Charged-particle spectroscopy with the Optical TPC

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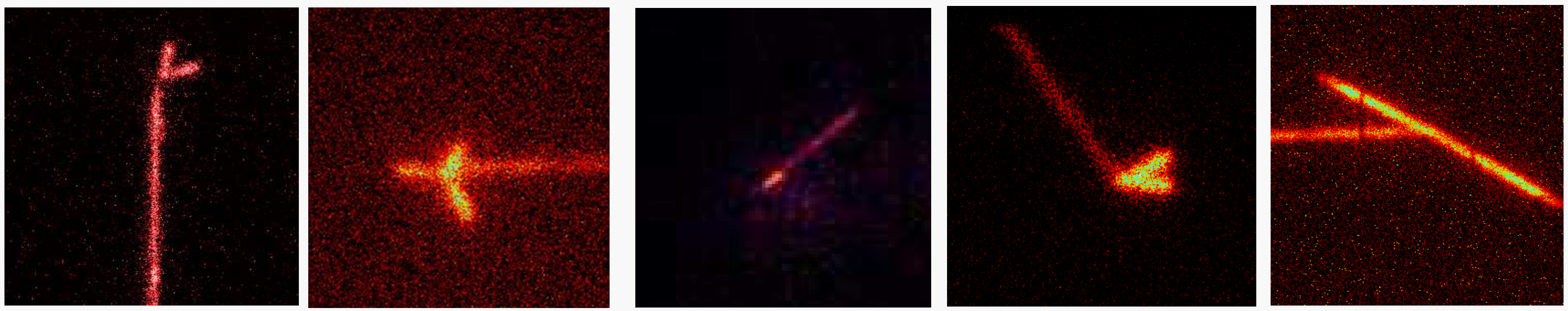
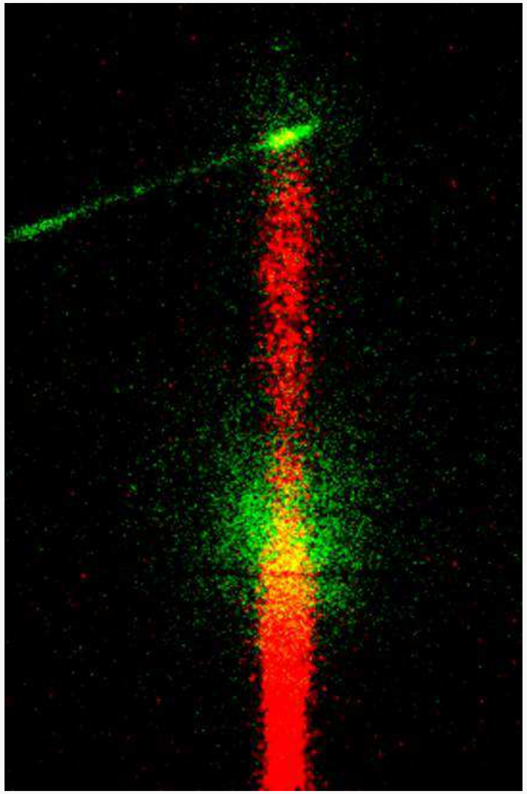


Outline



- Nuclei at the proton drip-line and beyond
  - Two-proton radioactivity
- Optical TPC
- Decay study of ^{45}Fe (and ^{43}Cr)
- Decay study of ^{48}Ni (and ^{46}Fe, ^{44}Cr)
- Beta-delayed 3p emission from ^{31}Ar
- Rare decay of ^{6}He
- Beta decay of ^{8}He
- New TPC for ELI-NP

Beyond the proton drip-line

Competition between two decay modes

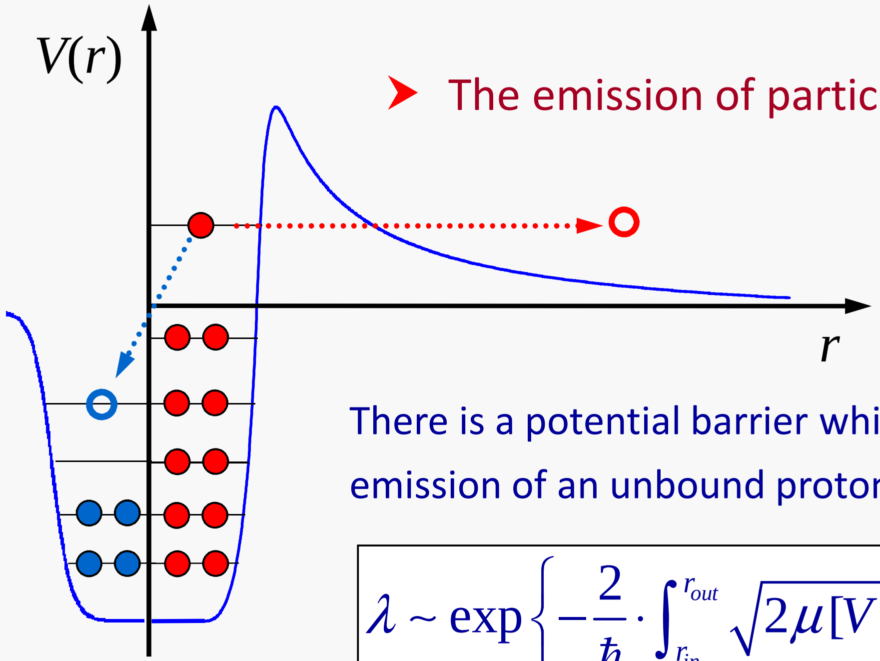
- The β^+ decay

Probability of transition:

$$\lambda \sim Q^5$$

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

→ $T_{1/2} > 1\ \mathrm{ms}$



- The emission of particles

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

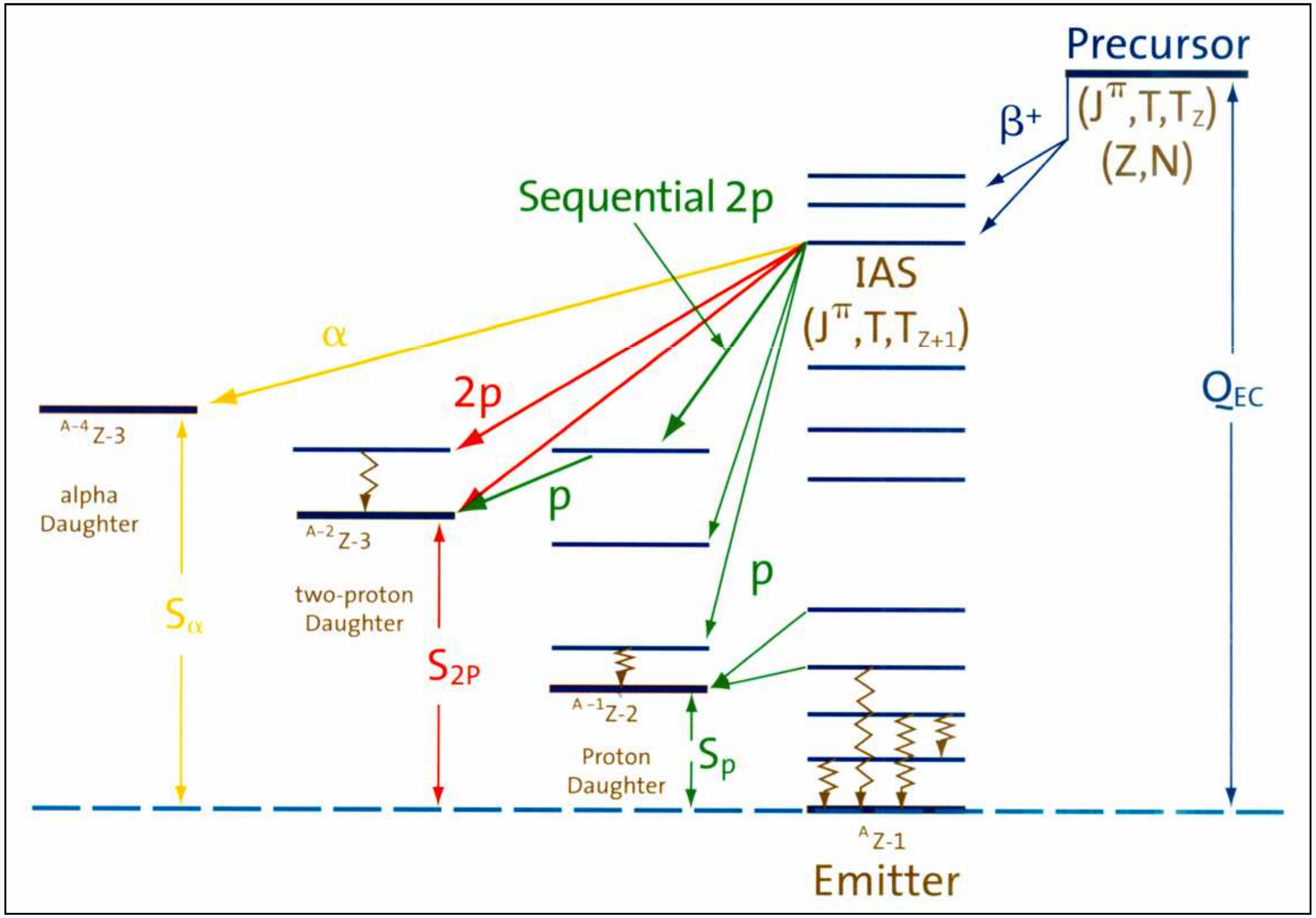
$$\lambda \sim \exp\left\{-\frac{2}{\hbar}\cdot\int_{r_{in}}^{r_{out}}\sqrt{2\mu[V(r)-Q_p]}\cdot dr\right\}$$

→ To find where the drip-line actually is and to predict which decay will happen, precise estimates of atomic masses are required!

→ To study particle radioactivity fast techniques are needed!

β-delayed particle emission

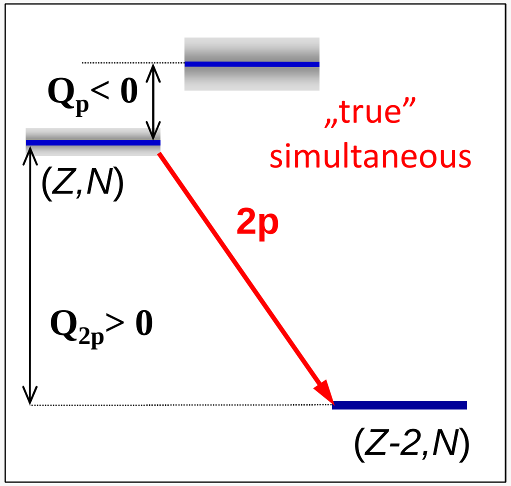
- When the β decay energy is large, many exotic channels are available

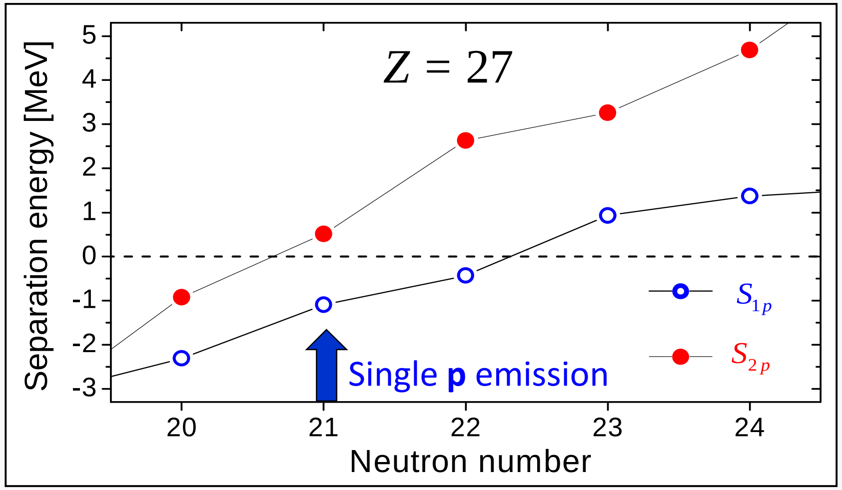


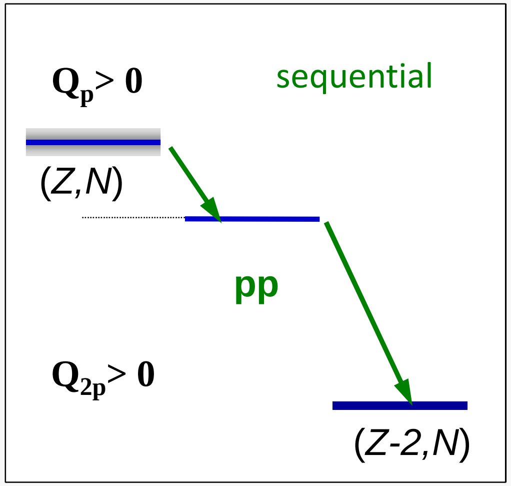
Blank and Borge, Progress in Part. Nucl. Phys. 60 (2008) 403

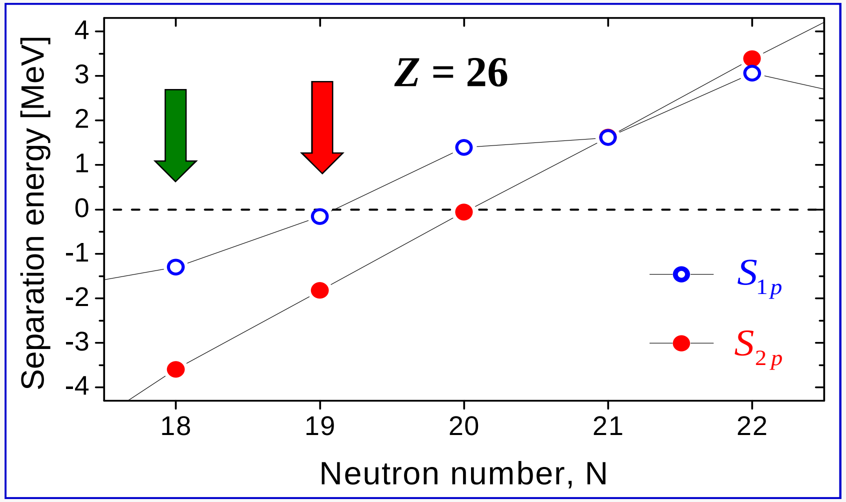
p and 2p emission

- The limit of „existence” beyond the proton drip-line is determined by emission of protons





