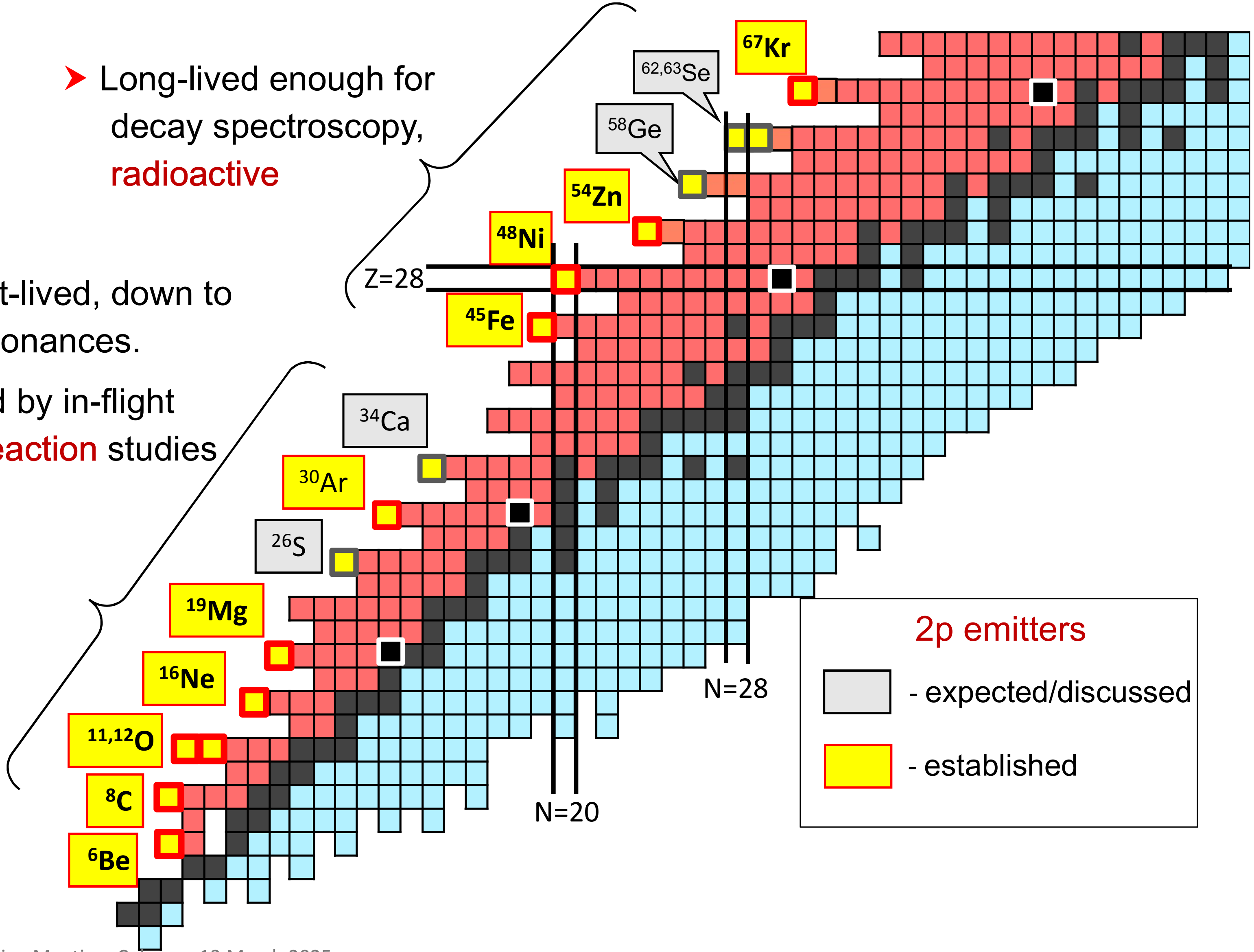
Currently running at 16 kW
Designed to 400 kW !



