Exotic Decays with Emission of Charged Particles

Marek Pfützner

Nuclear Physics Division
University of Warsaw

18 years ago...

Atomic nuclei at extreme values of temperature, spin and isospin

The Current Status of 2p Emission Studies

Marek Pfützner

Institute of Experimental Physics

Warsaw University

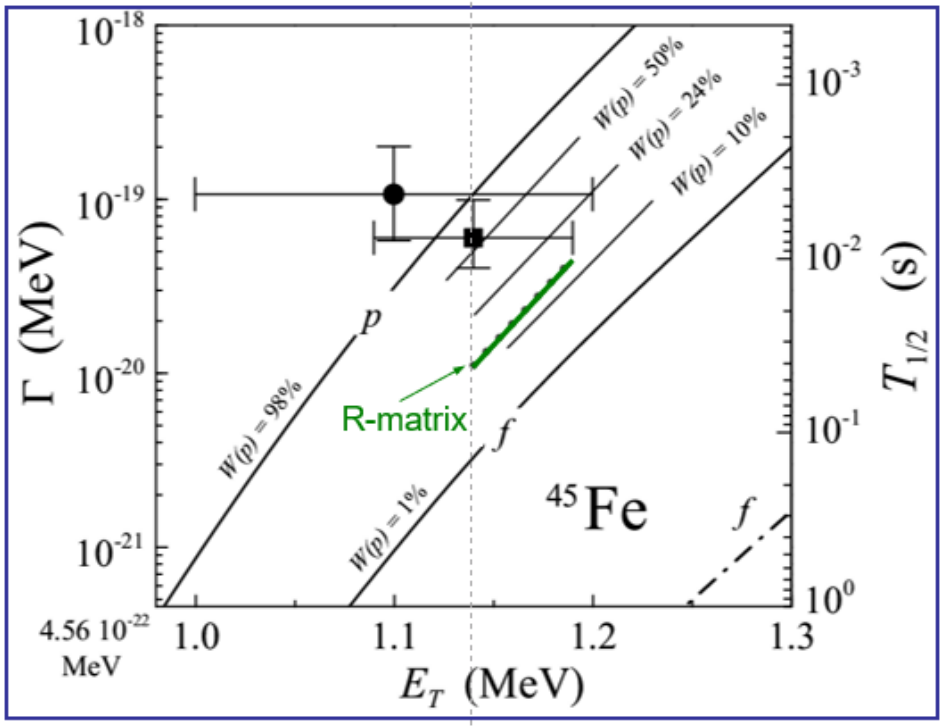
XXXIX Zakopane School of Physics
August 31 – September 5, 2004

18 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



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

18 years ago...

A possible solution

Optical Time Projection Chamber (OTPC)

G. Charpak et al., NIM A269 (1988) 142

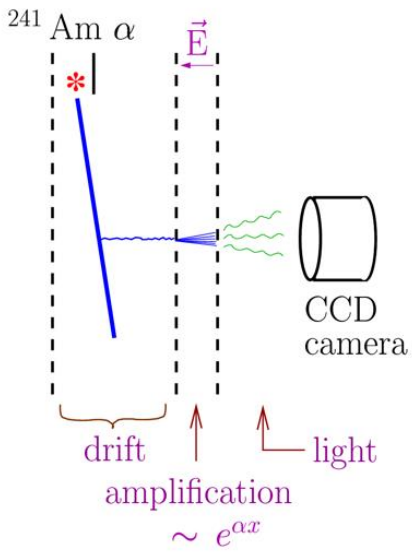


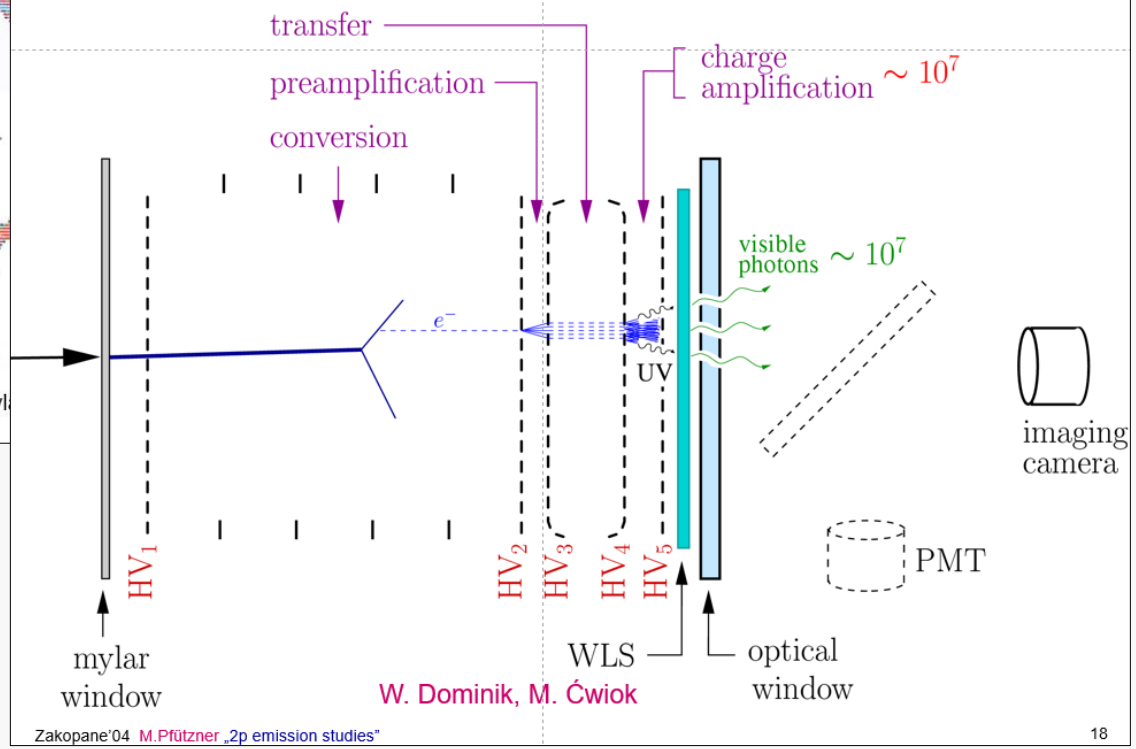
Image examples of α-particle tracks

TEA = Triethyl

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

But we already had an idea!

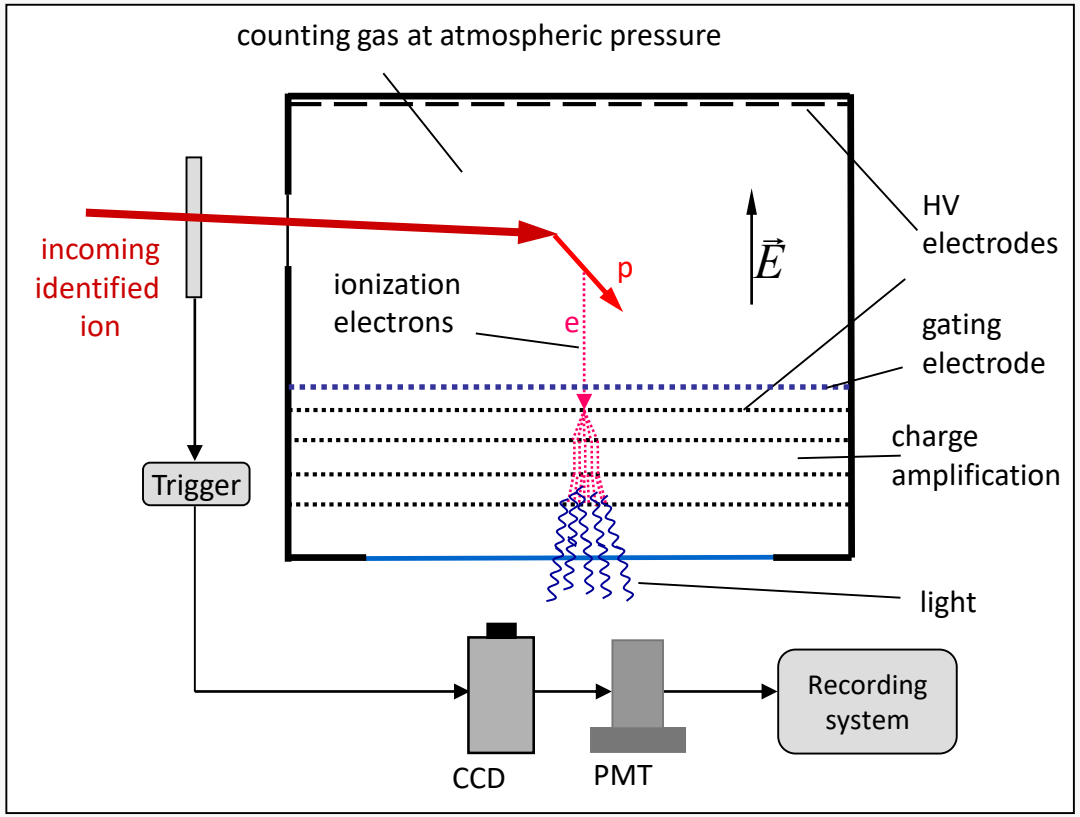
Design of the Optical TPC

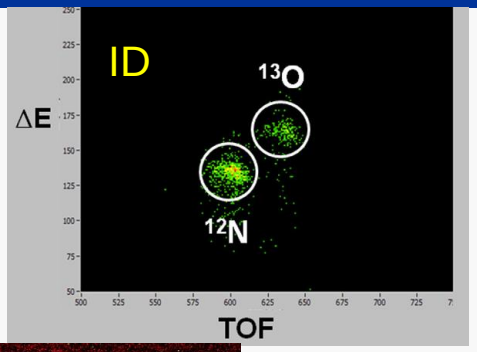


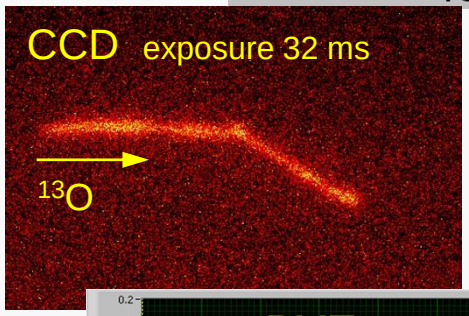
Zakopane'04 M.Pfützner „2p emission studies" 18

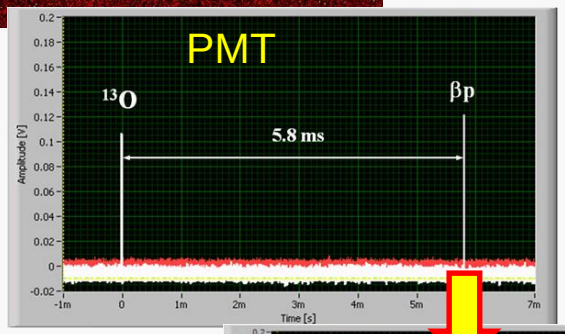
The Warsaw OTPC

Time projection chamber with optical readout (OTPC)