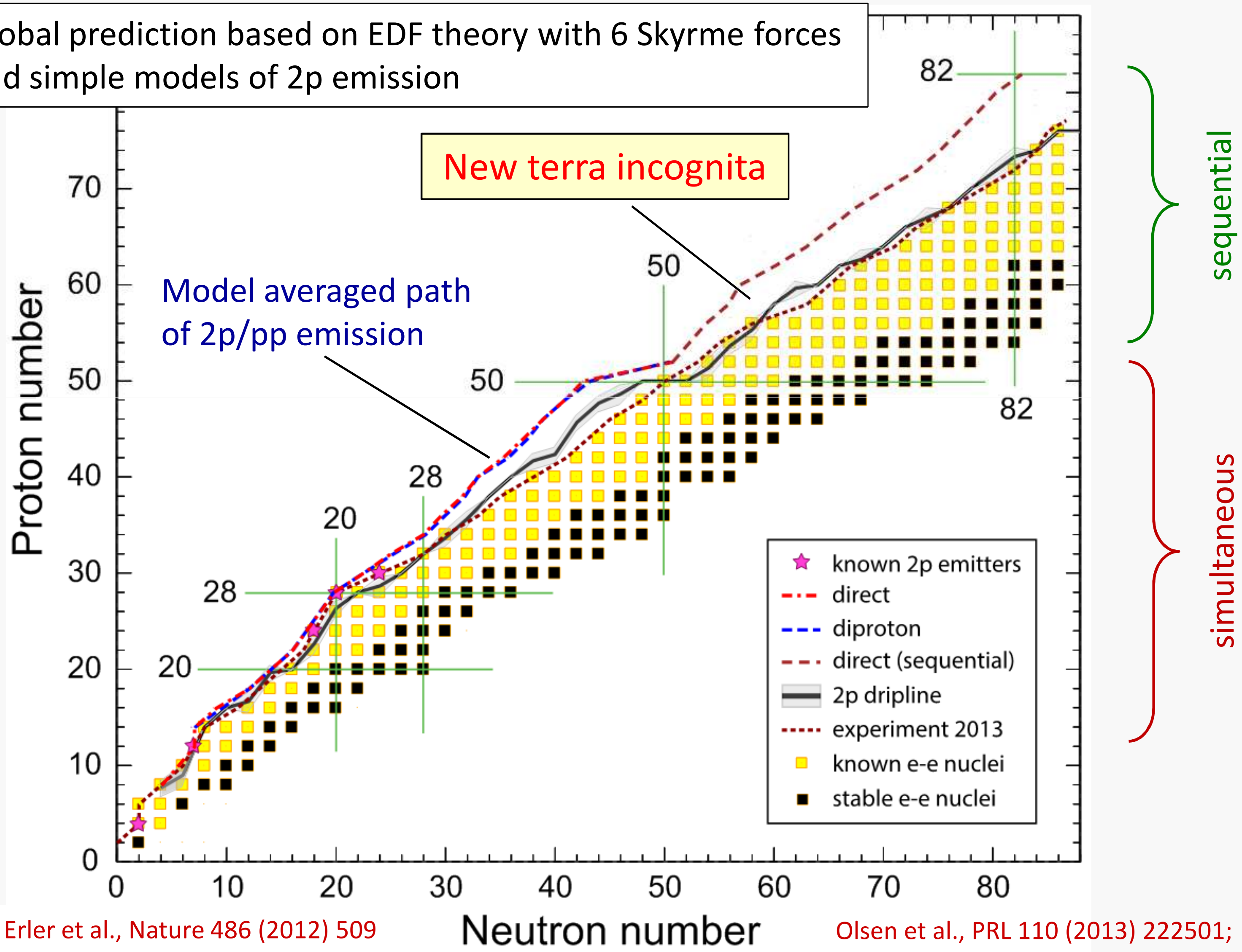




V.I. Goldanskii, Nucl. Phys. 19 (60) 482

Full 2p landscape

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

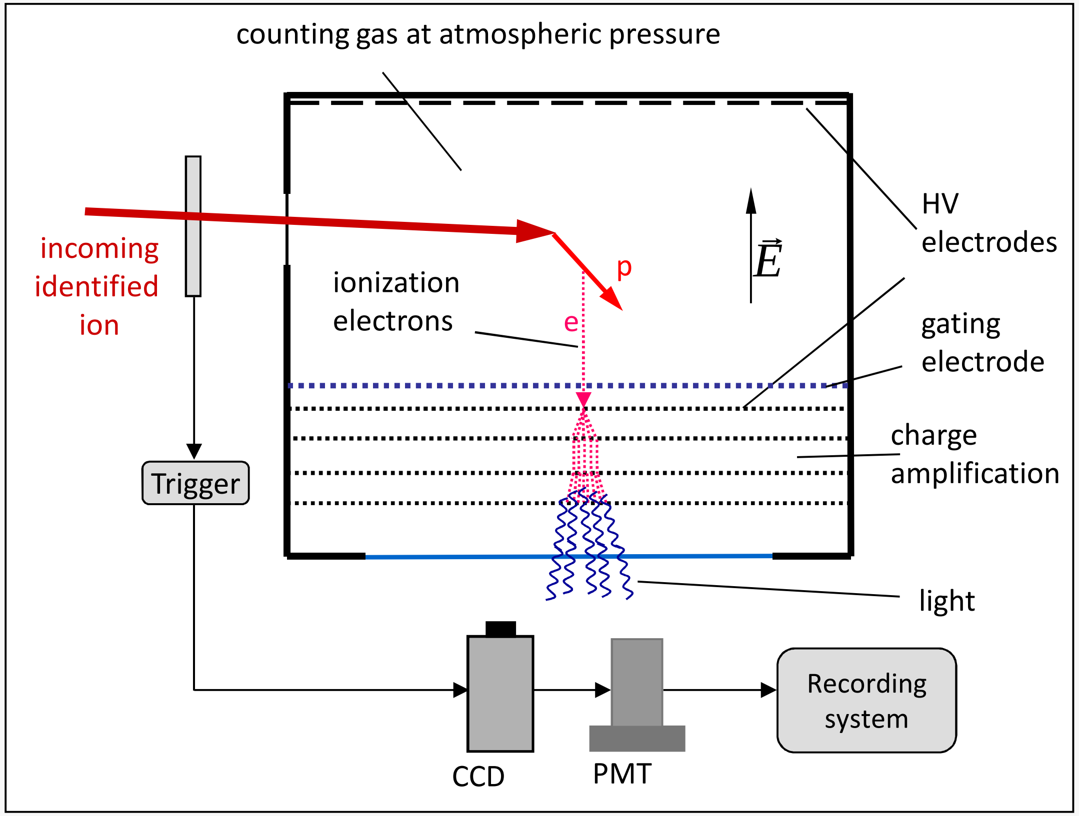


Erler et al., Nature 486 (2012) 509

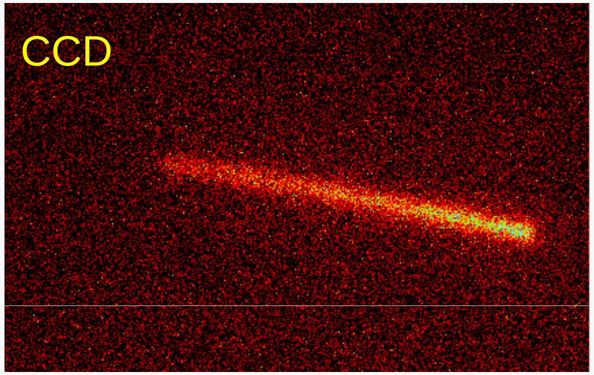
Olsen et al., PRL 110 (2013) 222501; PRL 111 (2013) 139903 (E)

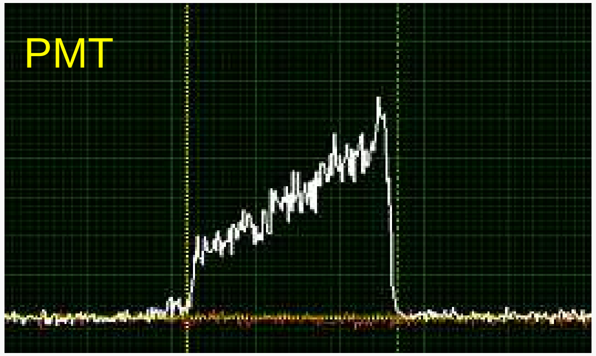
TPC detector

Time projection chamber with optical readout (OTPC)



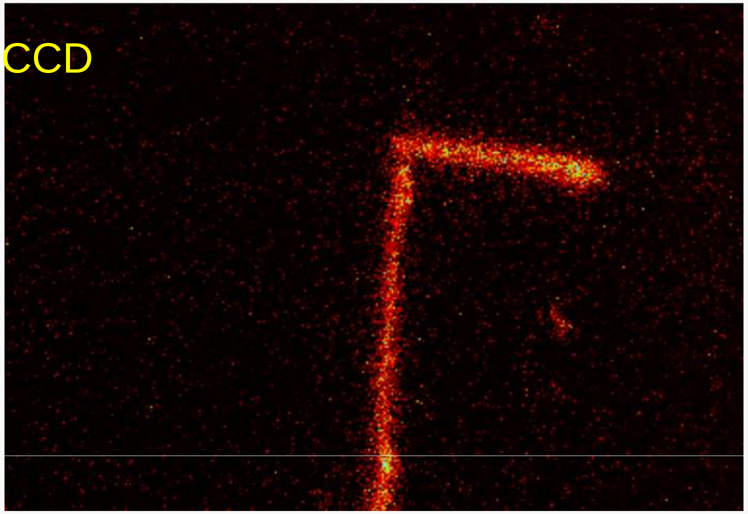
α particle

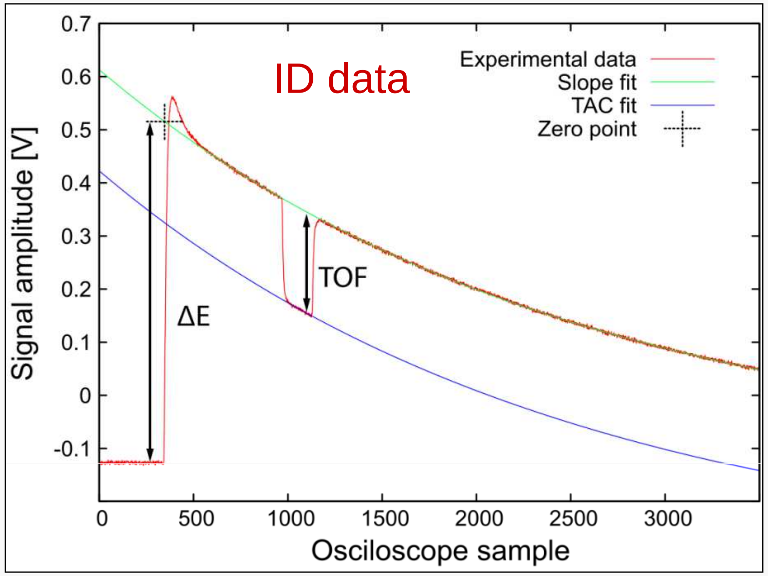


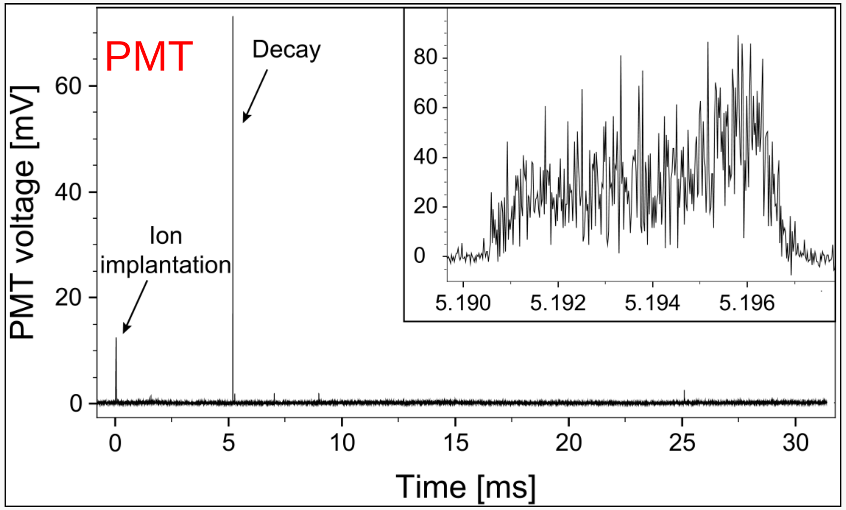


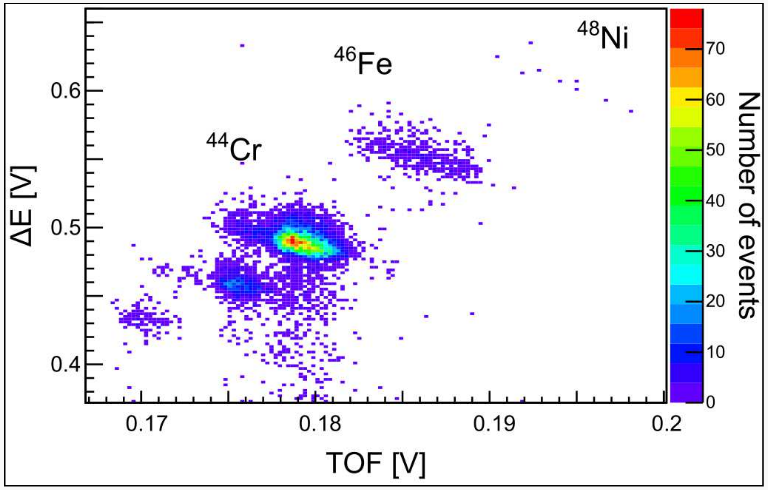
- Combination of the CCD image with the PMT waveform allows to fully reconstruct the track in three dimensions

Raw data and ion ID



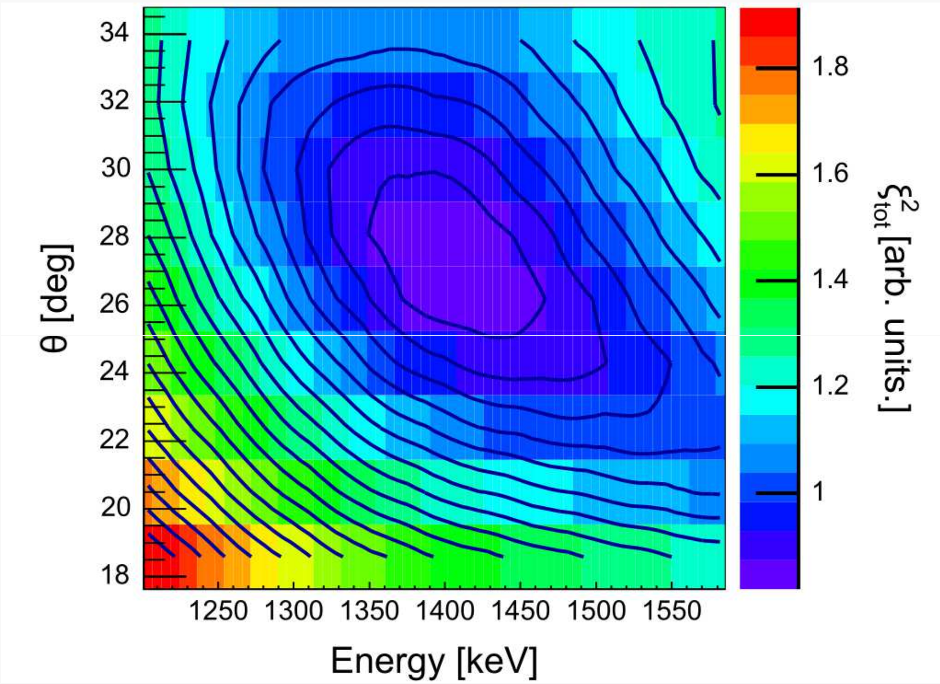


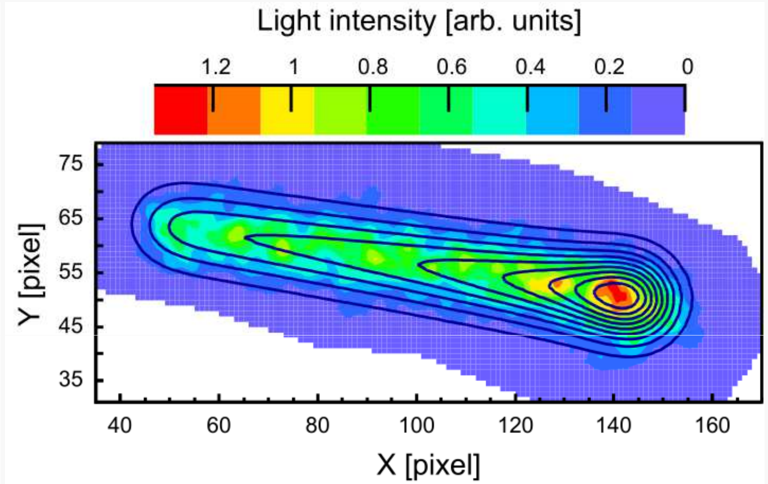




Track reconstruction

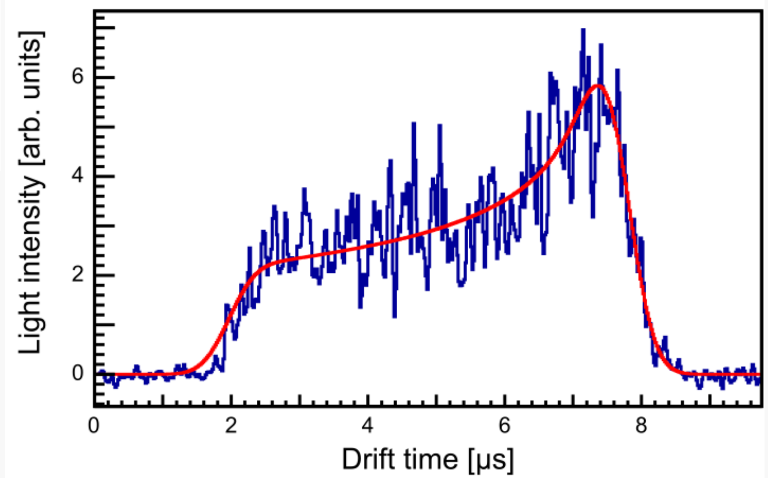
- A track is reconstructed by comparing the data with the SRIM simulation