^{48}Ni 2p decays

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



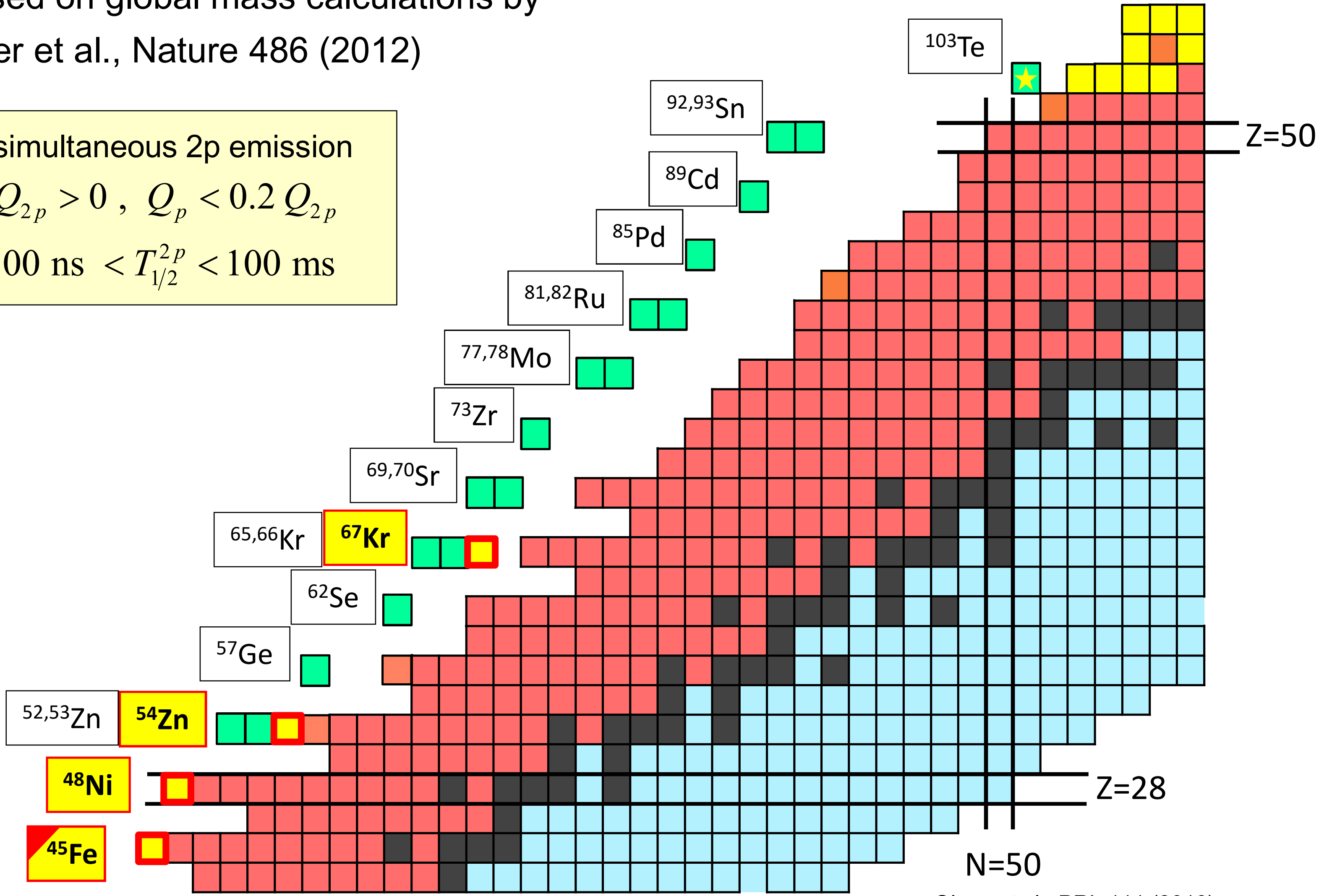
Global 2p predictions (I)

