Exotic Decays of Atomic Nuclei

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University of Warsaw

58th International Winter Meeting on Nuclear Physics
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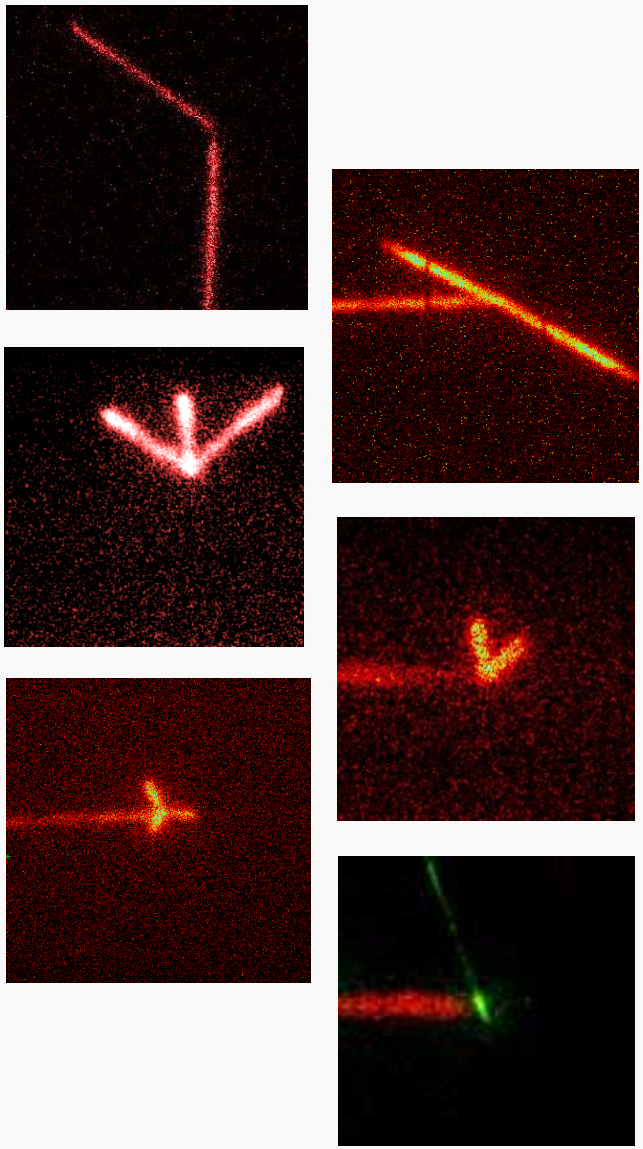
Plan



- Introduction:

  chart of nuclides, exotic nuclei,

  exotic decays

- OTPC – nuclear photography

- Two-proton radioactivity

  ^{45}Fe, ^{48}Ni, ^{54}Zn

- Emission of β-delayed particles

  ^{31}Ar, ^{27}S, ^{6}He, ^{11}Be

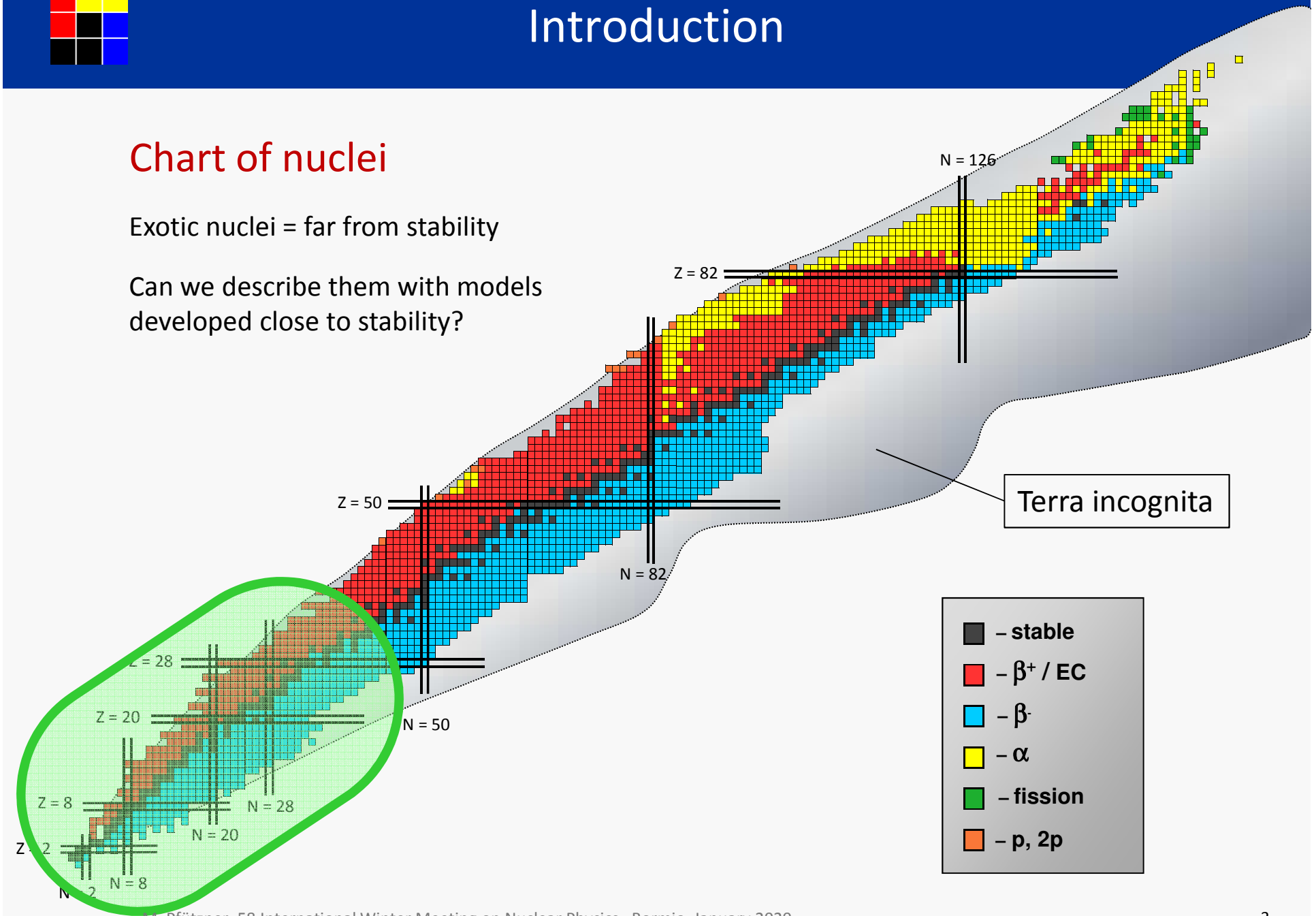
- Summary

Introduction

Chart of nuclei

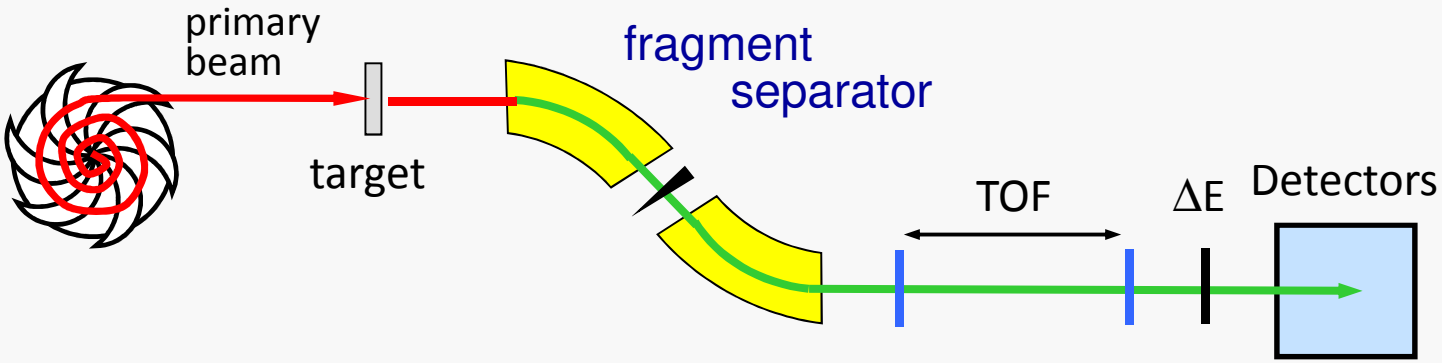
Exotic nuclei = far from stability

Can we describe them with models developed close to stability?



Projectile fragmentation

- A method of choice for the production of most exotic, short lived nuclei



LISE @ GANIL

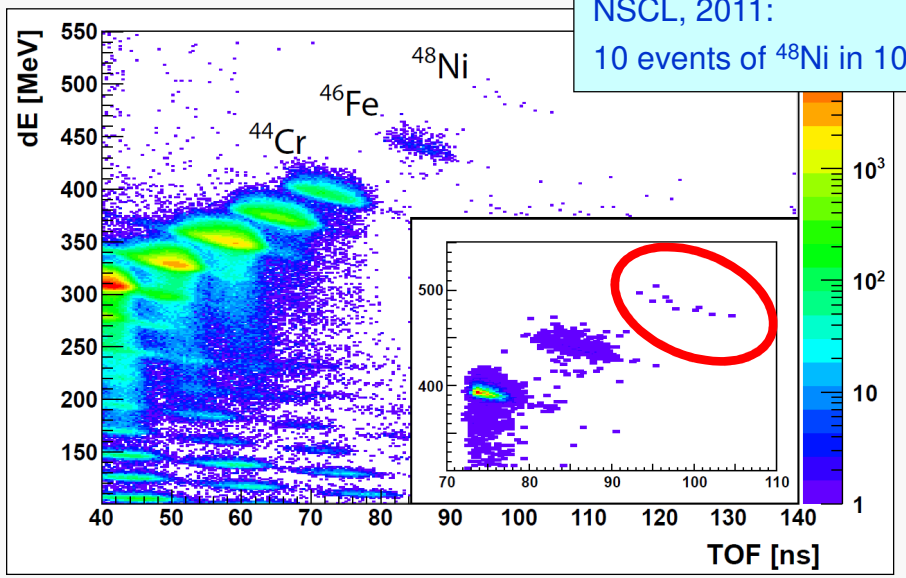
FRS @ GSI

A1900 @ NSCL

BigRIPS @ RIKEN

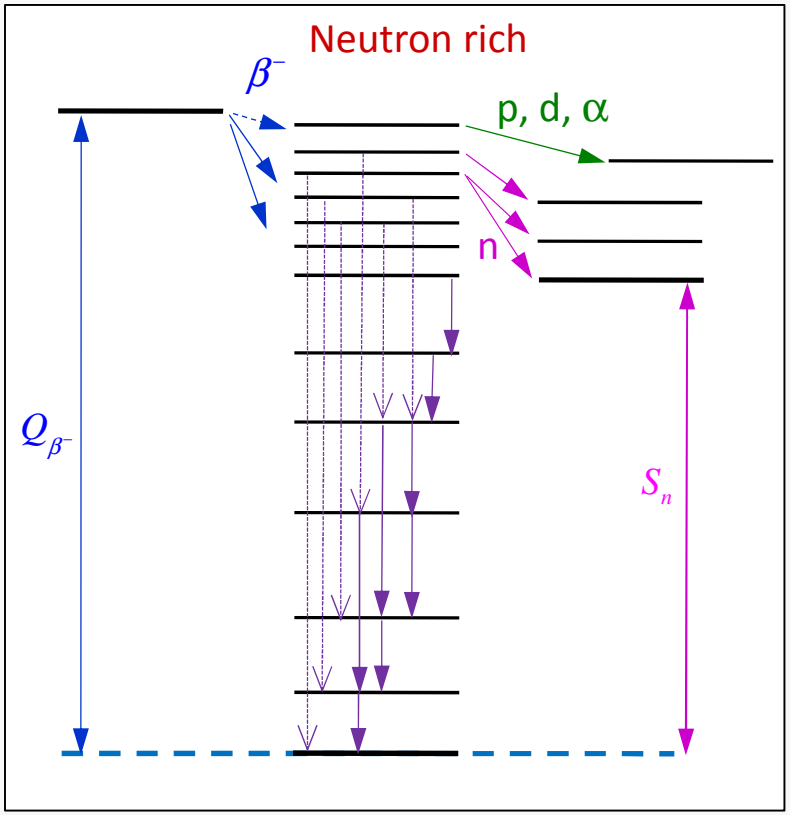
Key features:

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



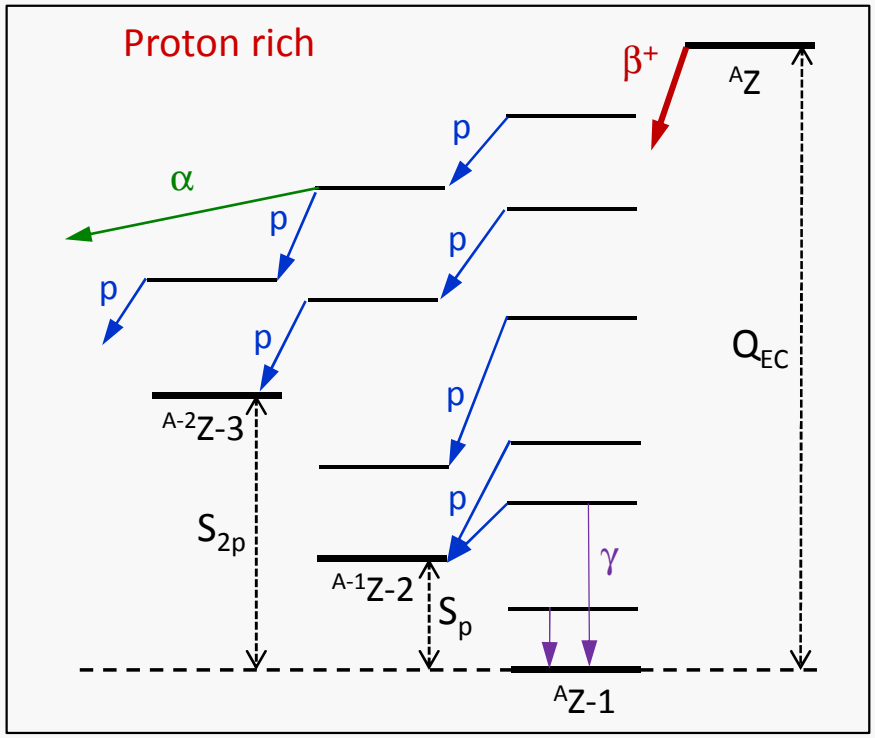
β-delayed particle emission

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



Neutron halos → charged particles

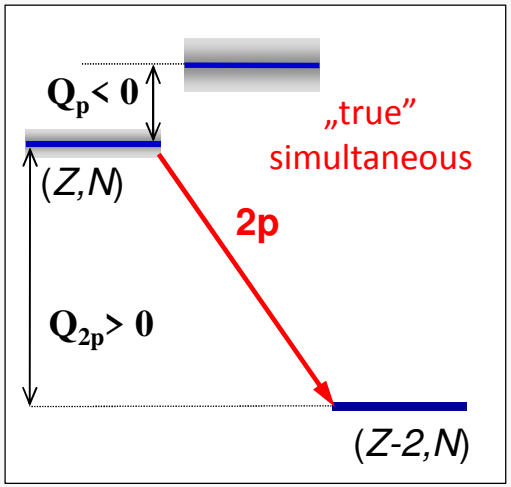
Gamma spectroscopy → *Pandemonium* effect!