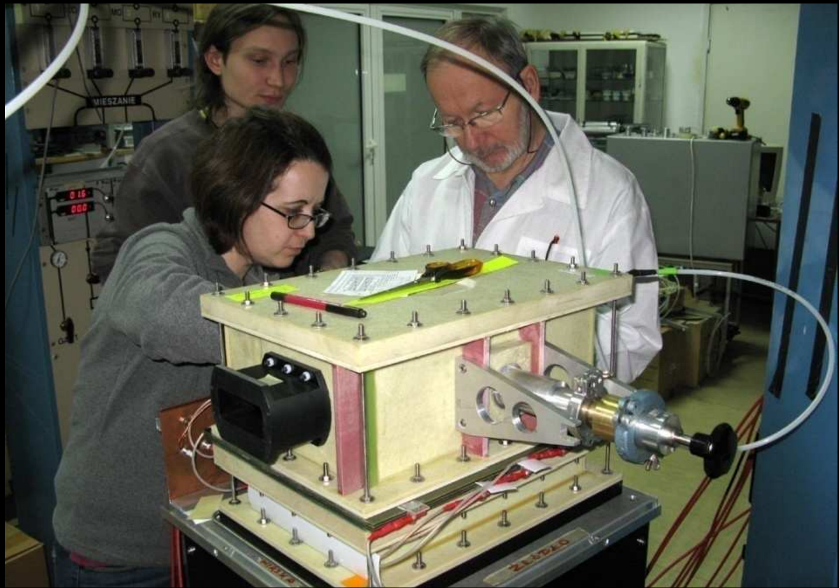
E_p = 1393 (50)(6) keV

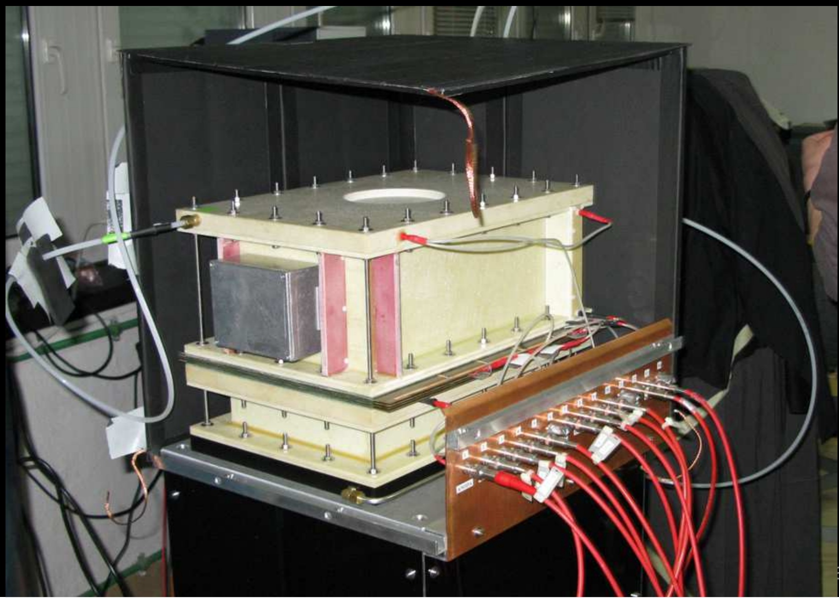
Θ = 28 (4)(1)°



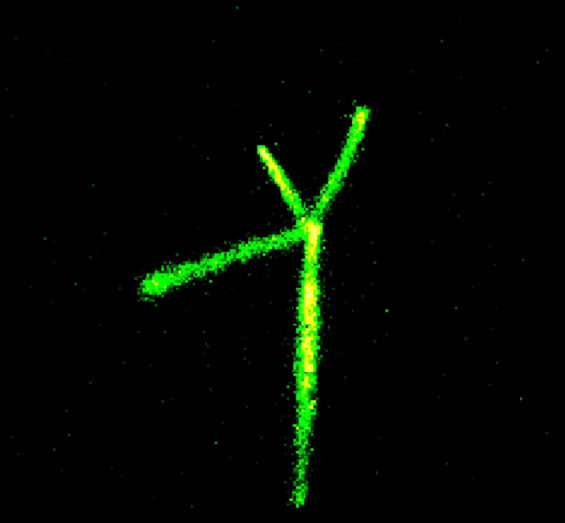
Pomorski et al., PRC 90 (14) 014311

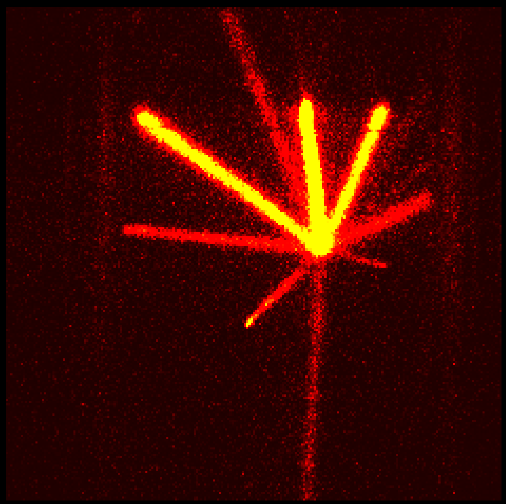
OTPC





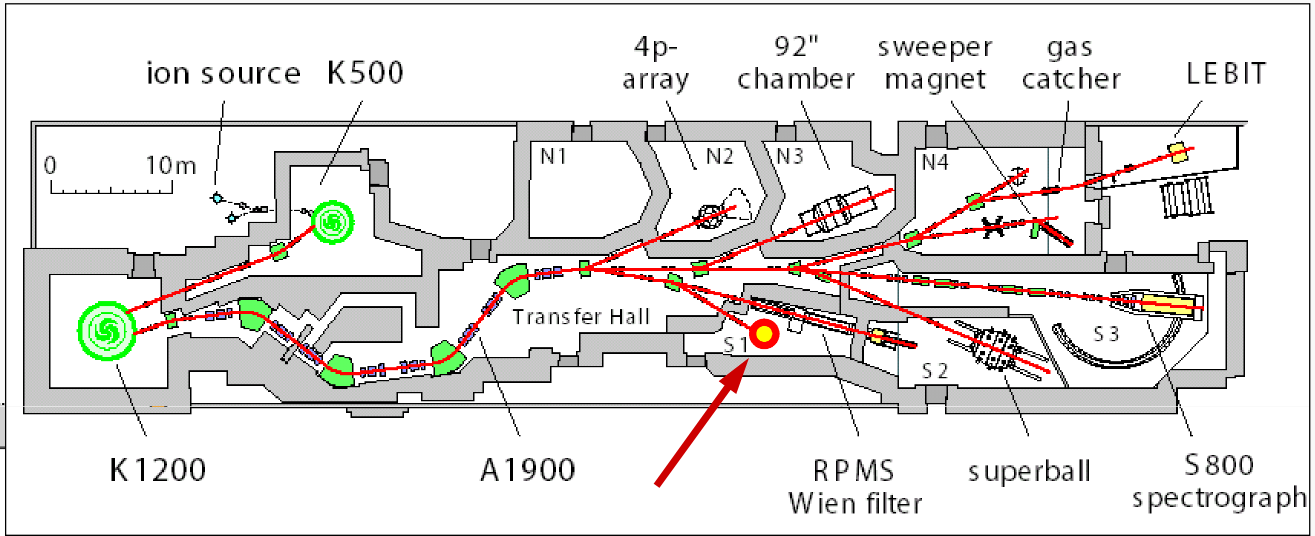
OTPC

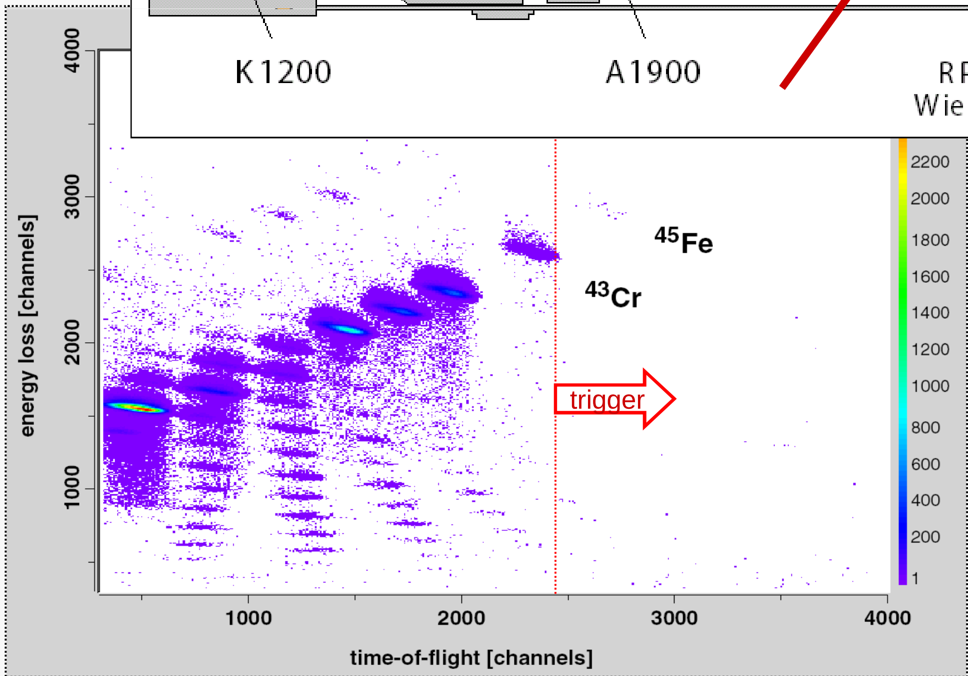


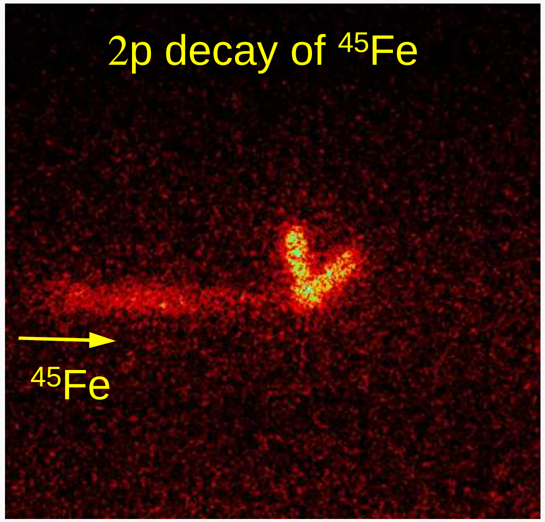


Study of ^{45}Fe

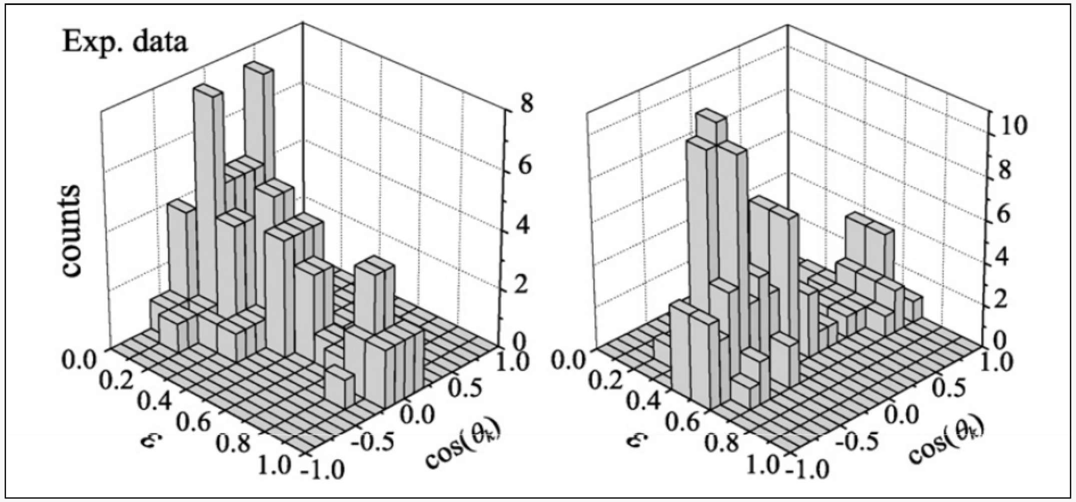
- NSCL/MSU, February 2007: ^{58}Ni at 161 MeV/u + $^{nat}Ni \rightarrow {}^{45}Fe$

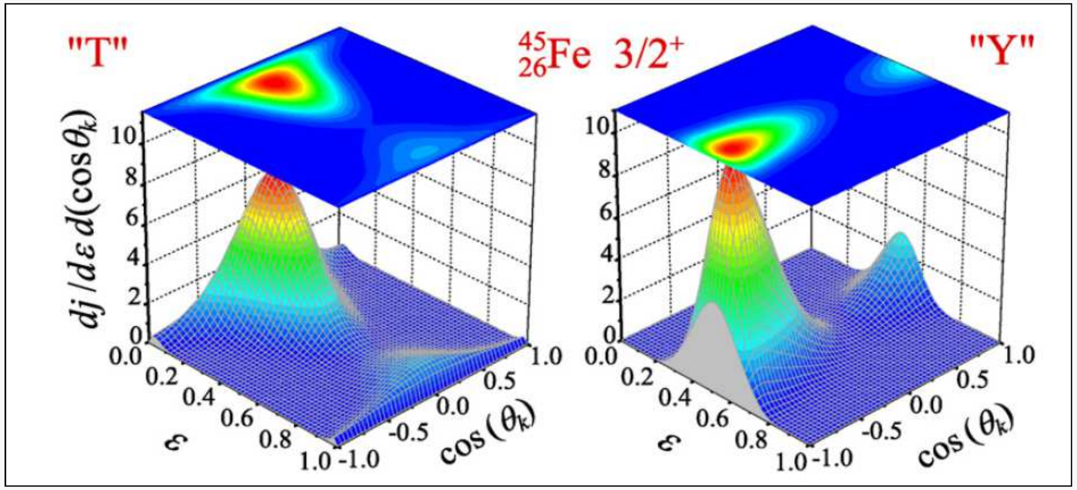






p-p momentum correlations for ^{45}Fe



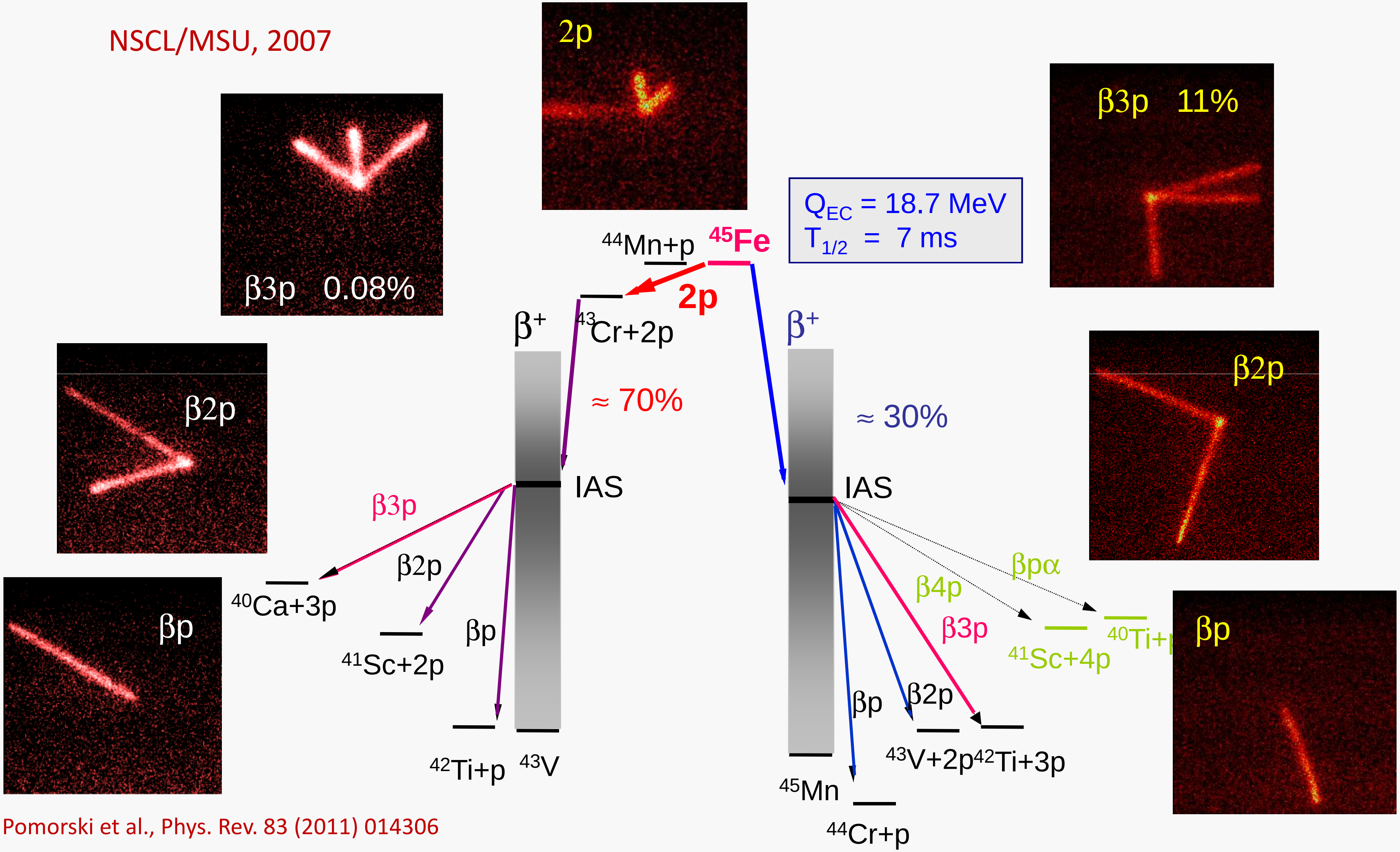


- Proton-proton momentum correlations measured for ^{45}Fe are complex and indicate a genuine 3-body phenomenon
- Good agreement with the 3-body model of Grigorenko et al.

