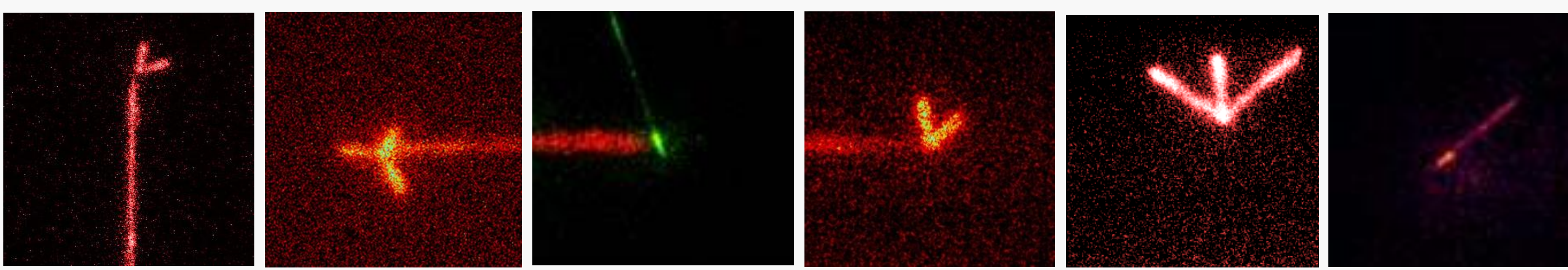
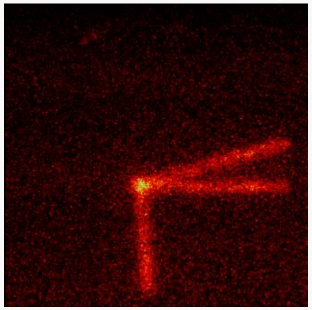
# Exotic nuclear decays studied with digital photography

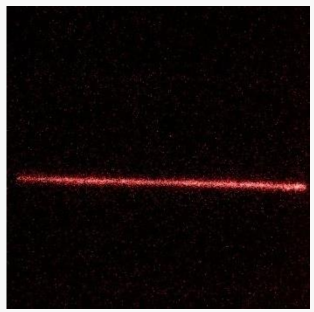
Marek Pfützner

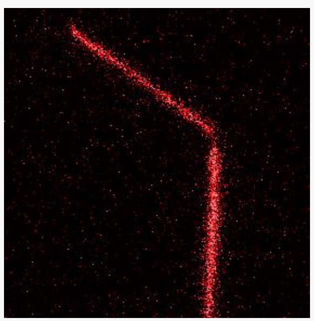
Nuclear Physics Division
University of Warsaw

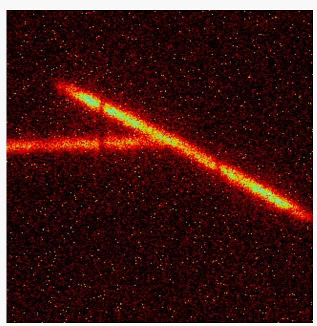


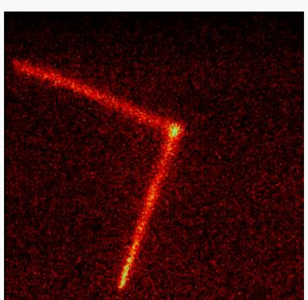
# Plan











- Introduction:

  chart of nuclides, exotic nuclei
- 2p radioactivity
- Warsaw Optical Time Projection Chamber
- 2p radioactivity again: $^{45}$Fe, $^{48}$Ni, $^{54}$Zn
- Emission of $\beta$-delayed particles

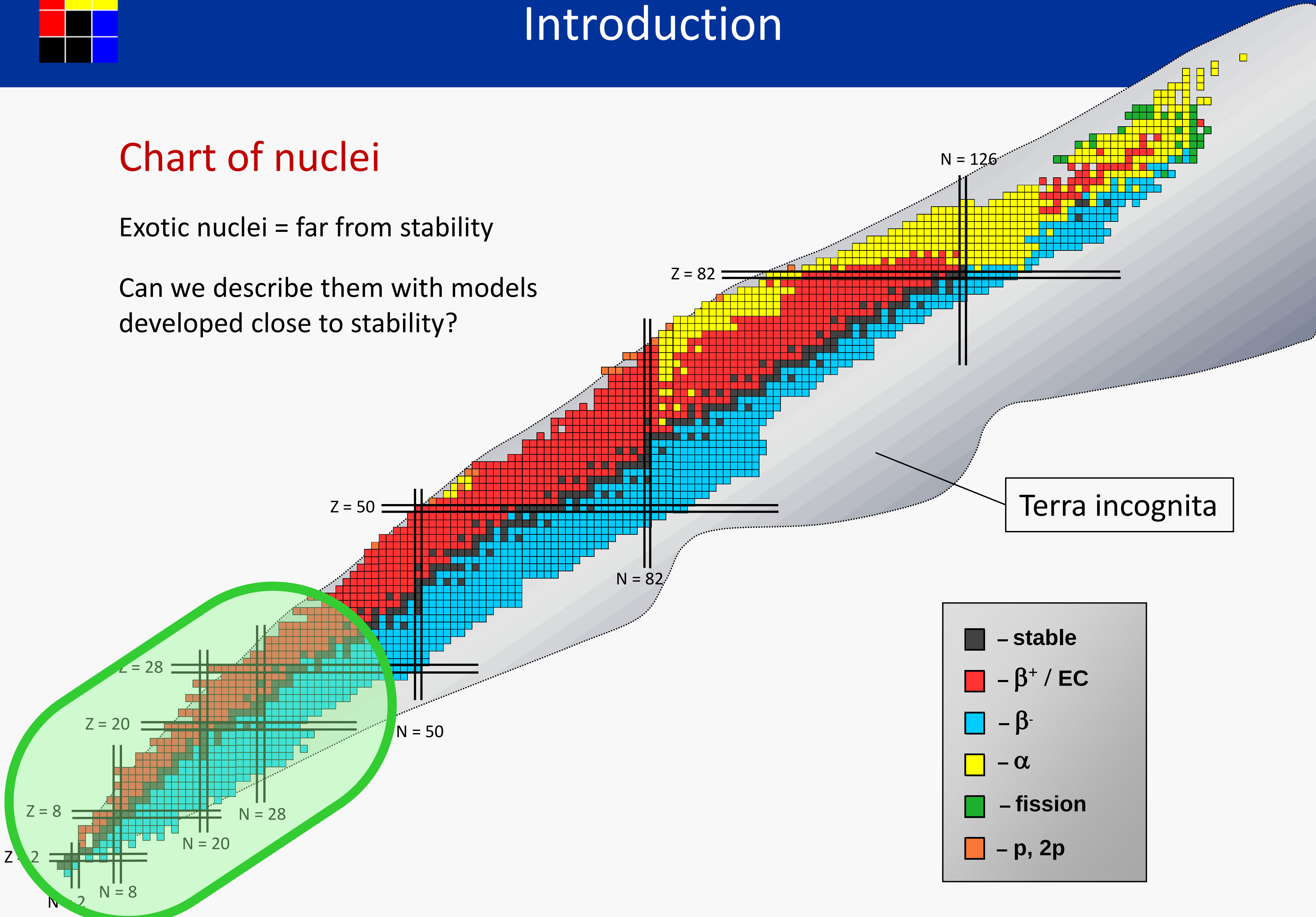
  $^{45}$Fe, $^{43}$Cr, $^{31}$Ar, $^{27}$S, $^{6}$He, $^{11}$Be
- Summary

# Introduction

## Chart of nuclei

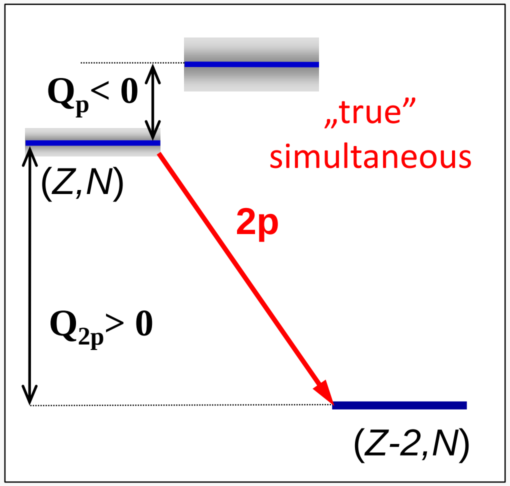
Exotic nuclei = far from stability

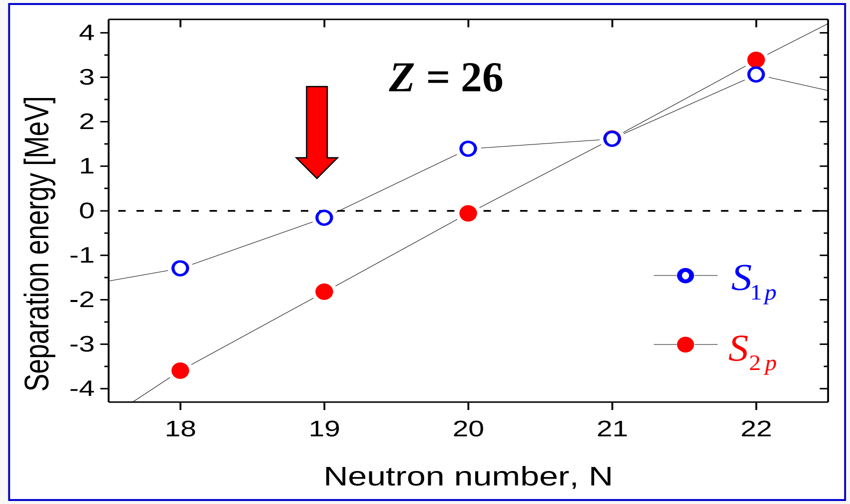
Can we describe them with models developed close to stability?