- Predictions of the direct model based on global mass calculations by Erler et al., Nature 486 (2012)

simultaneous 2p emission

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

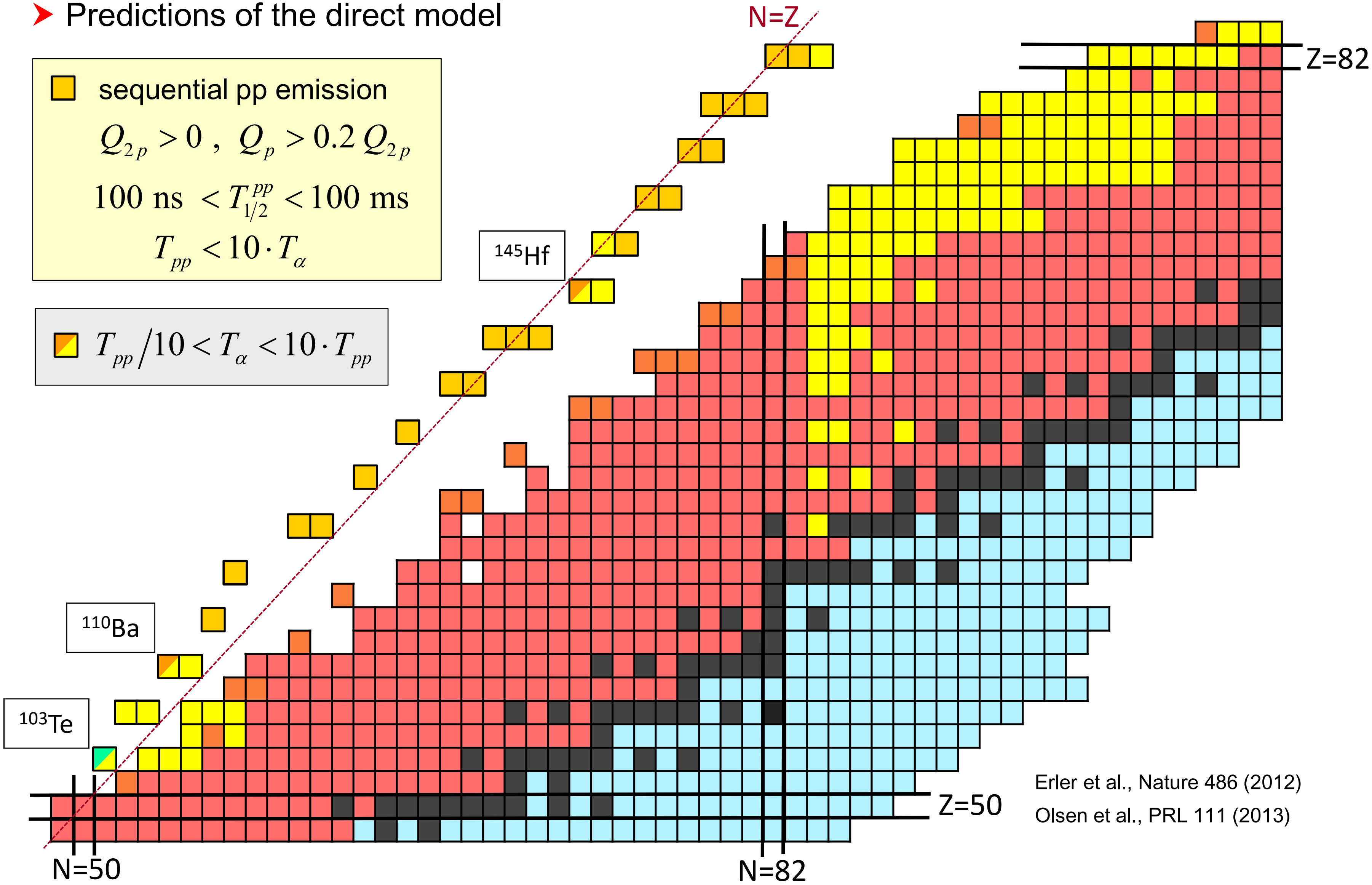
$$100 \text{ ns } < T_{1/2}^{2p} < 100 \text{ ms}$$