Miernik *et al.*, PRL 99 (07) 192501 Grigorenko *et al.*, PLB 677 (2009) 30 MP, Karny, Grigorenko, Riisager, RMP 84 (12) 567

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

NSCL/MSU, 2007

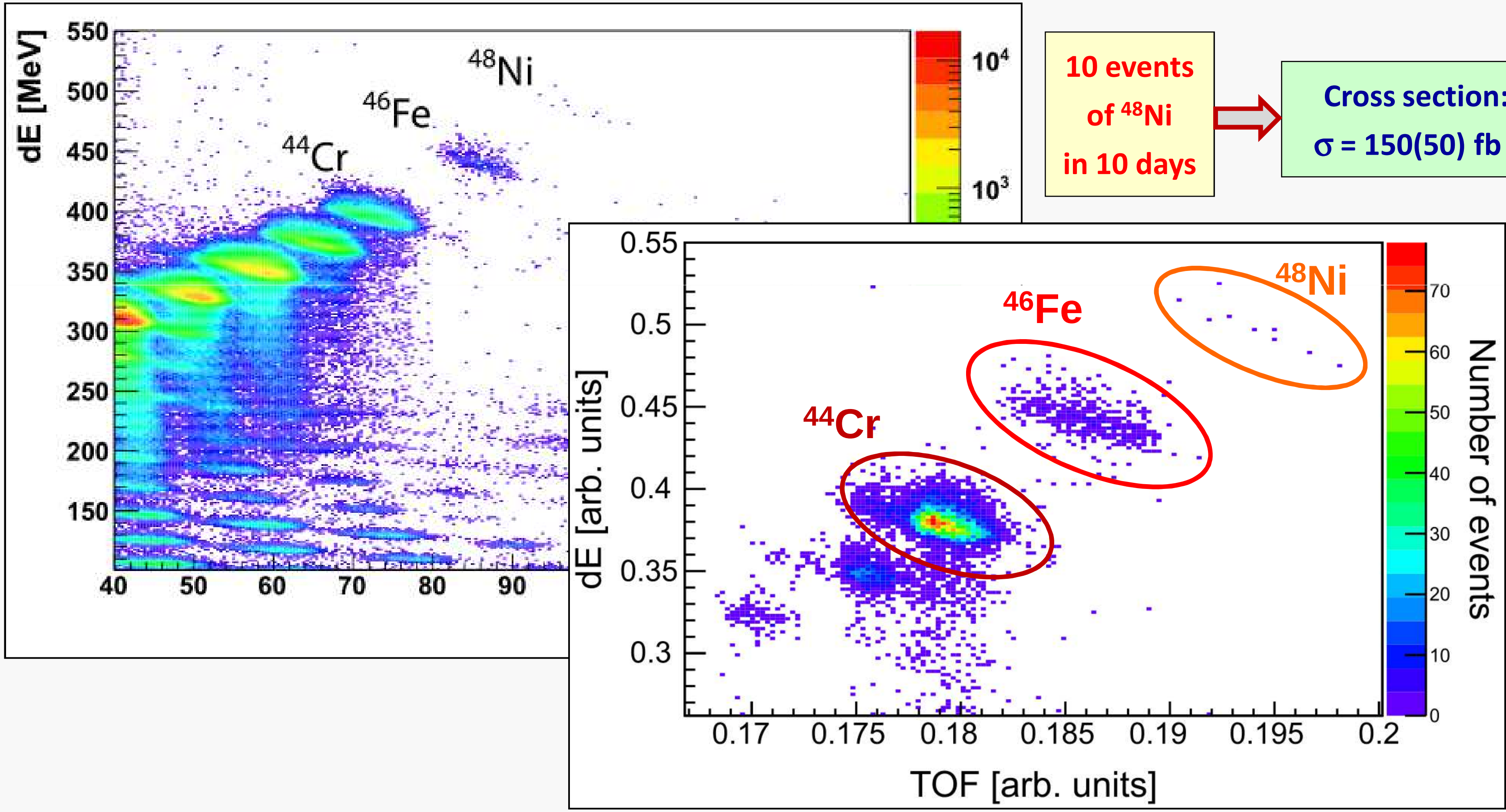


Pomorski et al., Phys. Rev. 83 (2011) 014306

Miernik et al., PRL 99 (07) 192501

Study of ^{48}Ni

- NSCL/MSU, March 2011: ^{58}Ni at 160 MeV/u + ^{nat}Ni → ^{48}Ni

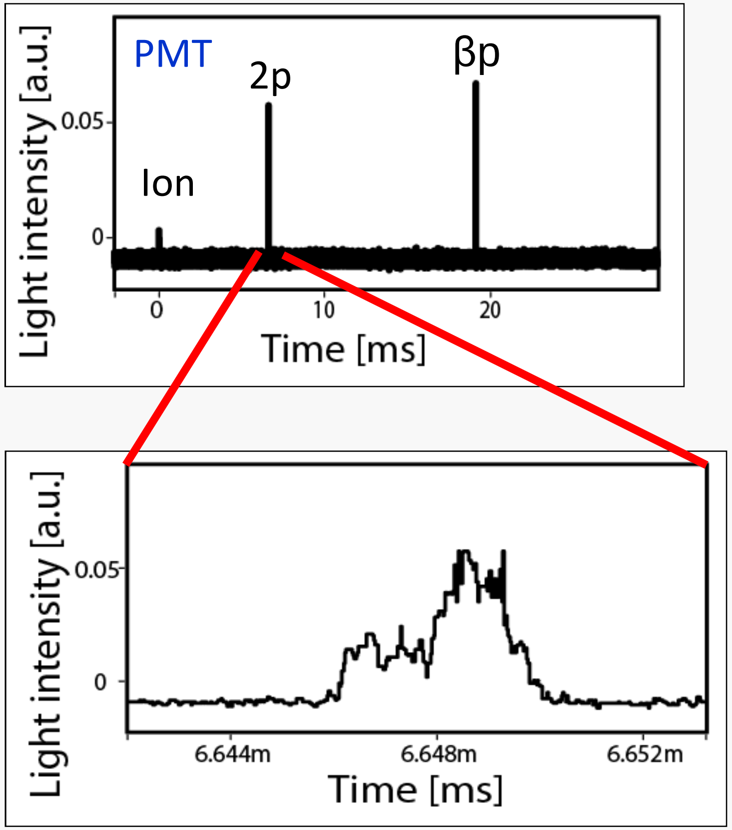


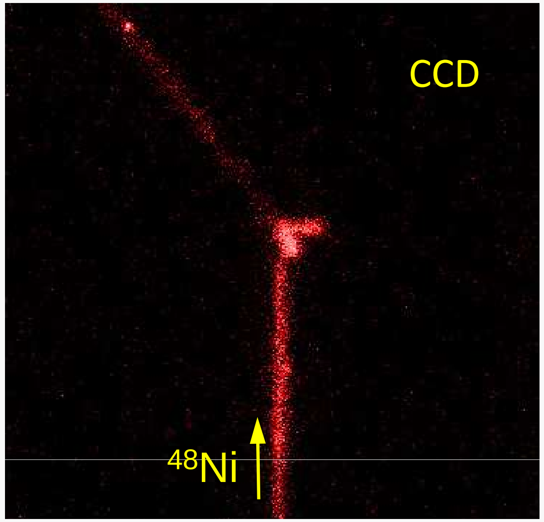
10 events of ^{48}Ni in 10 days

Cross section: σ = 150(50) fb !

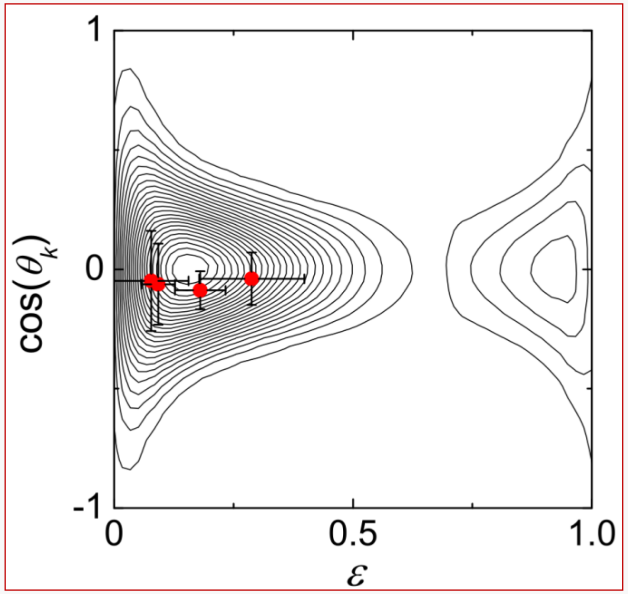
Pomorski et al., PRC 90 (14) 014311

2p decay of ^{48}Ni





Four 2p events of ^{48}Ni ⇒ Q_{2p} **= 1.29 (4) MeV**



Pomorski et al., PRC 90 (14) 014311

β-delayed protons from ^{44}Cr

5542 identified ions of ^{44}Cr

4098 properly stopped

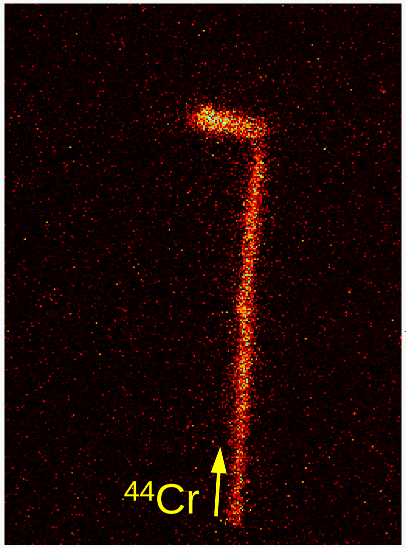
183 decays observed

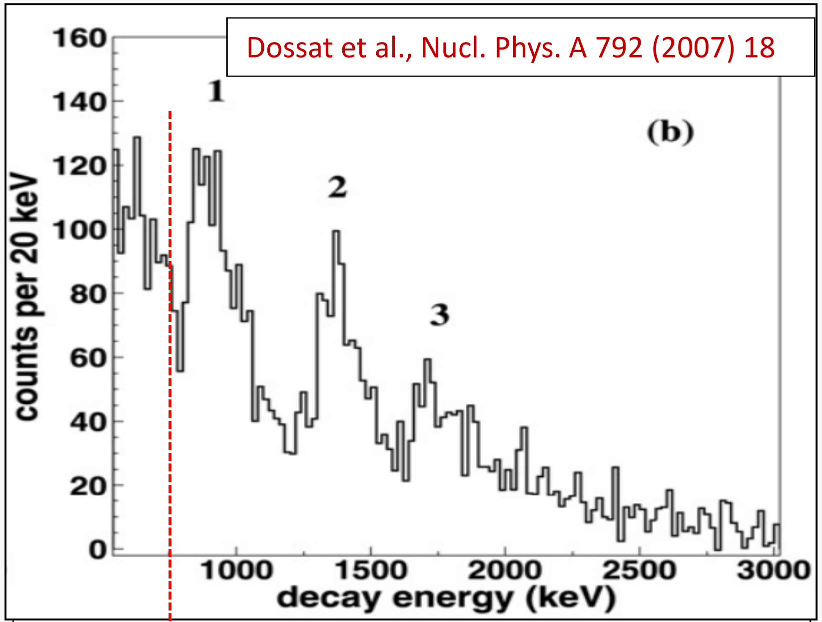
→ $b_p = 10(1)\%$

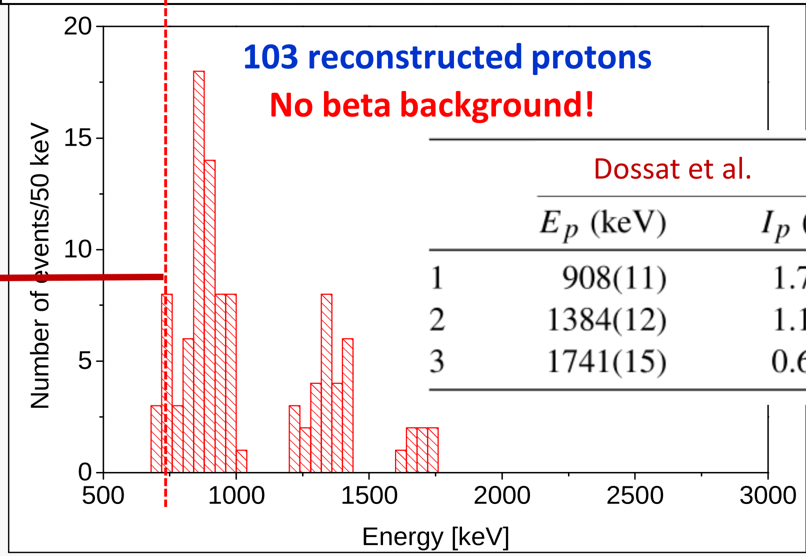
Dossat : $b_p = 14.0(9)\%$

A clear new line at 740(20) keV

$I_p = 0.6(2)\%$







	Dossat et al.		This work
	E_p (keV)	I_p (%)	
1	908(11)	1.7(3)	**2.7(5)%**
2	1384(12)	1.1(3)	**1.4(3)%**
3	1741(15)	0.6(3)	**0.5(2)%**

Pomorski et al., PRC 90 (14) 014311

β-delayed protons from ^{46}Fe

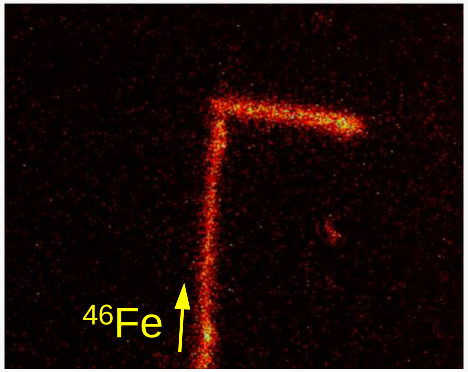
471 identified ions of ^{46}Fe

269 properly stopped

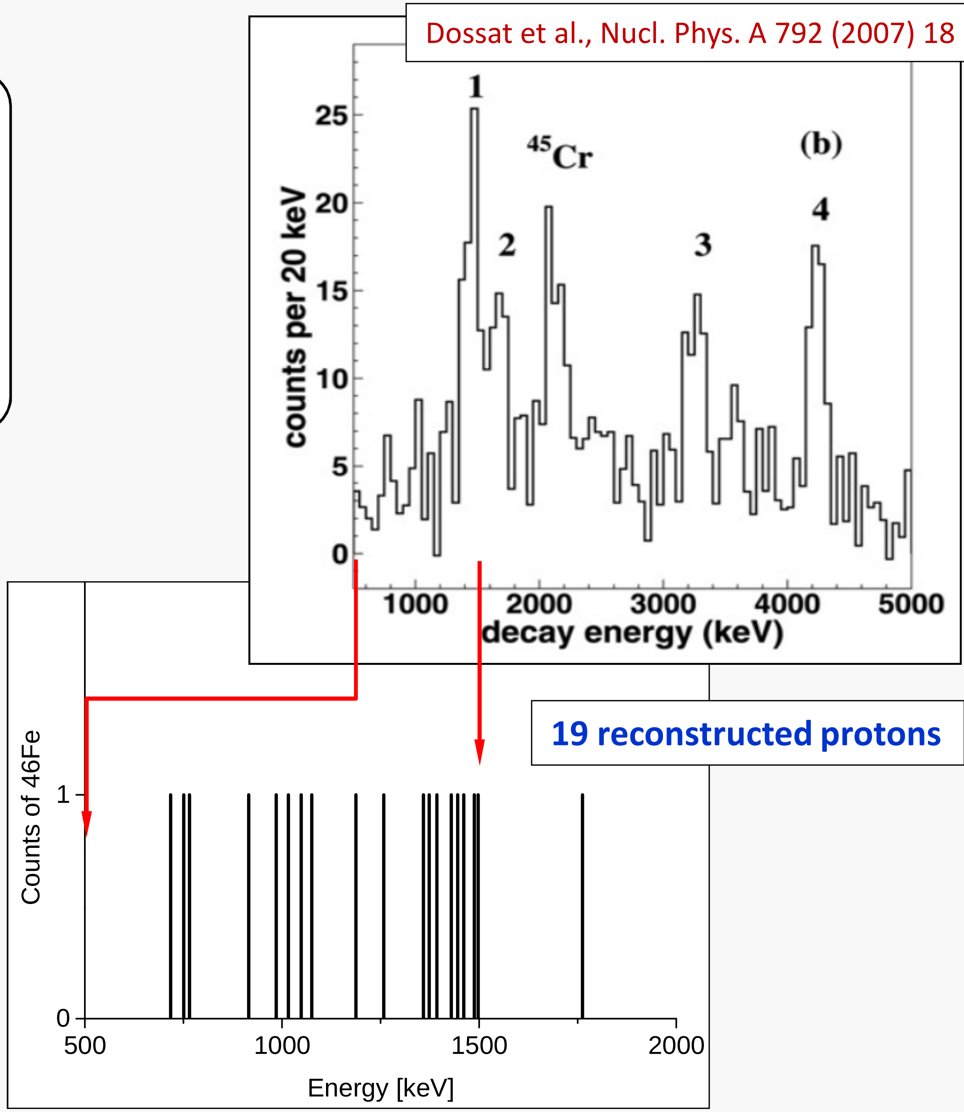
148 decays observed

→ $b_p = 66(4)\%$

Dossat : $b_p = 79(4)\%$



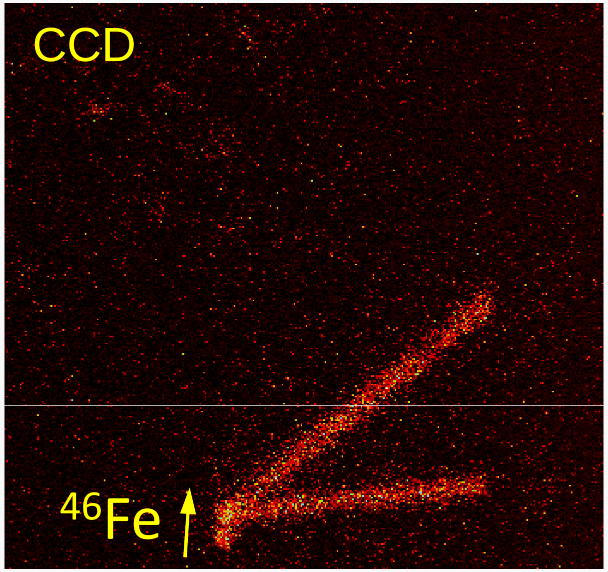
Dossat et al., Nucl. Phys. A 792 (2007) 18