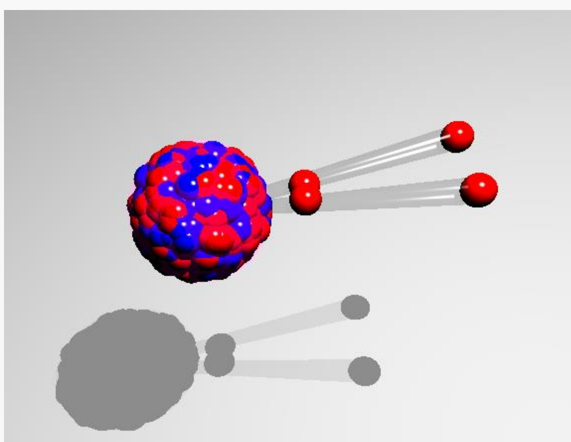


# *2p* radioactivity

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

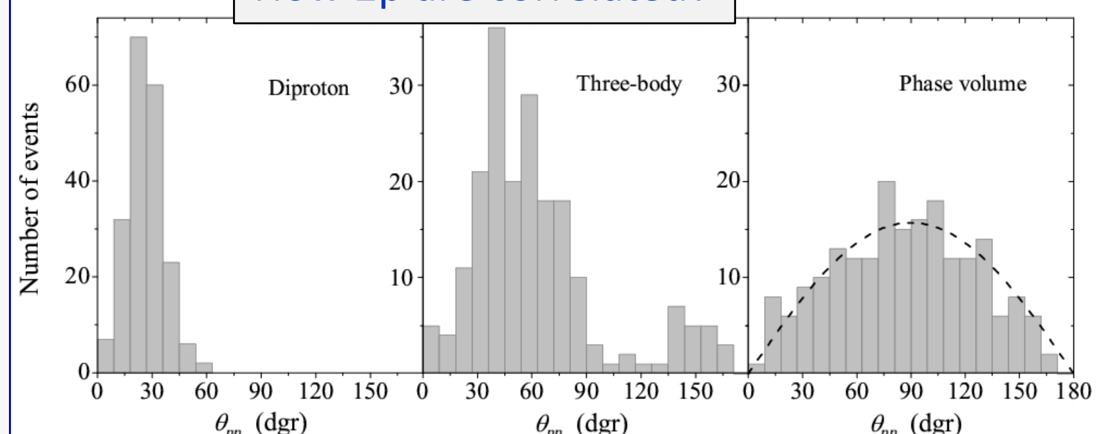


Goldanskii, Nucl. Phys. 19 (60) 482

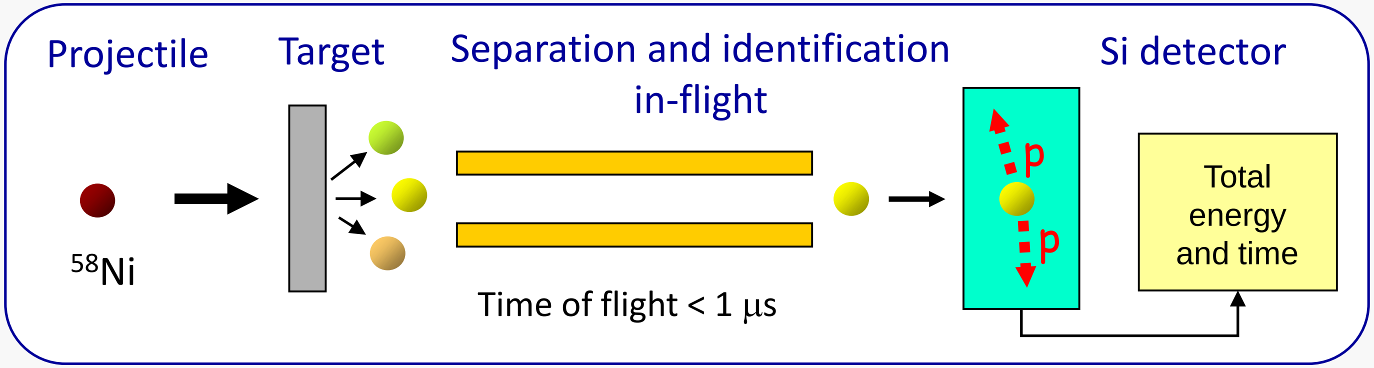
How 2p are correlated?

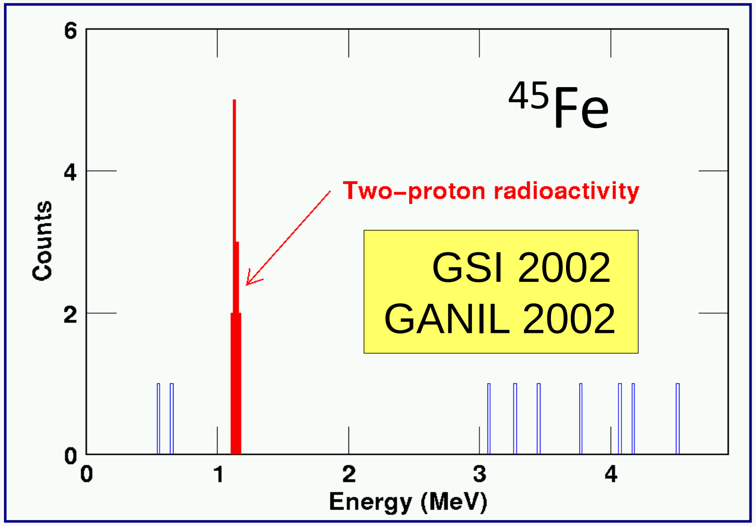


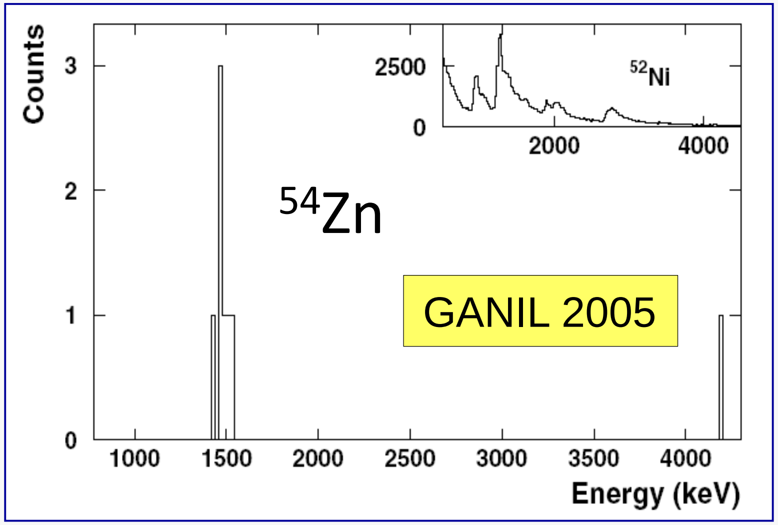

L. Grigorenko (2003)

# *2p* first evidence

- Implantation into Si array – good measurement of energy, but protons not resolved!



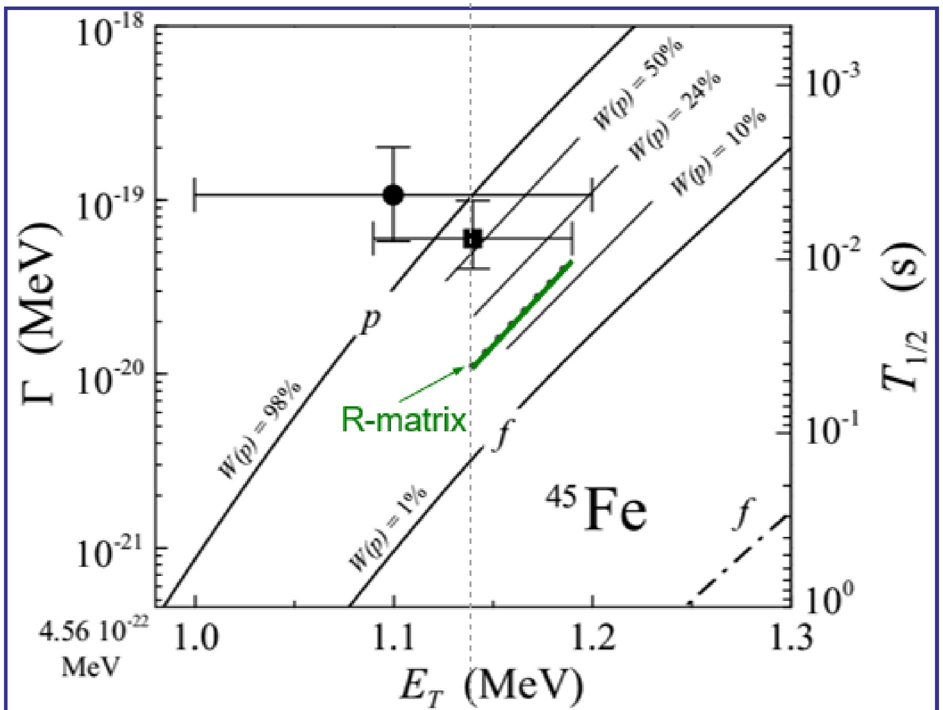



# 20 years ago...

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

3-body : L.V. Grigorenko and M.V. Zhukov, PRC68 (2003) 054005

R-matrix : : B.A. Brown, F.C. Barker, Proc. PROCON'03, p.118



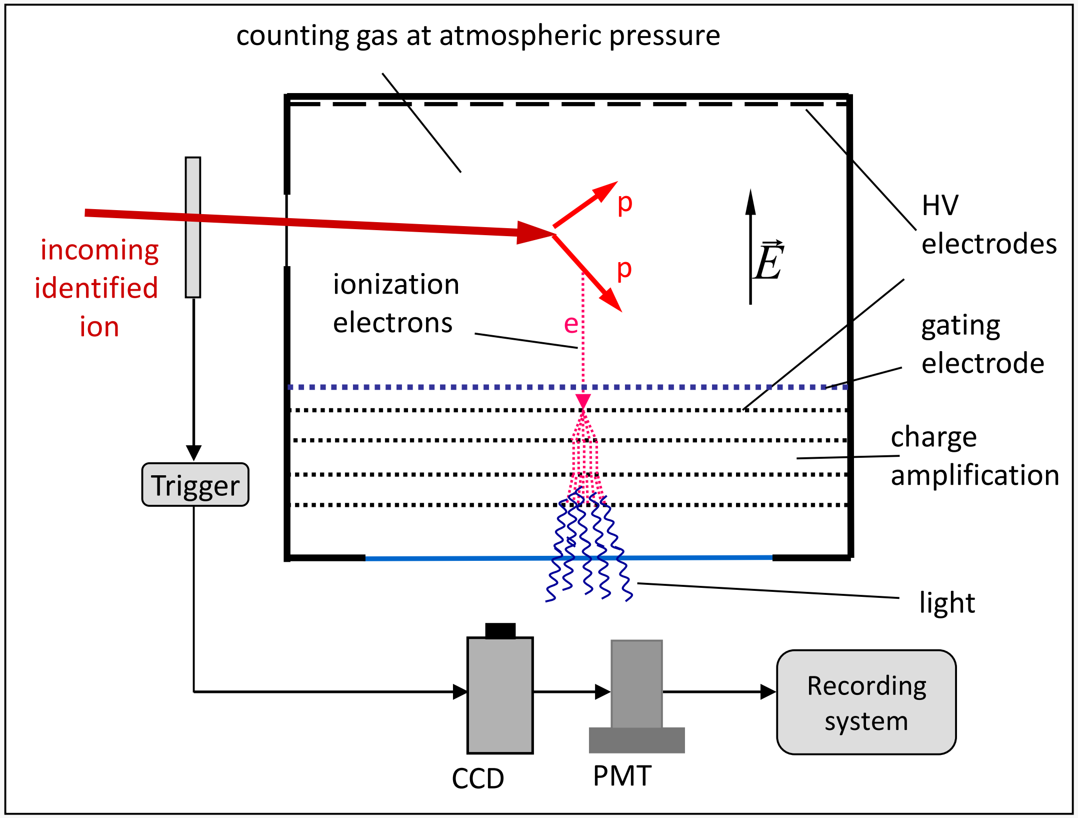

Zakopane'04 M.Pfützner „2p emission studies" 9

At that time we had only the half-life and the total decay energy!

→ Need to record two protons separately

# The Warsaw OTPC

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

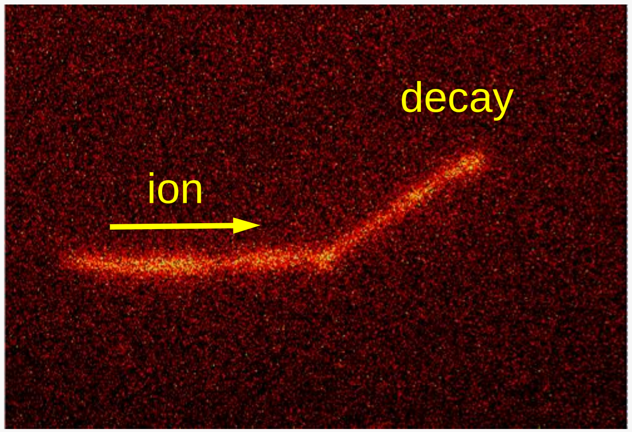



- Combination of the CCD image with the PMT waveform allows full reconstruction of the track in 3-D

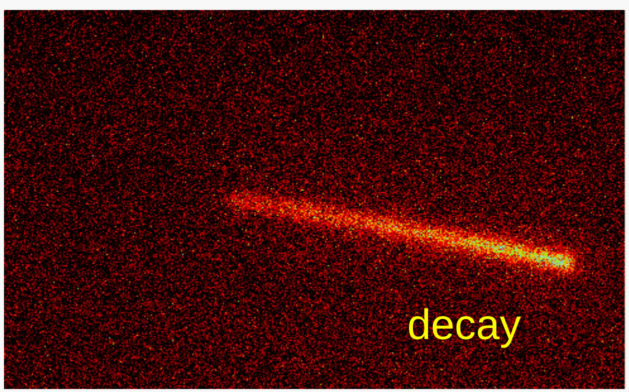
# Event data

## CCD image

tracks of the ion and emitted particle(s)