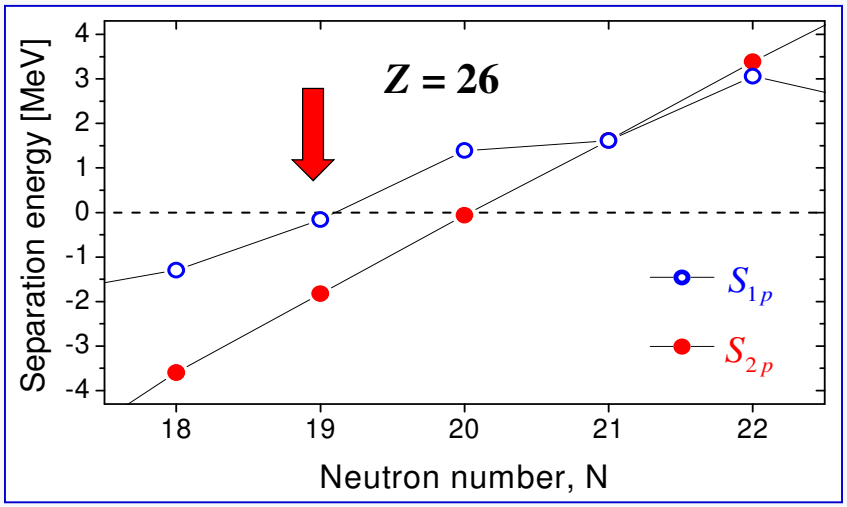


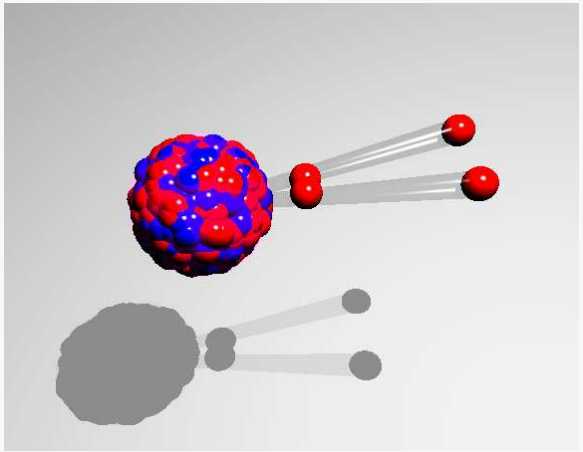
- Strong beta transitions to highly excited states are suppressed by kinematics and appear as weak radiation channels
- Low-energy delayed protons may be of interest to astrophysics

2p radioactivity

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

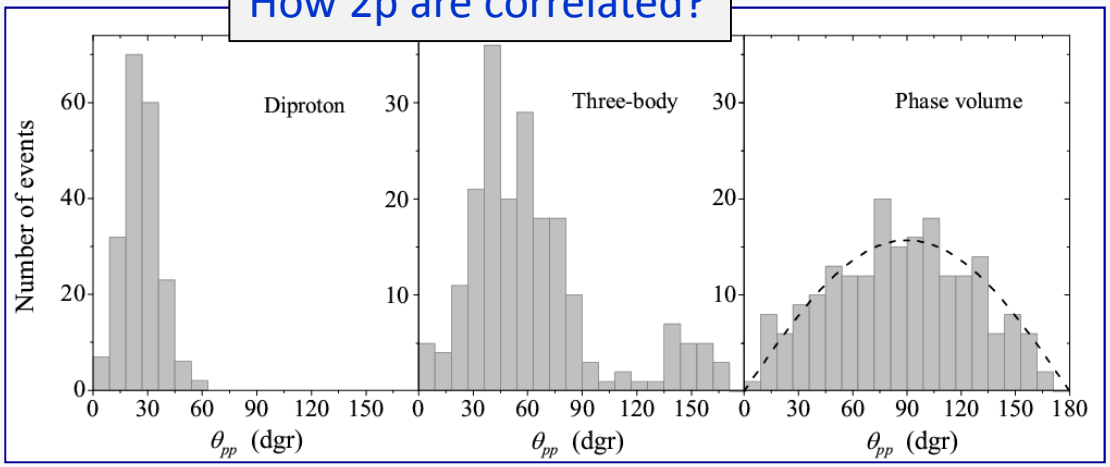






Goldanskii, Nucl. Phys. 19 (60) 482

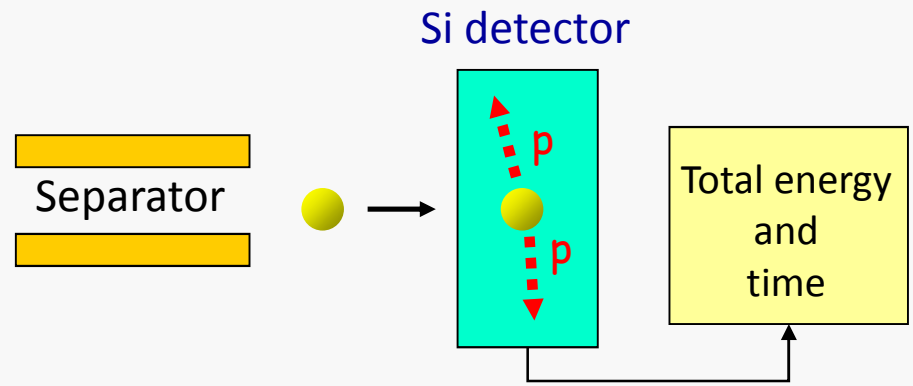
How 2p are correlated?

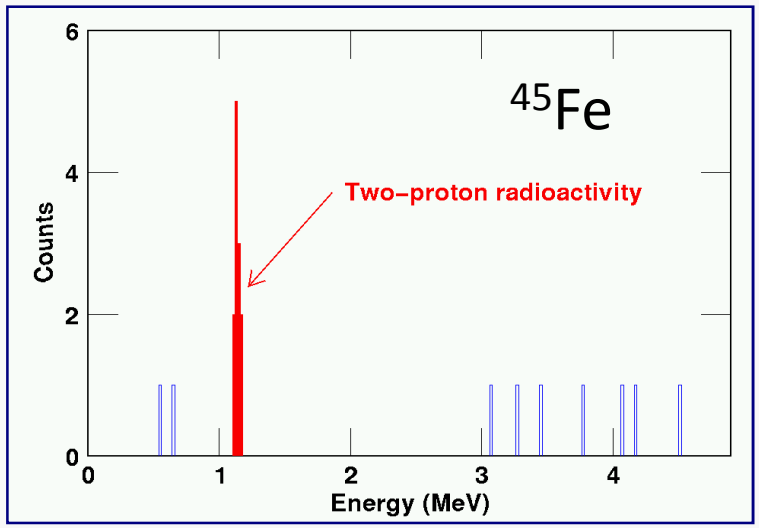


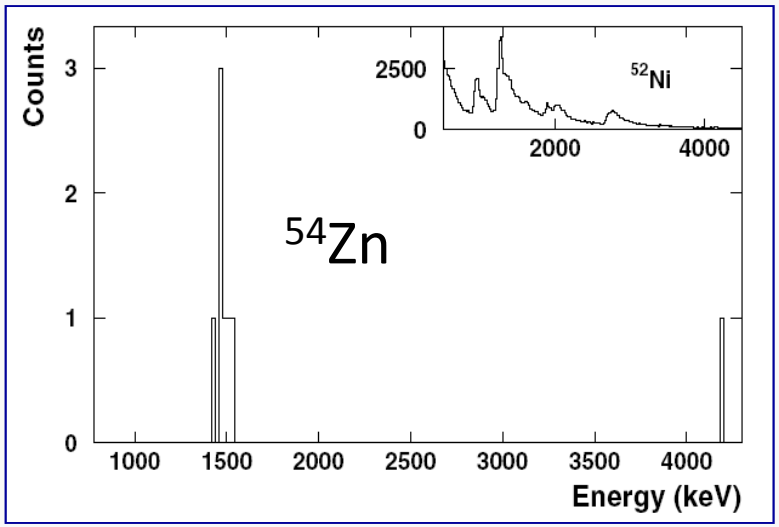
L. Grigorenko, for the proposal to NSCL (2003)