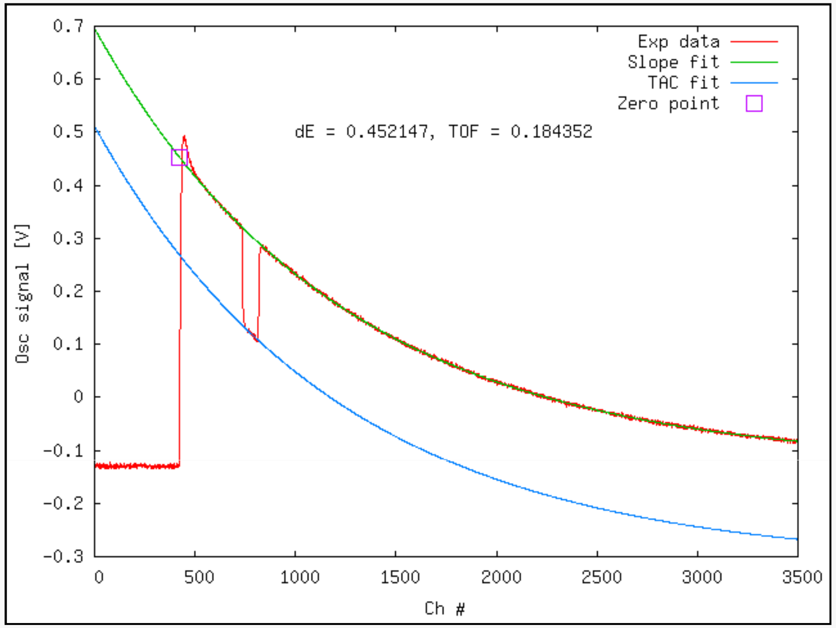


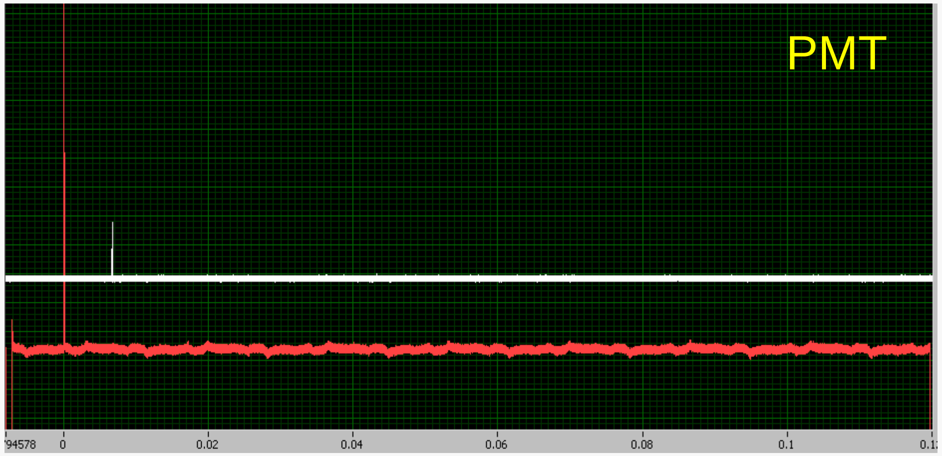
Pomorski et al., PRC 90 (14) 014311

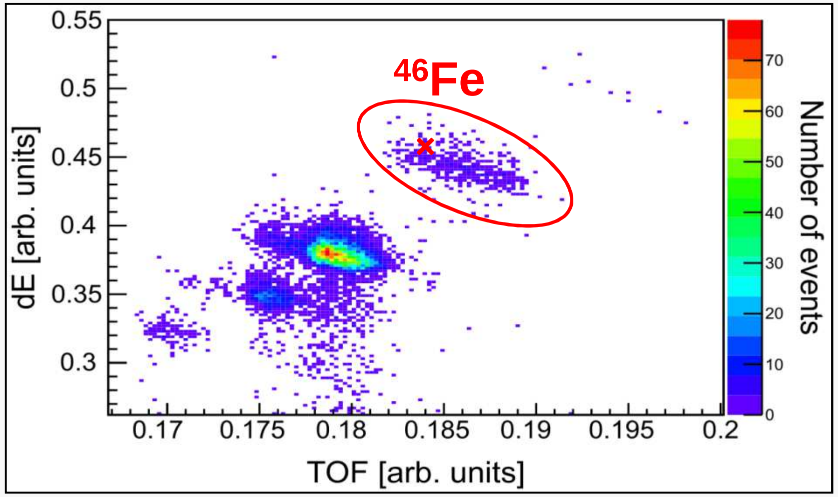
β2p channel in ^{46}Fe

- One good event!







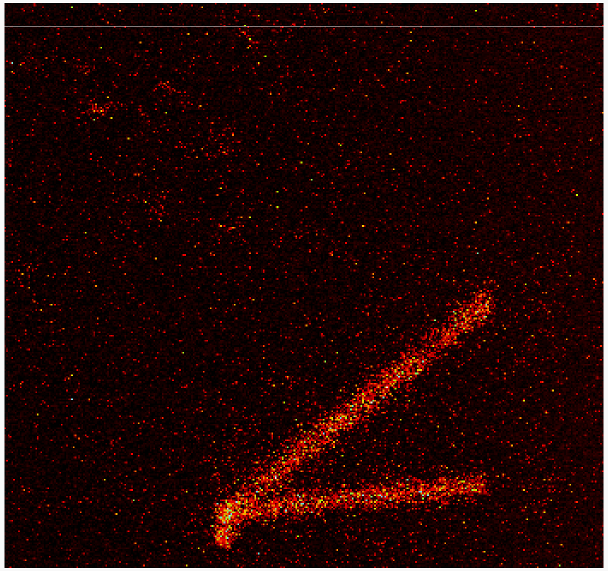


β2p channel in ^{46}Fe

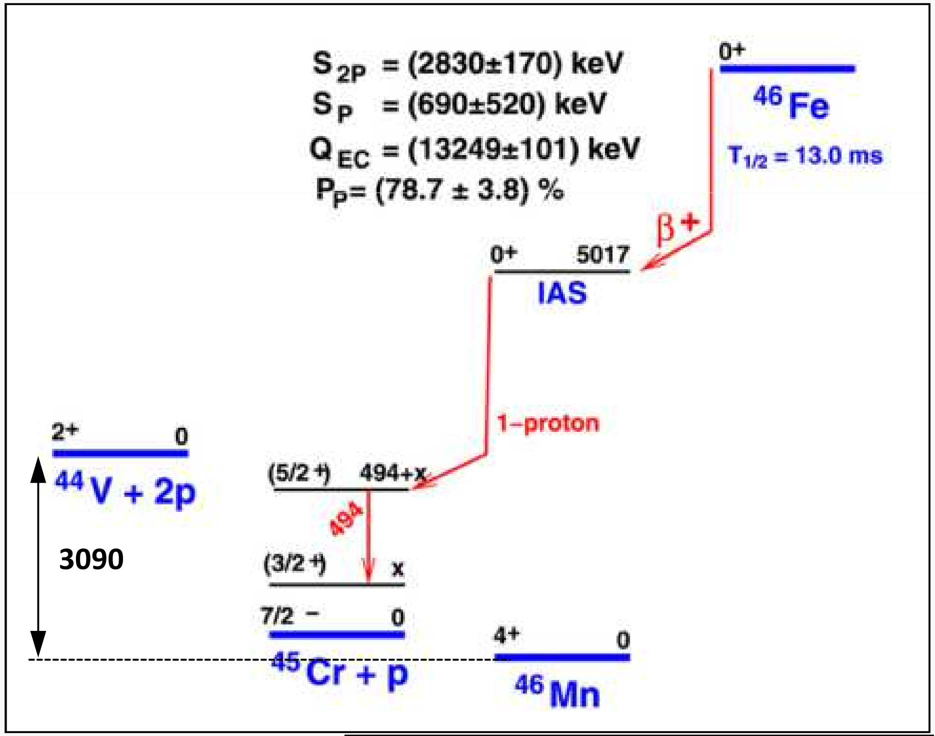
- Both protons escaped the detector. From the length of tracks we know only that:

$$E_1 > 1.96 \text{ MeV}$$
$$E_2 > 1.67 \text{ MeV}$$
$$E_1 + E_2 > 3.63 \text{ MeV}$$

This cannot go through the IAS!

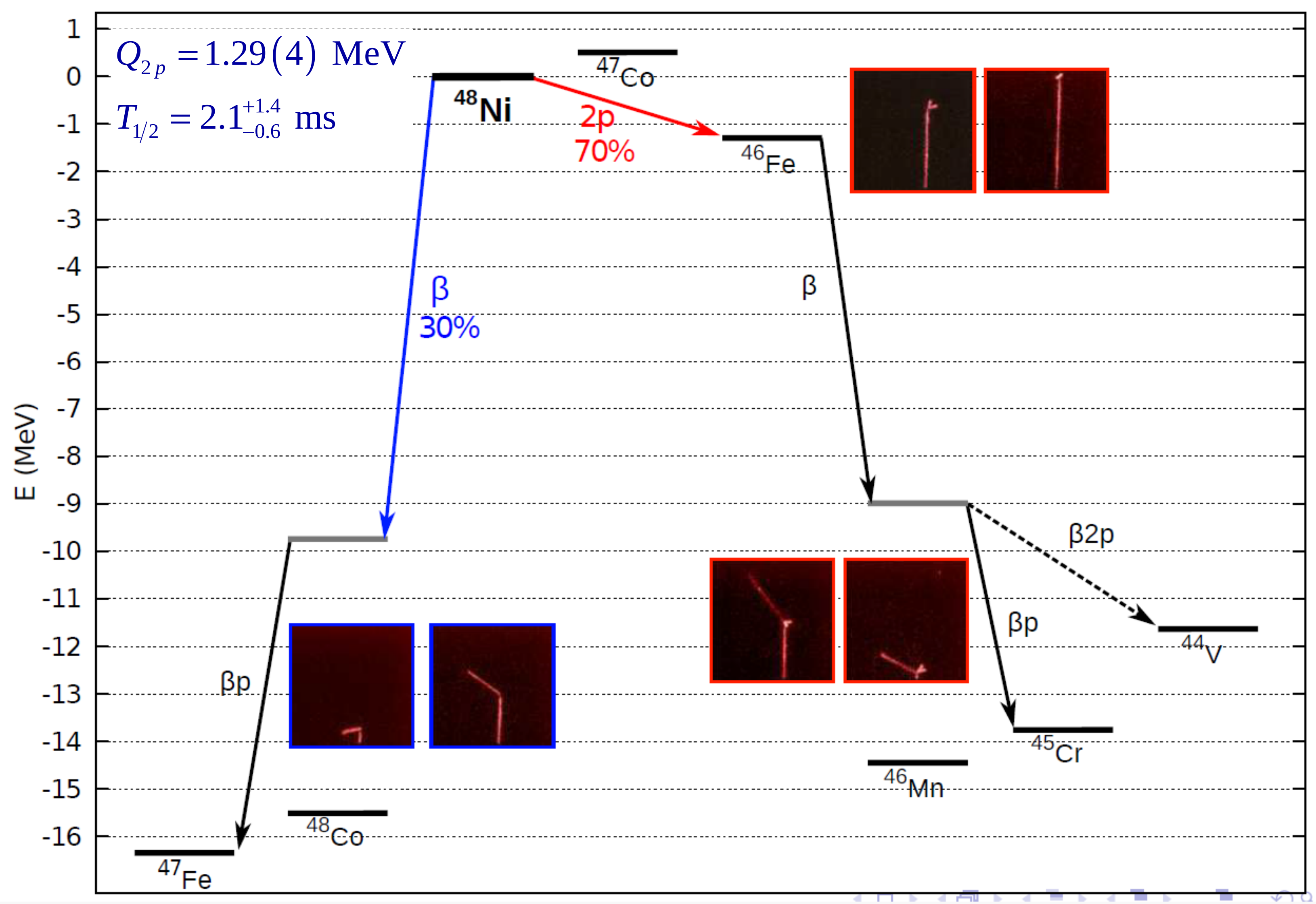


Pomorski et al., PRC 90 (14) 014311



Dossat et al., Nucl. Phys. A 792 (2007) 18

Decay scheme of ^{48}Ni



β3p in ^{31}Ar

PHYSICAL REVIEW C VOLUME 45, NUMBER 1 JANUARY 1992

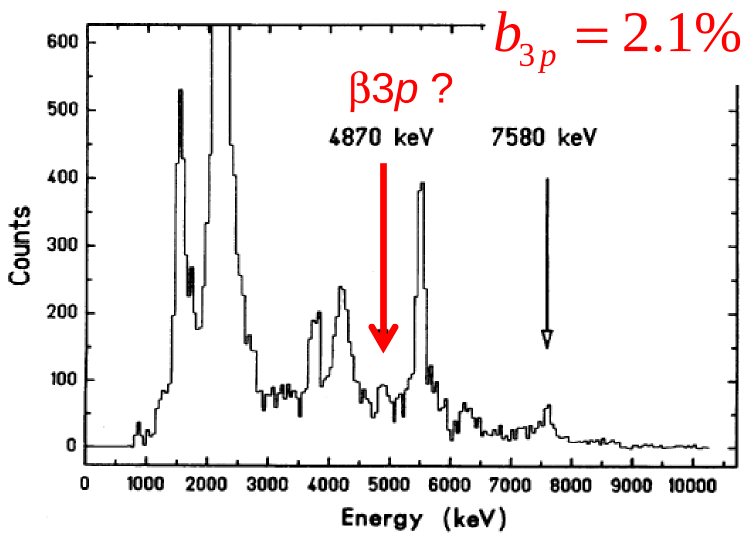
Decay modes of ^{31}Ar and first observation of β-delayed three-proton radioactivity

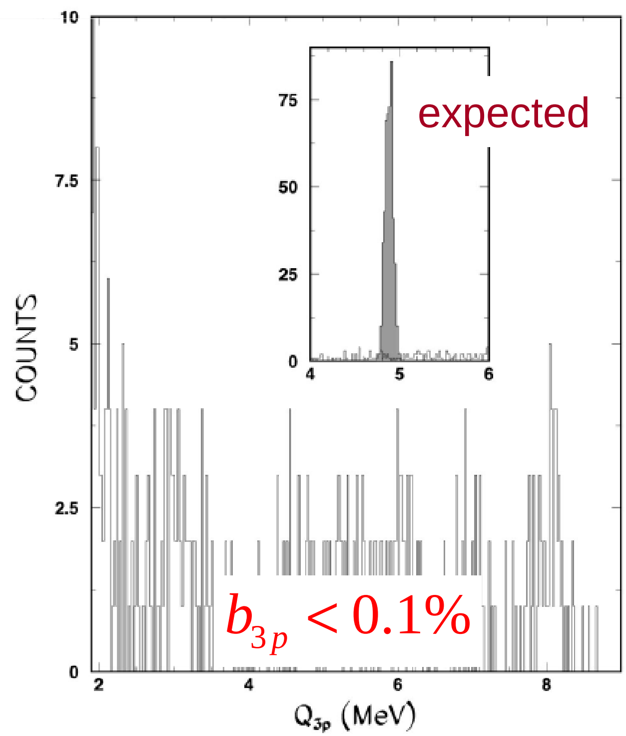
D. Bazin,* R. Del Moral, J. P. Dufour, A. Fleury, F. Hubert, and M. S. Pravikoff
Centre d'Etudes Nucléaires de Bordeaux–Gradignan, Le Haut Vigneau 33175 Gradignan CEDEX, France

PHYSICAL REVIEW C VOLUME 59, NUMBER 4 APRIL 1999

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

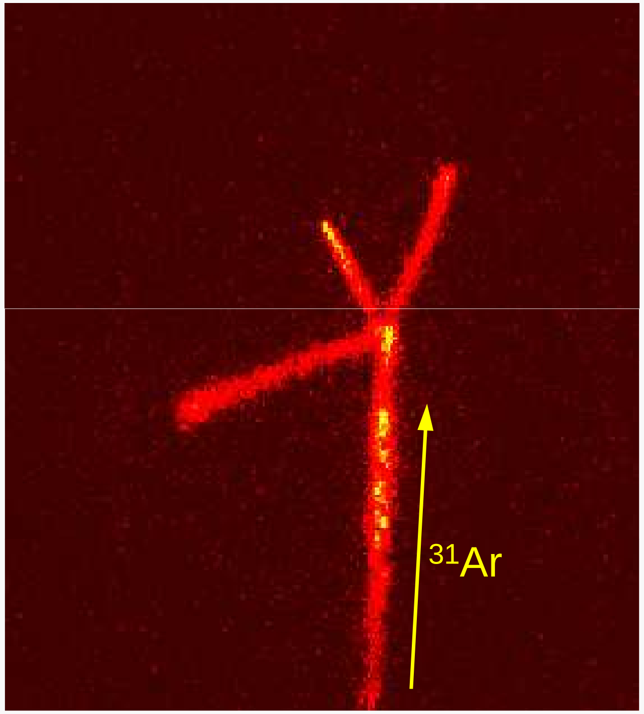
H. O. U. Fynbo,[1] L. Axelsson,[2] J. Äystö,[3] M. J. G. Borge,[4] L. M. Fraile,[4] A. Honk
A. Jokinen,[3] B. Jonson,[2] I. Martel,[5,†] I. Mukha,[1,‡] T. Nilsson,[2,§] G. Nyman,[2] M. Oin
M. H. Smedberg,[2] O. Tengblad,[4] F. Wenander,[2] and the ISOLDE