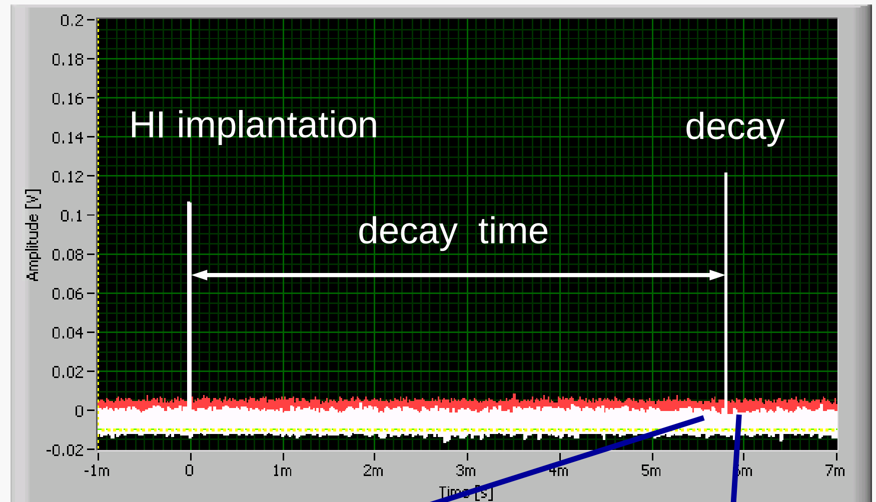



or only emitted particle(s)

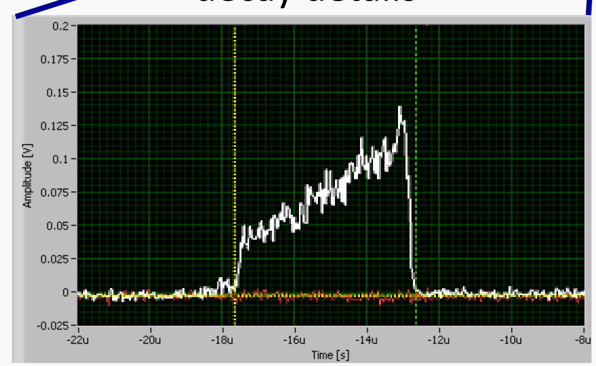



## PMT signal sampled

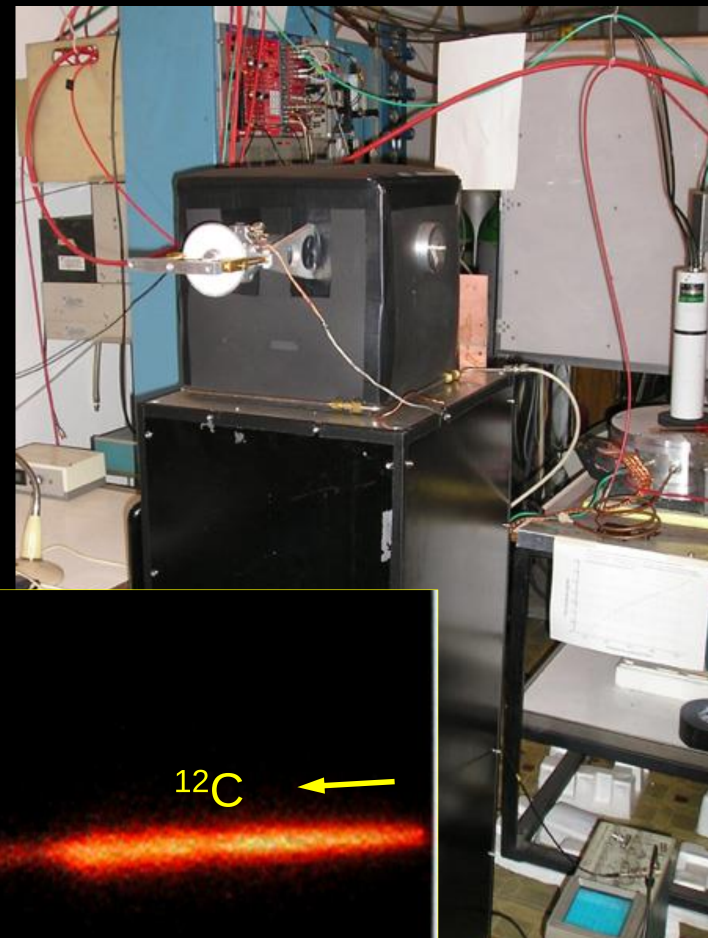
time sequence of events

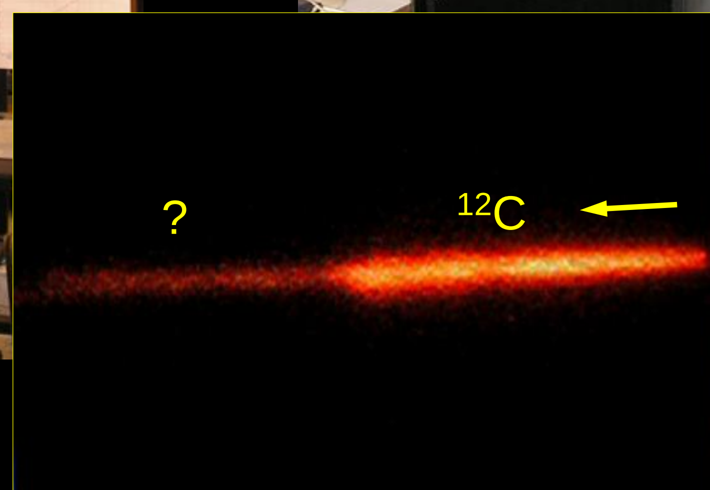



decay details



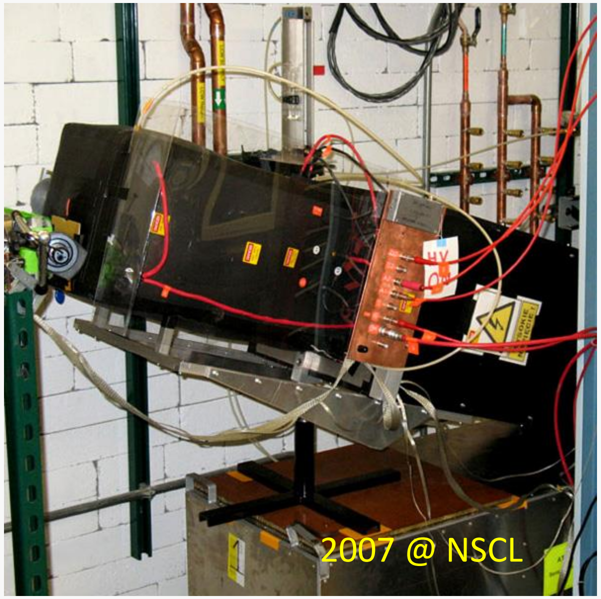
# OTPC - prototype



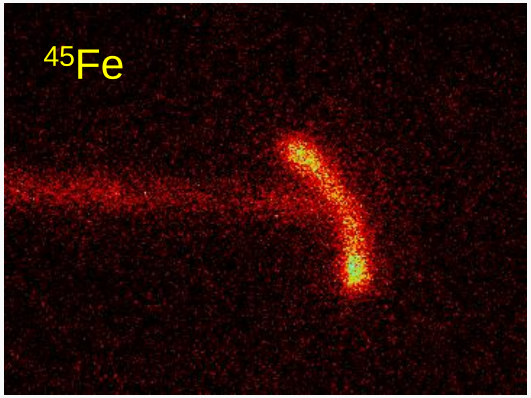



March 2006 @ Warszawa

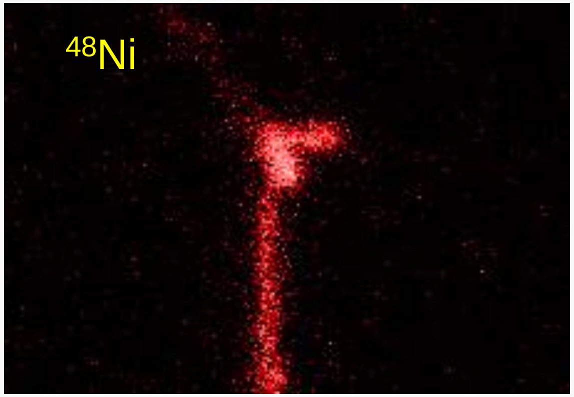
# OTPC milestones



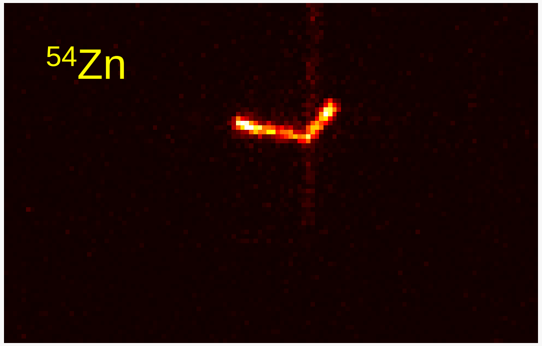



Miernik et al., PRL 99 (07) 192501



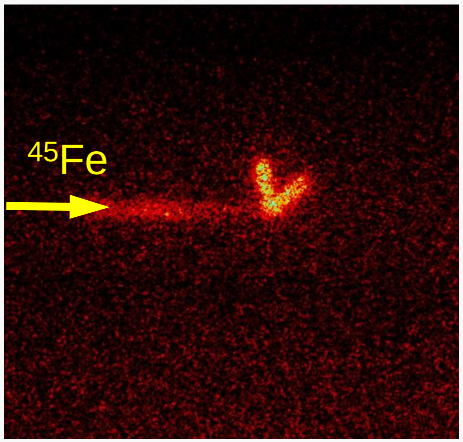

Pomorski et al., PRC 83 (2011) 061303(R)

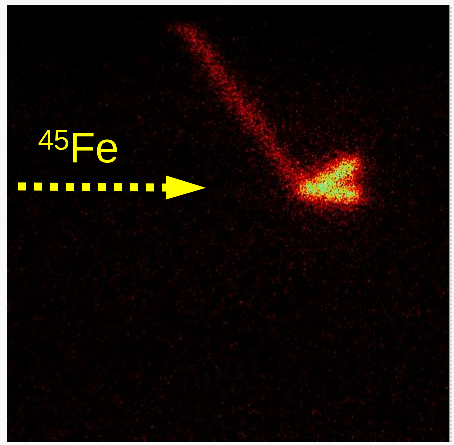



Kubiela et al., to be published (2023)

# *p-p* momentum correlations for $^{45}Fe$

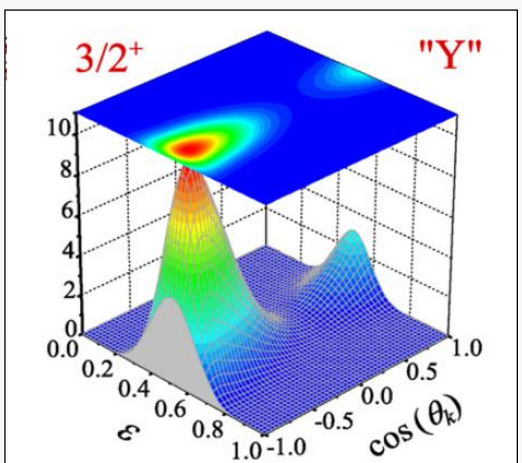
NSCL: $^{58}Ni$ @ 161 MeV/u + Ni → $^{45}Fe$