2p radioactivity with Si detectors

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

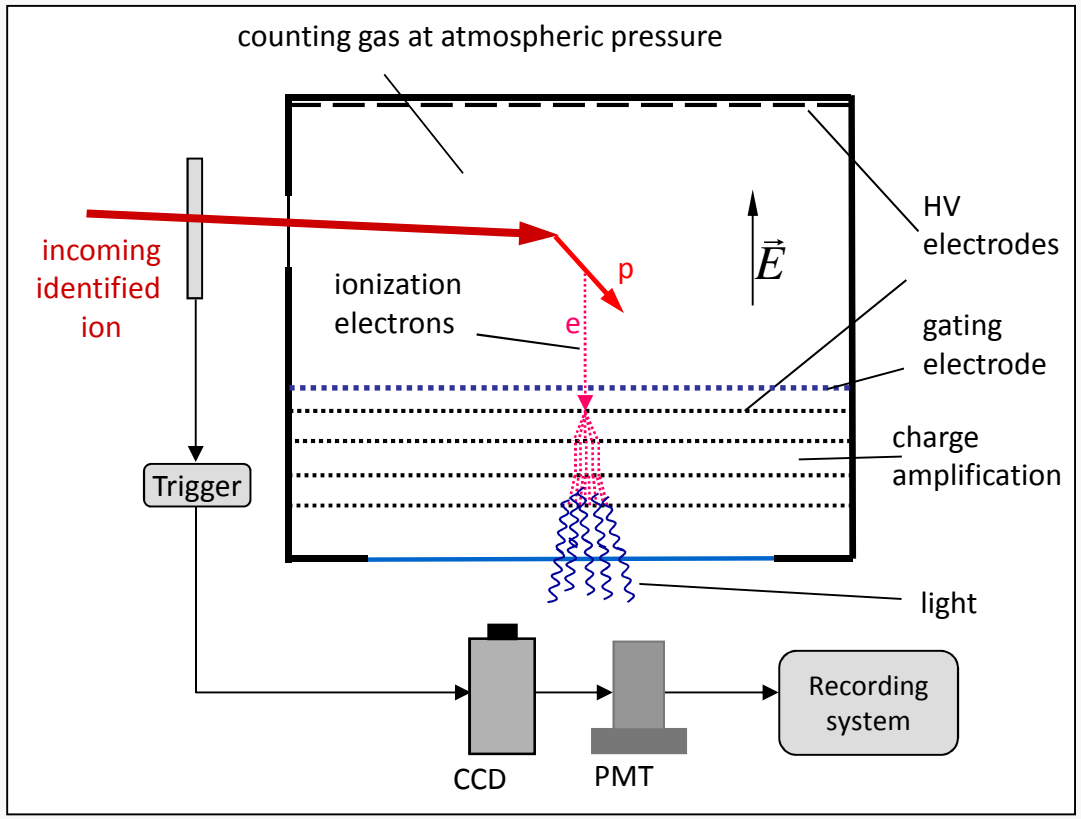




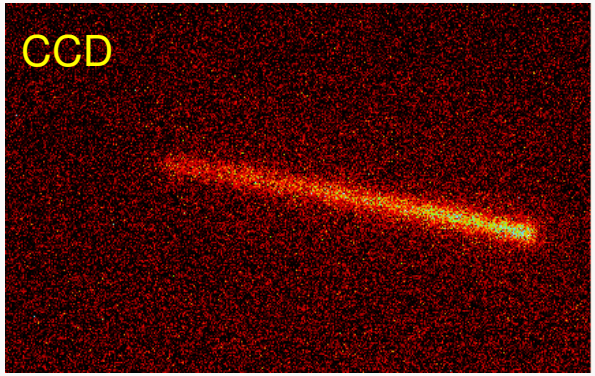


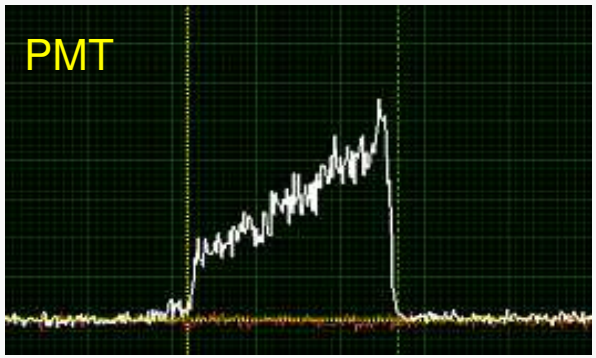
The Warsaw OTPC

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



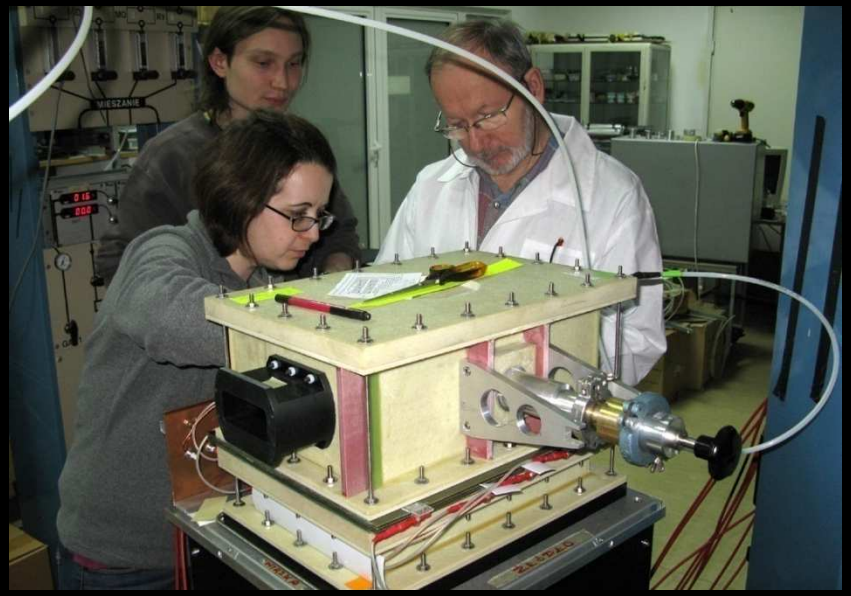
α particle

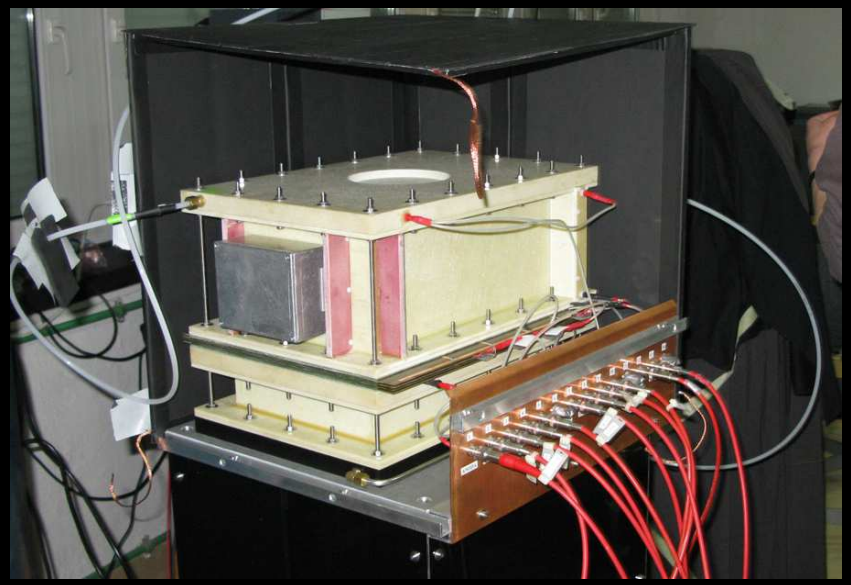


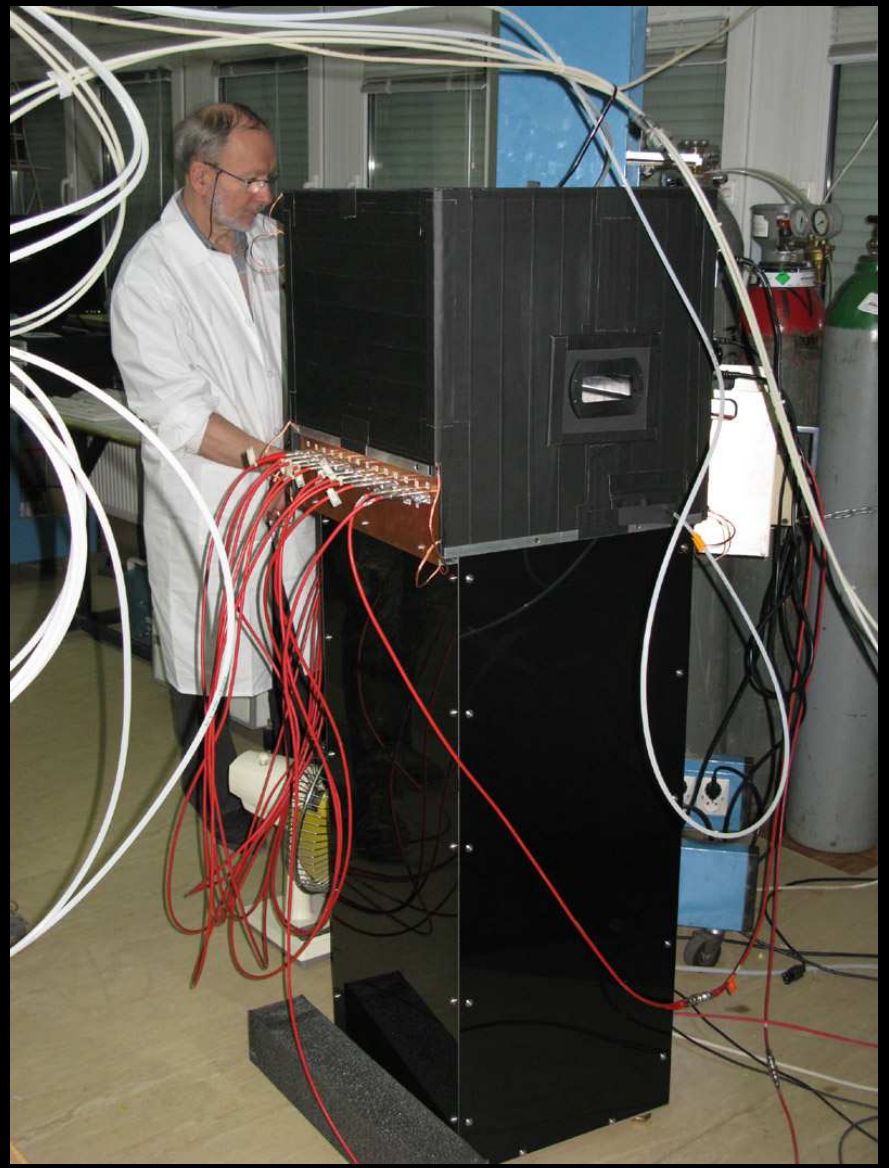


- Combination of the CCD image with the PMT waveform allows to fully reconstruct the track in three dimensions

OTPC

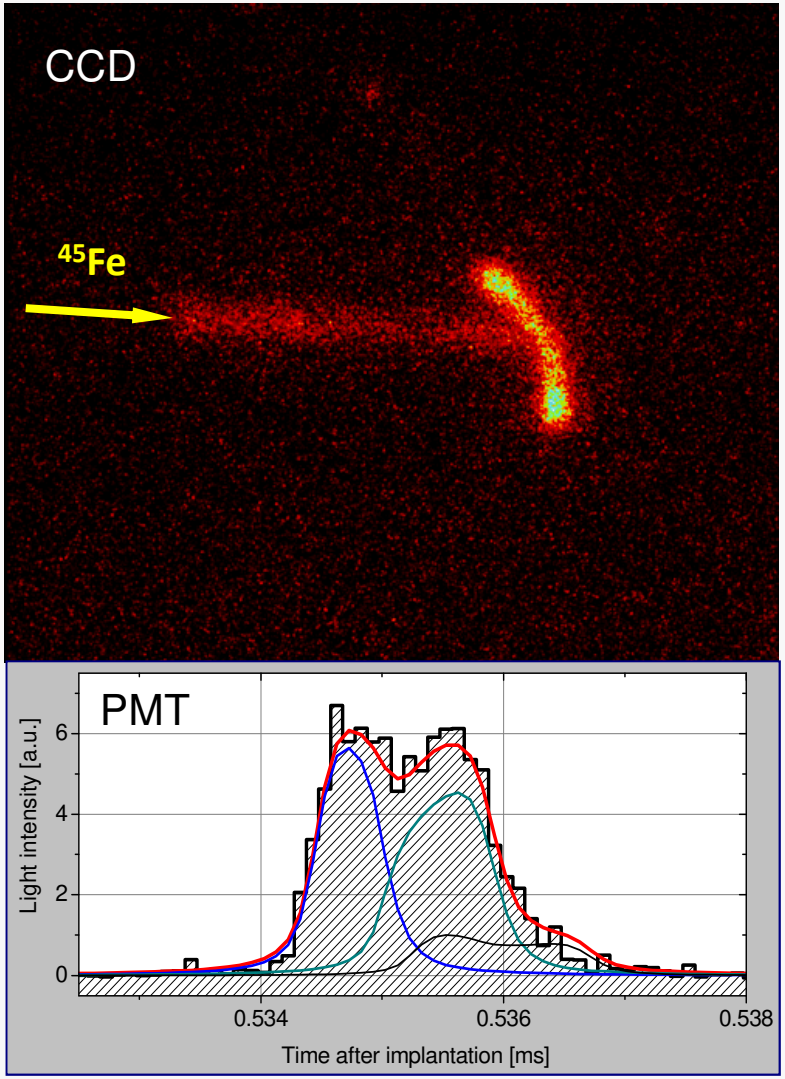




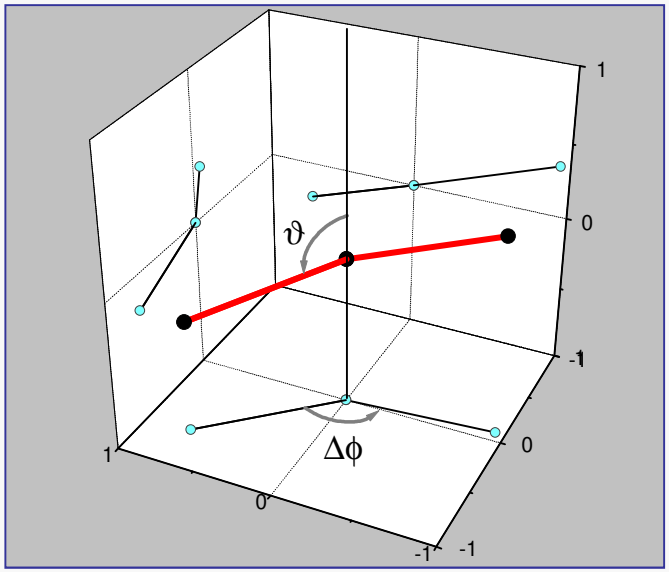


2p decay of ^{45}Fe

- OTPC @ A1900 (NSCL/MSU), 2007: ^{58}Ni at 161 MeV/u + ^{nat}Ni → ^{45}Fe



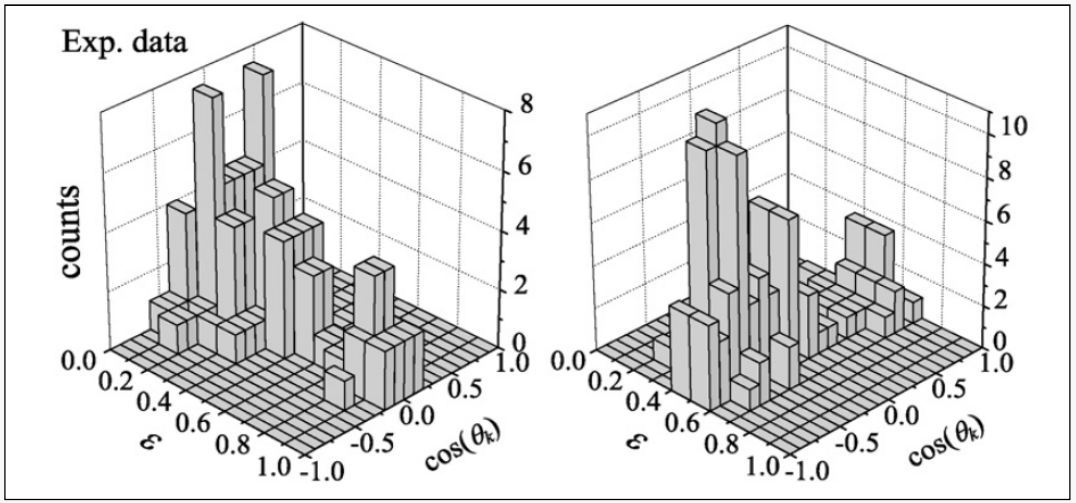
- Full reconstruction in 3D was possible

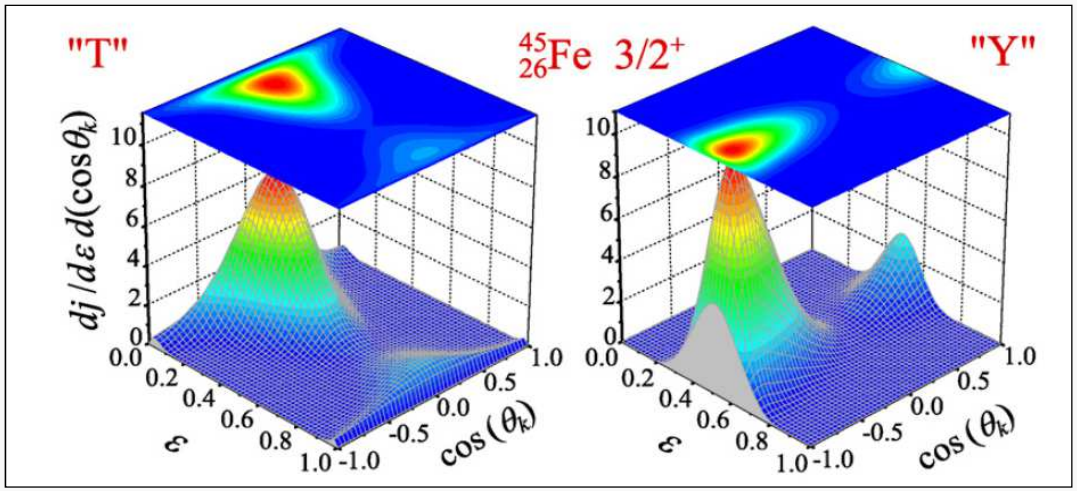


K. Miernik et al., PRL 99 (07) 192501

87 events of 2p decay reconstructed

p-p momentum correlations for ^{45}Fe





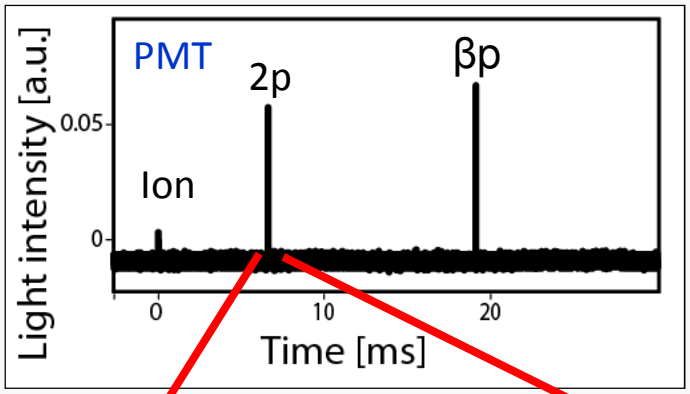
- Proton-proton momentum correlations measured for ^{45}Fe are complex and indicate a genuine 3-body phenomenon
- Good agreement with the 3-body model of Grigorenko et al.
- According to the model, the correlation picture depends on the structure of the initial state

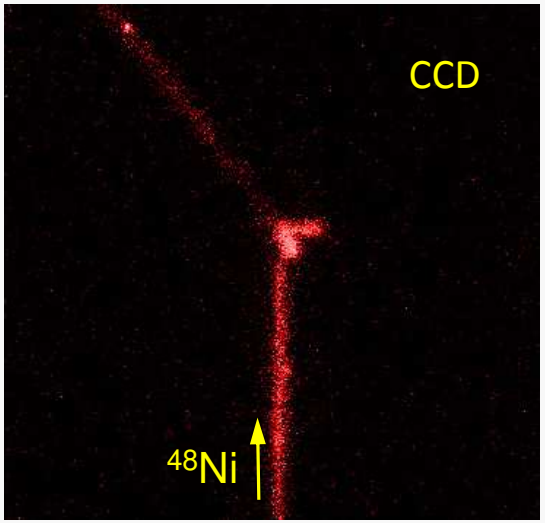
Miernik *et al.,* PRL 99 (07) 192501 Grigorenko *et al.*, PLB 677 (2009) 30

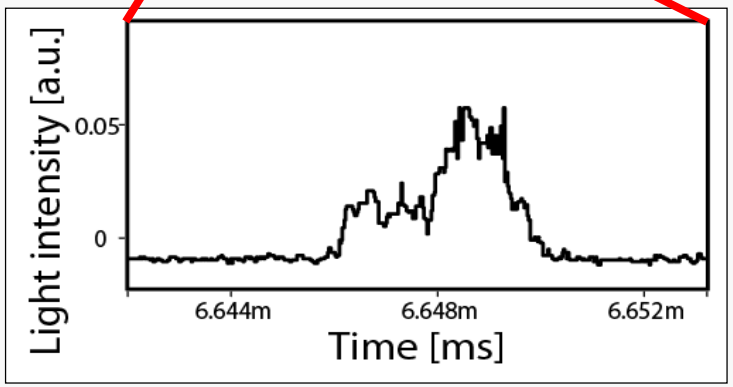
2p decay of ^{48}Ni

- OTPC @ A1900 (NSCL/MSU), 2011:

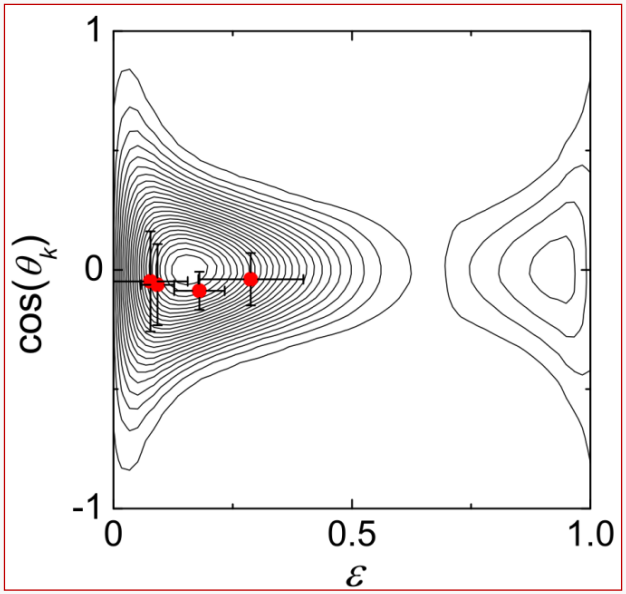
  ^{58}Ni at 161 MeV/u + ^{nat}Ni → ^{48}Ni







Four 2p events of ^{48}Ni



 Pomorski et al., PRC 90 (14) 014311

2p decay of ^{54}Zn

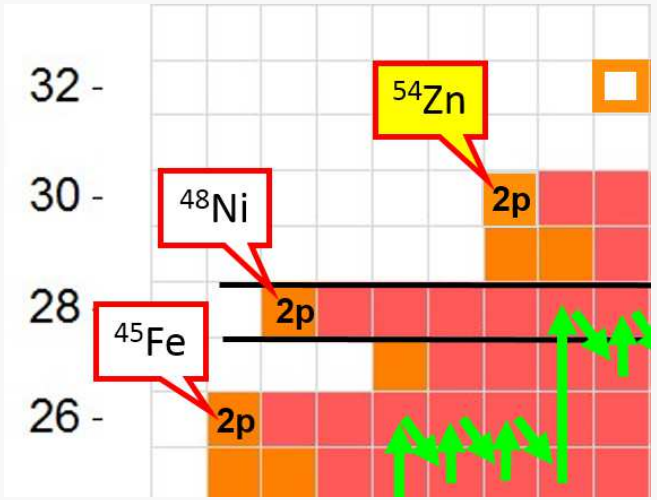
➤ Can we see the Z=28 shell closure in the p-p correlations?