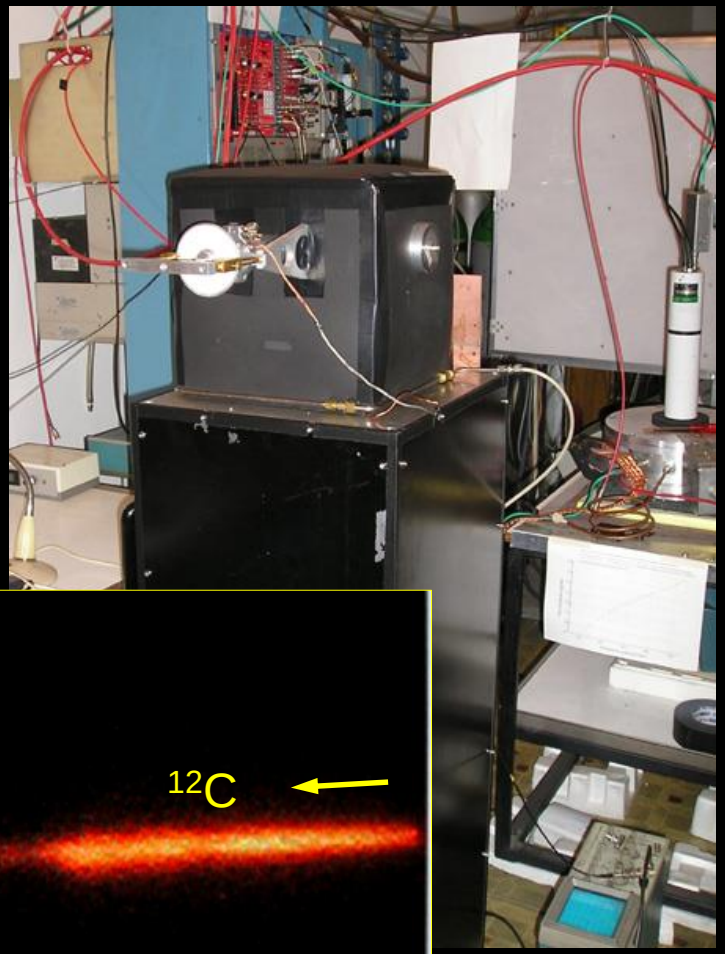


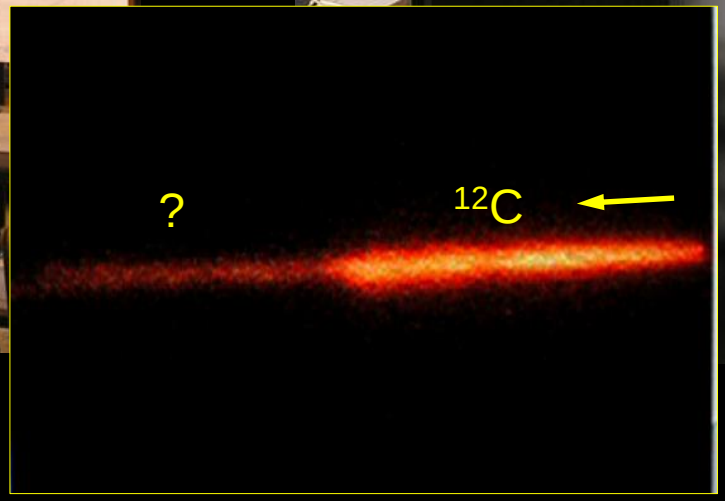


- Combination of the CCD image with the PMT waveform allows to fully reconstruct the track in three dimensions

Talk by Adam Kubiela and poster # 18 by Victor Guadilla

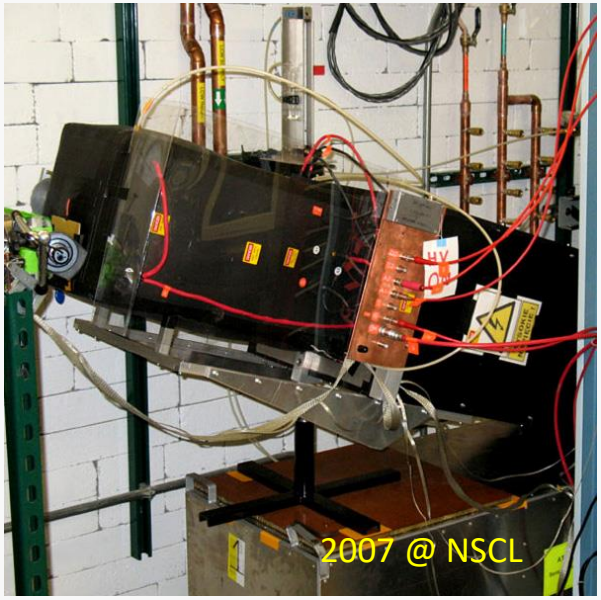
OTPC - prototype

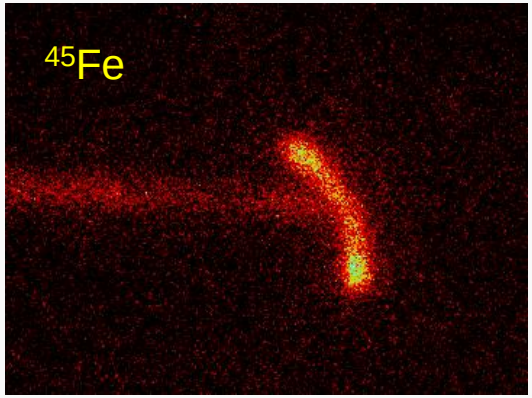




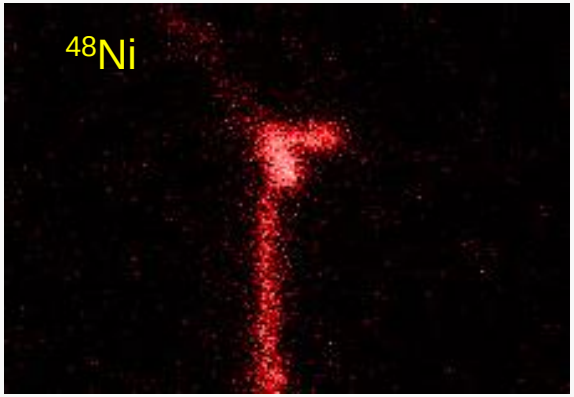
March 2006 @ Warszawa

OTPC milestones

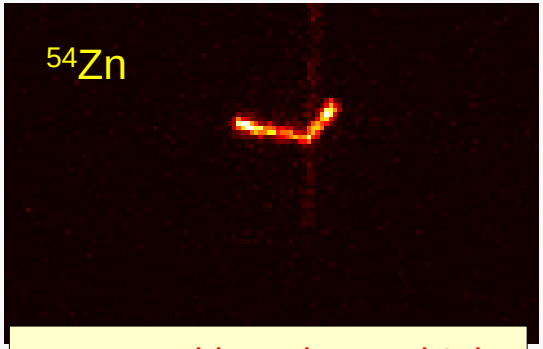




Miernik et al., PRL 99 (07) 192501



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

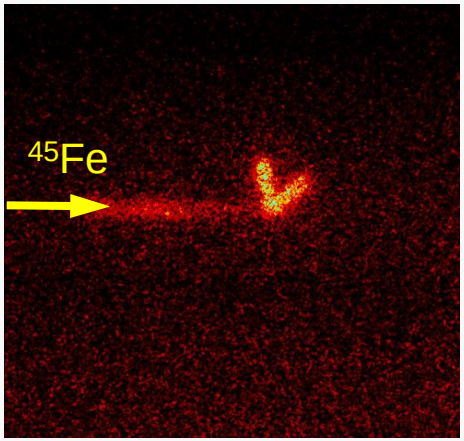


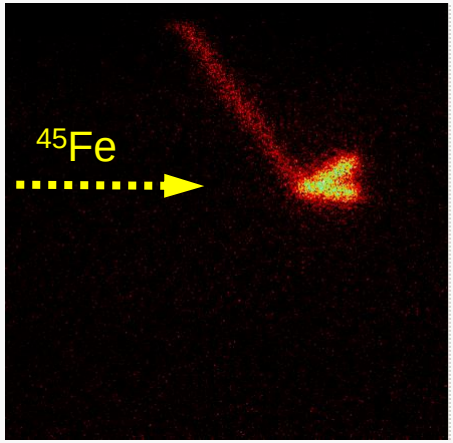
Presented by Adam Kubiela

Kubiela et al., to be published (2022)

p-p momentum correlations for ^{45}Fe

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

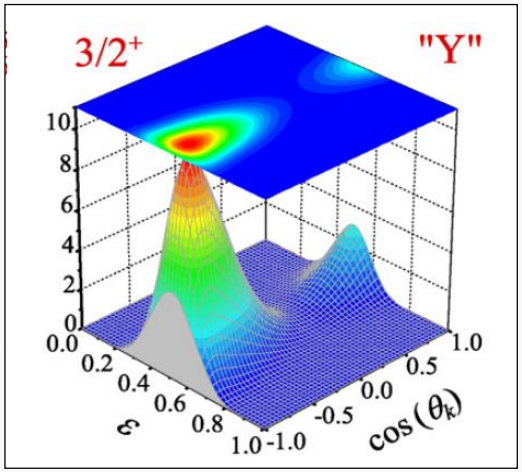


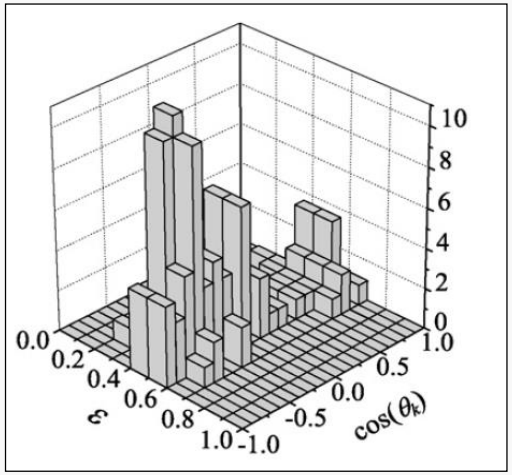


Miernik et al., PRL 99 (2007) 192501

75 events reconstructed

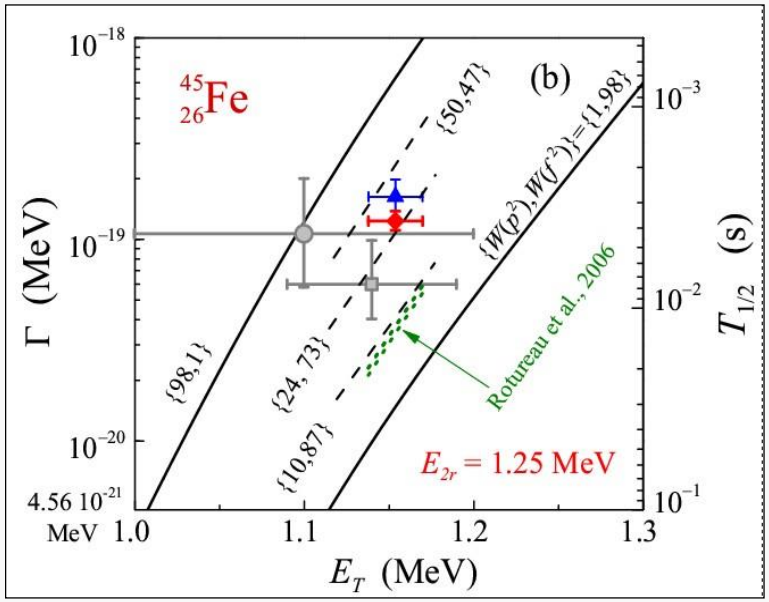
- Proton-proton correlations are complex and indicate a genuine 3-body phenomenon
- Good agreement with the 3-body model of Grigorenko et al.
- The correlation picture depends on the initial wave function