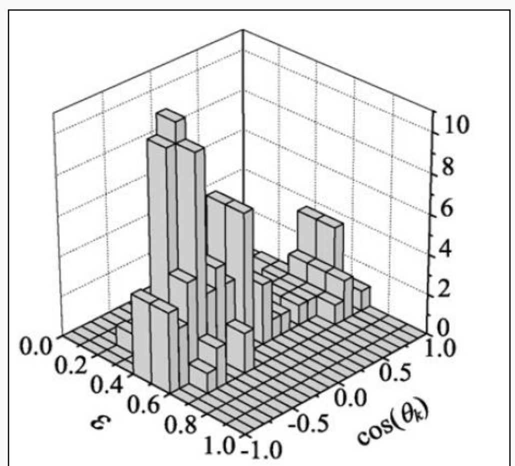



Miernik et al., PRL 99 (2007) 192501

75 events reconstructed



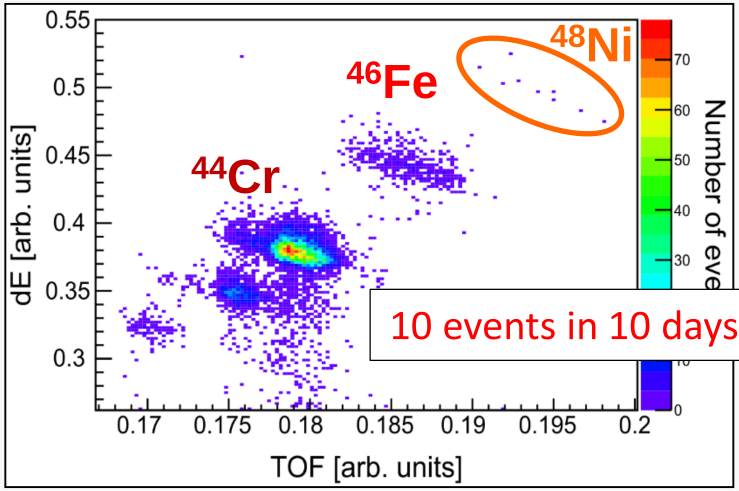




Grigorenko *et al.*, Phys. Lett. B 667 (2009) 30

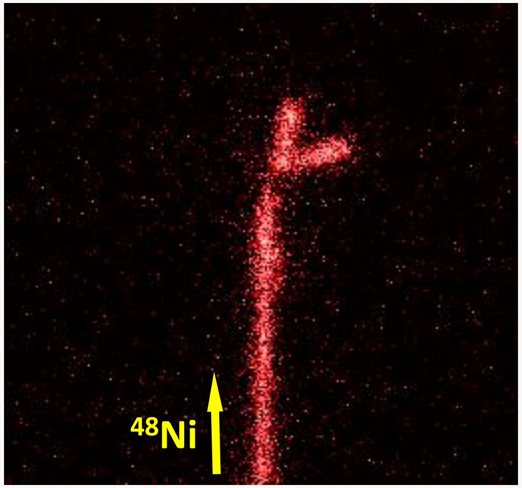
- Proton-proton correlations are complex and indicate a genuine 3-body phenomenon
- Good agreement with the 3-body model of Grigorenko et al.
- The correlation picture depends on the initial wave function

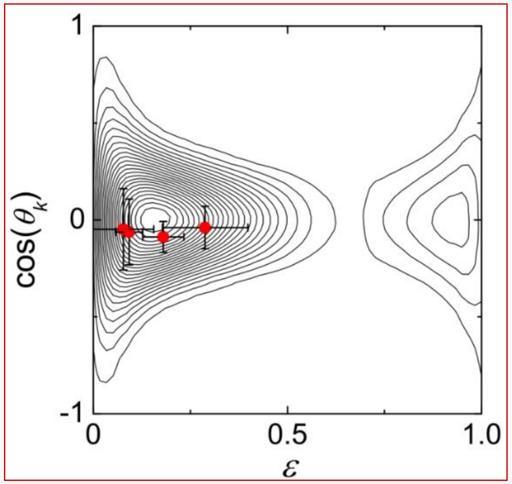
# *2p* radioactivity of $^{48}$Ni

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




10 events in 10 days



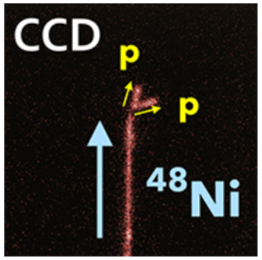




Pomorski et al., PRC 83 (2011) 061303(R)

To be continued @FRIB

## *Physical Review C* 50$^{th}$ 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.

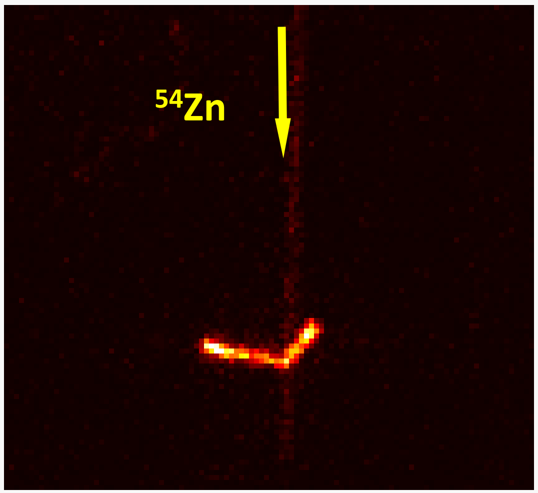
First observation of two-proton radioactivity in $^{48}$Ni

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

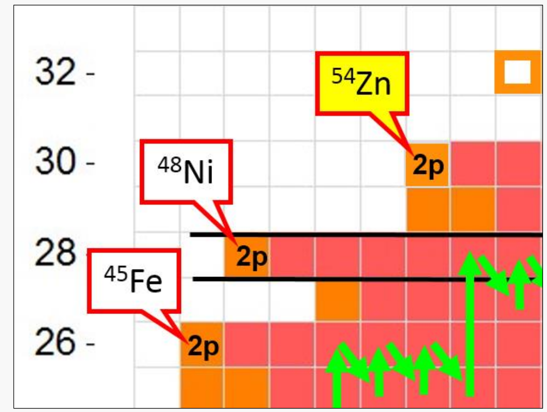
# *2p* decay of $^{54}Zn$

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

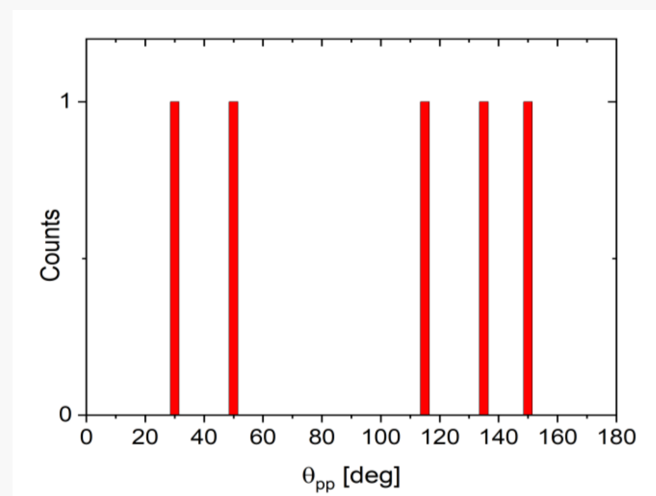
The production X-section: $\sigma = 3.5 \pm 0.8 \pm 0.7$ fb




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

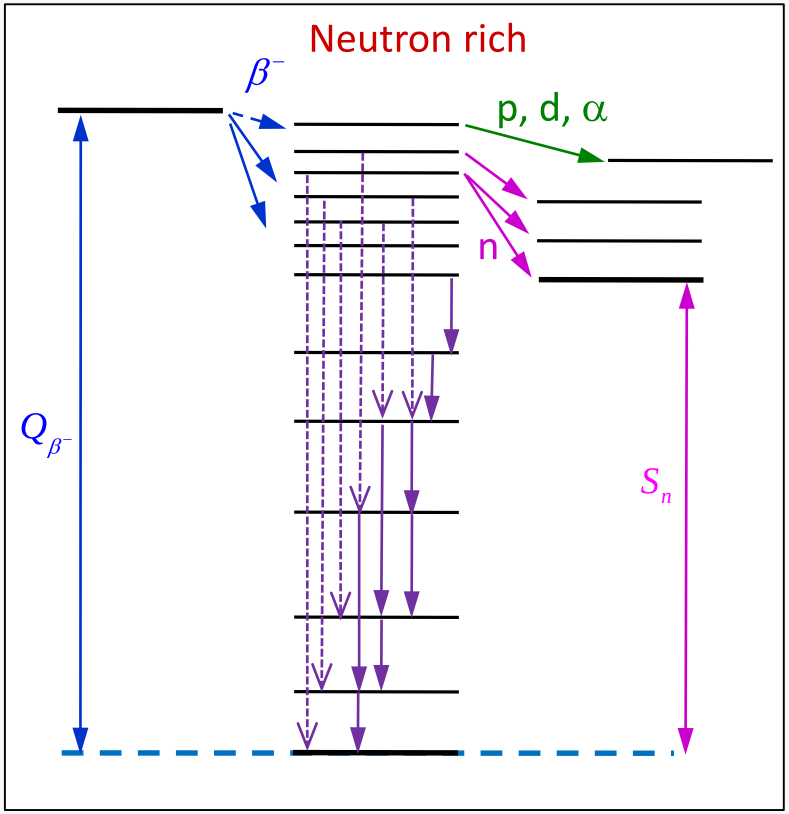


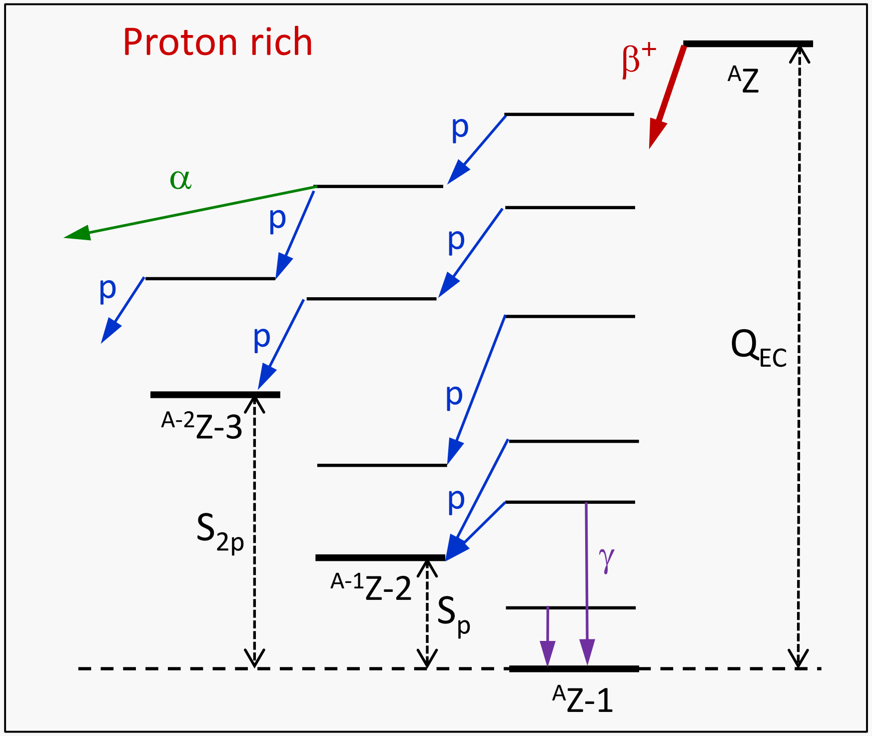

For 5 events we could determine the angle between both protons



# β-delayed particle emission

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



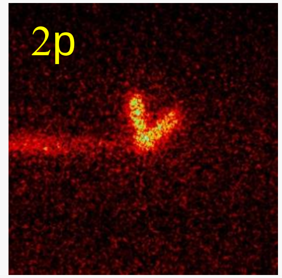

Neutron halos → charged particles

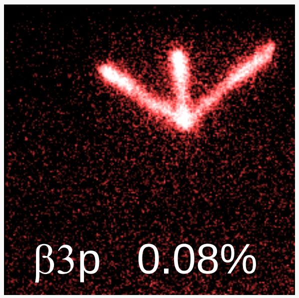
Gamma spectroscopy → *Pandemonium* effect!