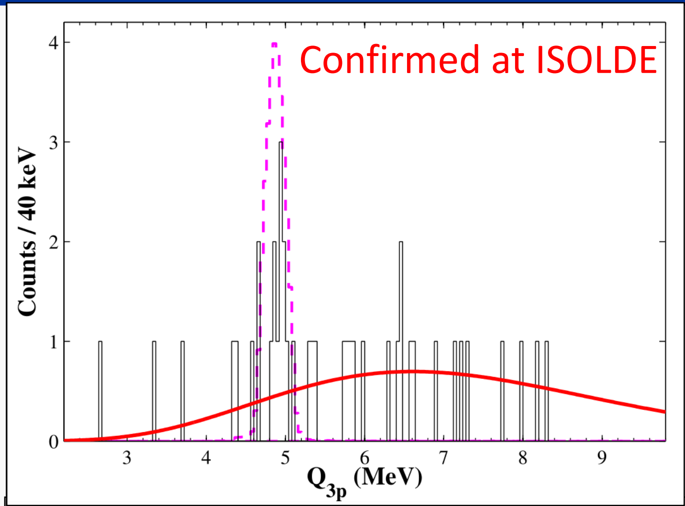


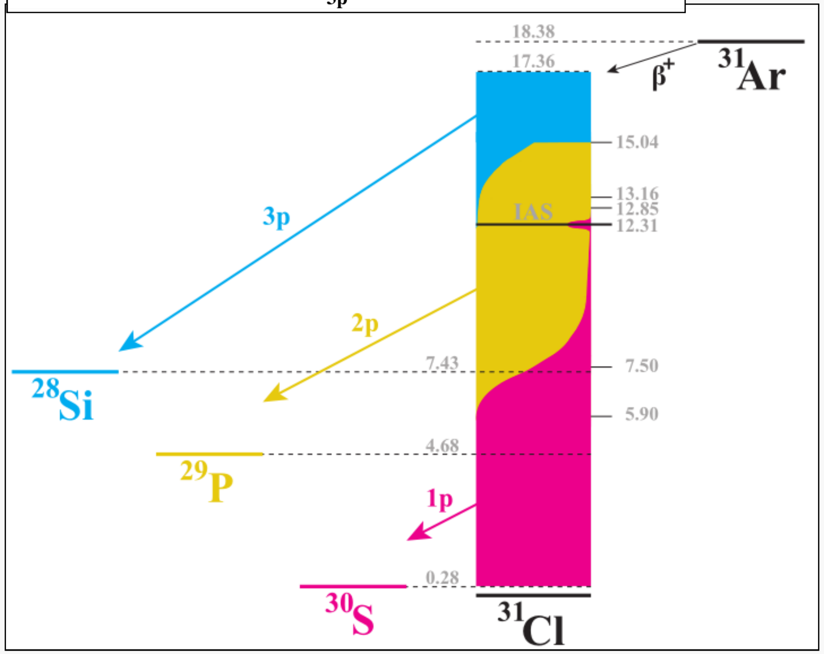
β3p in ^{31}Ar

- Experiment at FRS, August 2012



Lis et al., to be published

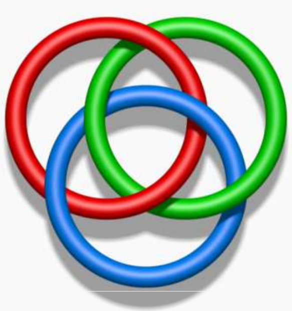


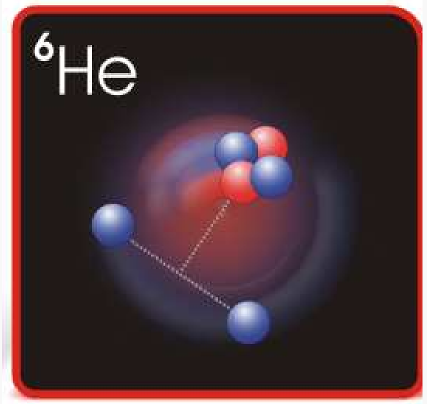


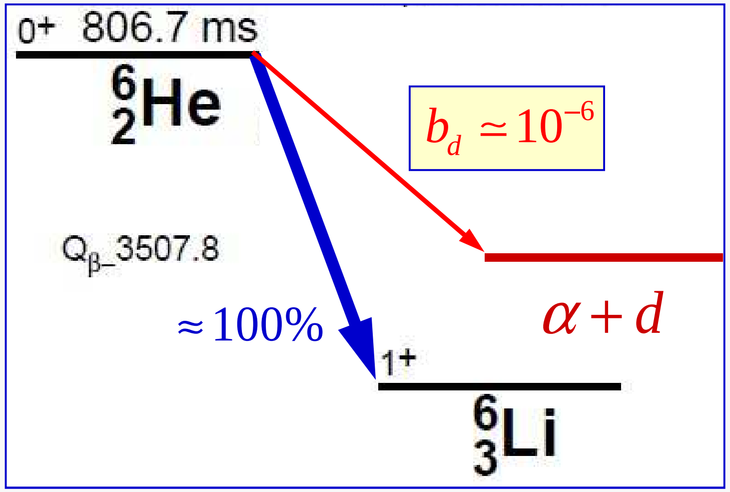
Koldste et al., PRC 89 (2014) 064315

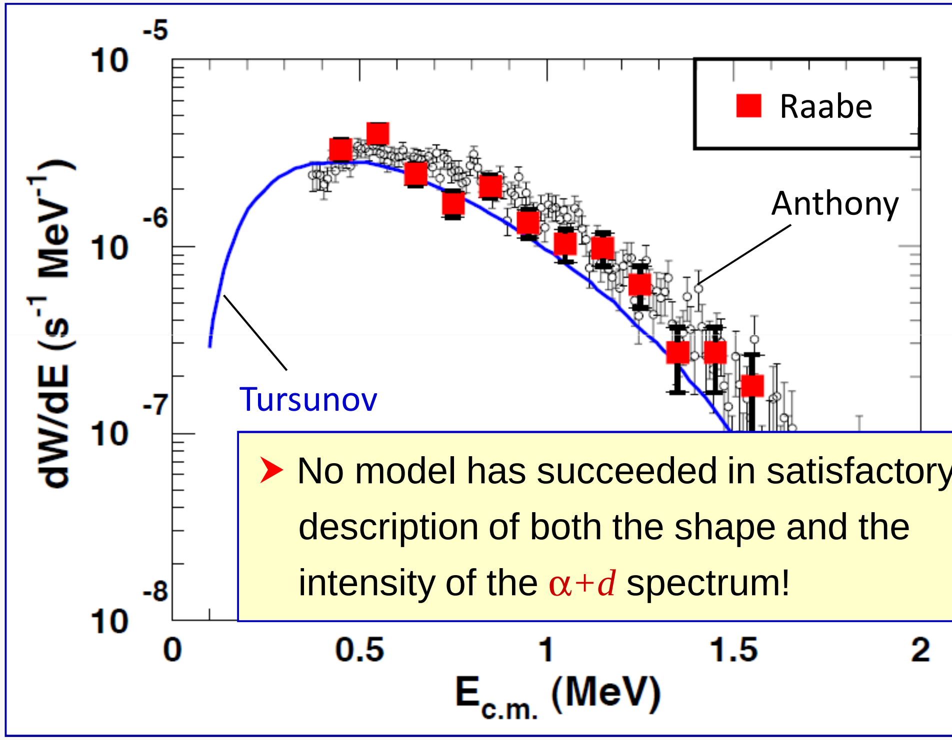
Decay of ^{6}He into α + *d*

- ^{6}He has a very weak decay branch to α + *d*









- No model has succeeded in satisfactory description of both the shape and the intensity of the α+*d* spectrum!

- Due to β-background, it was not possible to determine the spectrum below $E_{CM} \cong$ 400 keV!

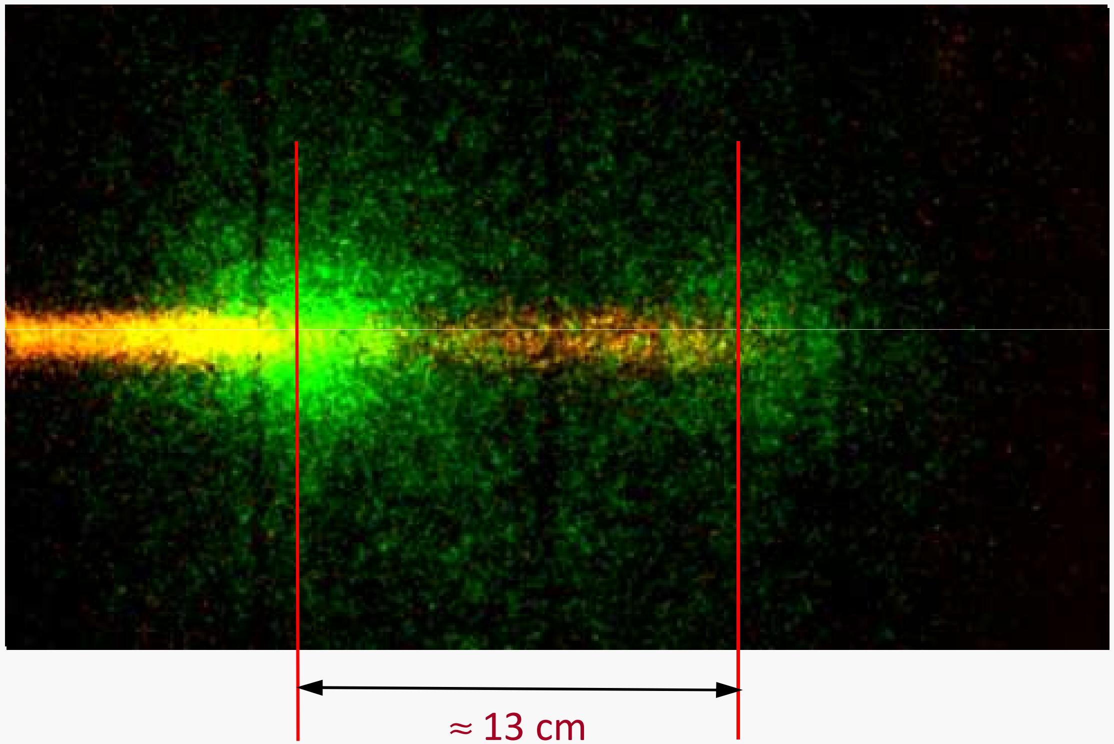
R. Raabe et al., Phys. Rev. C80 (2009) 054307

^{6}He into OTPC at ISOLDE

- Experiment at CERN-ISOLDE, August 2012

A bunch of ≈ 10^{3}-10^{4} ^{6}He ions, accelerated to 3 MeV/u by REX-Isolde, is implanted into the OTPC

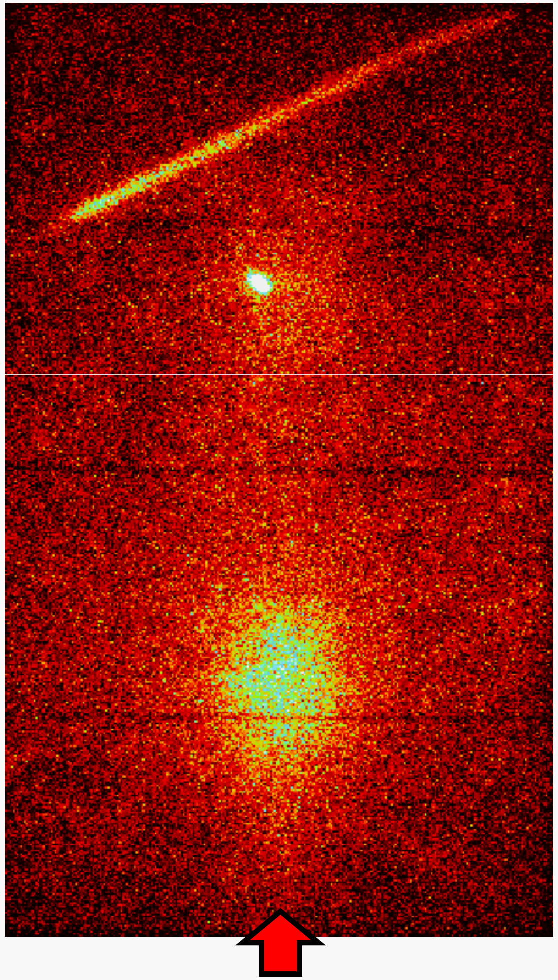
Data are taken for 650 ms exposure. Light from many beta decays is seen as a smeared cloud around the implantation points



- The difference in the depth of implantation corresponds to the energy loss of ^{6}He in a layer of 5 μm of Cu + 2 μm of Au

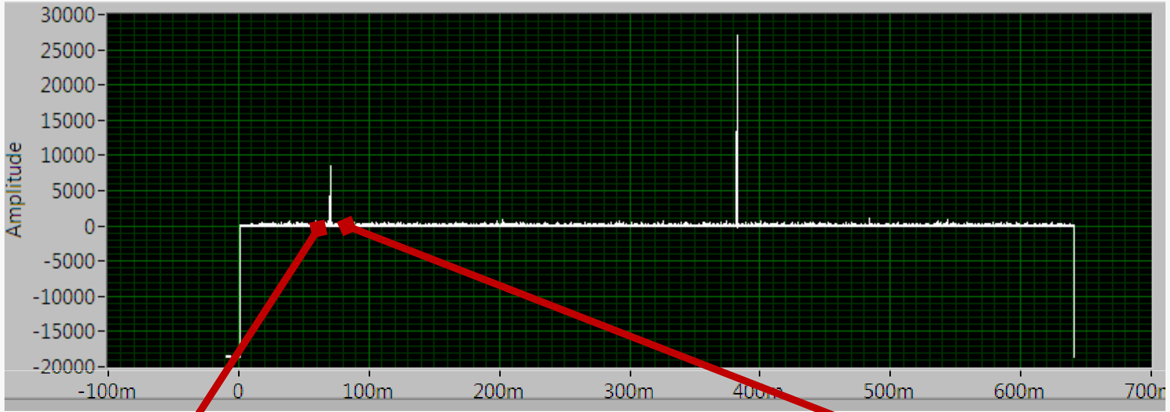
Decay of ^{6}He with OTPC at ISOLDE

CCD image, 650 ms exposure

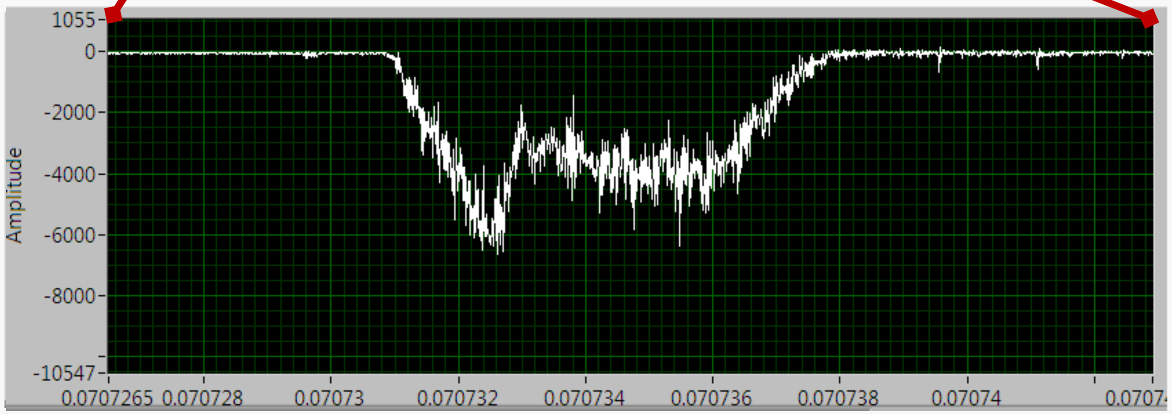


Bunch of 10^{3}-10^{4} ^{6}He ions

PMT slow sampling, 1 MHz (rough history of what happened)

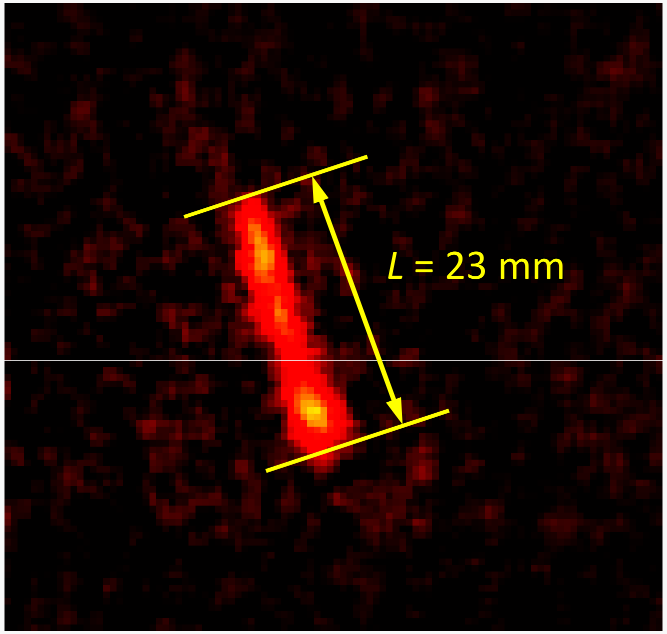


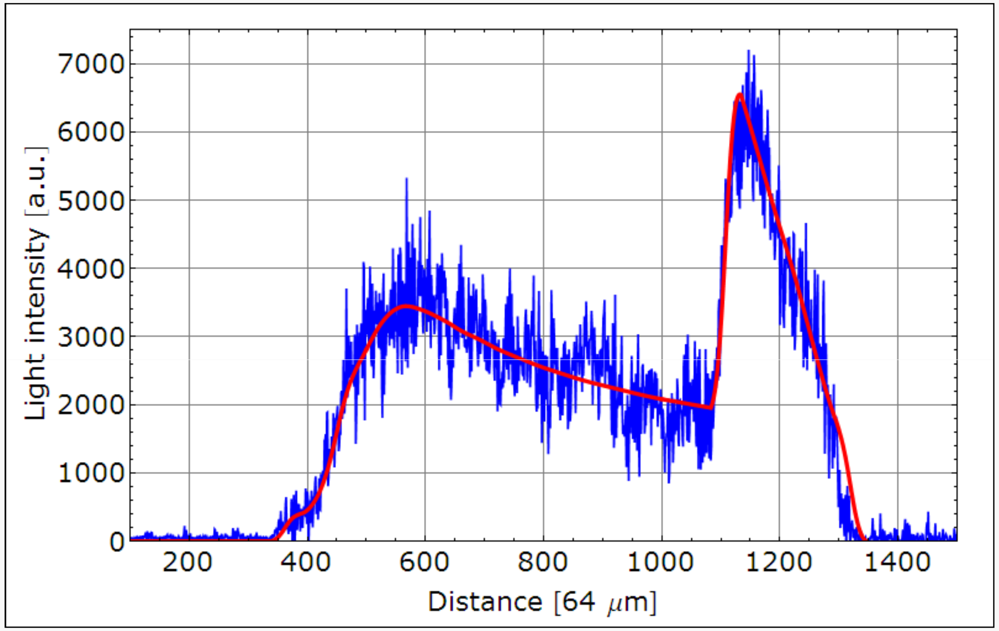
PMT fast sampling, 100 MHz (fine details of events)