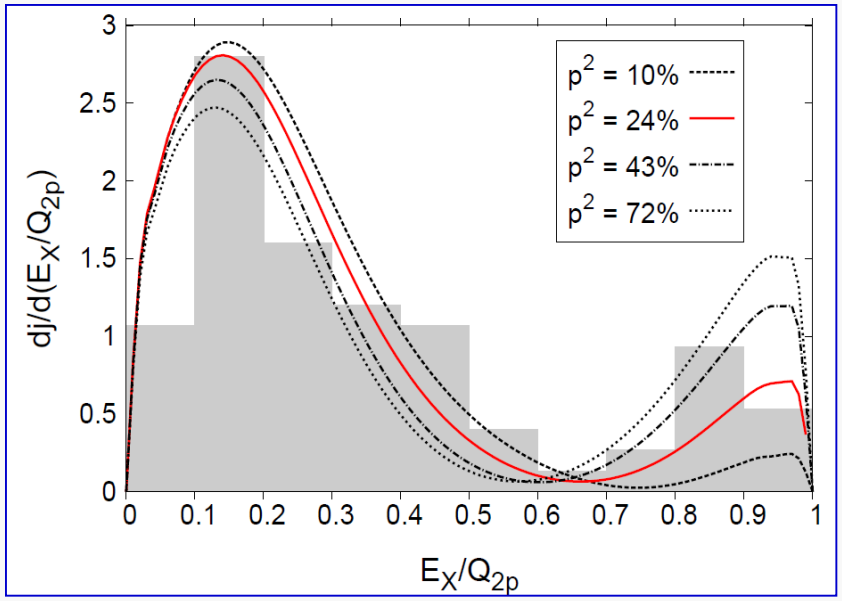




Grigorenko *et al.*, Phys. Lett. B 667 (2009) 30

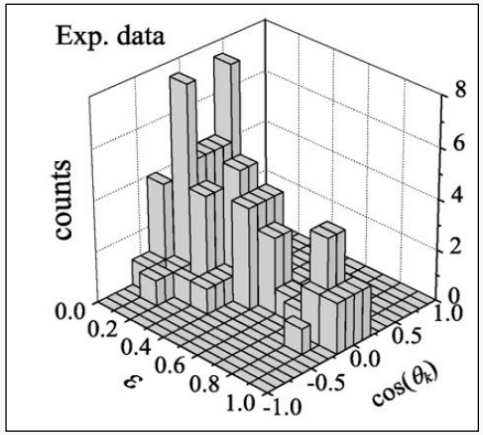
p-p momentum correlations for ^{45}Fe

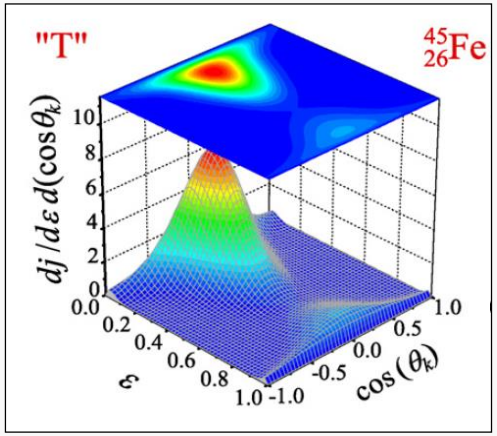




Result for ^{45}Fe: W(p^2) = 0.3±0.1

- 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





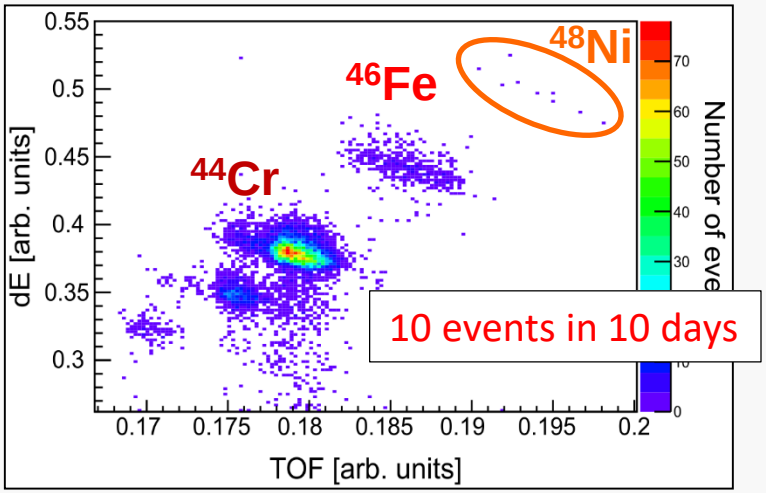
Miernik *et al.*, EPJA 42 (2009) 431

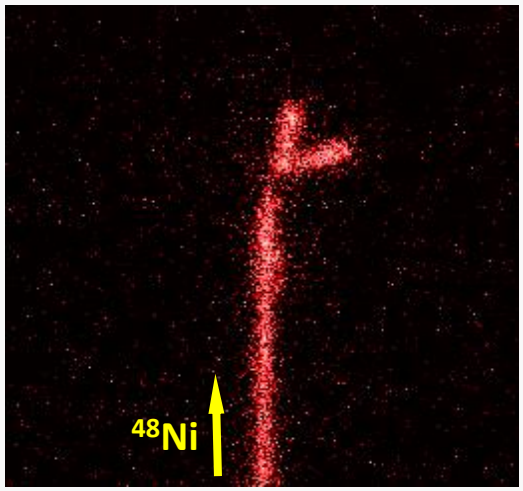
M.P. et al., Rev. Mod. Phys. 84 (2012) 567

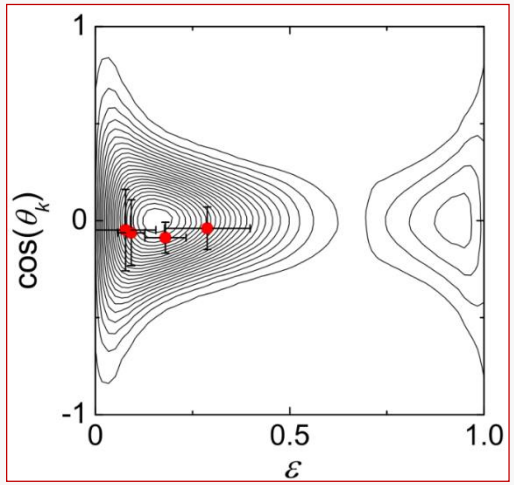
Grigorenko *et al.*, PLB 677 (2009) 30

2p radioactivity of ^{48}Ni

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





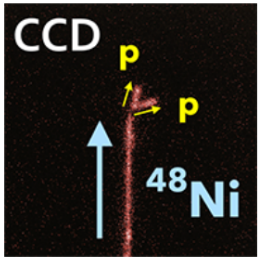


Pomorski et al., PRC 83 (2011) 061303(R)

To be continued @FRIB

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.

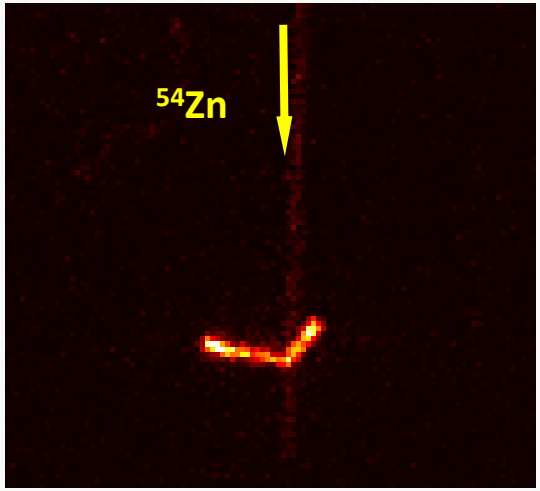
First observation of two-proton radioactivity in ^{48}Ni

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

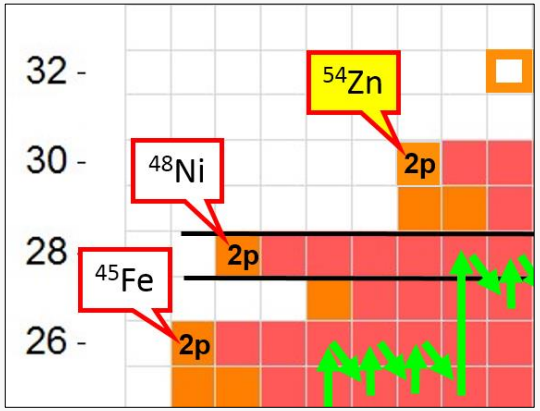
RIKEN, 2019: ^{78}Kr @ 350 MeV/u + ^{9}Be → ^{54}Zn

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

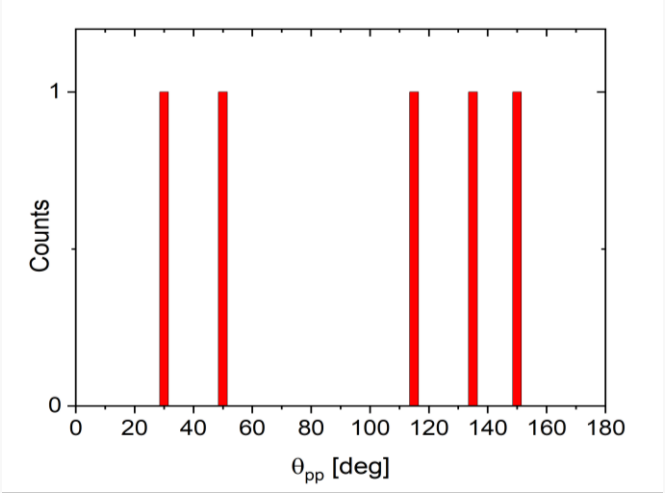


Presented by Adam Kubiela

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



For 5 events we could determine the angle between both protons



p-p correlations around Z=28

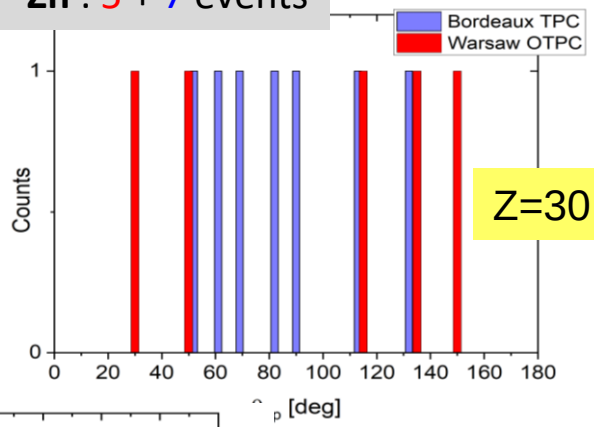
$$R_{>90} = \frac{N(\theta > 90°)}{N_{tot}}$$

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

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

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

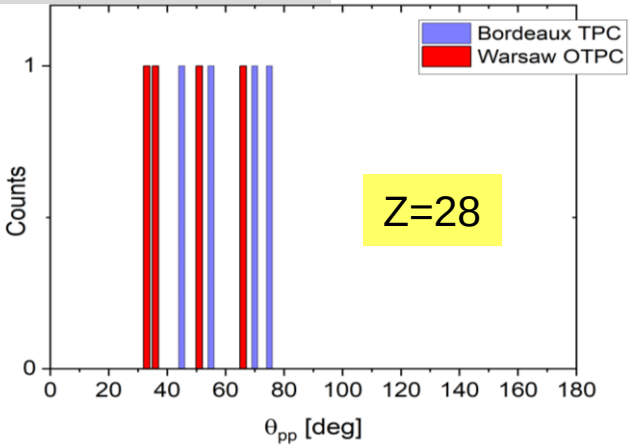
^{54}Zn : 5 + 7 events



Ascher et al
PRL 107 (2011)

Kubiela et al.,
to be published

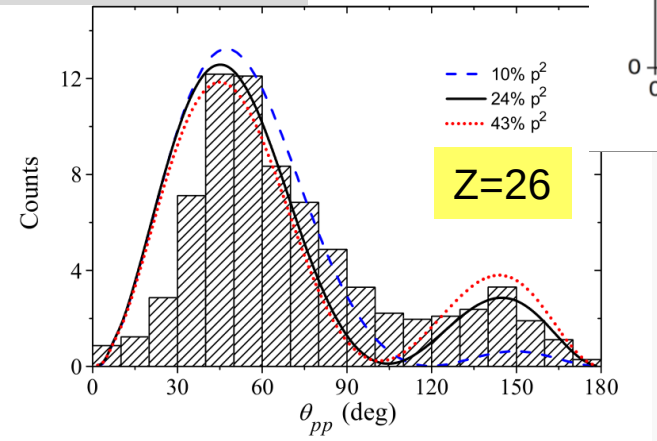
^{48}Ni : 4 + 4 events



Ortega-Moral et al.,
to be published

Pomorski et al
PRC 90 (2014)

^{45}Fe : 75 events



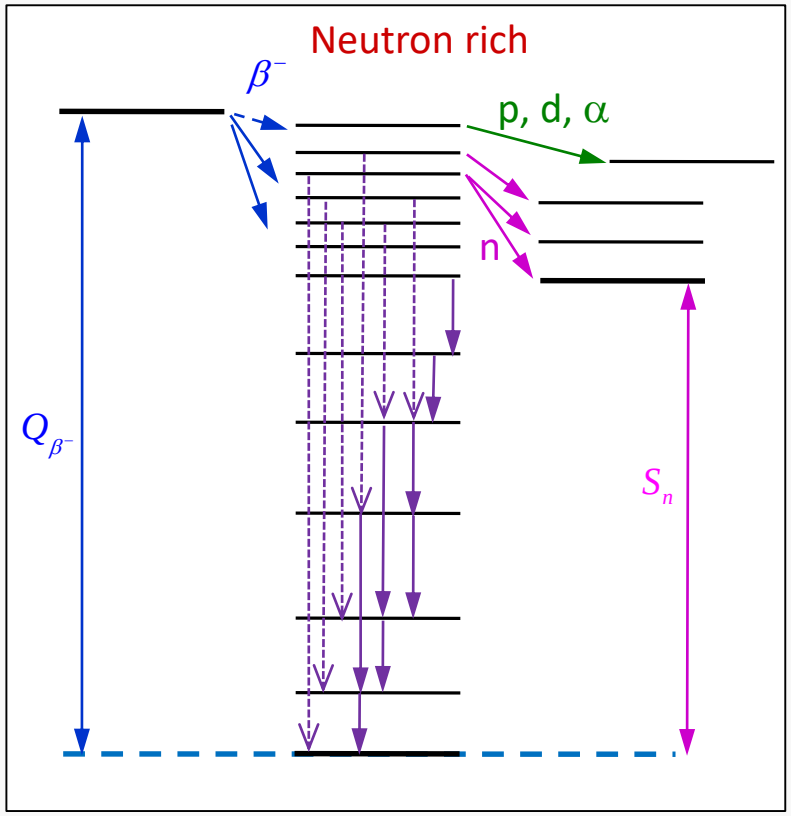
Miernik et al
PRL 99 (2007)