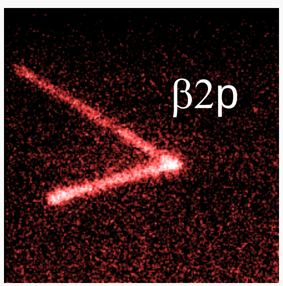
- Strong beta transitions to highly excited states are suppressed by kinematics and appear as weak radiation channels
- Low-energy delayed protons may be of interest to astrophysics

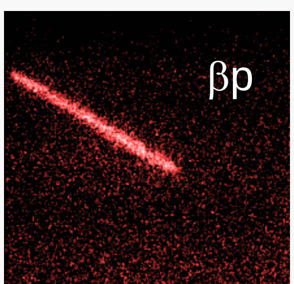
# Decays of $^{45}$Fe and $^{43}$Cr

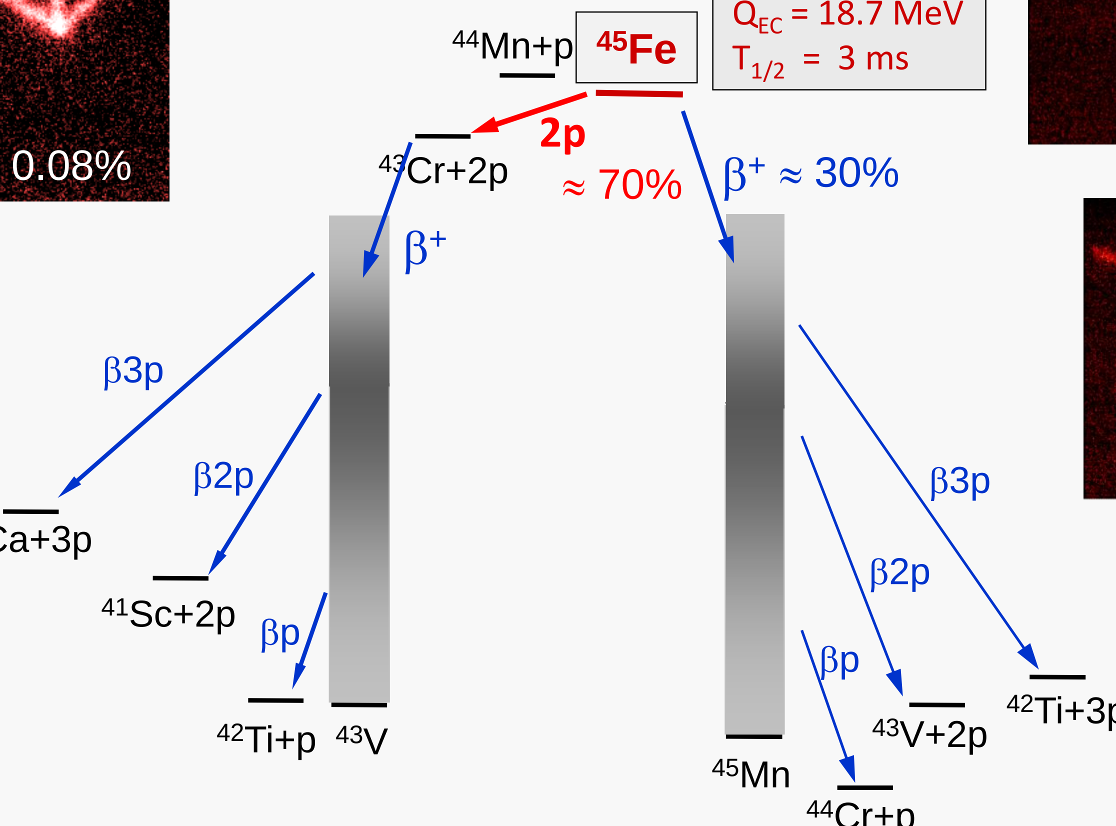
NSCL/MSU, 2007

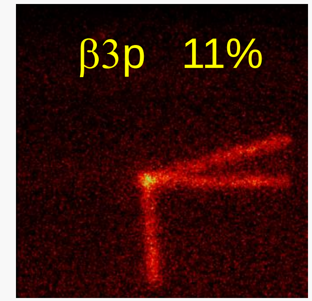


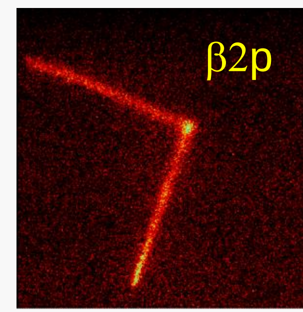



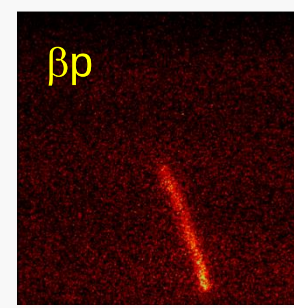




Pomorski et al., PRC 83 (2011) 014306

Miernik et al., PRL 99 (07) 192501

# β3p in $^{31}$Ar?

PHYSICAL REVIEW C VOLUME 45, NUMBER 1 JANUARY 1992

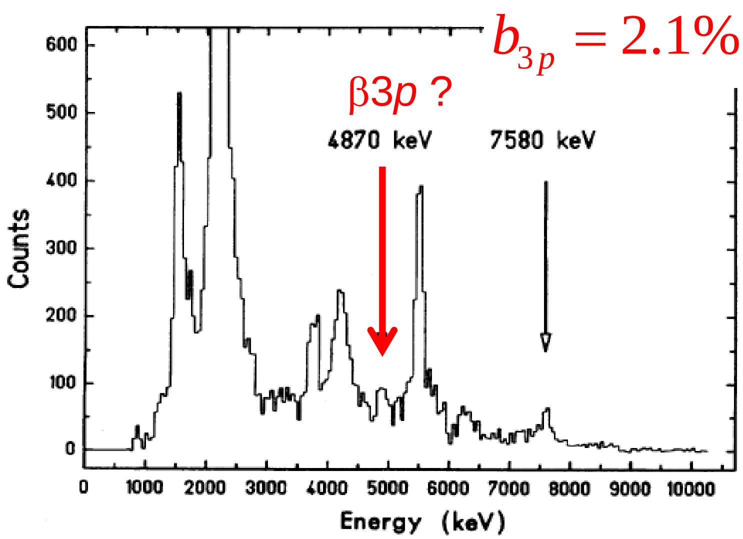
**Decay modes of $^{31}$Ar and first observation of $\beta$-delayed three-proton radioactivity**

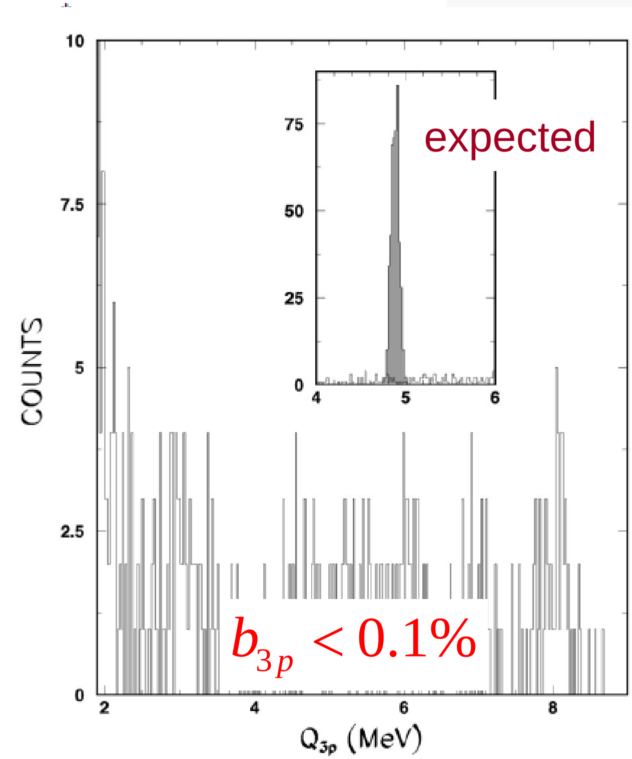
D. Bazin,* R. Del Moral, J. P. Dufour, A. Fleury, F. Hubert, and M. S. Pravikoff
*Centre d'Etudes Nucléaires de Bordeaux–Gradignan, Le Haut Vigneau 33175 Gradignan CEDEX, France*

PHYSICAL REVIEW C VOLUME 59, NUMBER 4 APRIL 1999

**$^{31}$Ar examined: New limit on the $\beta$-delayed three-proton branch**

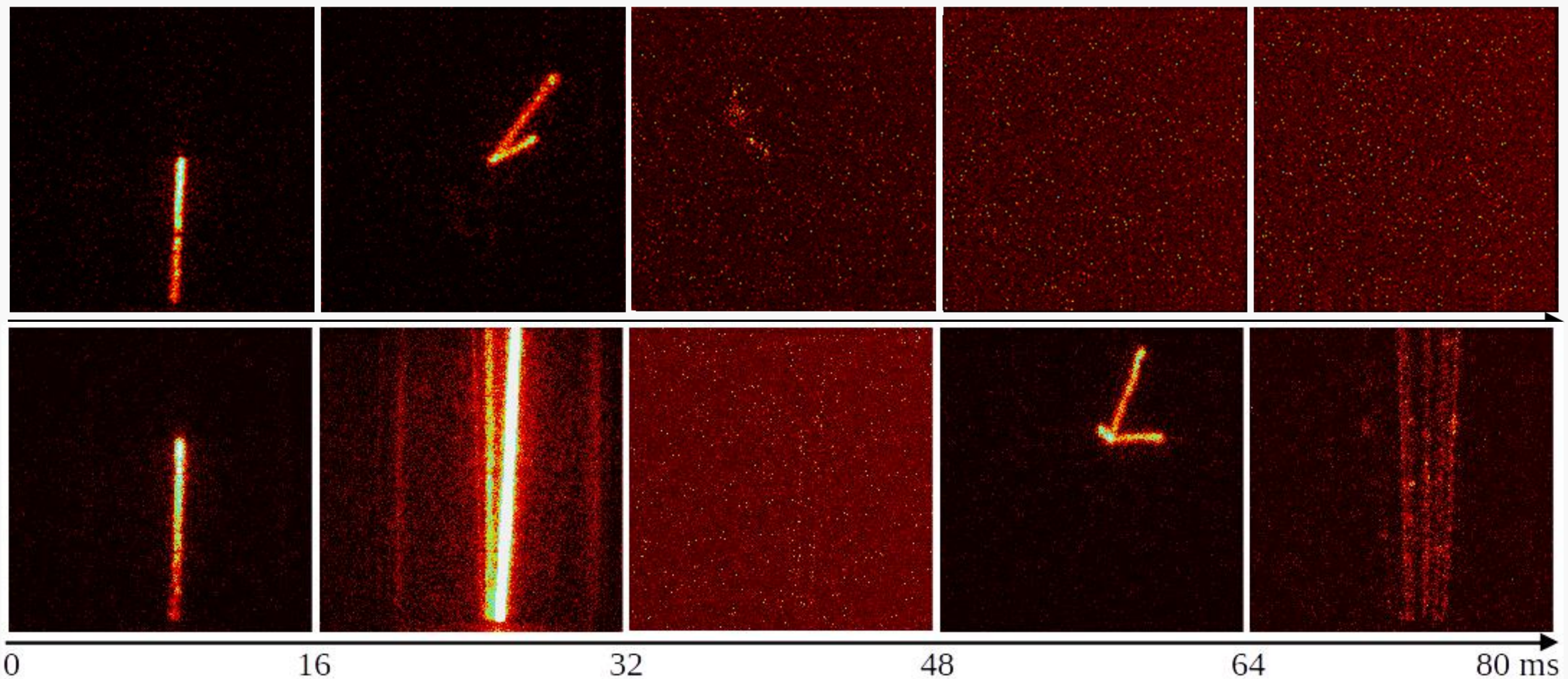
H. O. U. Fynbo,[1] L. Axelsson,[2] J. Äystö,[3] M. J. G. Borge,[4] L. M. Fraile,[4] A. Honk
A. Jokinen,[3] B. Jonson,[2] I. Martel,[5,†] I. Mukha,[1,‡] T. Nilsson,[2,§] G. Nyman,[2] M. Oin
M. H. Smedberg,[2] O. Tengblad,[4] F. Wenander,[2] and the ISOLDE