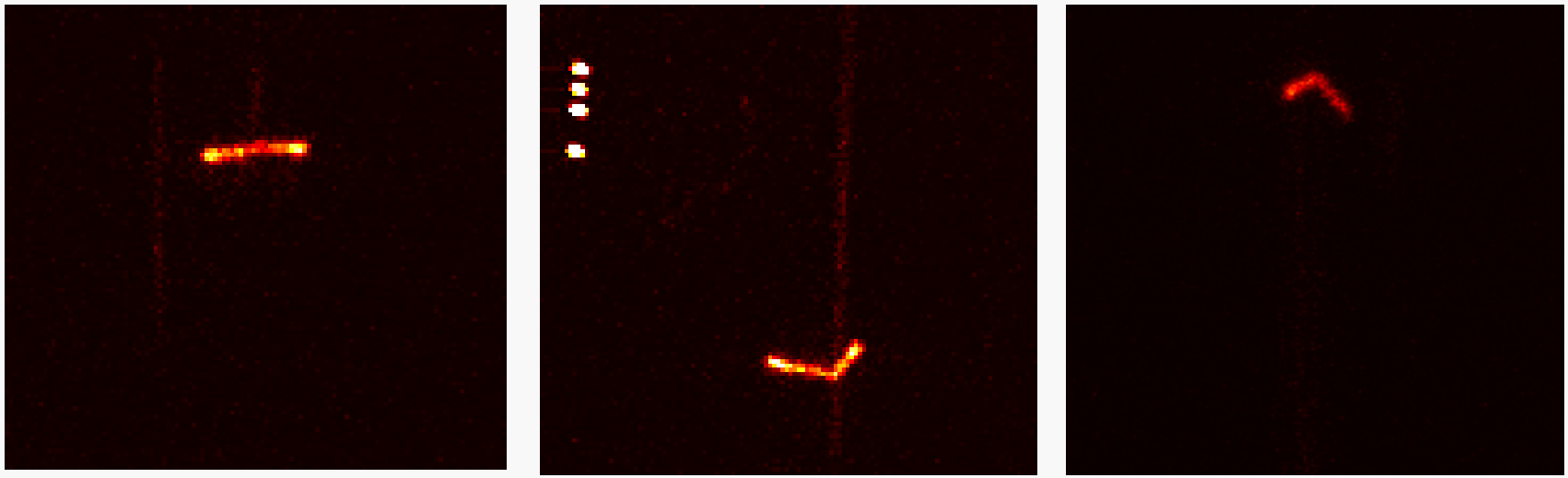
Experiment at BigRIPS, RIKEN, April 2019

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

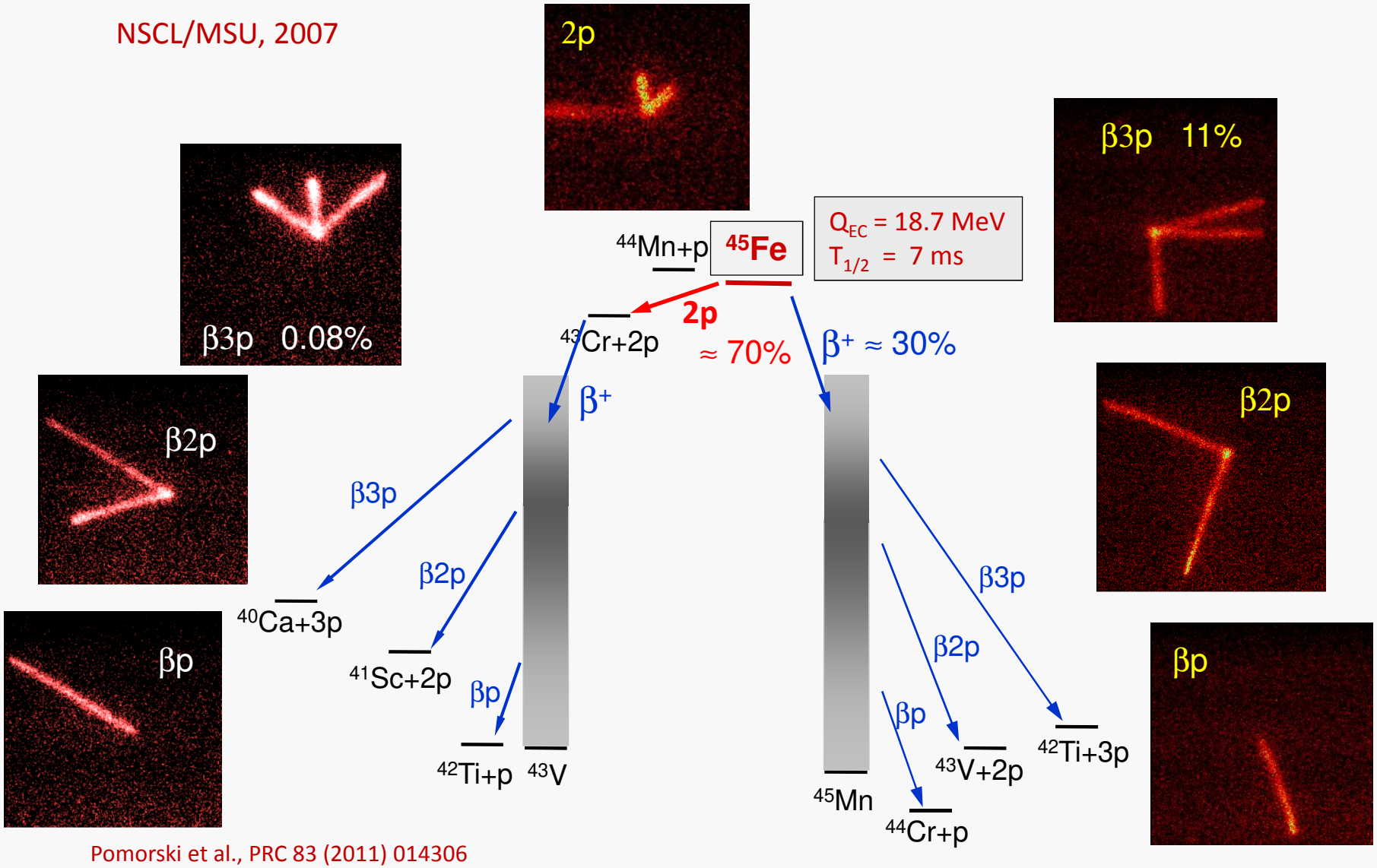
The beam intensity was great: 300 pnA
but the cross section was found
much smaller than expected

➔ Only a few 2p decay events observed ☹





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



β3p in ^{31}Ar?

PHYSICAL REVIEW C VOLUME 45, NUMBER 1 JANUARY 1992

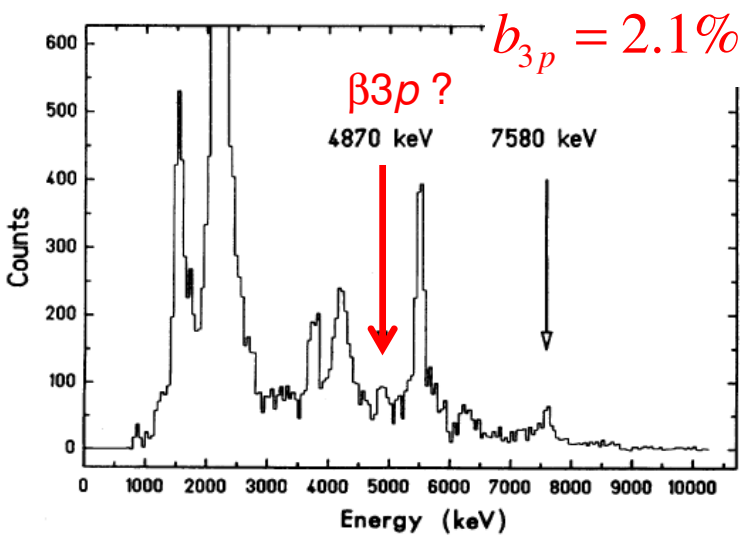
Decay modes of ^{31}Ar and first observation of β-delayed three-proton radioactivity

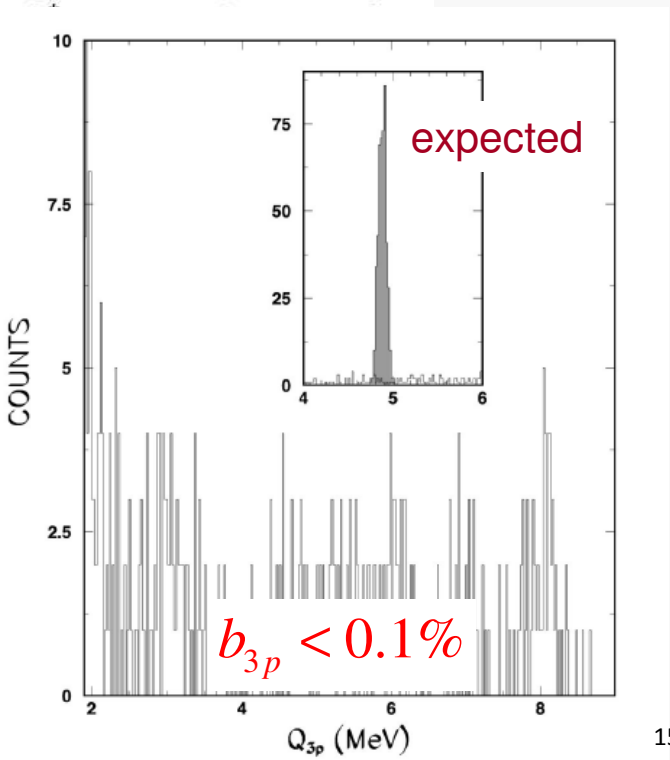
D. Bazin,* R. Del Moral, J. P. Dufour, A. Fleury, F. Hubert, and M. S. Pravikoff
Centre d'Etudes Nucléaires de Bordeaux–Gradignan, Le Haut Vigneau 33175 Gradignan CEDEX, France

PHYSICAL REVIEW C VOLUME 59, NUMBER 4 APRIL 1999

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

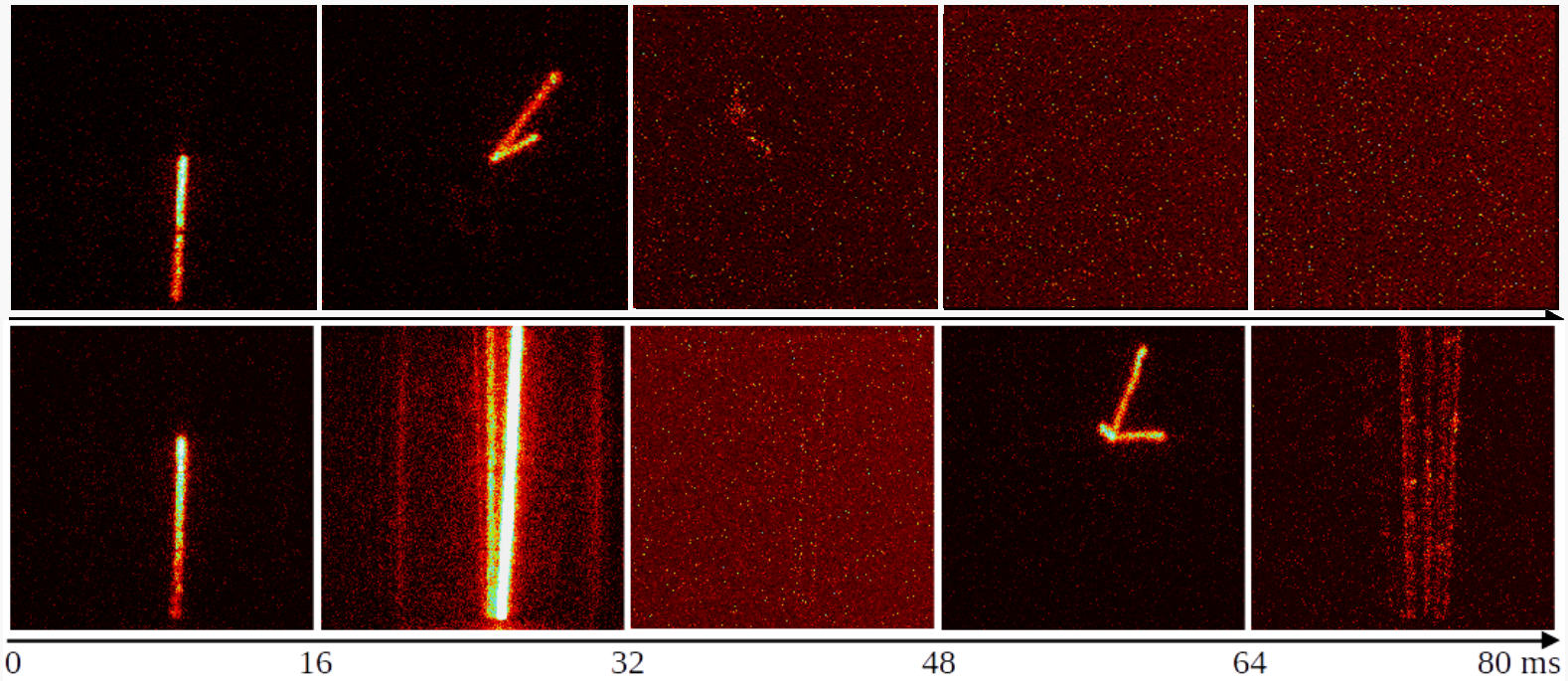
H. O. U. Fynbo,[1] L. Axelsson,[2] J. Äystö,[3] M. J. G. Borge,[4] L. M. Fraile,[4] A. Honk
A. Jokinen,[3] B. Jonson,[2] I. Martel,[5,†] I. Mukha,[1,‡] T. Nilsson,[2,§] G. Nyman,[2] M. Oin
M. H. Smedberg,[2] O. Tengblad,[4] F. Wenander,[2] and the ISOLDE