- Practically no background in the PMT traces

Event reconstruction



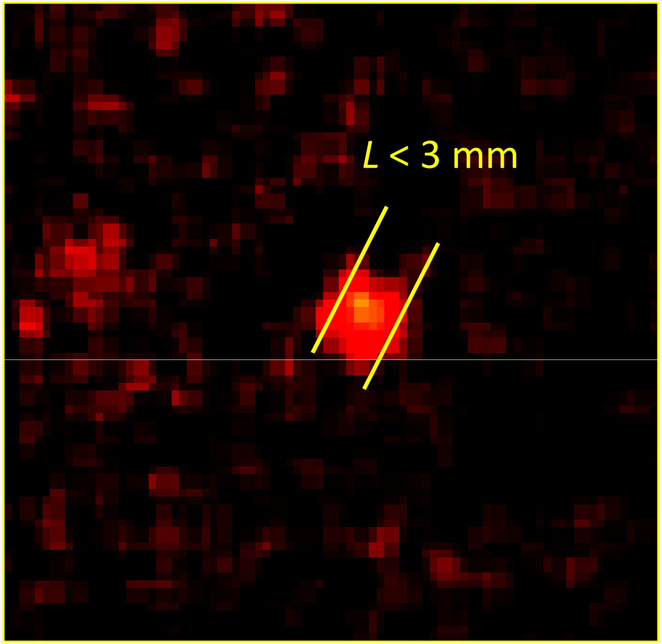


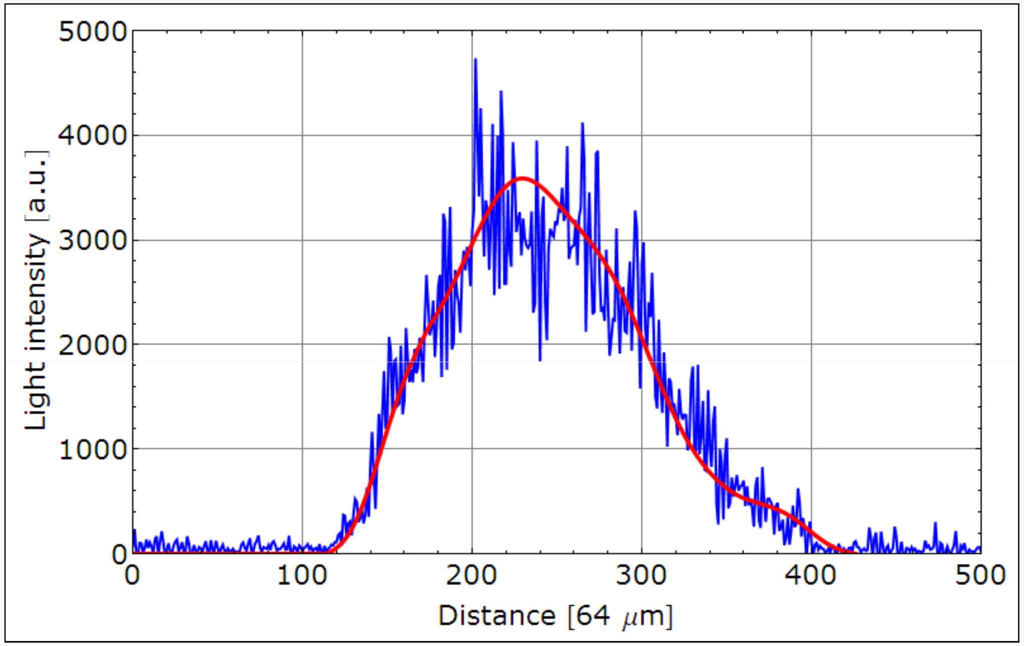
Horizontal length: 23 mm
Vertical length : 62 mm

Total length = 66 mm
Angle = 69°

Energy = 1000 ± 30 keV

Event reconstruction





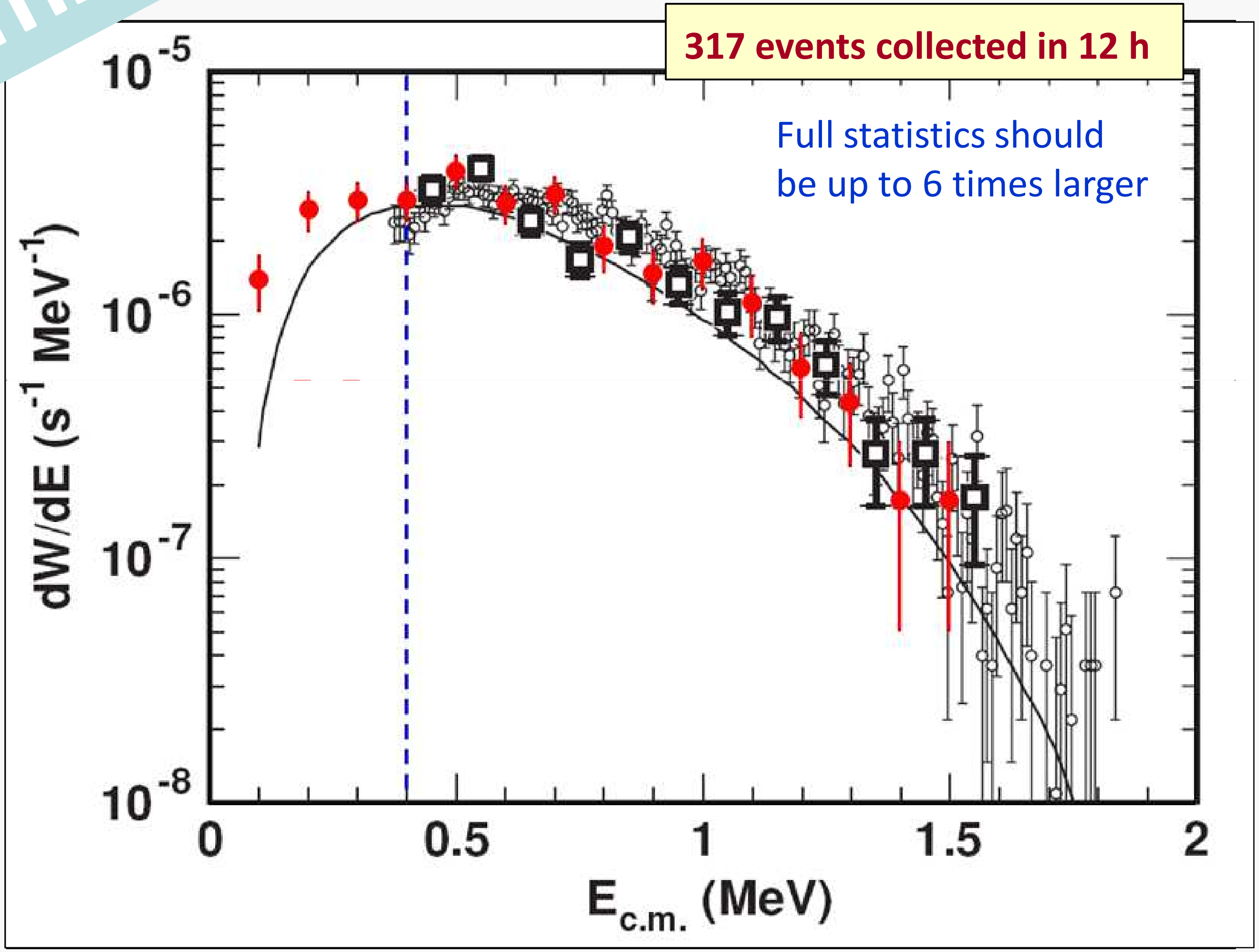
Horizontal length: 3 mm
Vertical length : 16 mm

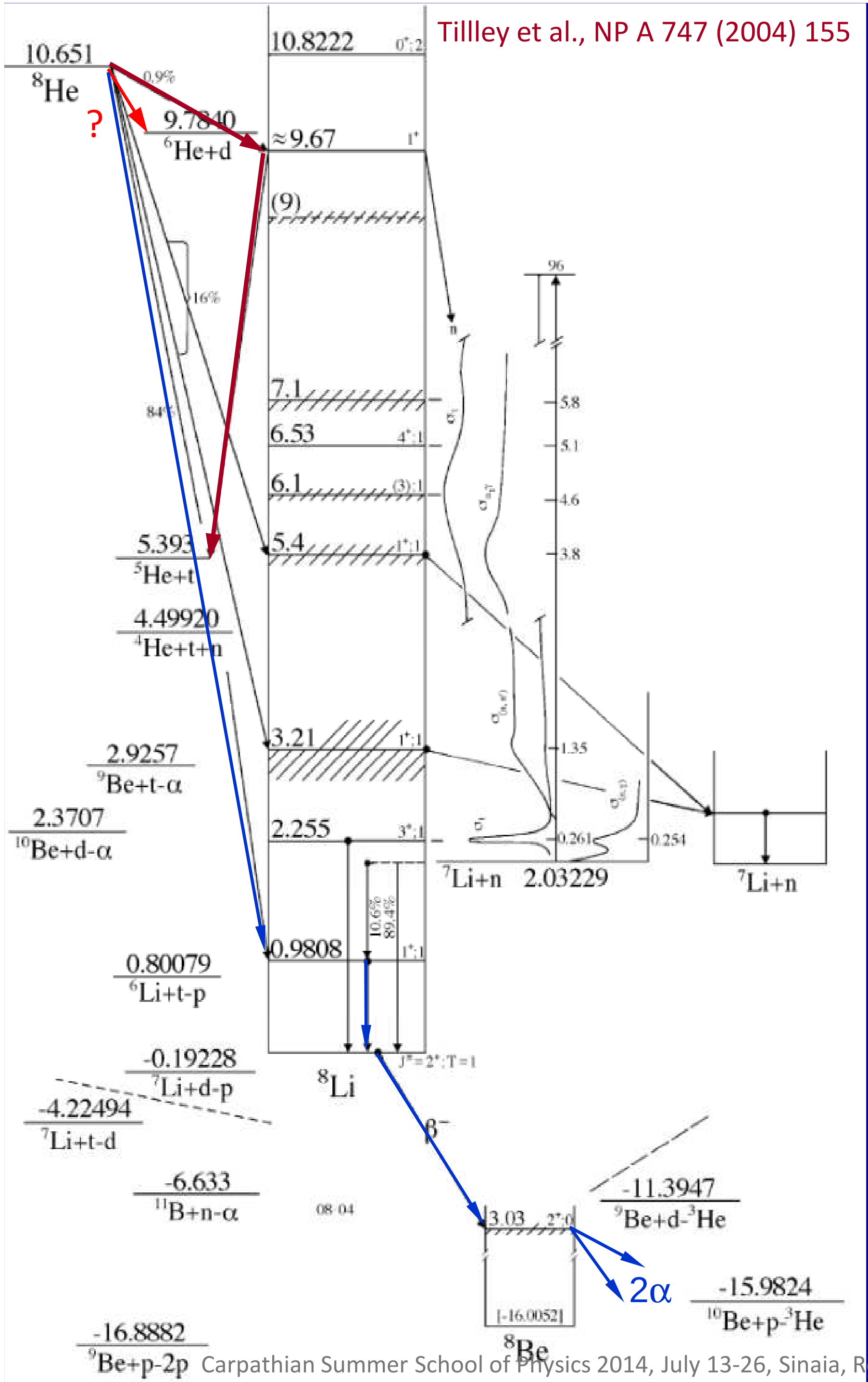
Total length = 16 mm
Angle = 80°

Energy = 150 ± 10 keV

The spectrum

Preliminary!





Tillley et al., NP A 747 (2004) 155

β decay of ^{8}He

- The previous experiment on ^{8}He β decay :

  ISOLDE (1992)

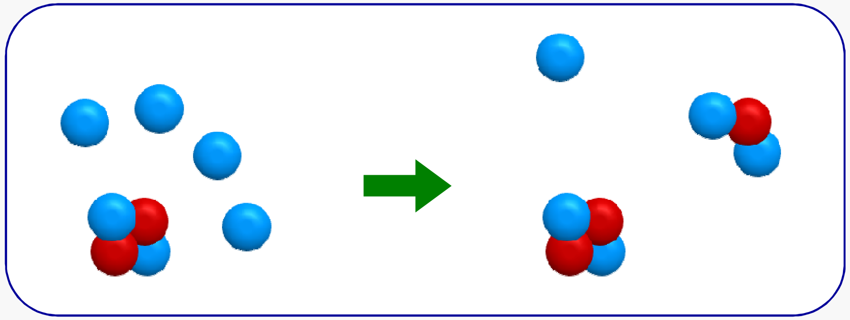
  M. Borge et al., NP A 560 (1993) 664

- Observation of strong β-delayed triton channel

$$^{8}\mathrm{He} \rightarrow {}^{8}\mathrm{Li}^{*} \rightarrow \alpha + \mathrm{t} + \mathrm{n}$$

The branching: $(8.0 \pm 0.5) \times 10^{-3}$

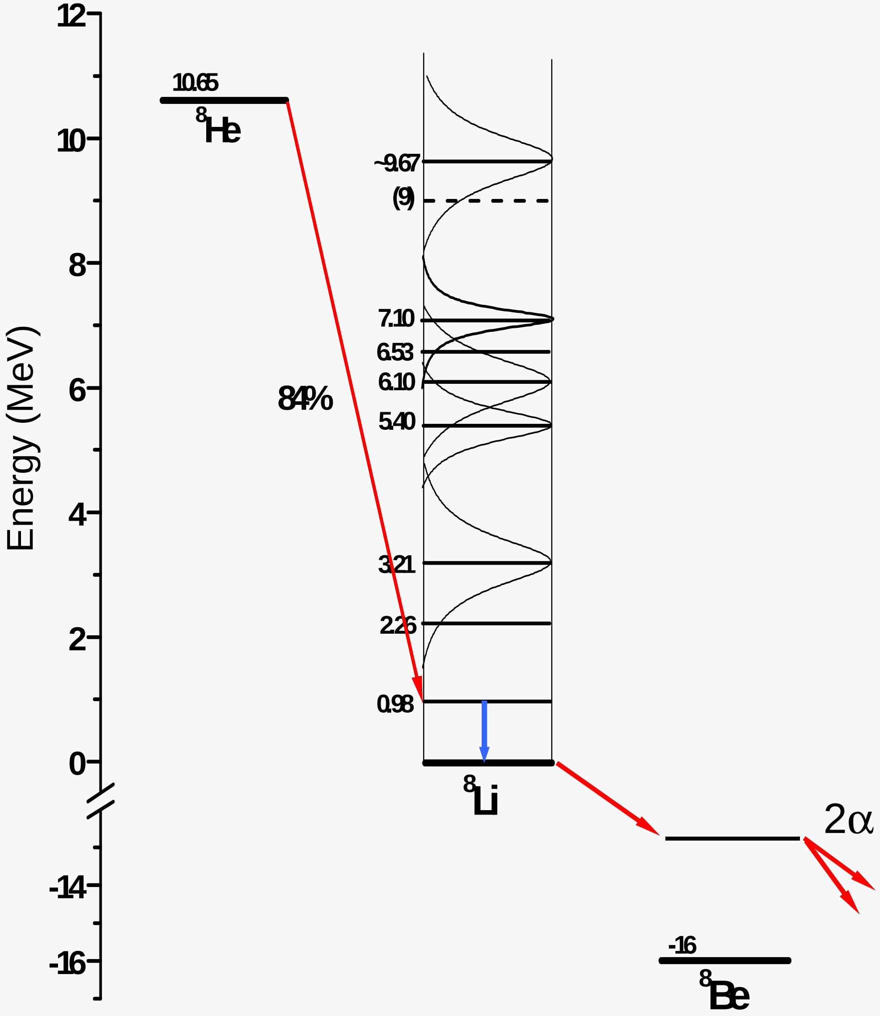
→ $B_{GT} \geq 5.2$, log $ft = 2.9$!