# Decay of $^{31}$Ar

- GSI-FRS, August 2012, beam from the synchrotron – we cannot stop it upon trigger ☹
- → A new acquisition mode – a series of shorter expositions („movie")

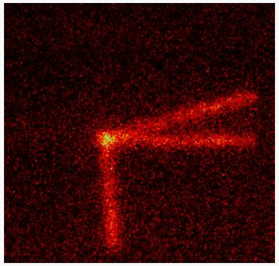



- 21 000 „interesting movies" inspected individually
- → 13 events of β3p decay of $^{31}$Ar found

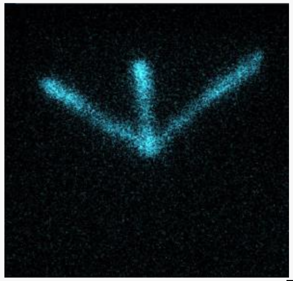
Lis et al., PRC 91, 064309 (2015)

| Channel | Events | Branching [%] |
|---|---|---|
| $\beta 0p$ | 5984 | $22.6(3)^a$ |
| $\beta 1p$ | 13157 | 68.3(3) |
| $\beta 2p$ | 1729 | 9.0(2) |
| $\beta 3p$ | 13 | 0.07(2) |

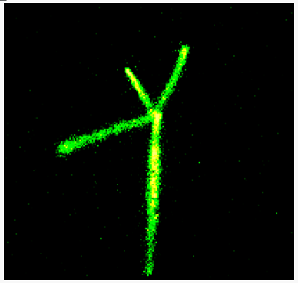
# All known cases of β3p



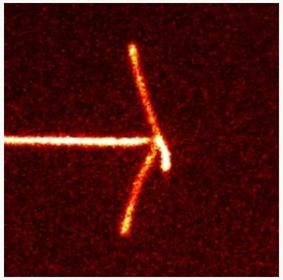
$^{45}$Fe
NSCL 2007
Miernik et al., PRC 76 (2007) 041304(R)



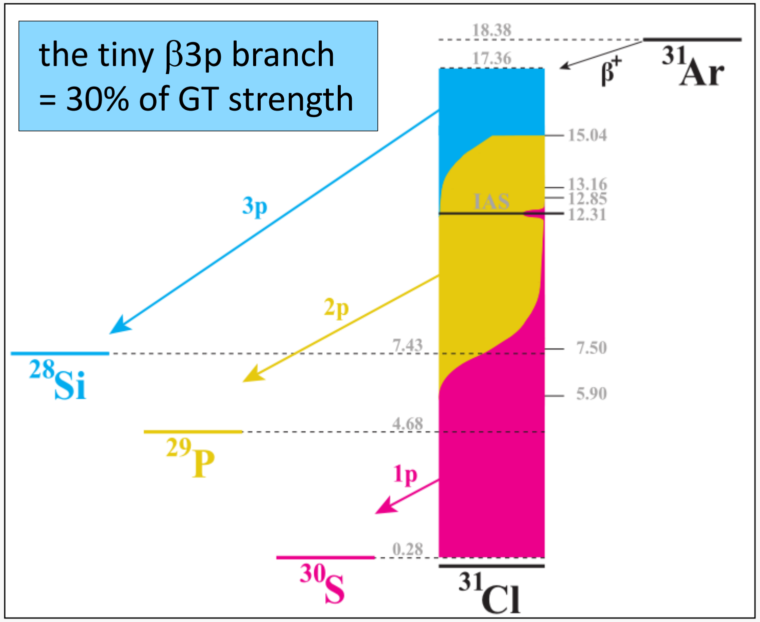
$^{43}$Cr
NSCL 2007
Pomorski et al., PRC 83 (2011) 014306



$^{31}$Ar
GSI 2012
Lis et al., PRC 91 (2015) 064309



$^{23}$Si
Texas A&M 2017
Ciemny et al., PRC 106 (2022) 014317

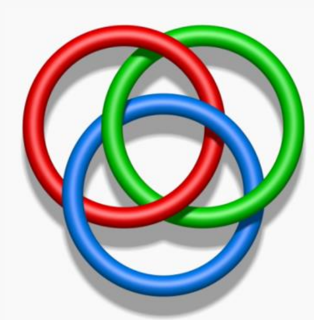


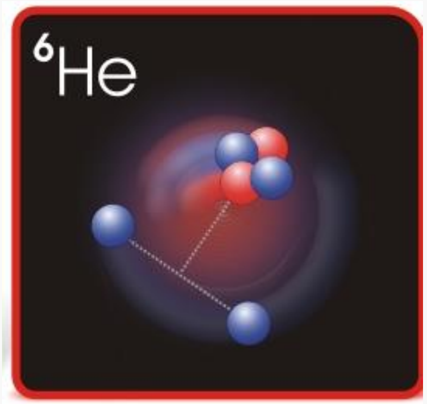

Koldste et al., PRC 89 (2014) 064315

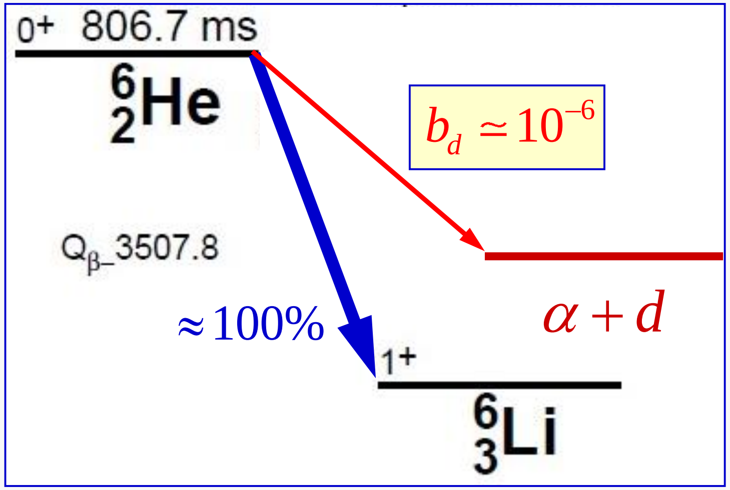
New!
$^{49}$Ni β3p observed @GANIL in 2022 with ACTAR TPC: presented in Zakopane'22 by Aurora Ortega Moral

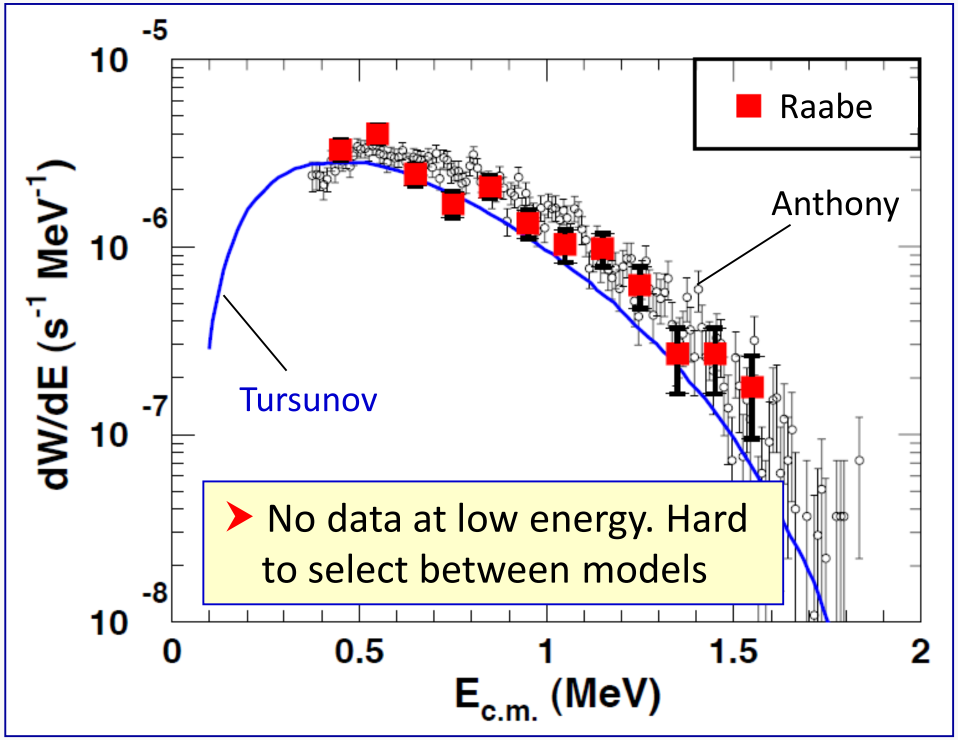
# Probing the 2n halo of $^6He$

- $^6$He decays into $\alpha + d$ with a very low branching





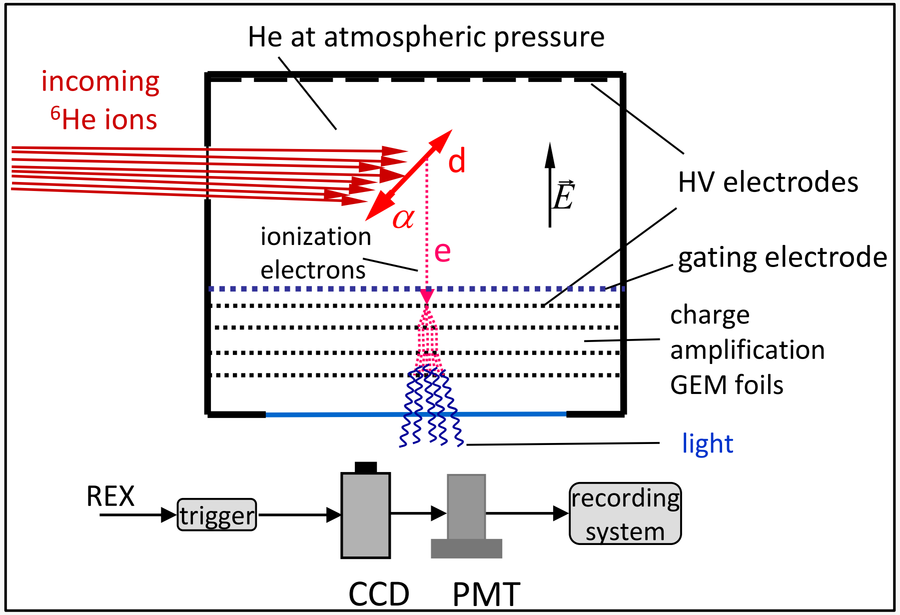

- Because of large β background, the spectrum below $E_{CM} \cong 400$ keV could not be measured

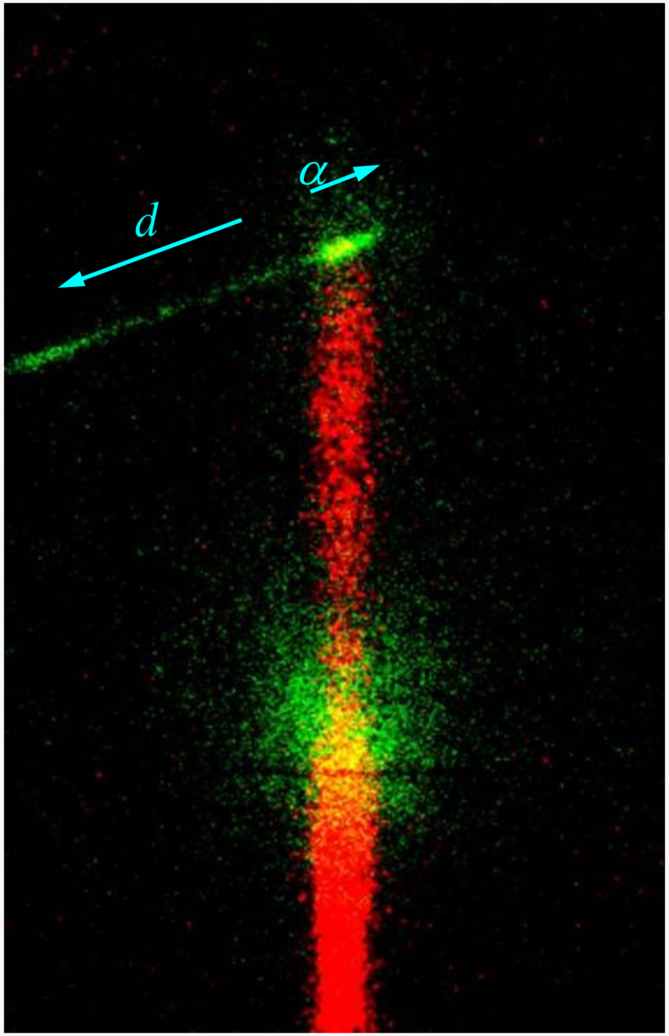
R. Raabe et al., Phys. Rev. C80 (2009) 054307