^{31}Ar at the FRS – „movie" mode

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



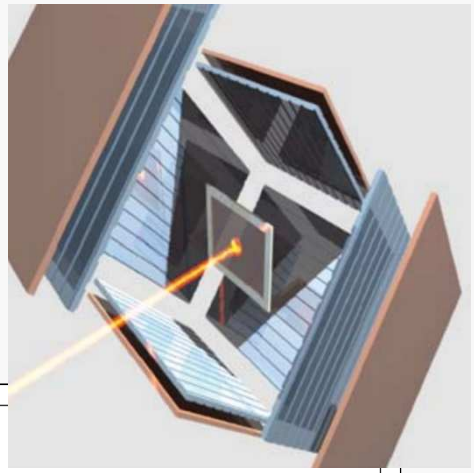
- 21 000 „interesting movies" inspected individually
- → 13 events of β3p decay of ^{31}Ar found

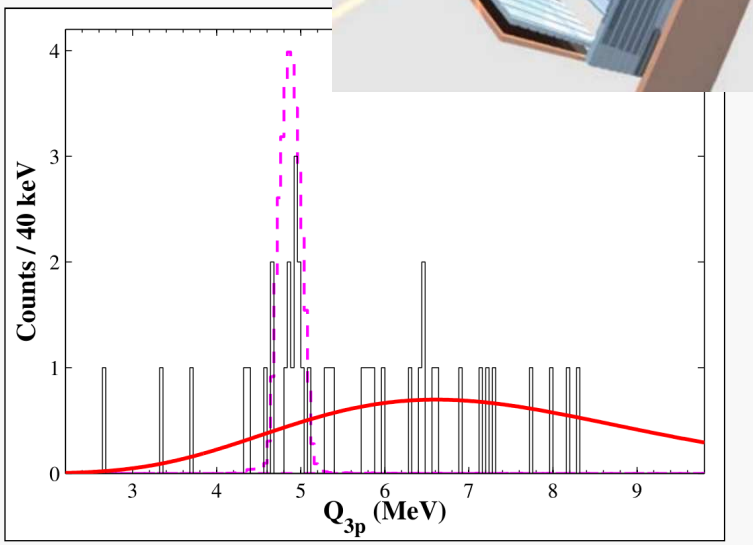
Lis et al., PRC 91, 064309 (2015)

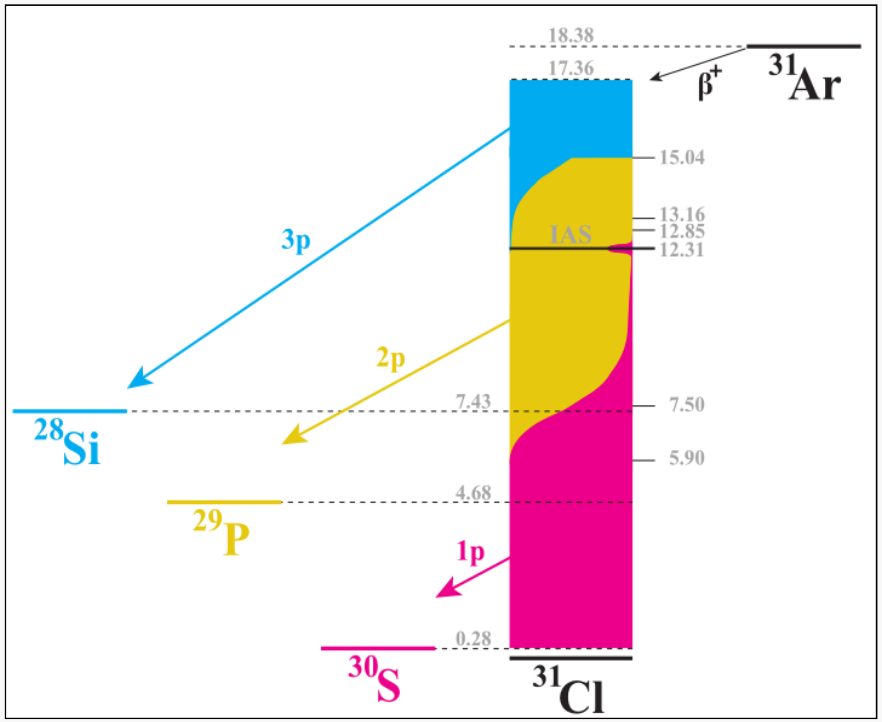
Channel	Events	Branching [%]
$\beta 0p$	5984	$22.6(3)^a$
$\beta 1p$	13157	68.3(3)
$\beta 2p$	1729	9.0(2)
$\beta 3p$	13	0.07(2)

β3p in ^{31}Ar

- β3p decay channel of ^{31}Ar confirmed by ISOLDE using Si Cube





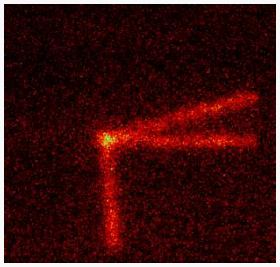


→ Very small branching corresponds to about 30% of total GT strength

Koldste et al., PRC 89 (2014) 064315

→ The estimated β3p branching: 0.08(4)%

All cases of β3p

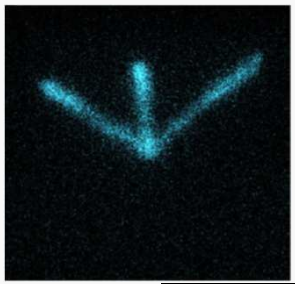


^{45}Fe

NSCL 2007

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

What next?

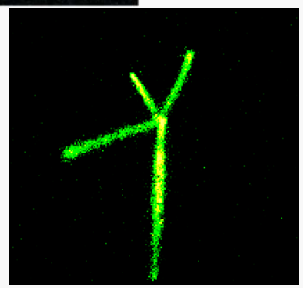


^{43}Cr

NSCL 2007

Pomorski et al., PRC 83 (2011) 014306

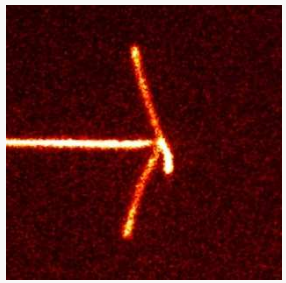
^{27}S?



^{31}Ar

GSI 2012

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



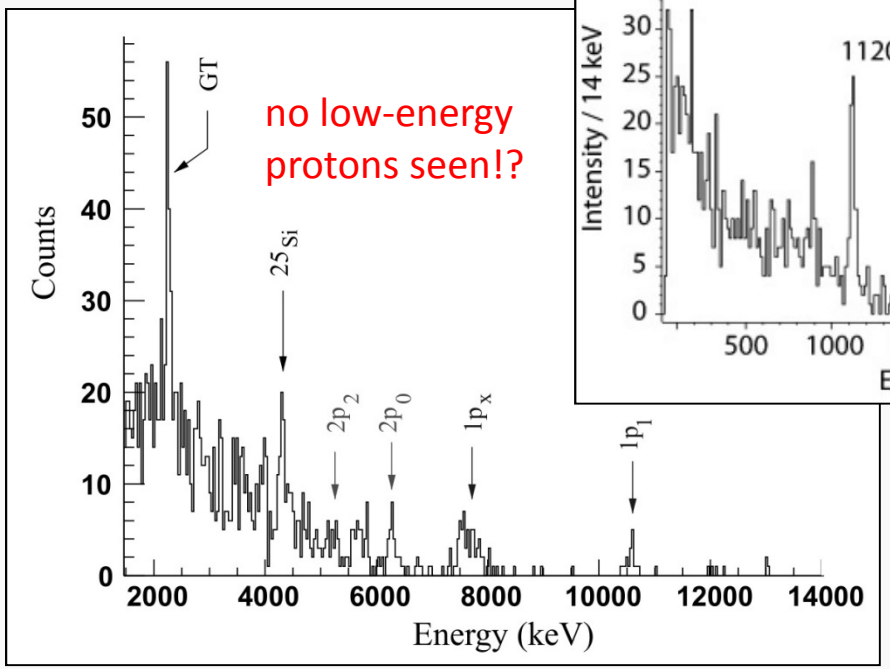
^{23}Si

Texas A&M 2017

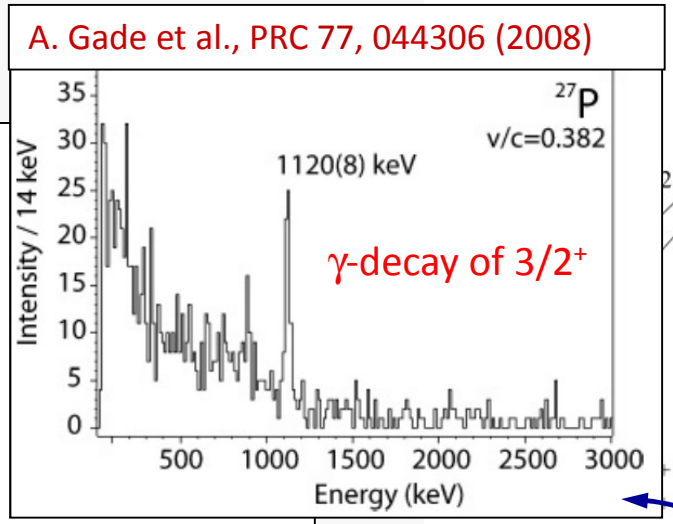
Ciemny et al., to be published

Case of ^{27}S

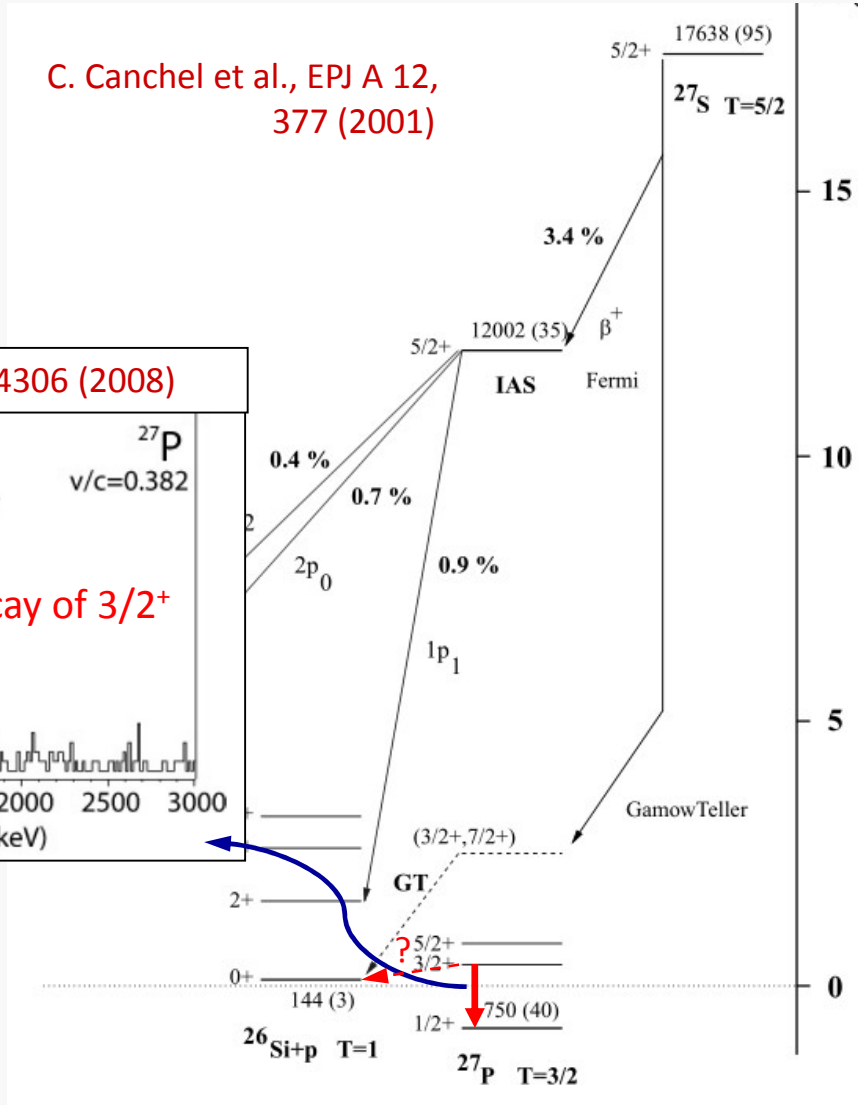
- Nucleosynthesis of cosmic γ-ray emitter **^{26}Al** may be by-passed by **^{25}Al(p,γ) ^{26}Si(p,γ) ^{27}P**
- → The latter may be probed by **β decay of ^{27}S**
- → No protons from 3/2$^+$ in ^{27}P were seen,
- → But there is a γ line !