Olsen et al., PRL 111 (2013)

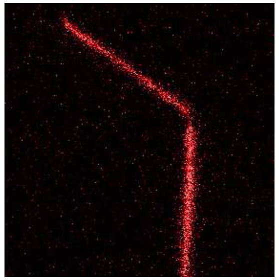
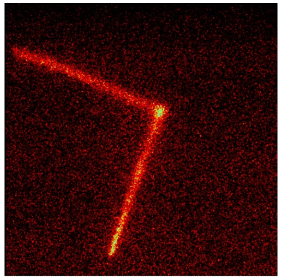
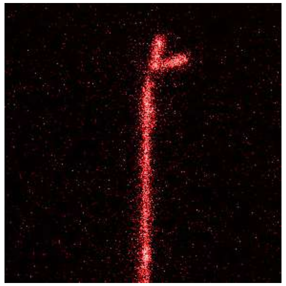
Global 2p predictions (II)

- Predictions of the direct model



Erler et al., Nature 486 (2012)
Olsen et al., PRL 111 (2013)

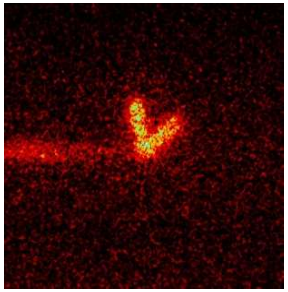
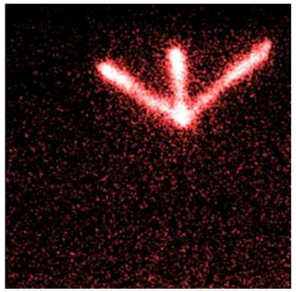
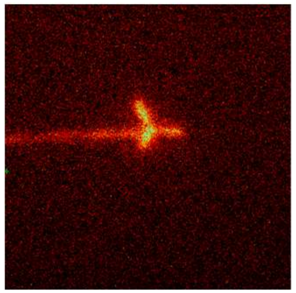
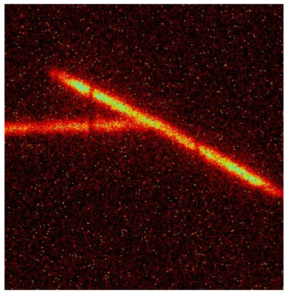
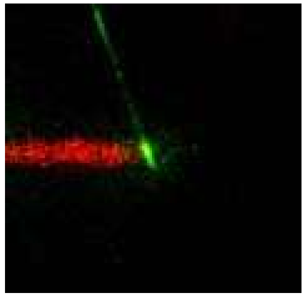
Summary

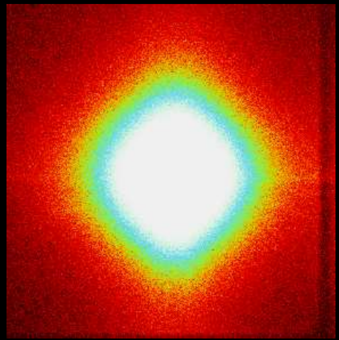
Two-proton radioactivity:

- Predicted 65 years ago
- Observed in ^{45}Fe 23 years ago
- Exhibit essentially 3-body character
- Comprehensive theoretical description not yet available
- Expected in all even-Z elements between Fe and Te
- Data of large statistics recently obtained at FRIB for ^{45}Fe, ^{48}Ni and ^{54}Zn
- Many more to come soon at new facilities (FRIB, FAIR, ...)

- Optical TPC is a good tool to study rare particle emission

Thank you!



Most of the work was done by:

- Chiara Mazzocchi
- Zenon Janas
- Wojciech Dominik
- Henryk Czyrkowski
- PhD students:
  - Krzysztof Miernik
  - Marcin Pomorski
  - Sławomir Mianowski
  - Aleksandra Lis/Ciemny
  - Adam Kubiela
  - Natalia Sokołowska
  - Aleksandra Skruch