# „Bunch" mode for $^6$He @ISOLDE

## Experiment at ISOLDE, August 2012

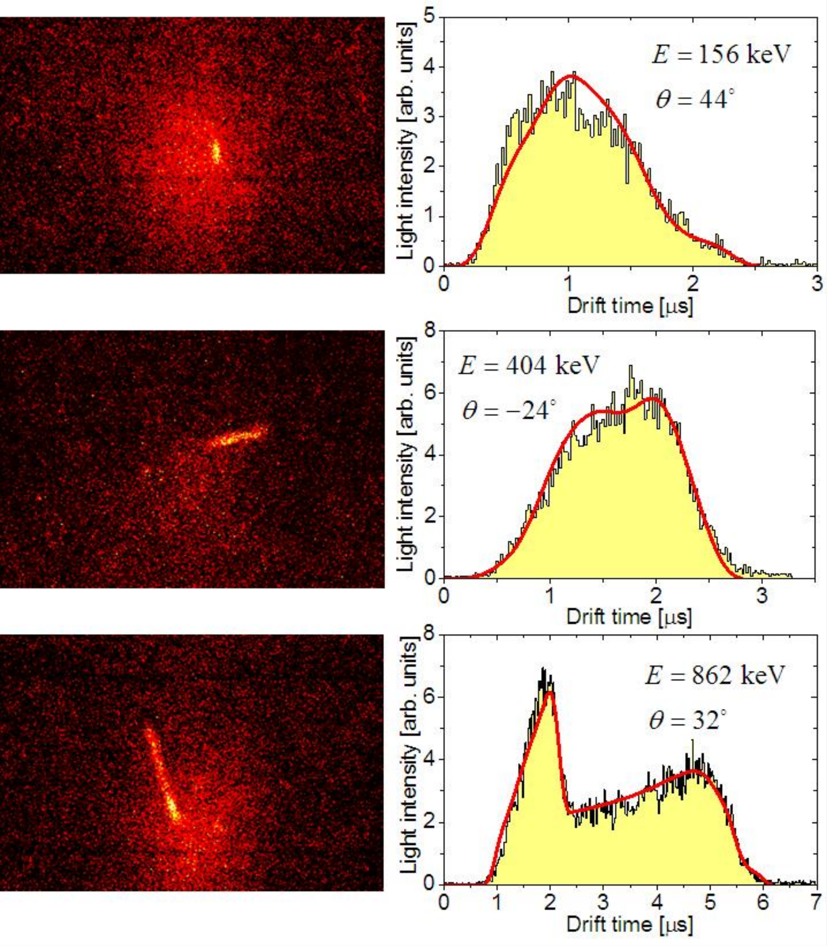
- Bunches of about $10^4$ ions of $^6$He accelerated by **REX-ISOLDE** to 3 MeV/u were implanted into the OTPC.
- After implantation, an exposure of 650 ms was started to see the decays.
- Clear images of decay events with $\alpha$ + *d* tracks were recorded.

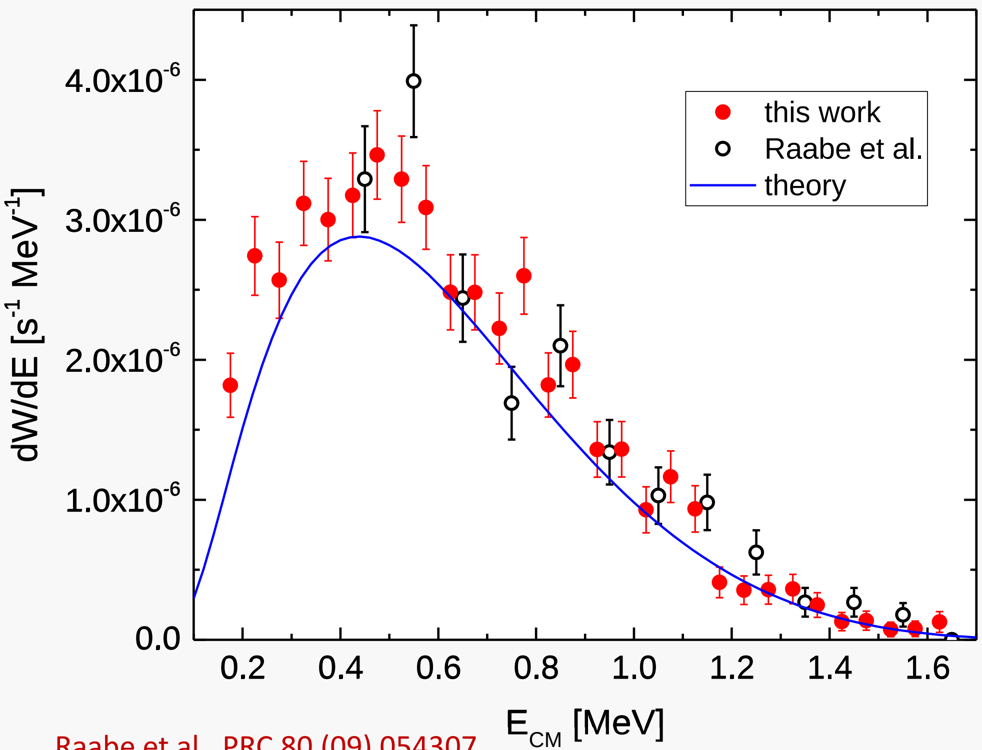



A CCD image showing a bunch of implanted $^6$He ions (red) and a $^6$He → $\alpha$ + *d* decay (green)

# The spectrum of $\alpha + d$




Raabe et al., PRC 80 (09) 054307

theory: Tursunov, Baye, Descouvemont, PRC73 (06) 014303

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

= 20% more than the theoretical prediction

1650 decay events reconstructed

M.P. et al., PRC 92, 014316 (2015)

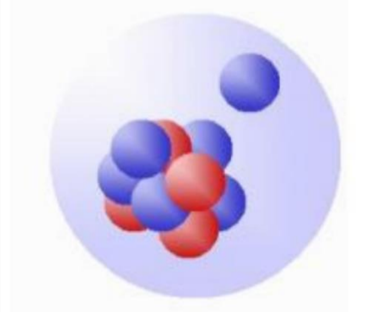
➔ By extending the spectrum to lower energy, we see 70% more intensity

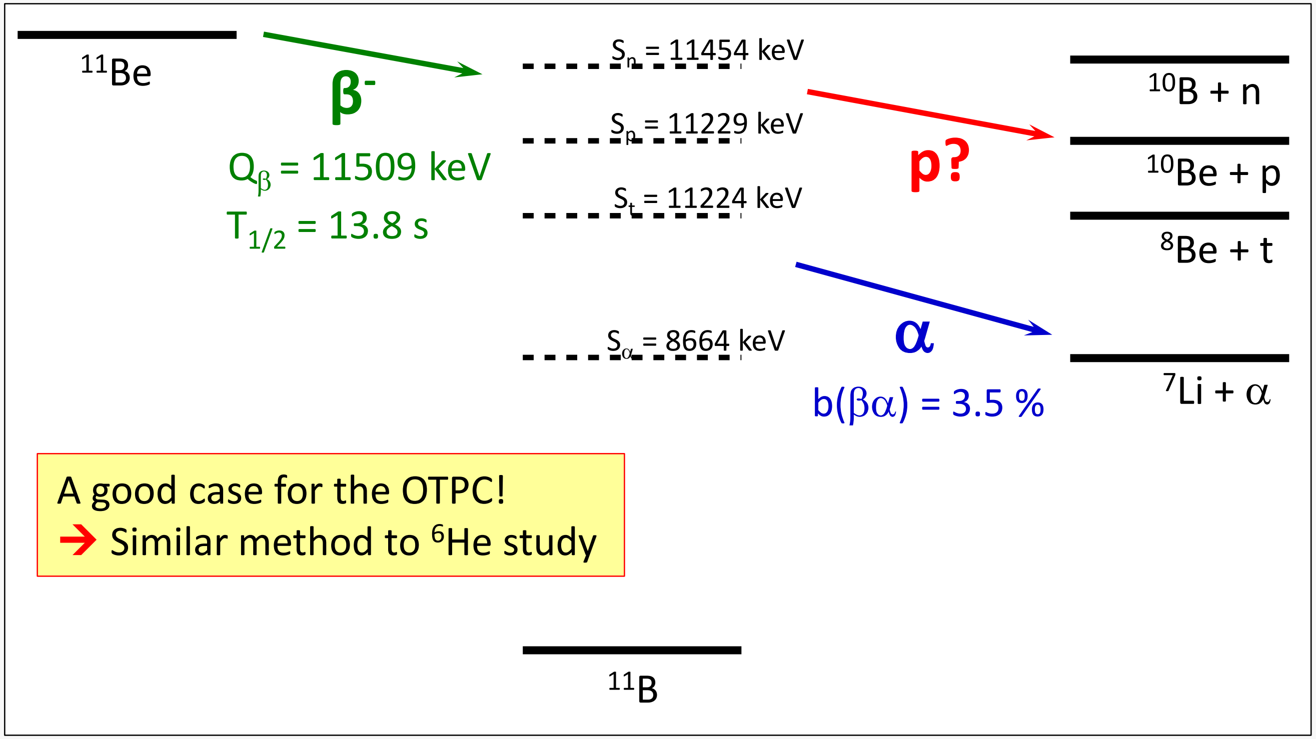
➔ Corrected model: Tursunov et al. PRC 97 (18) 014302

# A difficult case: $^{11}$Be βp?

- 1n halo nucleus
- The $\beta^{-}\alpha$ emission observed
- The $\beta^{-}p$ decay possible