A. Gade et al., PRC 77, 044306 (2008)



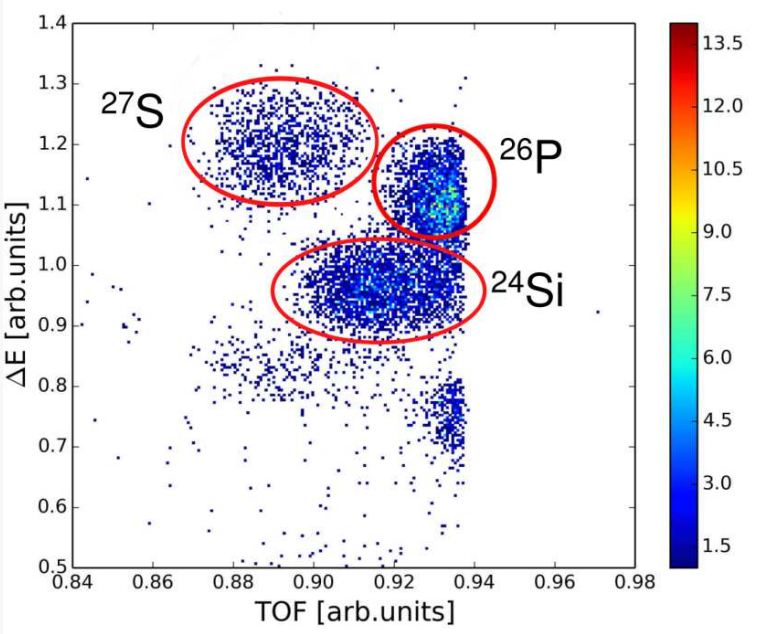
C. Canchel et al., EPJ A 12, 377 (2001)

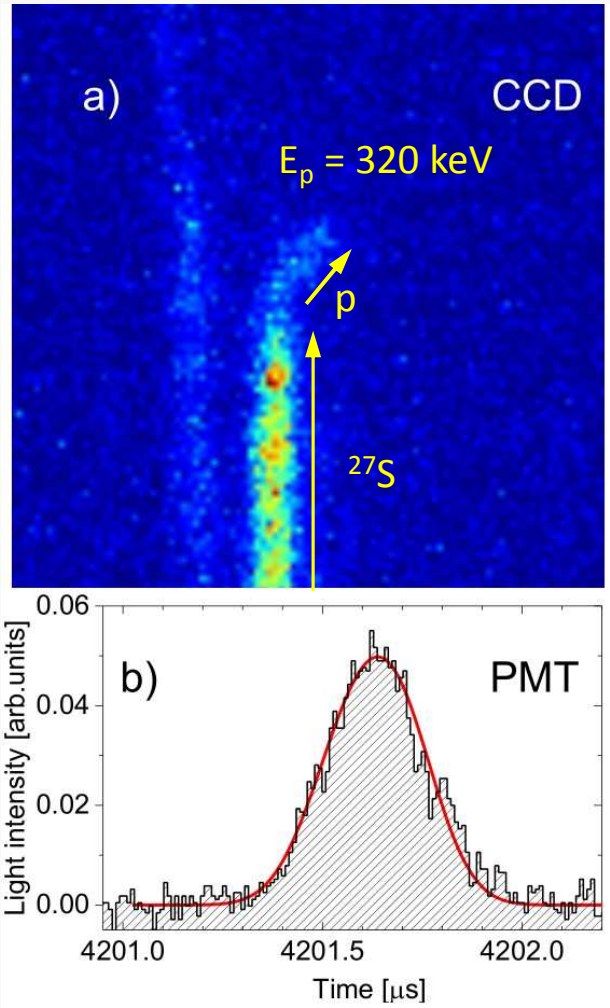


Experiment at Dubna

- Experiment at ACCULINNA (Dubna), November 2015

  Fragmentation of ^{32}S @ 51 MeV/nucleon



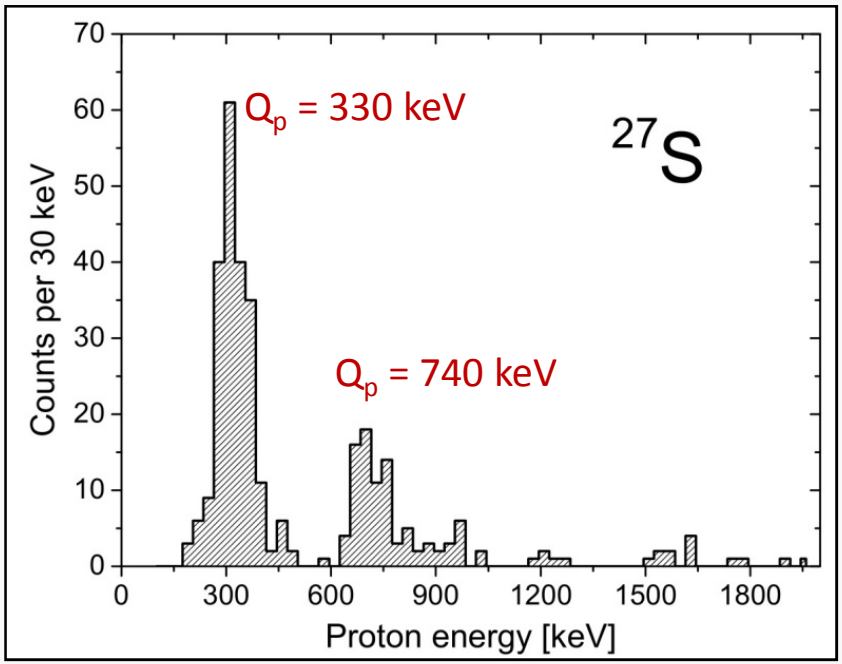


➔ About 1300 ions of **^{27}S** implanted;
700 decays seen

Ł. Janiak et al., PRC 95, 034315 (2017)

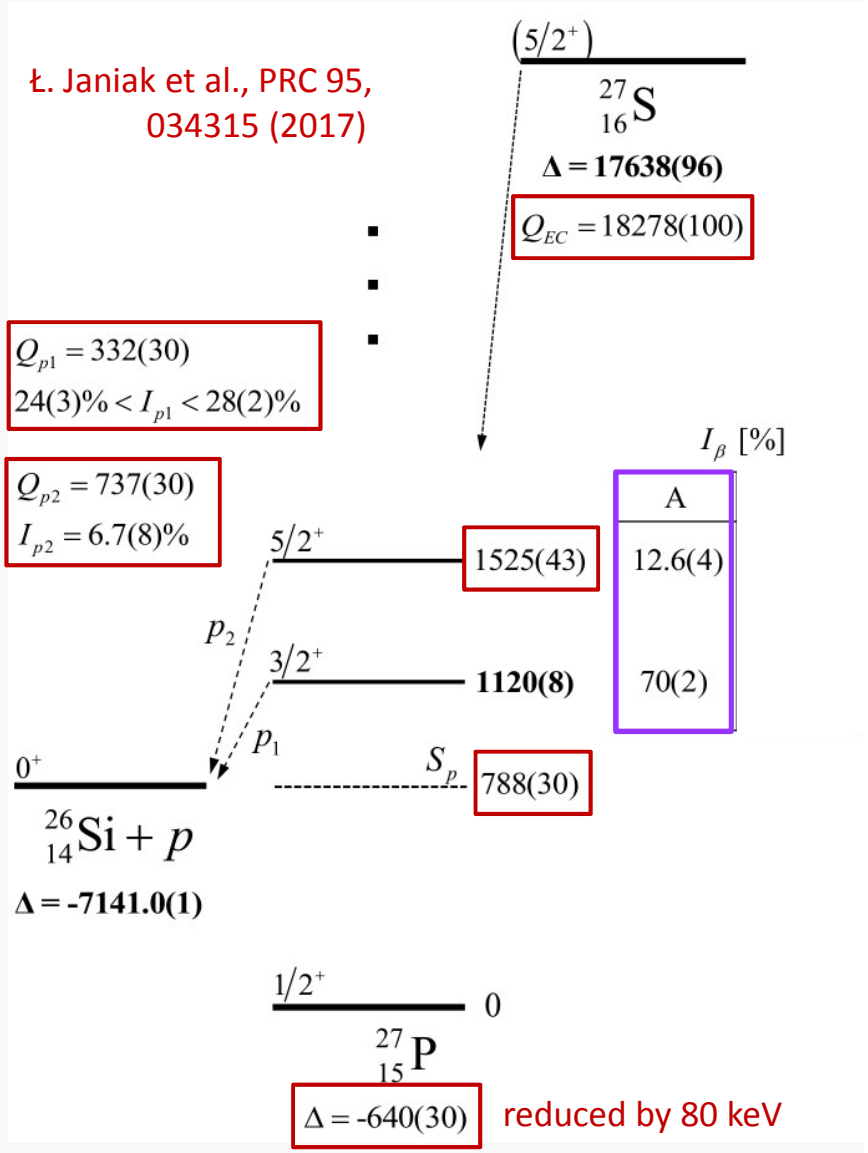
New decay scheme of ^{27}S

- We see a strong emission of low-energy protons!



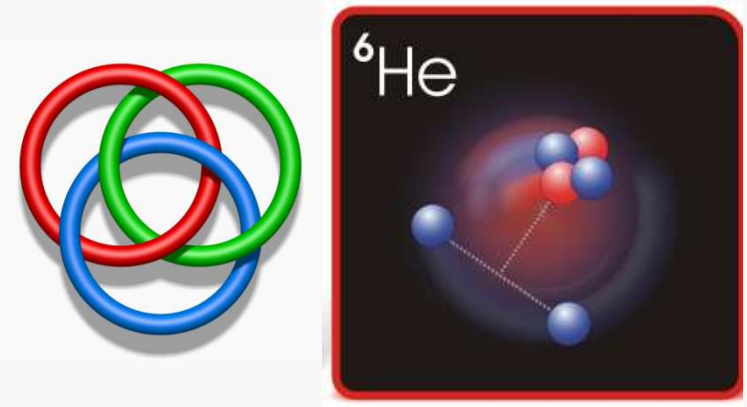
A) Isospin symmetry, log *ft* from decay of ^{27}Na
→ for 5/2$^+$: $\Gamma_p \approx \Gamma_\gamma$ very unlikely!

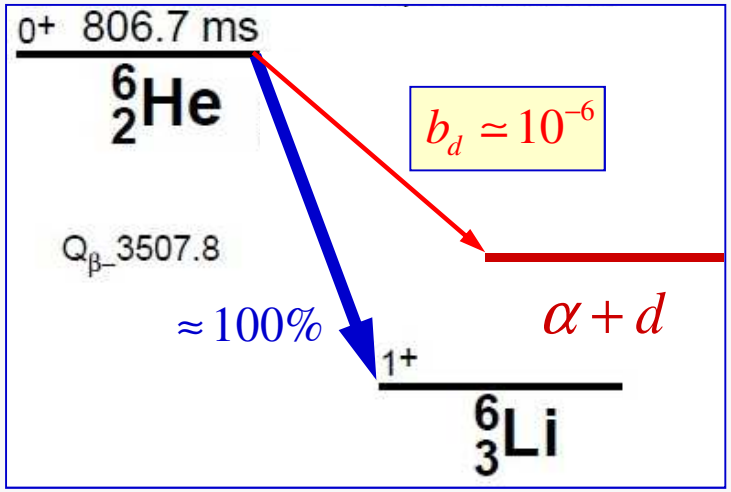
Ł. Janiak et al., PRC 95, 034315 (2017)

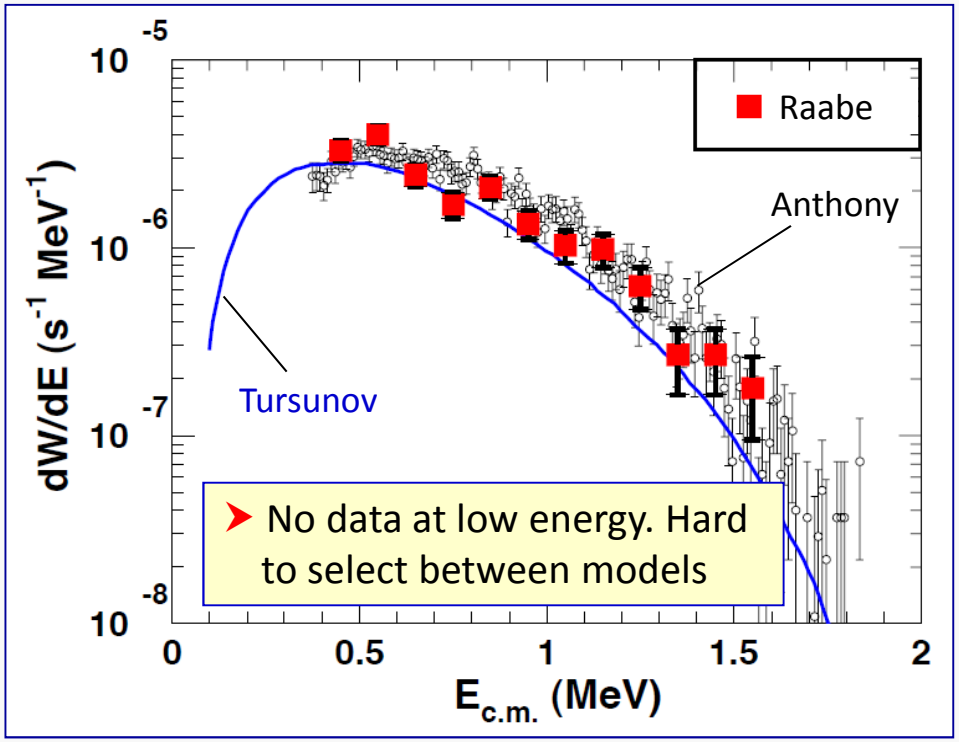


Probing the 2n halo of ^{6}He

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







- No data at low energy. Hard to select between models

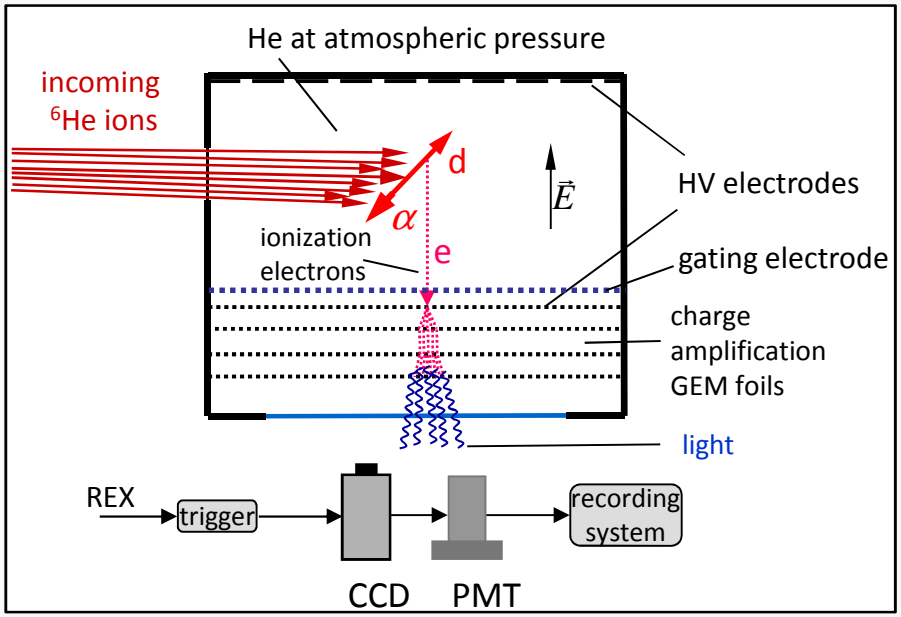
- Because of large β background, the spectrum below $E_{CM} \cong 400$ keV could not be measured

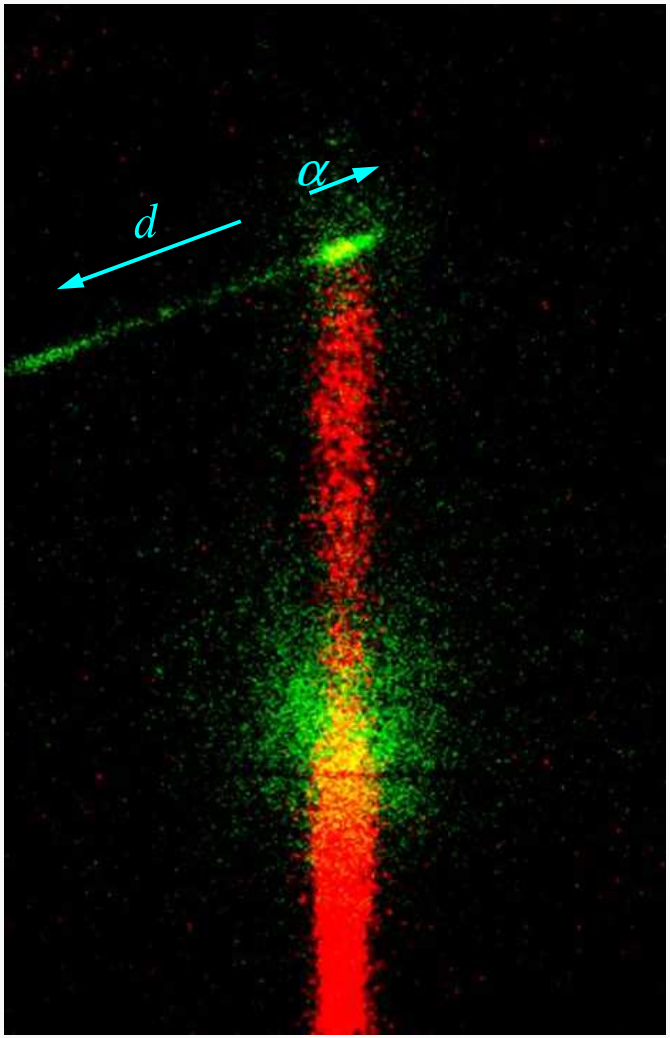
R. Raabe et al., Phys. Rev. C80 (2009) 054307