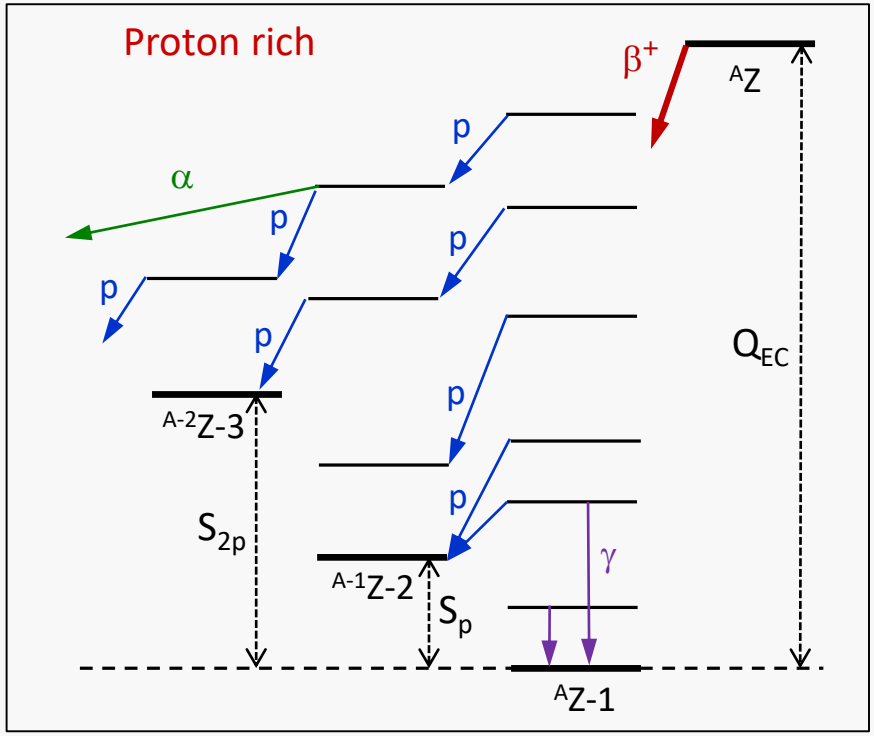
Statistics is too small, but...

... it looks like there is a difference!?

β-delayed particle emission

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





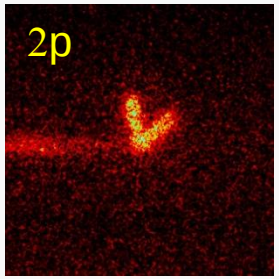
Neutron halos → charged particles

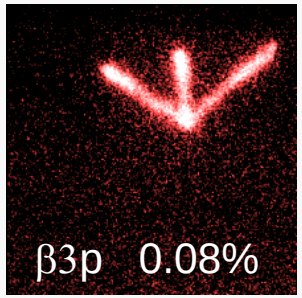
Gamma spectroscopy → *Pandemonium* effect!

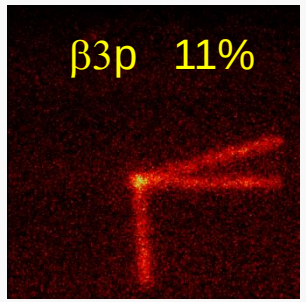
- Strong beta transitions to highly excited states are suppressed by kinematics and appear as weak radiation channels
- Low-energy delayed protons may be of interest to astrophysics

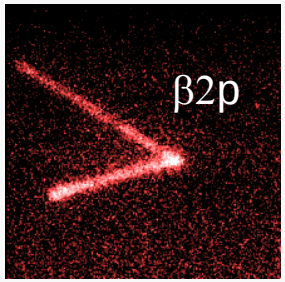
Decays of ^{45}Fe and ^{43}Cr

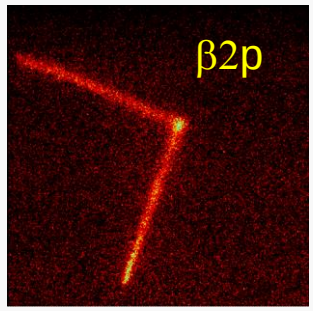
NSCL/MSU, 2007

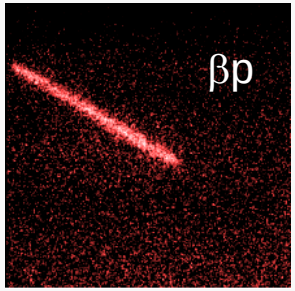


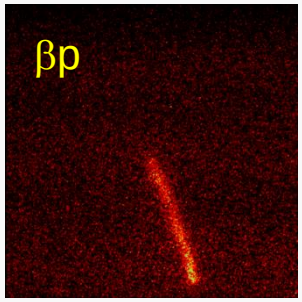












^{44}Mn+p — ^{45}Fe

Q_{EC} = 18.7 MeV

$T_{1/2}$ = 3 ms

^{43}Cr+2p

2p ≈ 70%

β$^+$ ≈ 30%

β$^+$

β3p

β2p

βp

^{40}Ca+3p

^{41}Sc+2p

^{42}Ti+p

^{43}V

^{45}Mn

^{44}Cr+p

^{43}V+2p

^{42}Ti+3p

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

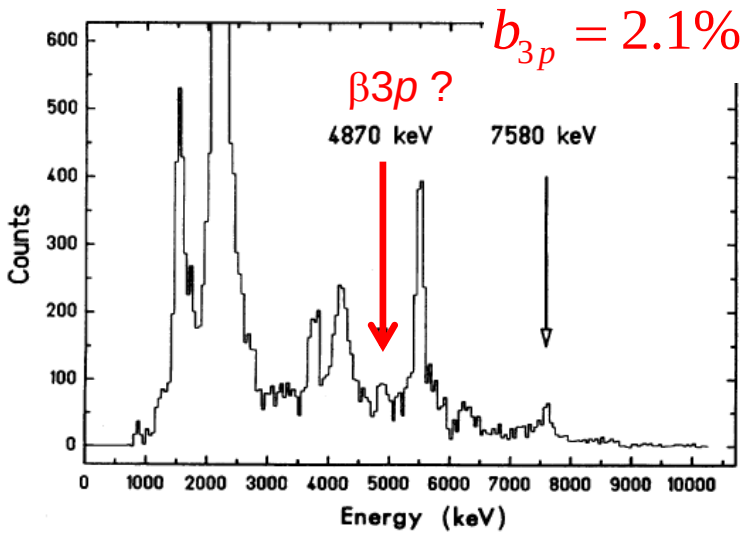
Decay modes of ^{31}Ar and first observation of β-delayed three-proton radioactivity

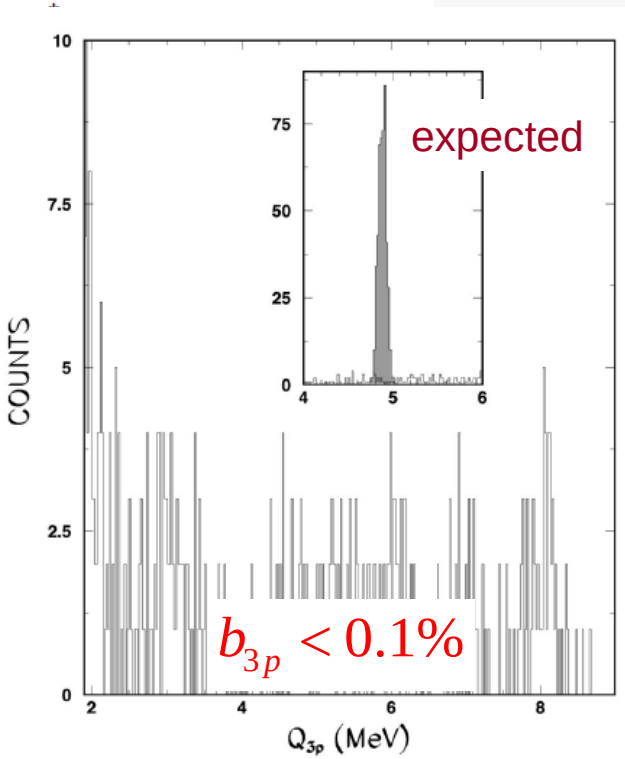
D. Bazin,* R. Del Moral, J. P. Dufour, A. Fleury, F. Hubert, and M. S. Pravikoff
Centre d'Etudes Nucléaires de Bordeaux–Gradignan, Le Haut Vigneau 33175 Gradignan CEDEX, France

PHYSICAL REVIEW C VOLUME 59, NUMBER 4 APRIL 1999

^{31}Ar examined: New limit on the β-delayed three-proton branch

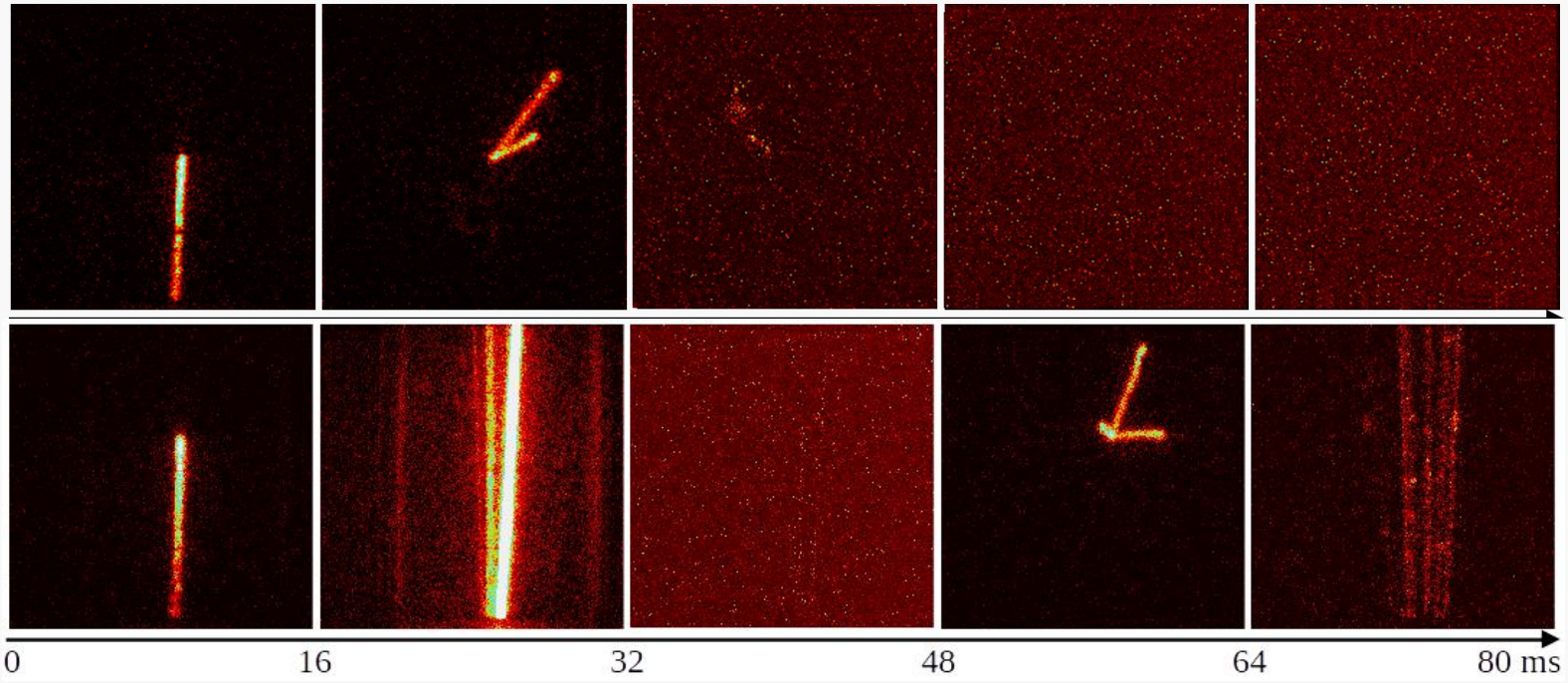
H. O. U. Fynbo,[1] L. Axelsson,[2] J. Äystö,[3] M. J. G. Borge,[4] L. M. Fraile,[4] A. Honk
A. Jokinen,[3] B. Jonson,[2] I. Martel,[5,†] I. Mukha,[1,‡] T. Nilsson,[2,§] G. Nyman,[2] M. Oin
M. H. Smedberg,[2] O. Tengblad,[4] F. Wenander,[2] and the ISOLDE





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")