  $Q_p$ = 281 keV, the predicted branching: $b_p < 10^{-6}$

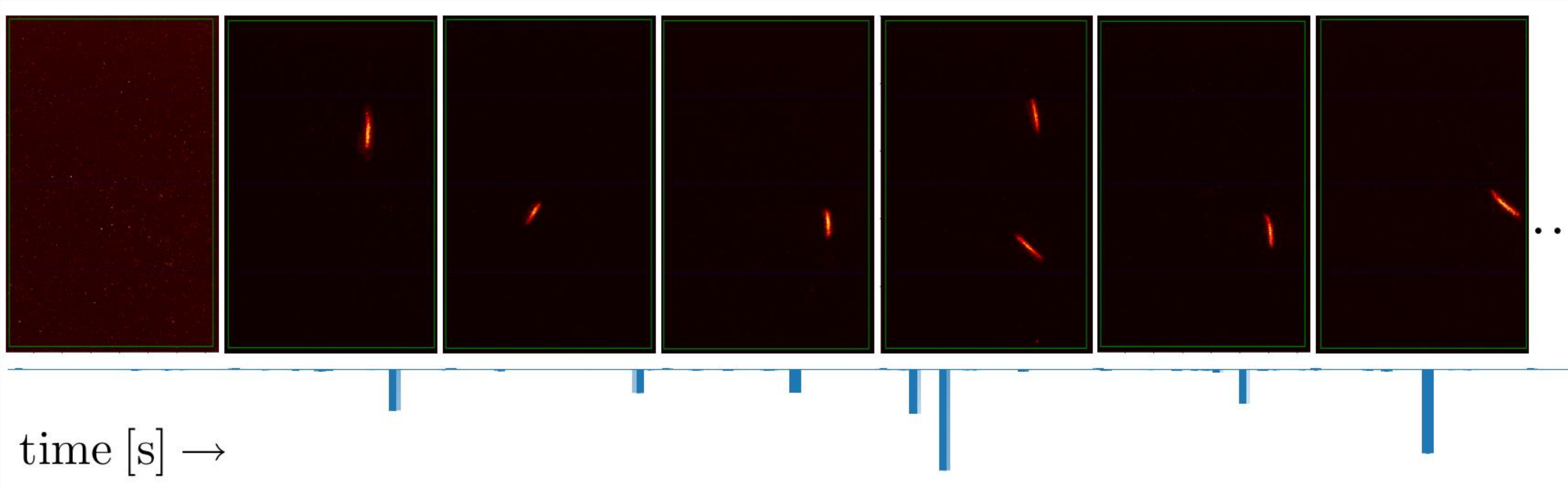




# $^{11}$Be @ ISOLDE

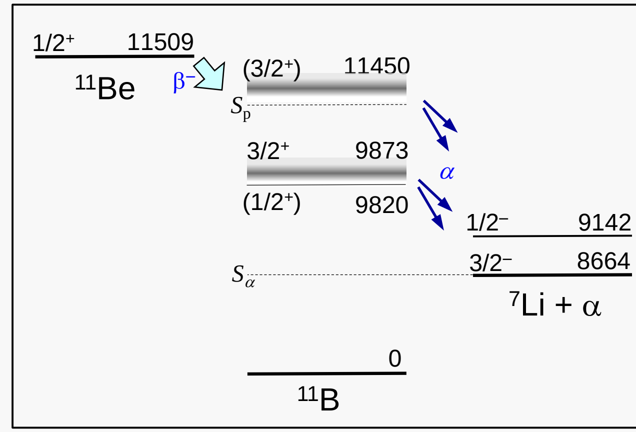
➤ Experiment at ISOLDE, 2018 → bunch and movie modes combined

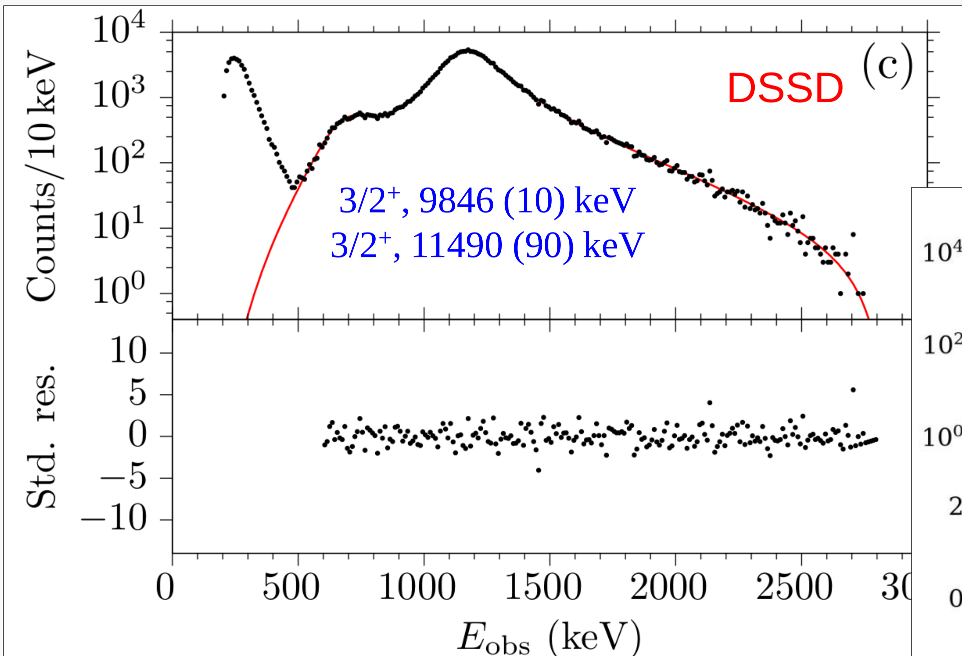
- Bunches of about $10^4$ ions of $^{11}$Be accelerated
  by **HIE-ISOLDE** to 7.5 MeV/ implanted into the OTPC every 1 min.
- After implantation: 252 frames of 33 ms (13 s) + 47 s break
- about 1.4 M frames recorded
  featuring about 1.5 M $\beta\alpha$ events



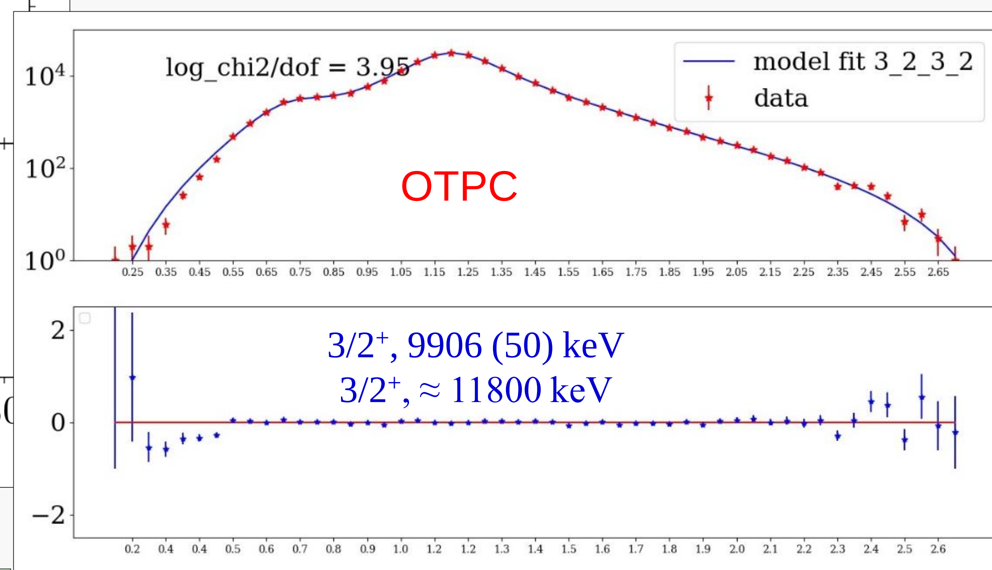
# βα decay of $^{11}$Be

- Relatively strong βα branch (3.5%) provides normalization but is a possible source of low-energy background
- → The α spectrum is not known below 500 keV




Refsgaard at al., PR C99, 044316 (2019)




→ We measured the BR(α) independently in a second experiment @ Catania: 3.4(5)%

Preliminary analysis of ≈200 k clean βα events

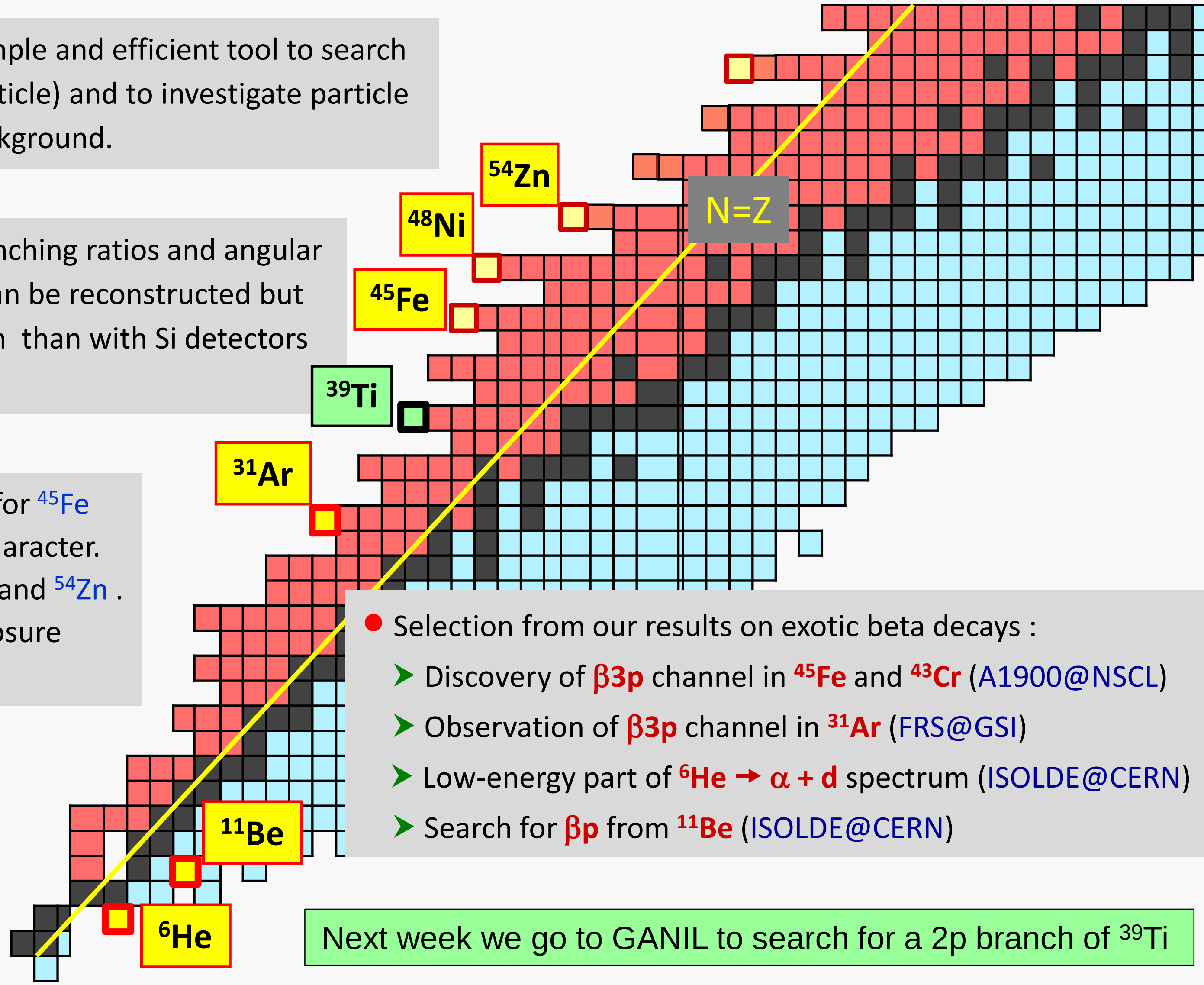
N. Sokołowska, PhD in preparation

# Summary

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

- It can provide precise branching ratios and angular correlations. Low energies can be reconstructed but with worse energy resolution  than with Si detectors – complementarity!

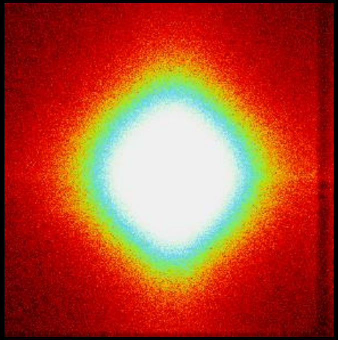
- *2p* correlations measured for $^{45}$Fe indicate non trivial 3-body character. Correlations needed for $^{48}$Ni and $^{54}$Zn . Can we see the Z=28 shell closure in the *2p* decay data?




- Selection from our results on exotic beta decays :
  - Discovery of **β3p** channel in **$^{45}$Fe** and **$^{43}$Cr** (A1900@NSCL)
  - Observation of **β3p** channel in **$^{31}$Ar** (FRS@GSI)
  - Low-energy part of **$^{6}$He → α + d** spectrum (ISOLDE@CERN)
  - Search for **βp** from **$^{11}$Be** (ISOLDE@CERN)

Next week we go to GANIL to search for a 2p branch of $^{39}$Ti

# Thank you!



The real work was mainly done by:

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