„Bunch" mode for ^{6}He @ISOLDE

➤ Experiment at ISOLDE, August 2012

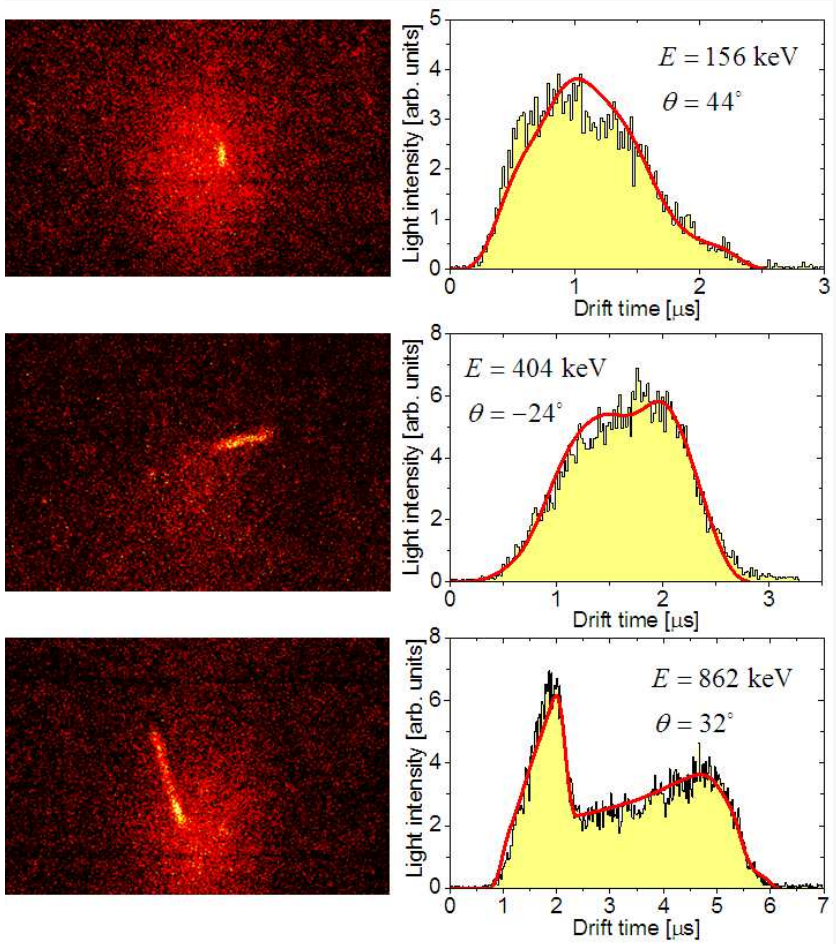
- Bunches of about 10^4 ions of ^{6}He accelerated by **REX-ISOLDE** to 3 MeV/u were implanted into the OTPC.
- After implantation, an exposure of 650 ms was started to see the decays.
- Clear images of decay events with α + *d* tracks were recorded.





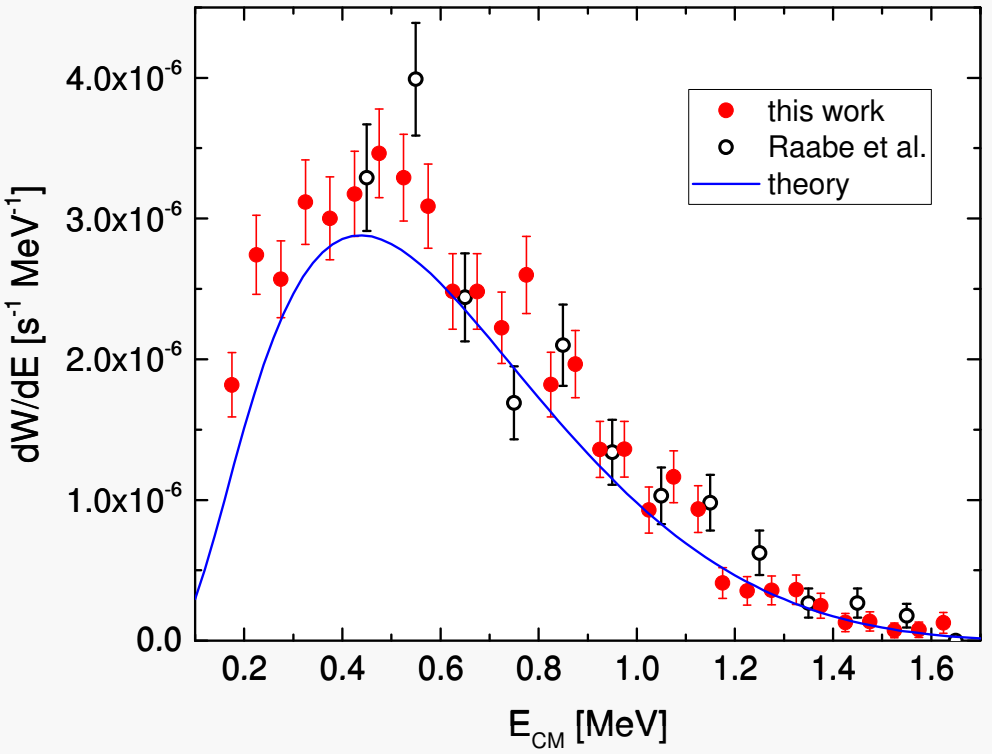
A CCD image showing a bunch of implanted ^{6}He ions (red) and a ^{6}He → α + *d* decay (green)

The spectrum of α + *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

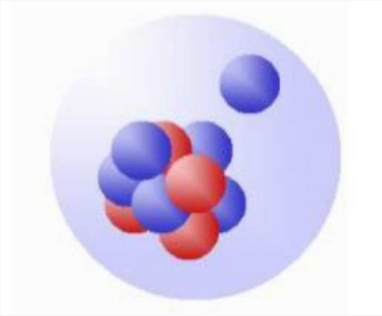
$B_{\alpha d}$ = (2.78 ± 0.07(stat) ± 0.17(sys)) × 10^{-6}
= 20% more than the theoretical prediction

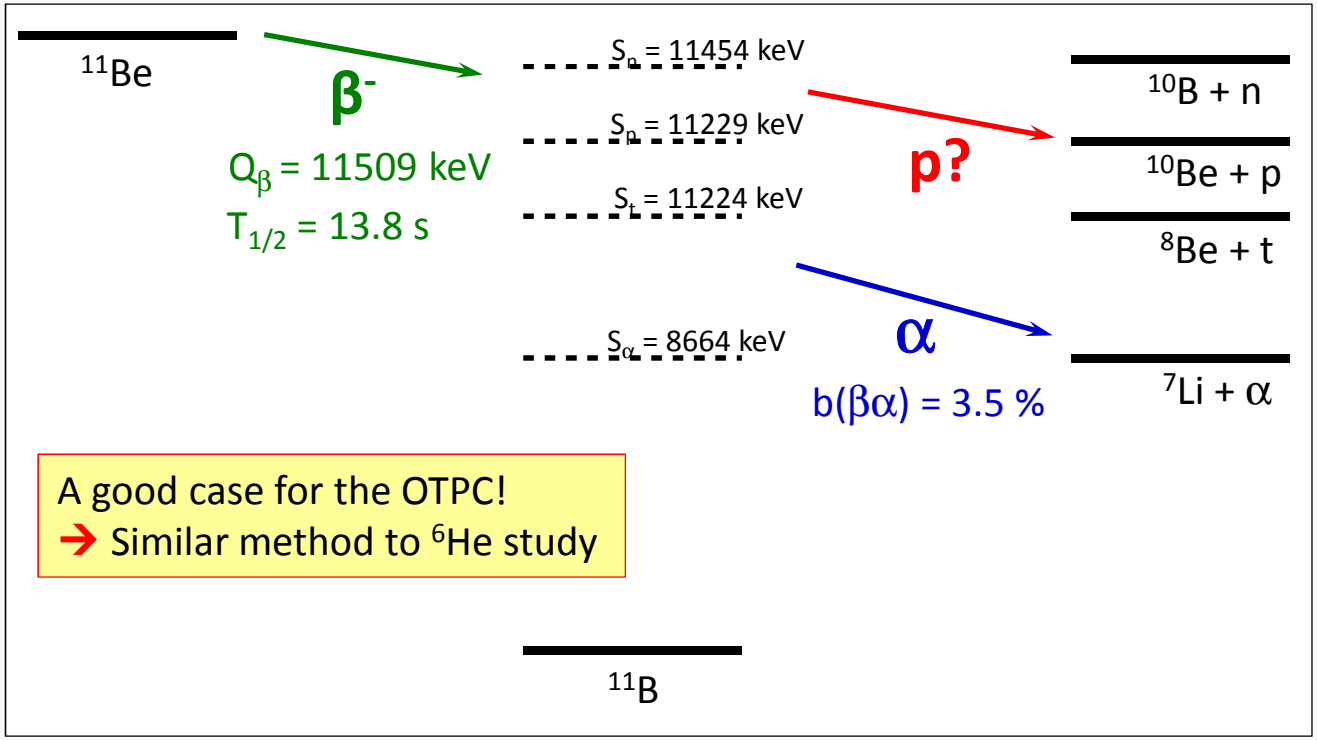
→ By extending the spectrum to lower energy, we see 70% more intensity

A difficult case: ^{11}Be βp?

- 1n halo nucleus
- The $\beta^-\alpha$ emission observed
- The β^-p decay possible but never seen

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





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

A curiosity

- The neutron lifetime puzzle: $\underbrace{\tau^{\text{bottle}} = 879.6 \pm 0.6 \text{ s}}_{\text{total lifetime}}$; $\underbrace{\tau^{\text{beam}} = 888 \pm 2 \text{ s}}_{\text{partial lifetime for } \beta \text{ decay}}$

- Perhaps there is a new, unseen before, decay channel of the neutron?
  A dark matter particle? Fornal & Grinstein PRL 120, 191801 (2018)

→ Assume: $n \rightarrow M_X + \ldots$ then, noting that ^{9}Be is stable:

$$937.993 \text{ MeV} < M_X < 939.565 \text{ MeV}$$

→ a narrow energy range of 1.572 MeV to test!

- If true, the neutron dark decay would happen in a nucleus if:

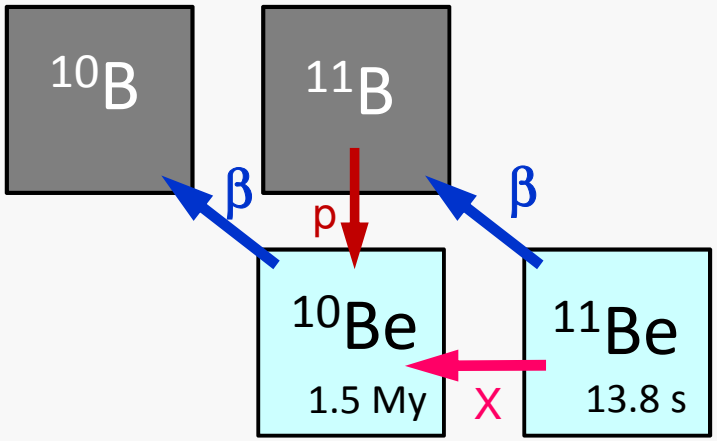
$$937.993 \text{ MeV} < M_X < m_n - S_n \qquad S_n < 1.572 \text{ MeV}$$

- Only a few practical cases exist which could be measured

M.P. & K. Riisager, PRC 97, 042501(R) (2018)

^{11}Be!

- The best case to search for nuclear neutron dark decay is ^{11}Be!



$S_n\left(^{11}\mathrm{Be}\right) = 501.6(3)$ keV

thus sensitive to:

$937.993\ \mathrm{MeV} < M_X < 939.063\ \mathrm{MeV}$

→ a range of 1.07 MeV

Expected branching for dark decay:

$b_X\left(^{11}\mathrm{Be}\right) < 2\times10^{-4}$

- The appearance of ^{10}Be atoms in a sample of collected ^{11}Be (ISOLDE) was found by the AMS technique → $b_p\left(^{11}\mathrm{Be}\right) = 8.3(9)\times10^{-6}$ Riisager at al., Phys. Lett. B 732 (2014) 305

- A claim from TRIUMF: $b_p\left(^{11}\mathrm{Be}\right) = 13(3)\times10^{-6}$ Ayyad at al., PRL 123 (2019) 082501

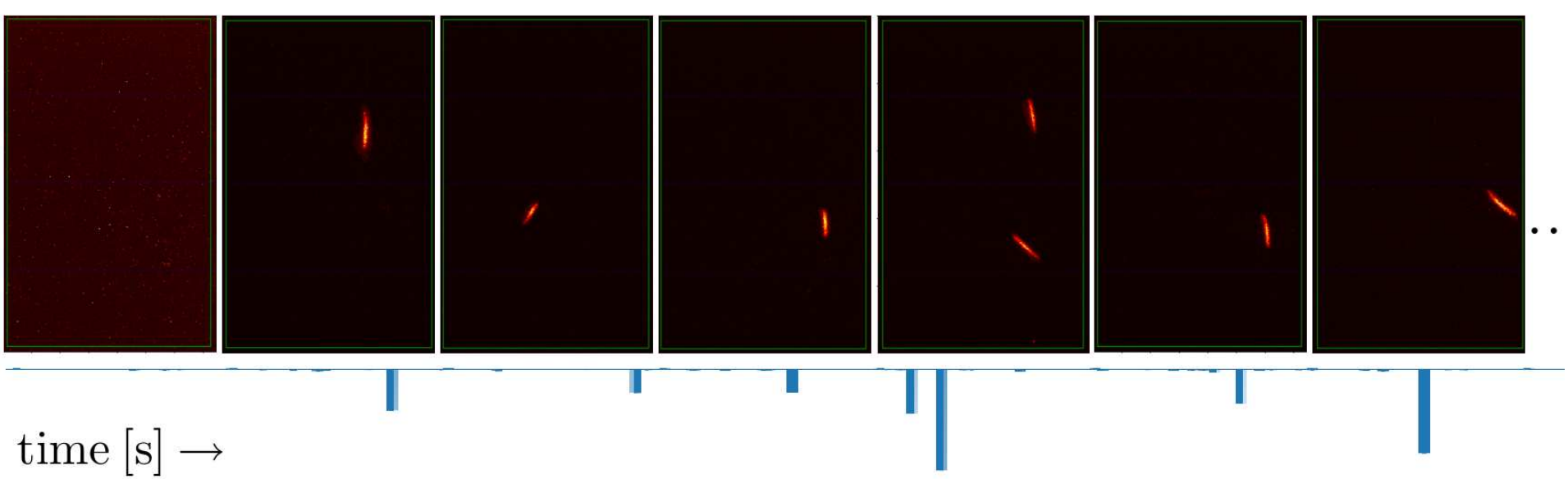
- However, the reanalysis of ISOLDE/AMS experiment → $b_p\left(^{11}\mathrm{Be}\right) < 2.2\times10^{-6}$