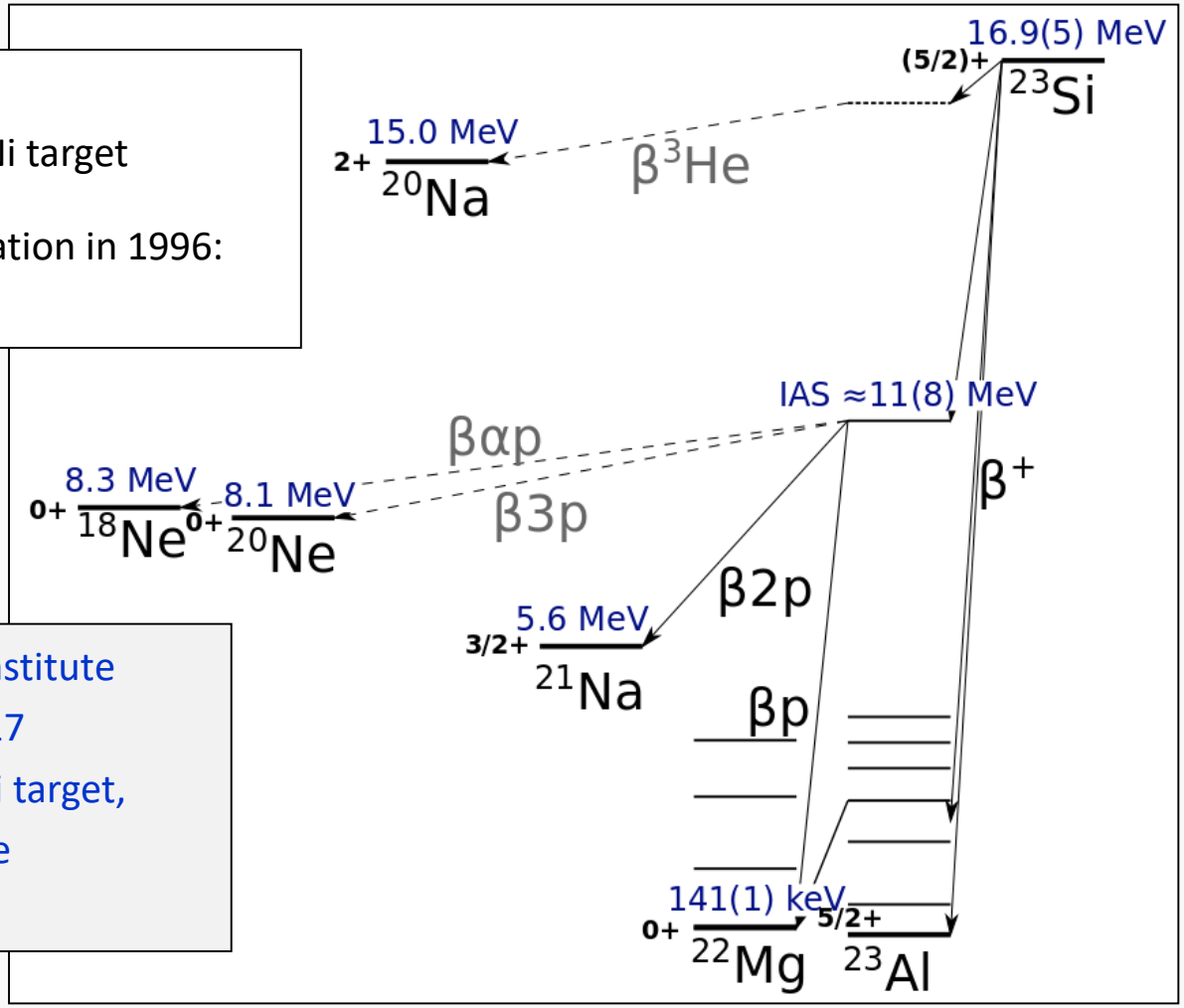
- 21 000 „interesting movies" inspected individually
- → 13 events of β3p decay of ^{31}Ar found

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)

Decay of ^{23}Si

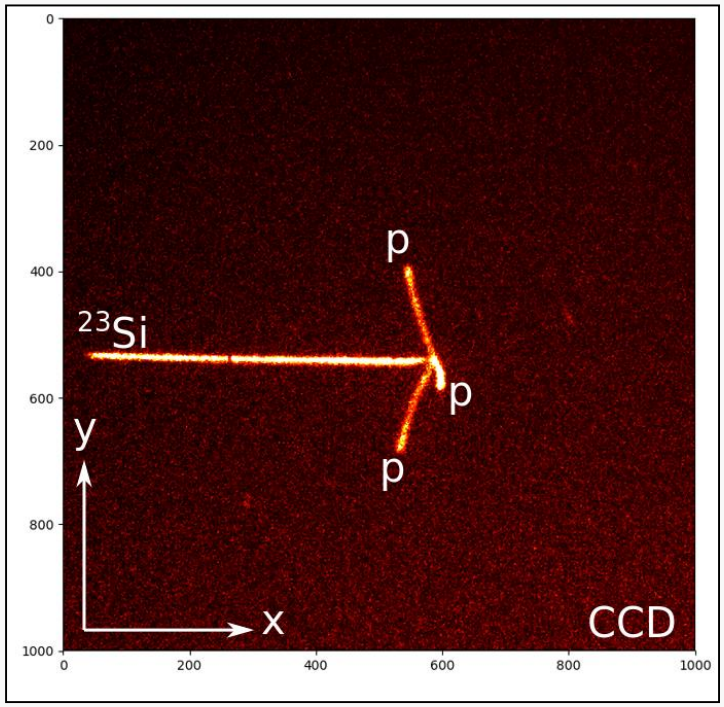
- First identification in 1986:
  ^{40}Ca fragmentation on a Ni target
- First spectroscopic information in 1996:
  $b_{\beta p}$ = 71% and $b_{\beta 2p}$ = 3.6%



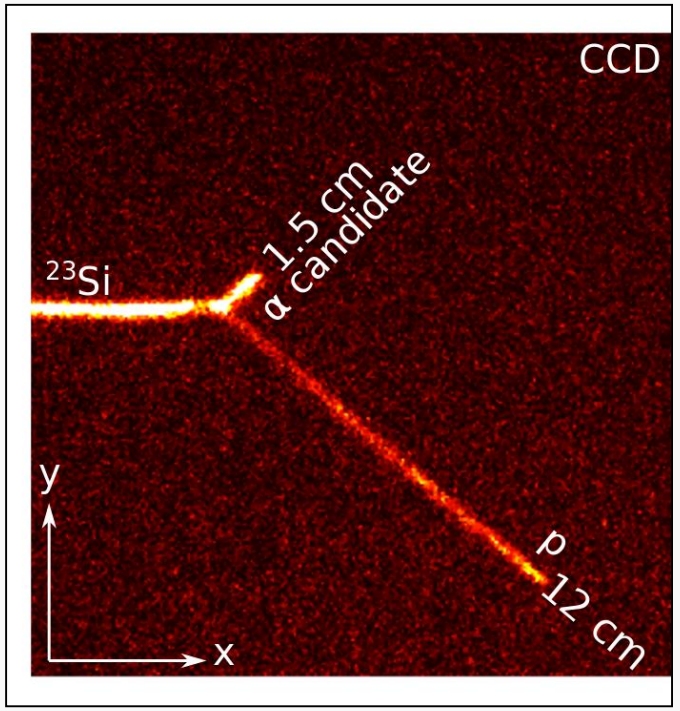
- Experiment at Cyclotron Institute
  Texas A&M University, 2017
  ^{28}Si fragmentation on a Ni target,
  OTPC installed behind the
  MARS Spectrometer

Decay of ^{23}Si

- β-delayed (multi) particle emission from ^{23}Si @ Texas A&M, MARS separator, 2017
  - over 7.5 k implanted ^{23}Si ions
  - branching ratios: $b_{\beta p}$ = 82(1)% and $b_{\beta 2p}$ = 7.7(4)% (lit. $b_{\beta p}$ = 71% and $b_{\beta 2p}$ = 3.6%)
  - first observation of β3p decay of ^{23}Si, $b_{\beta 3p} = 3^{+4}_{-2} \cdot 10^{-4}$ (2 events)
  - tentative observation of β αp decay of ^{23}Si, $b_{\beta \alpha p} = 1.4^{+3.3}_{-1.2} \cdot 10^{-4}$ (1 event)

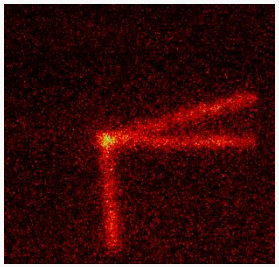


Ciemny et al., PRC 106 (2022) 014317



Seminar of A. Ciemny, 9 VI 2022

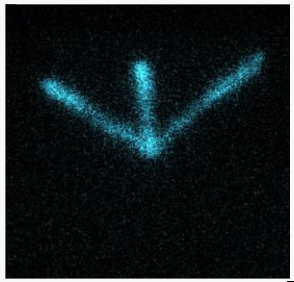
All known cases of β3p



^{45}Fe

NSCL 2007

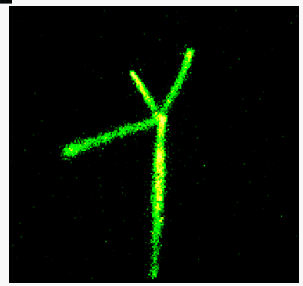
Miernik et al., PRC 76 (2007) 041304(R)



^{43}Cr

NSCL 2007

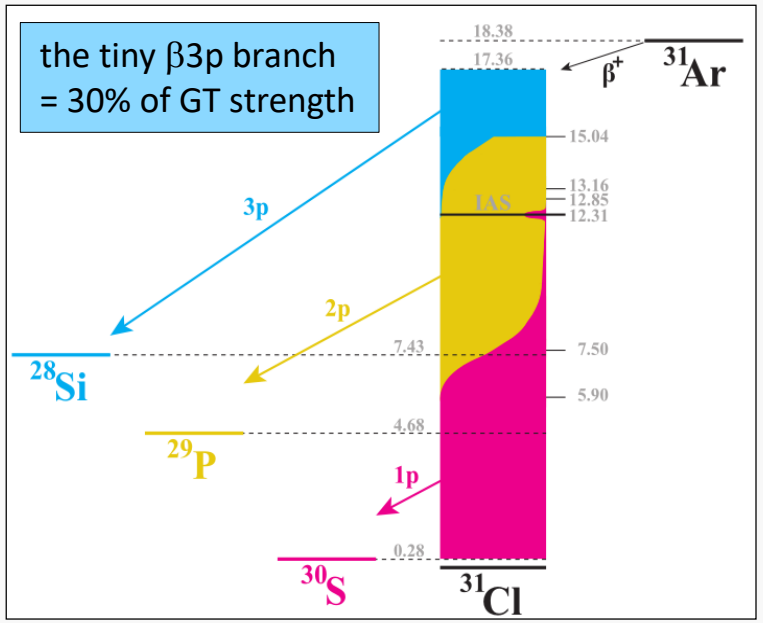
Pomorski et al., PRC 83 (2011) 014306



^{31}Ar

GSI 2012

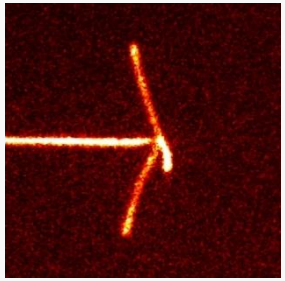
Lis et al., PRC 91 (2015) 064309



Koldste et al., PRC 89 (2014) 064315

New!