Riisager et al. arXiv: 8 Jan 2020

^{11}Be @ ISOLDE

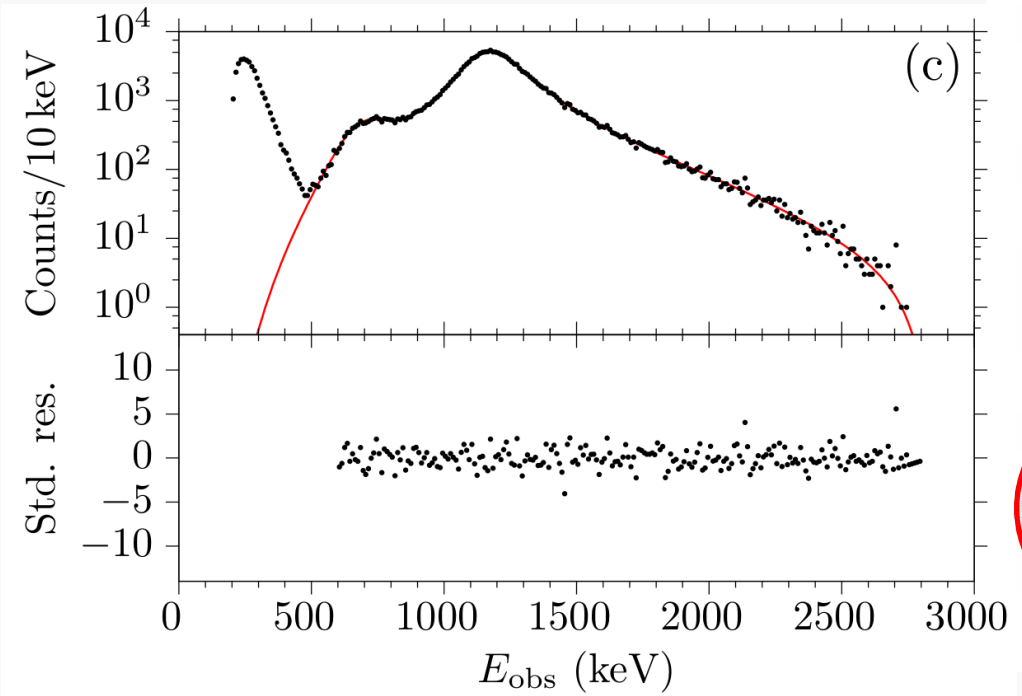
➤ Experiment at ISOLDE, 2018 → bunch and movie modes combined

- 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

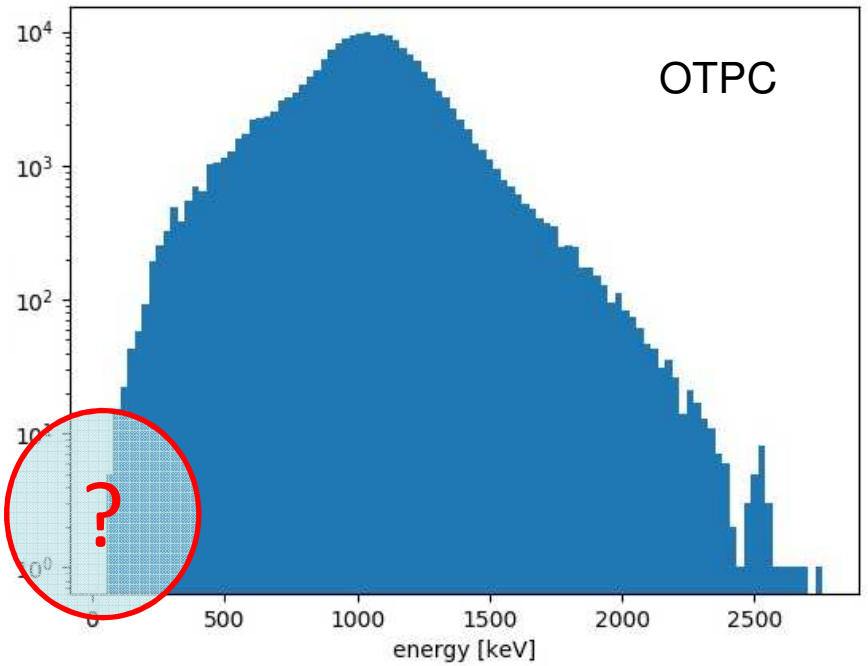


βα decay of ^{11}Be

- 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)



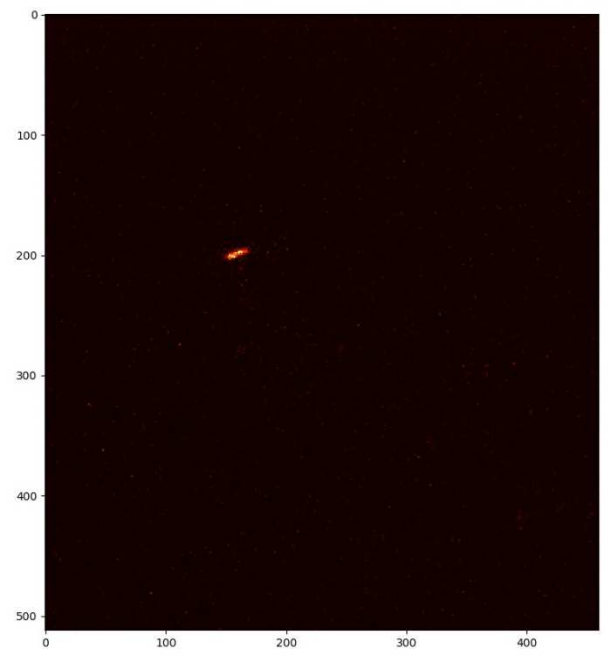
Preliminary analysis of ≈200 k clean βα events

N. Sokołowska, PhD in preparation

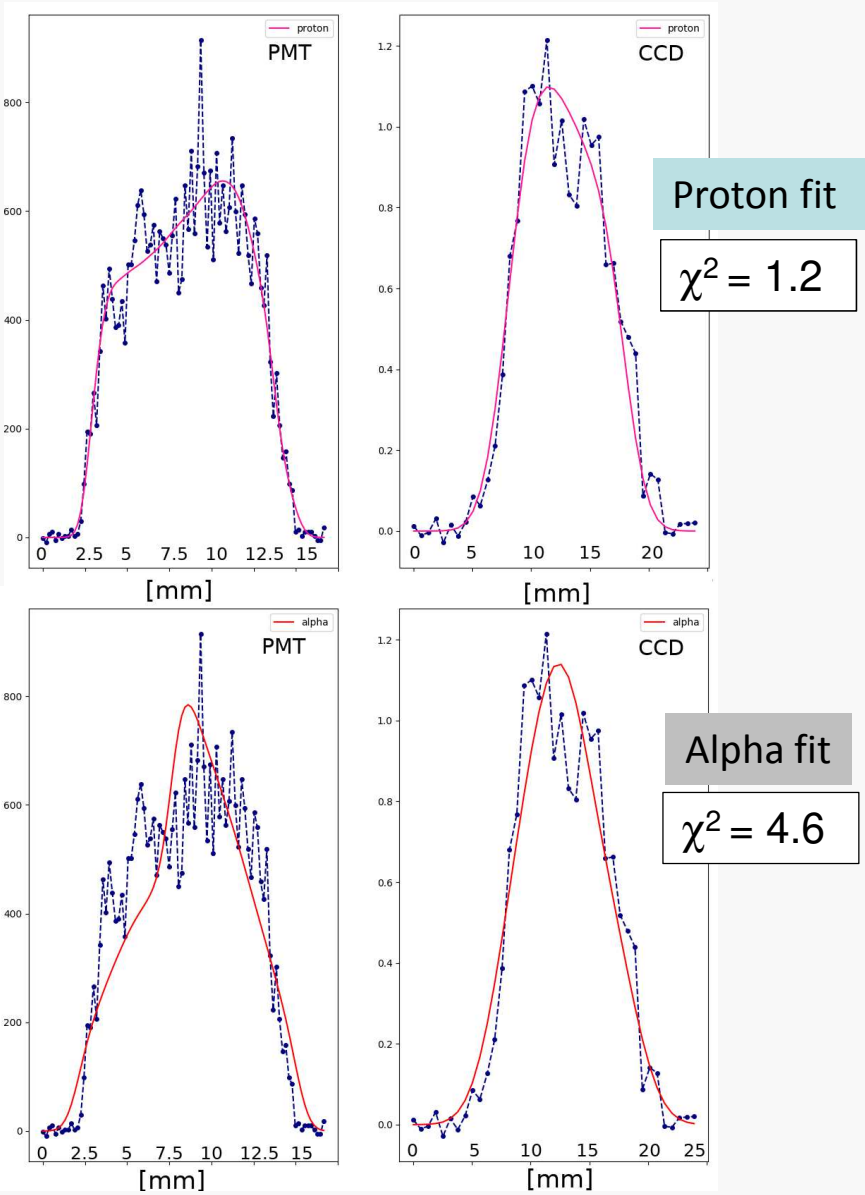
Evidence for βp

- We do see evidence for βp from ^{11}Be

- The main difficulty: it is hard to distinguish α + ^{7}Li from p + ^{10}Be below 200 keV



N. Sokołowska

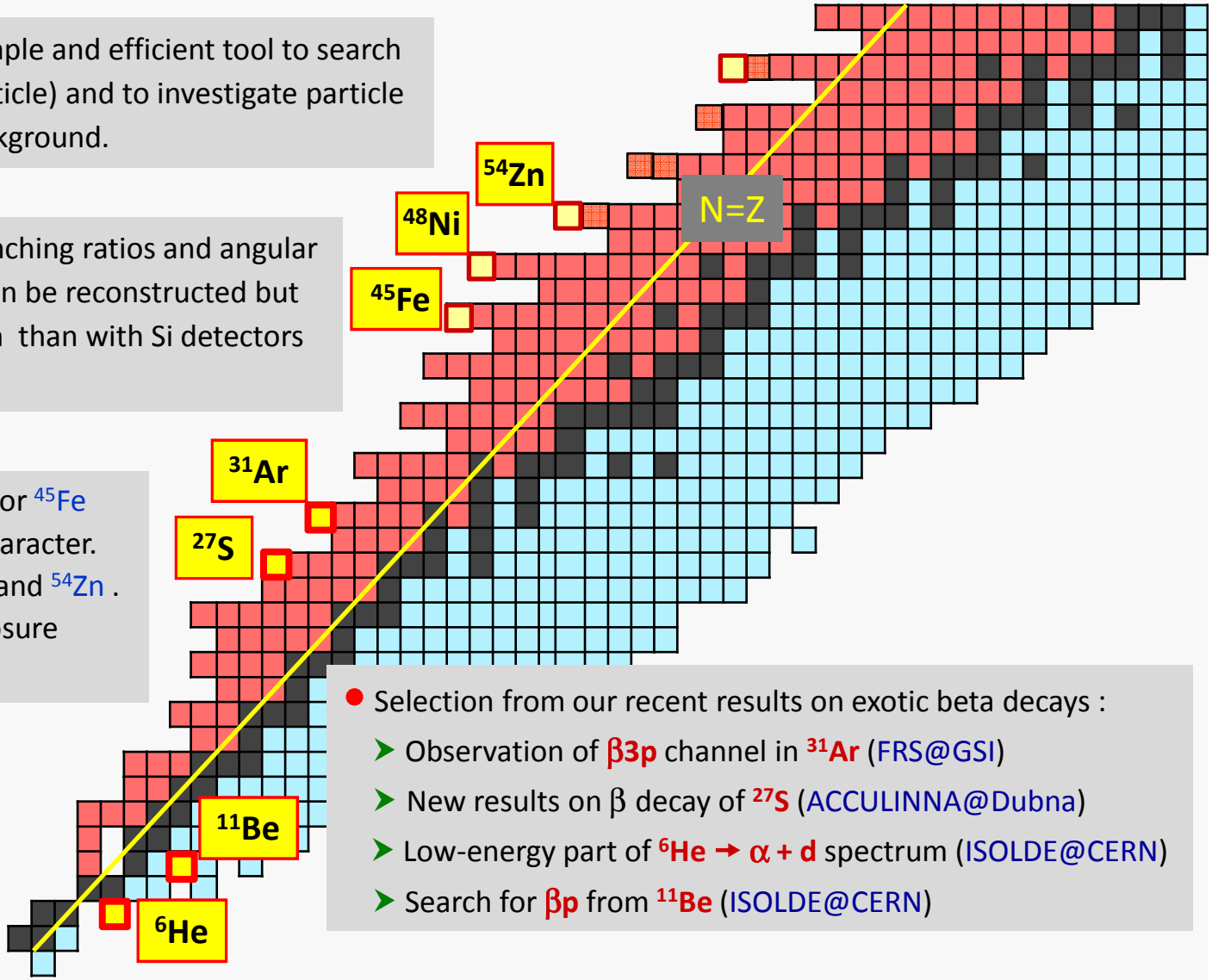


Summary

- 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 ^{27}S (ACCULINNA@Dubna)
  - Low-energy part of ^{6}He → α + d spectrum (ISOLDE@CERN)
  - Search for βp from ^{11}Be (ISOLDE@CERN)

Thank you!

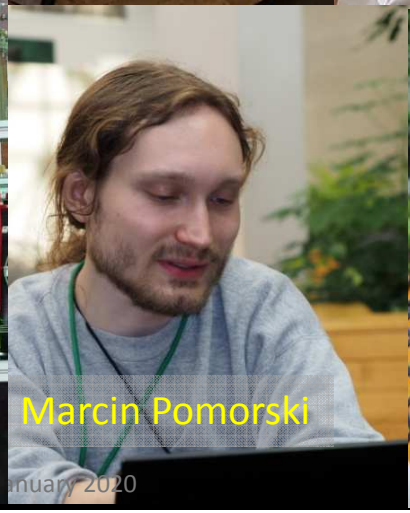

Wojtek Dominik

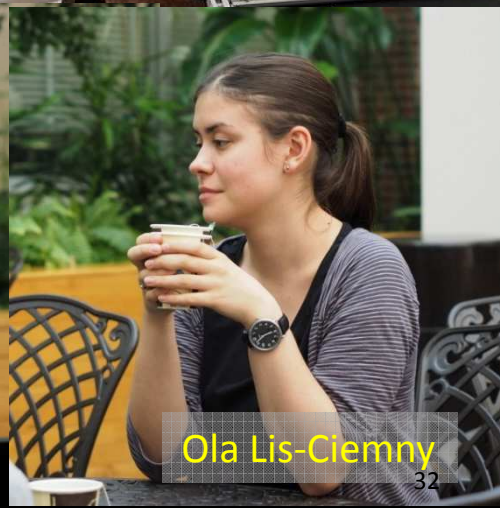

Chiara Mazzocchi


Natalia Sokołowska


Zenon Janas


Adam Kubiela


Marcin Pomorski


Ola Lis-Ciemny