^{49}Ni β3p observed @GANIL in 2022 with ACTAR TPC: presented on Tuesday by Aurora Ortega Moral



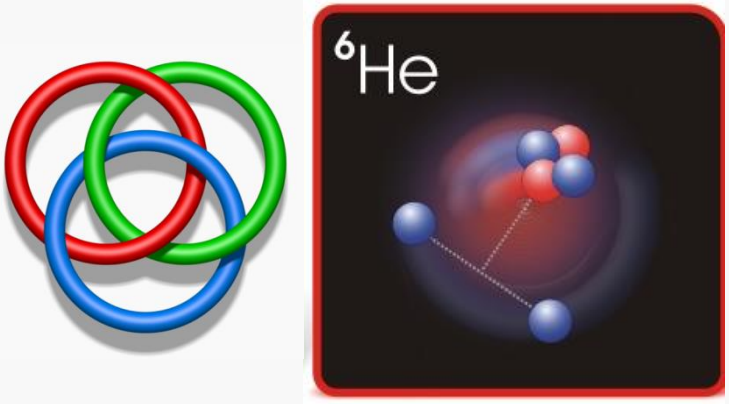
^{23}Si

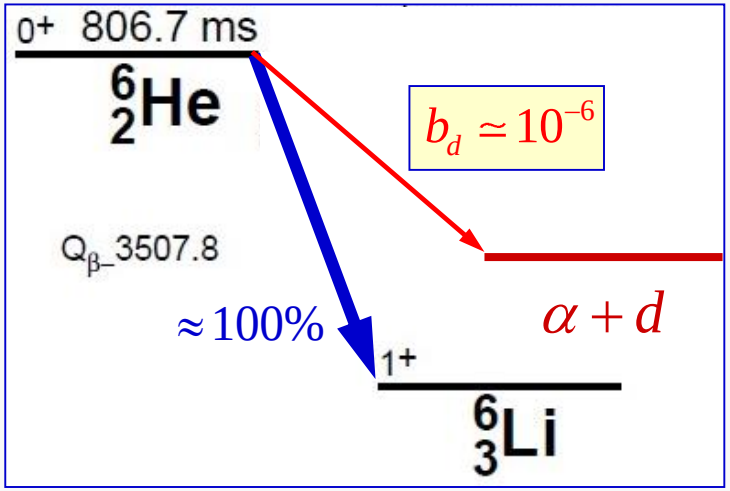
Texas A&M 2017

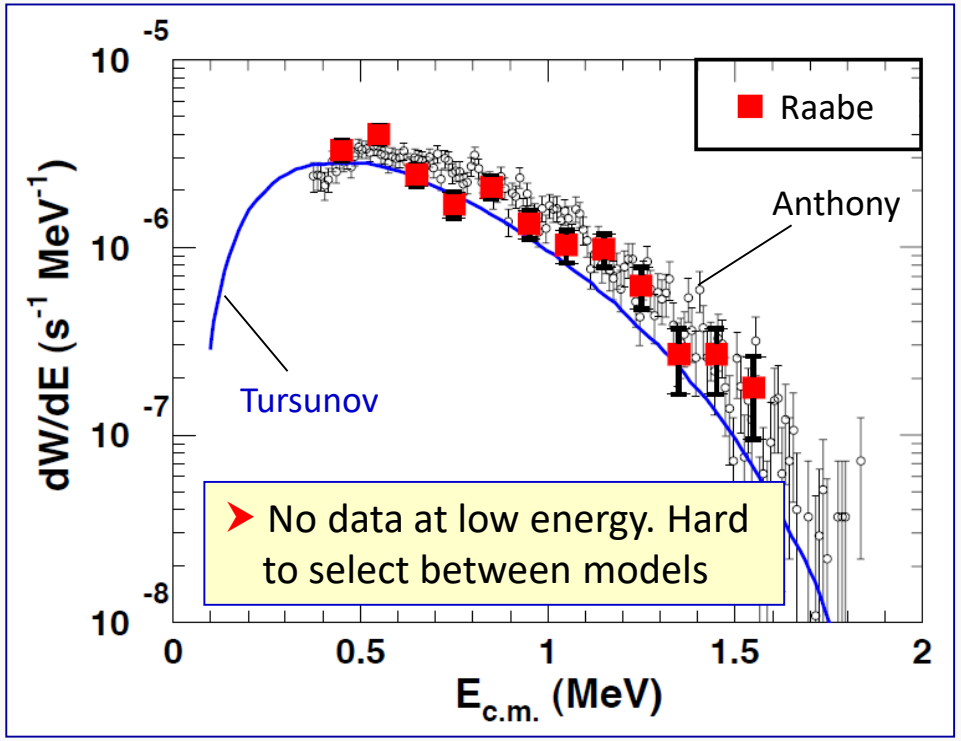
Ciemny et al., PRC 106 (2022) 014317

Probing the 2n halo of ^{6}He

- ^{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

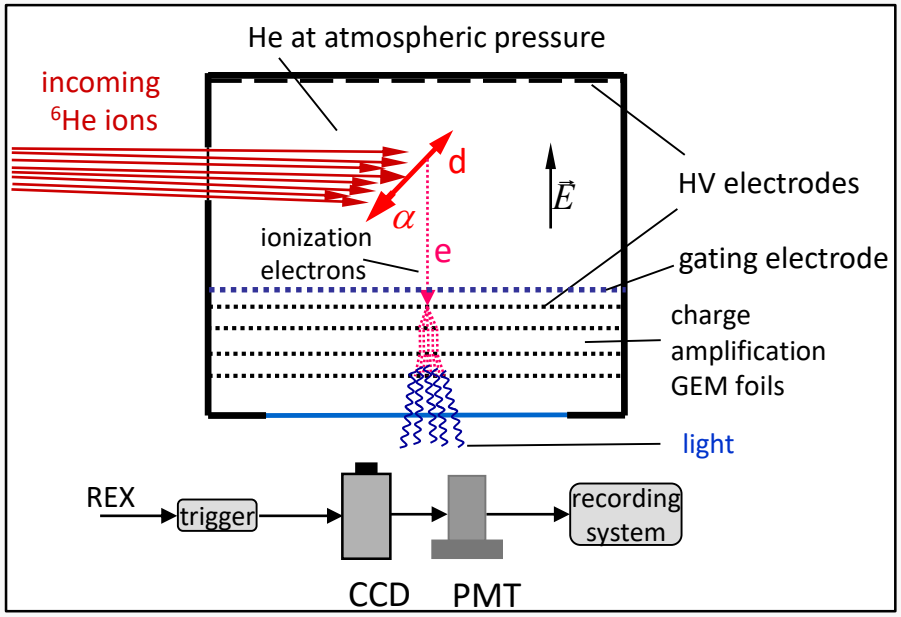
„Bunch” mode for ^{6}He @ISOLDE

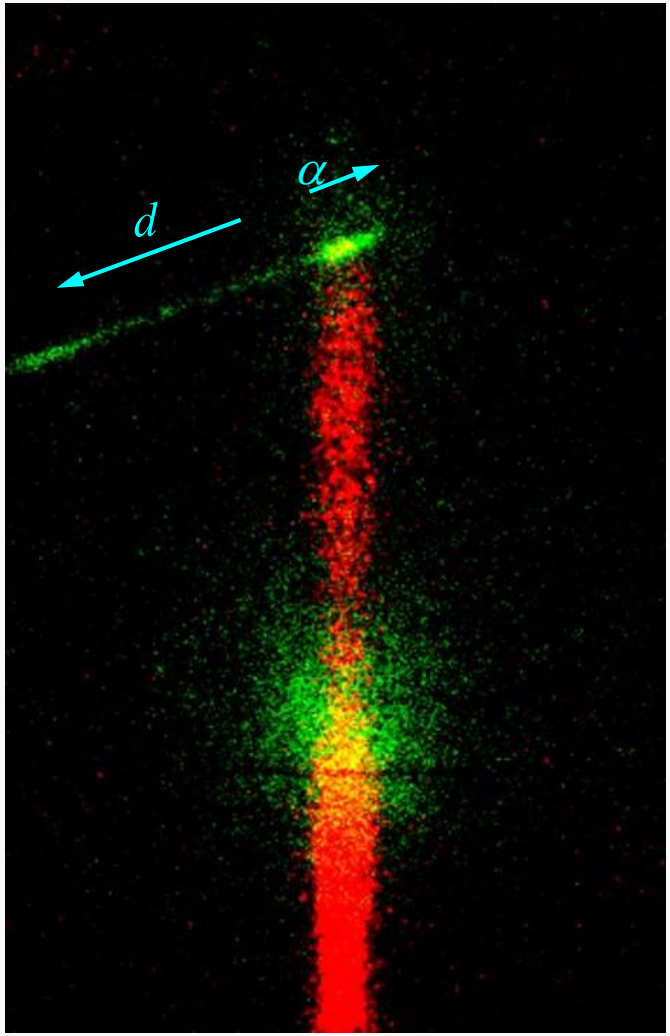
- Experiment at ISOLDE, August 2012

- 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.

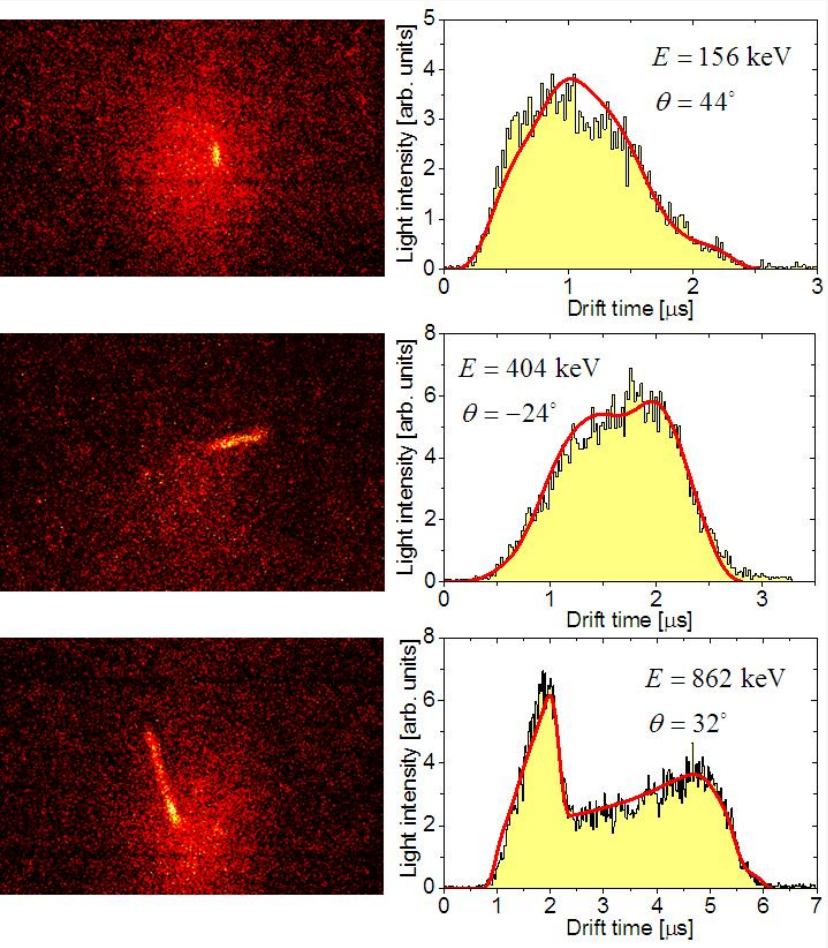
- Clear images of decay events with α + *d* tracks were recorded.





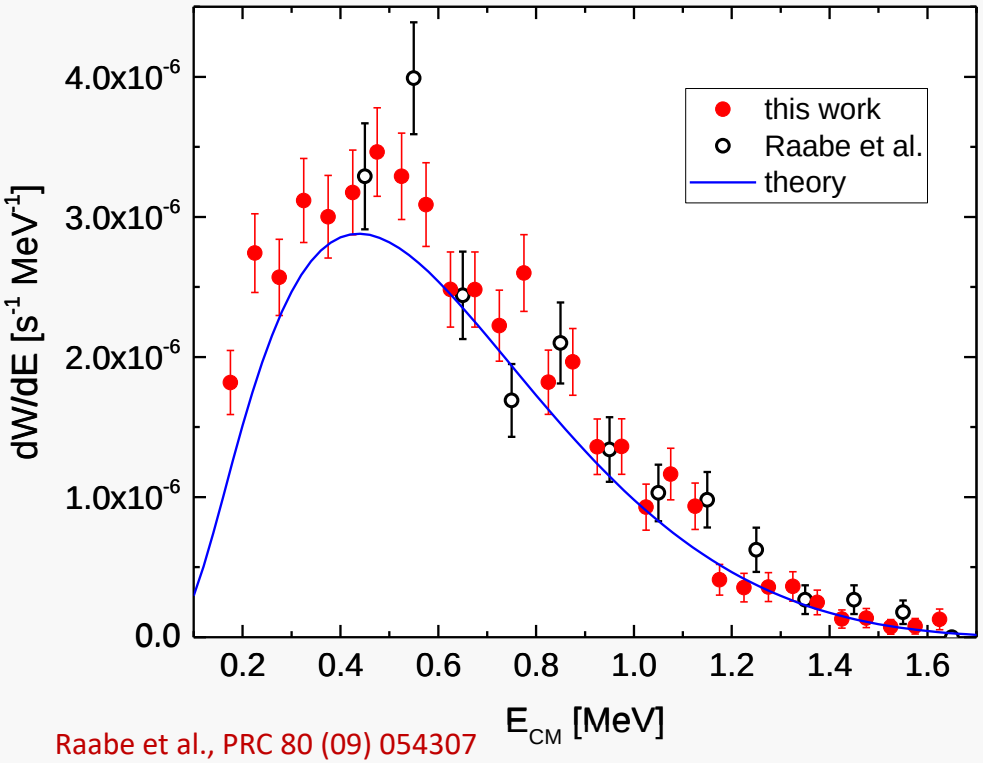
A CCD image showing a bunch of implanted ^{6}He ions (red) and a ^{6}He → α + *d* decay (green)

The spectrum of $\alpha + d$



1650 decay events reconstructed

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



Raabe et al., PRC 80 (09) 054307
theory: Tursunov, Baye, Descouvemont, PRC73 (06) 014303

$B_{\alpha d} = (2.78 \pm 0.07(stat) \pm 0.17(sys)) \times 10^{-6}$
= 20% more than the theoretical prediction

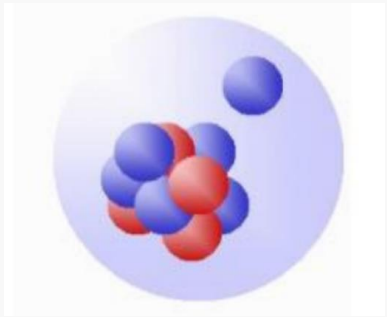
→ By extending the spectrum to lower energy, we see 70% more intensity

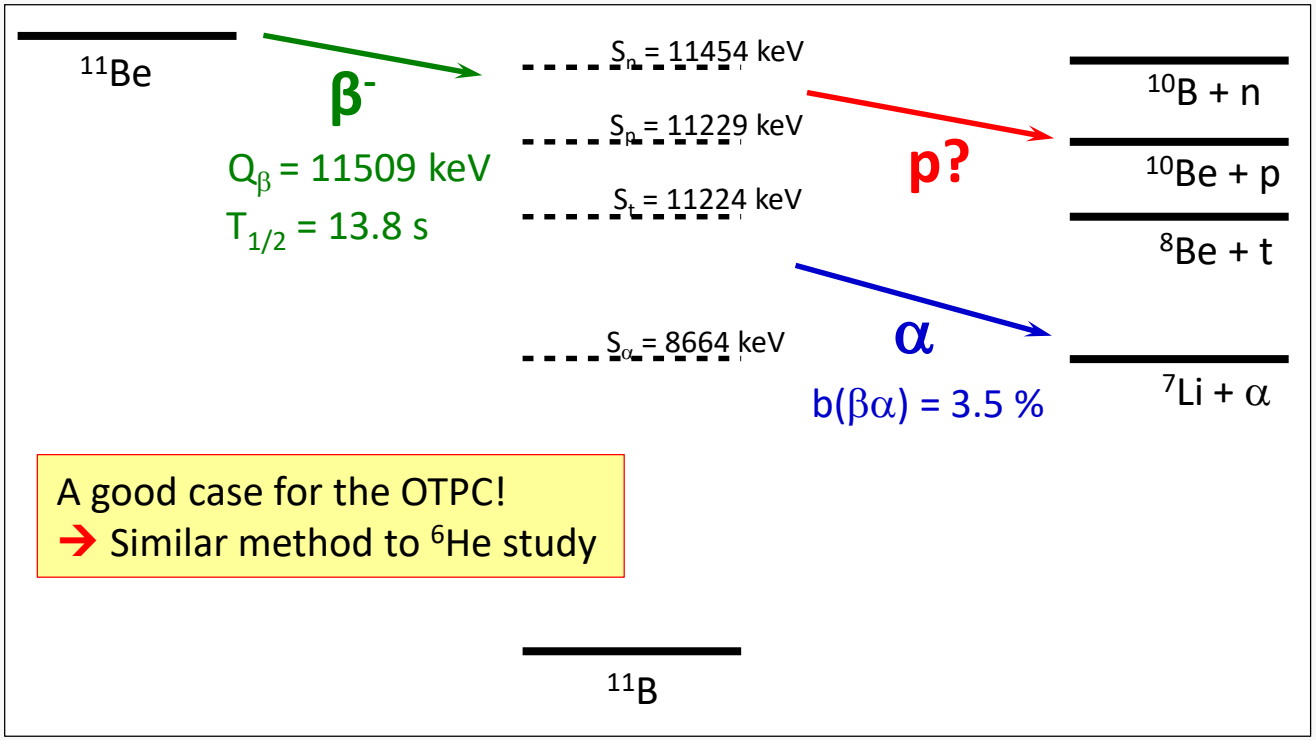
→ Corrected model: Tursunov et al. PRC 97 (18) 014302

A difficult case: ^{11}Be βp?

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

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



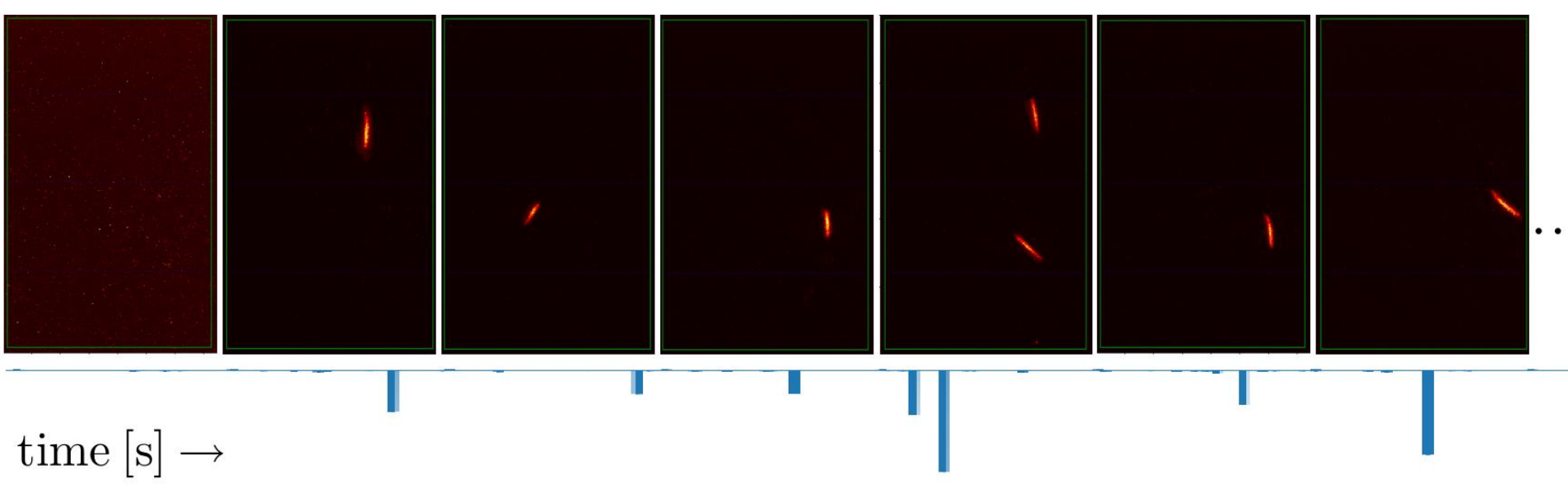


A good case for the OTPC!
→ Similar method to ^{6}He study

^{11}Be @ ISOLDE

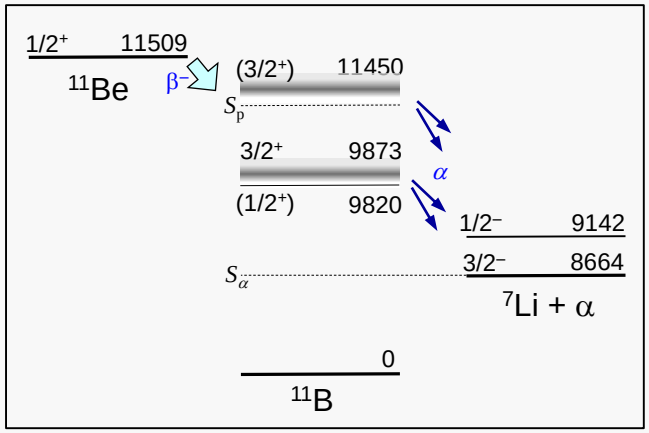
➤ Experiment at ISOLDE, 2018 → bunch and movie modes combined

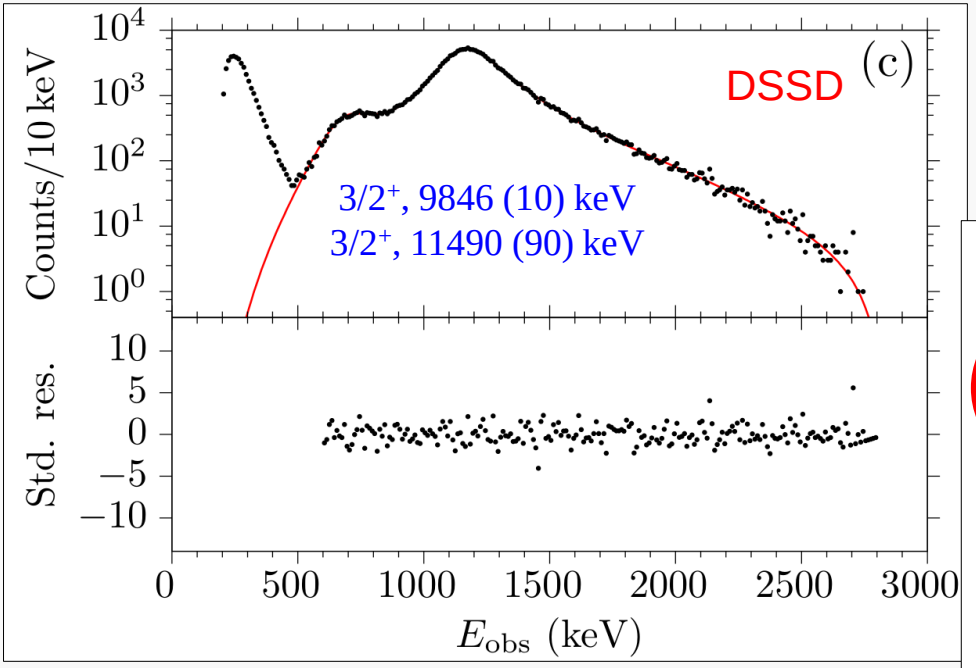
- Bunches of about 10^4 ions of ^{11}Be accelerated by **HIE-ISOLDE** to 7.5 MeV/ implanted into the OTPC every 1 min.
- After implantation: 252 frames of 33 ms (13 s) + 47 s break
- about 1.4 M frames recorded featuring about 1.5 M βα events



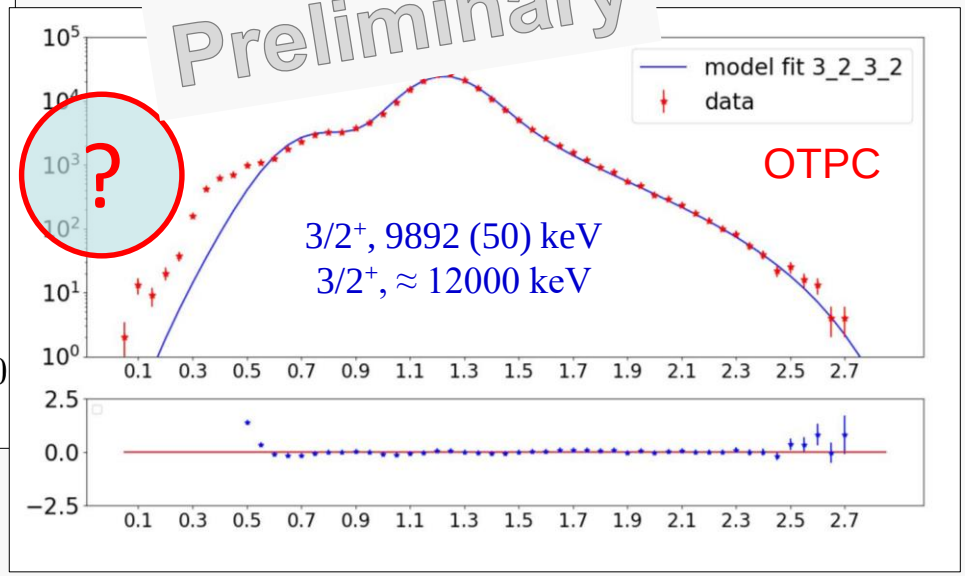
βα decay of ^{11}Be

- 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)

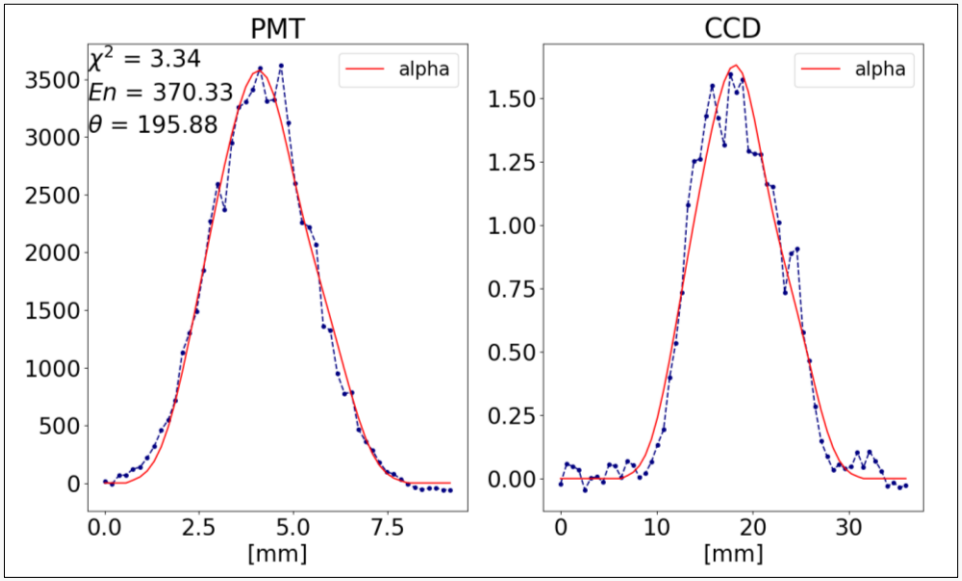


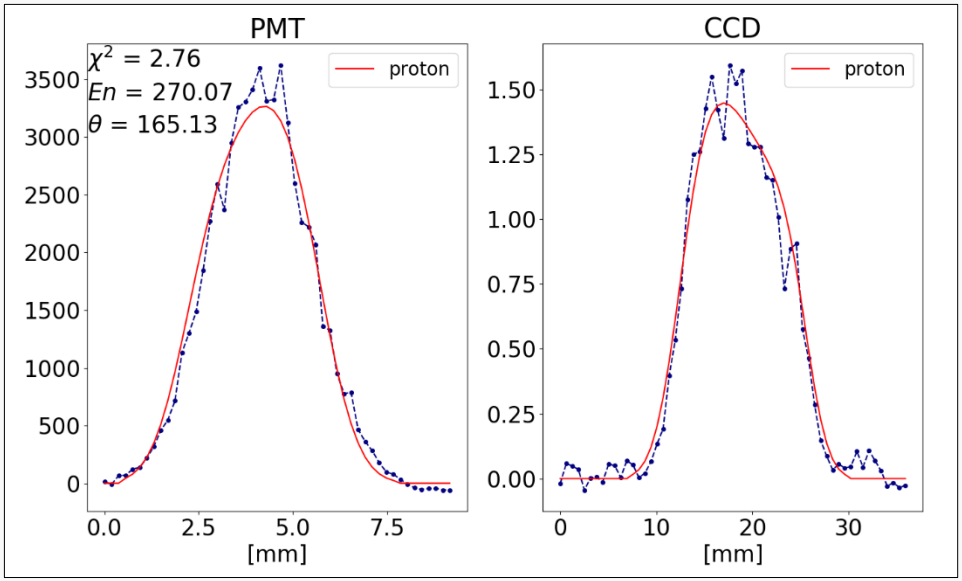
→ We measured the BR(α) independently in a second experiment @ Catania: 3.4(5)%

Preliminary analysis of ≈200 k clean βα events

N. Sokołowska, PhD in preparation

βα or βp?





- Low energy events may include:
  - α + ^{7}Li
  - p + ^{10}Be
  - t + ^{8}Be → t + α + α
  - all above but cut on the top wall

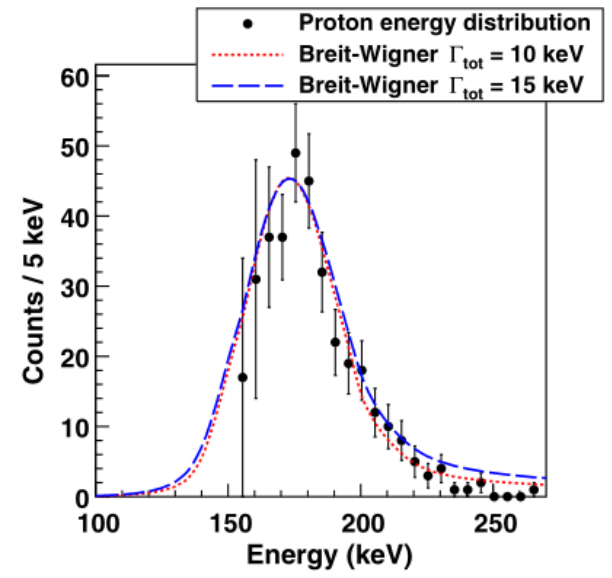
To be presented by N. Sokołowska at this seminar ...

Further measuremens focused on low-energy charged particles are needed!

Current status on ^{11}Be

- The appearance of ^{10}Be atoms in a sample of collected ^{11}Be (ISOLDE) was searched by the AMS technique → $b_p(^{11}\mathrm{Be}) = 8.3(9) \times 10^{-6}$ Riisager at al., Phys. Lett. B 732 (2014) 305

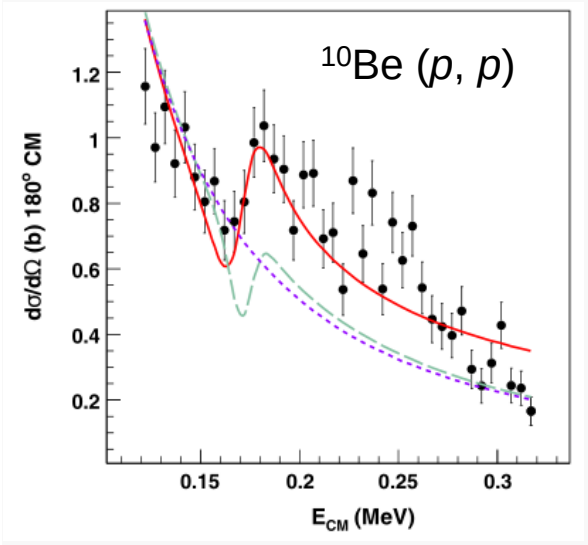
  Later corrected → $\boldsymbol{b_p(^{11}\mathrm{Be}) < 2.2 \times 10^{-6}}$ Riisager at al., EPJ A 56 (2020) 100



Ayyad at al., PRL 123, 082501 (2019)

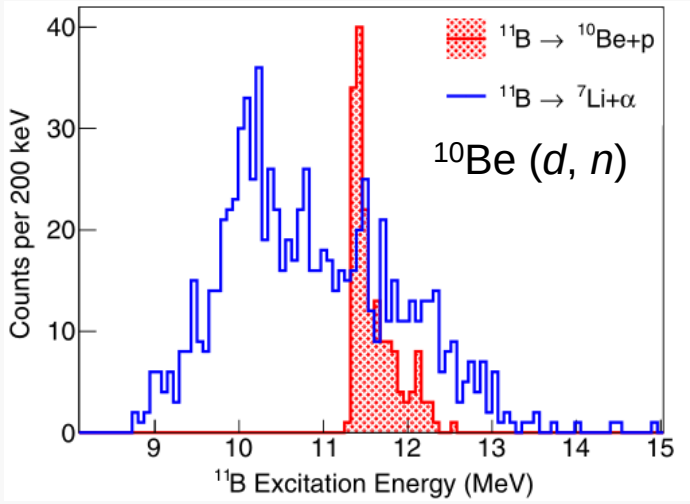
$E = 11425\ (20)$ keV,
$\Gamma = 12(5)$ keV, $(1/2^+, 3/2^+)$

$b_{\beta p} = 1.3\ (3) \cdot 10^{-5}$



Ayyad at al., PRL 129, 012501 (2022)

$E = 11400\ (20)$ keV,
$\Gamma_p = 4.4$ keV, $1/2^+$



Lopez-Saavedra at al., PRL 129, 012502 (2022)

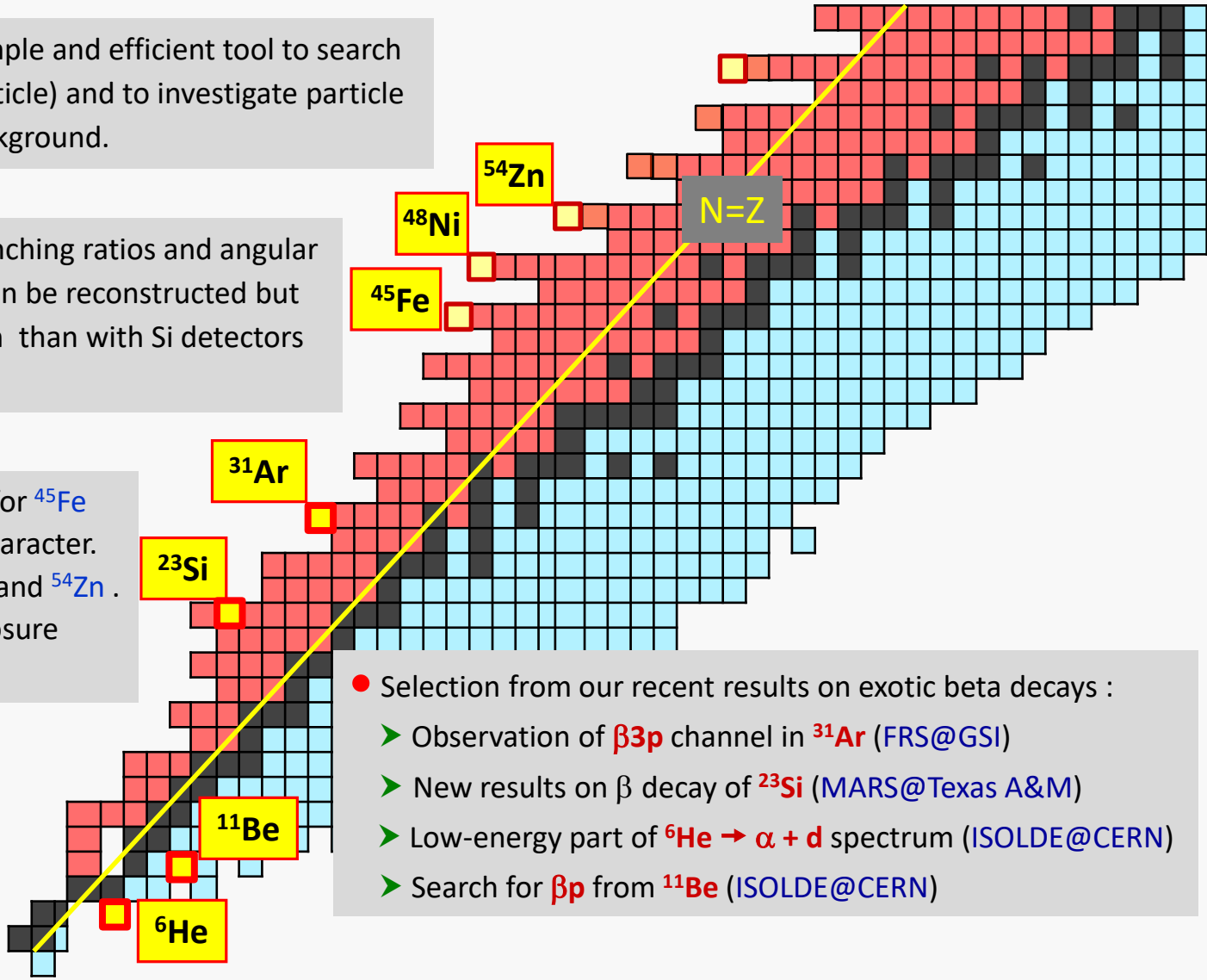
$E = 11440\ (40)$ keV,
$(1/2^+)$

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.

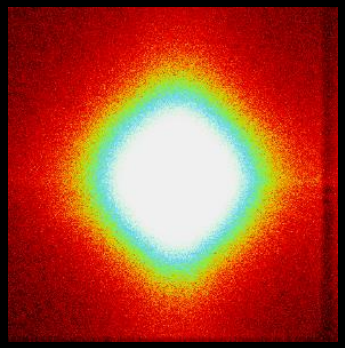
- It can provide precise branching ratios and angular correlations. Low energies can be reconstructed but with worse energy resolution than with Si detectors – complementarity!

- *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 recent results on exotic beta decays :
  - Observation of **β3p** channel in **^{31}Ar** (FRS@GSI)
  - New results on β decay of **^{23}Si** (MARS@Texas A&M)
  - Low-energy part of **^{6}He → α + d** spectrum (ISOLDE@CERN)
  - Search for **βp** from **^{11}Be** (ISOLDE@CERN)

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