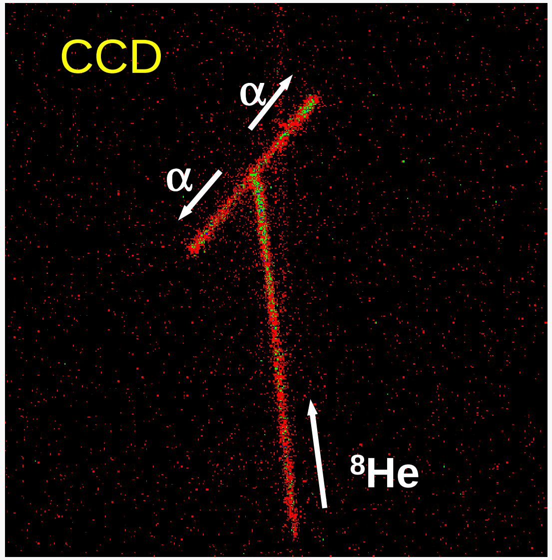


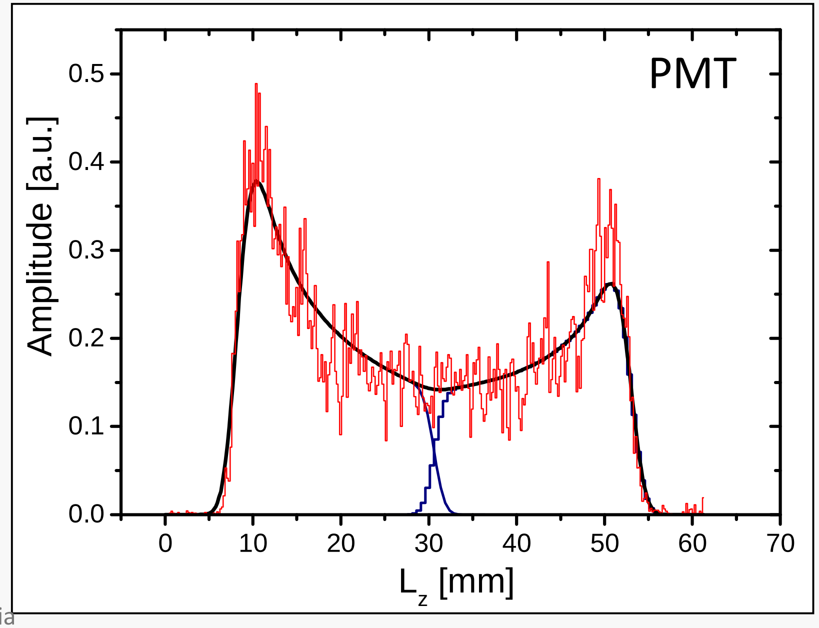
- Essentially, this is the tetra-neutron decay to a triton and a neutron! (If the clustering approximation is the good one).

Decays to particle bound states of ^{8}Li

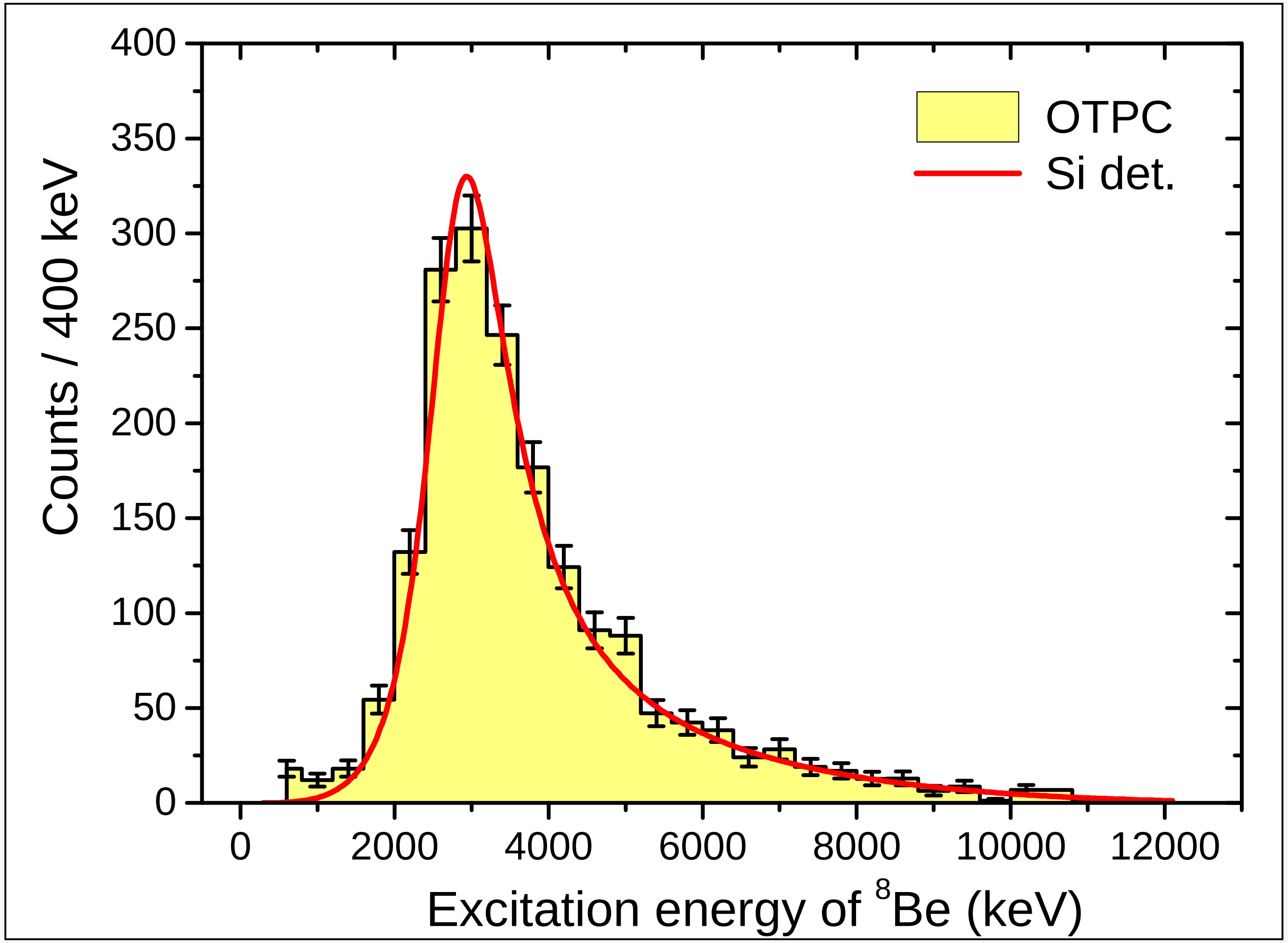
Dubna, Acculinna, 2009/2012





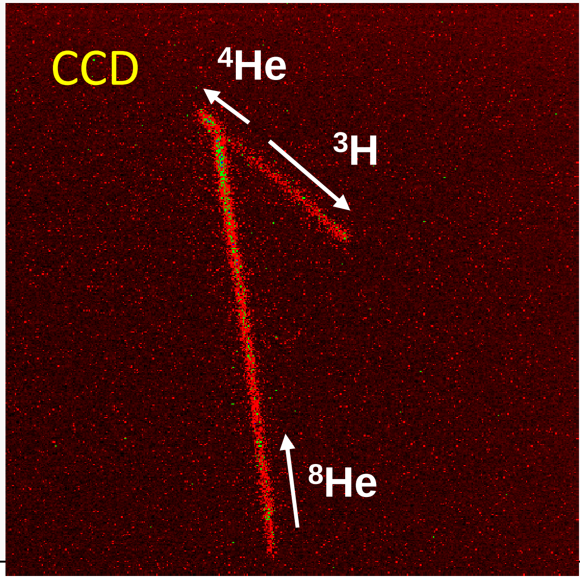


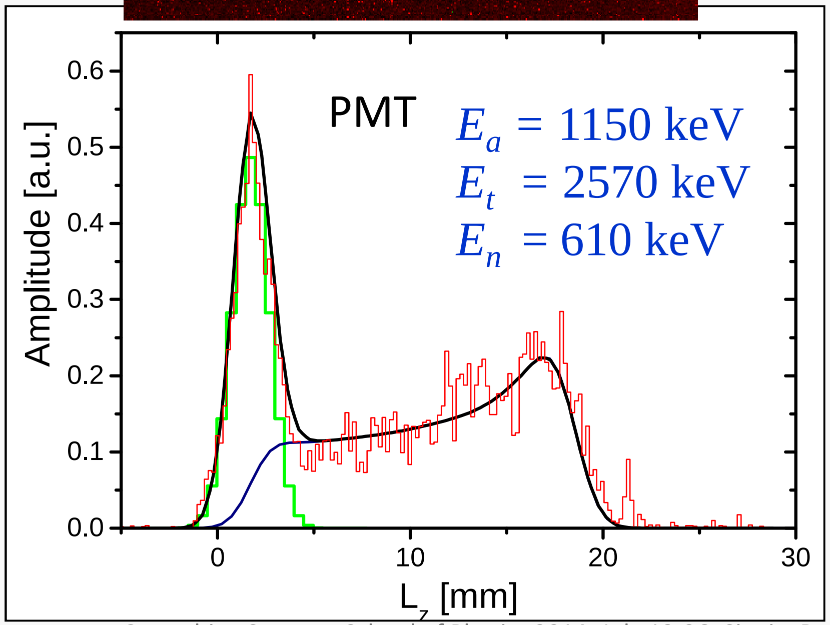
Final-state continuum in $^8Li \to 2\alpha$ decay

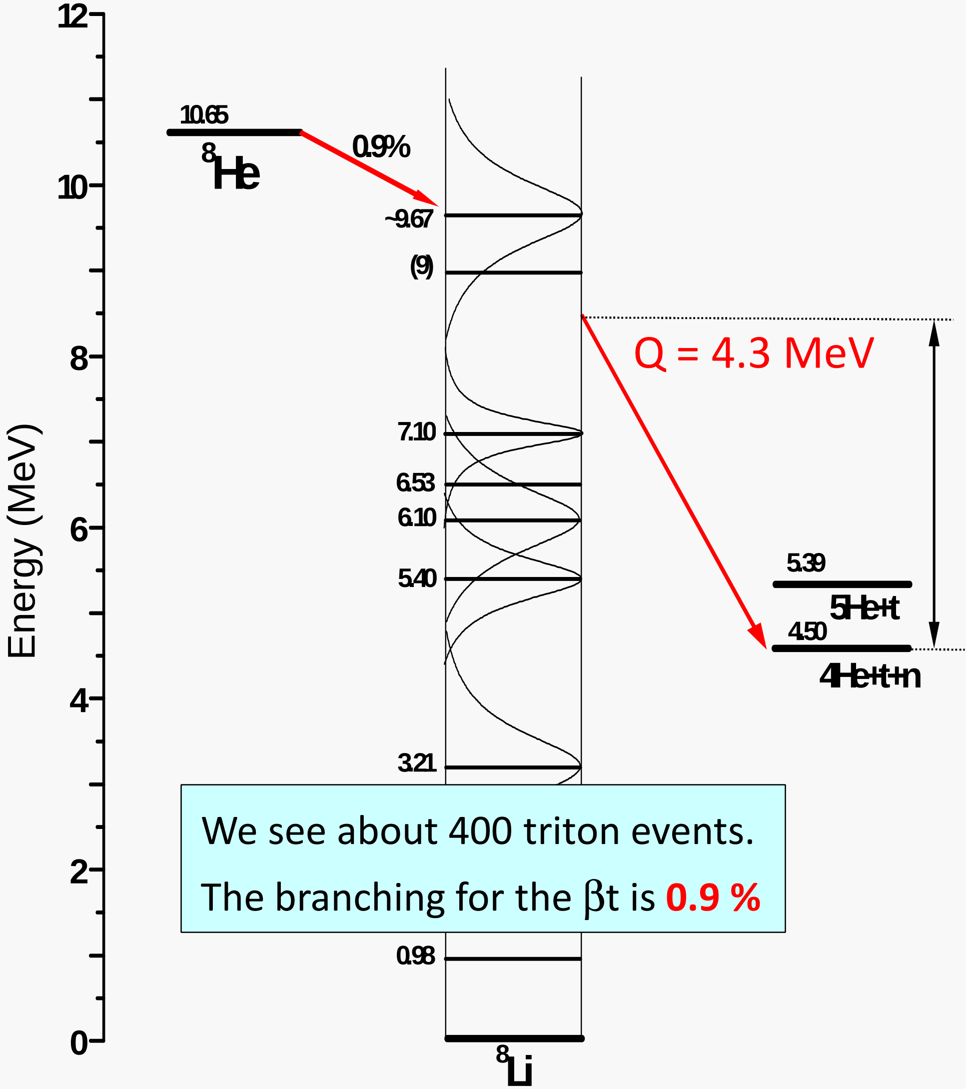


Mianowski, PhD thesis
Bhattacharya et al. PRC73(2006) 055802

Reconstruction of α-t-n decay event



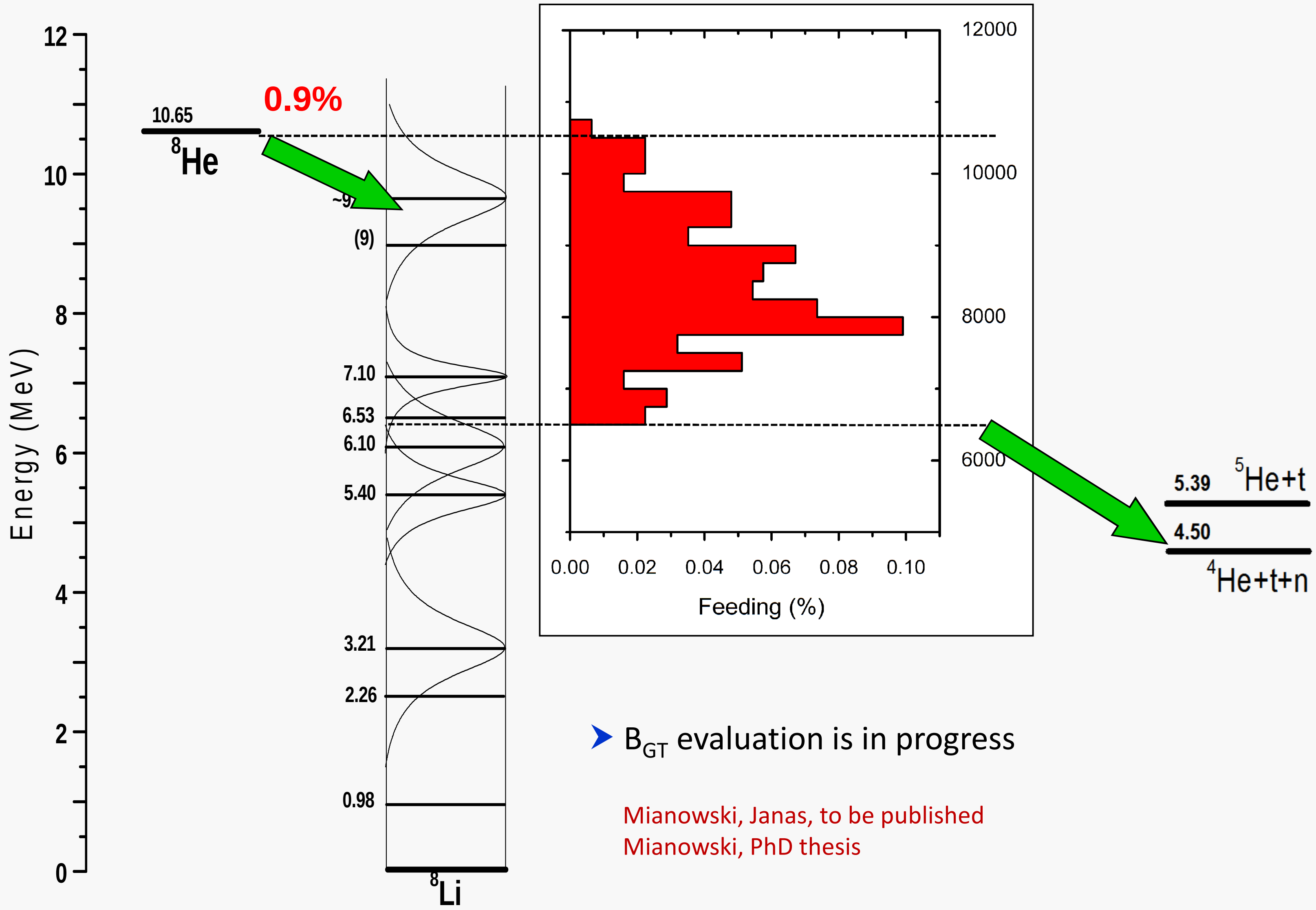




We see about 400 triton events.

The branching for the βt is **0.9 %**

Feeding of α-t-n decaying states

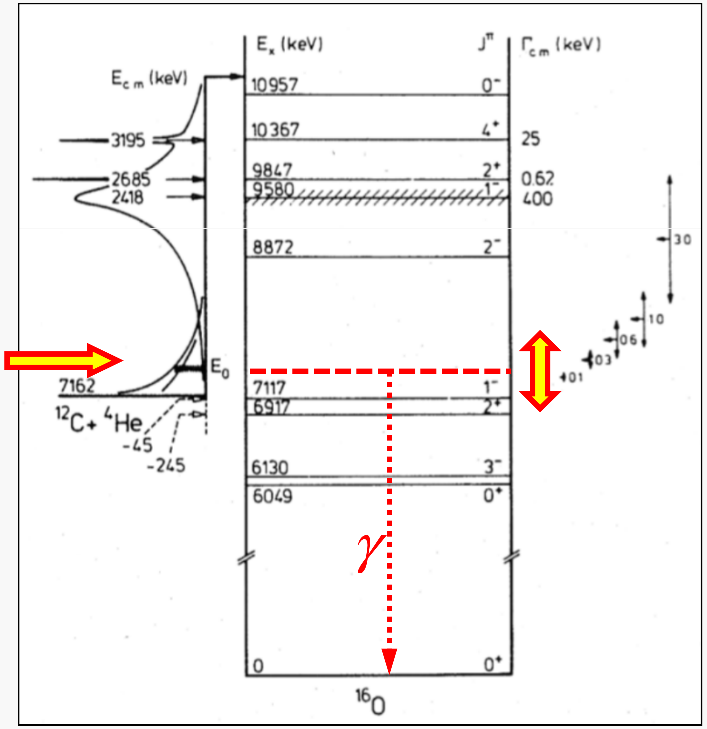


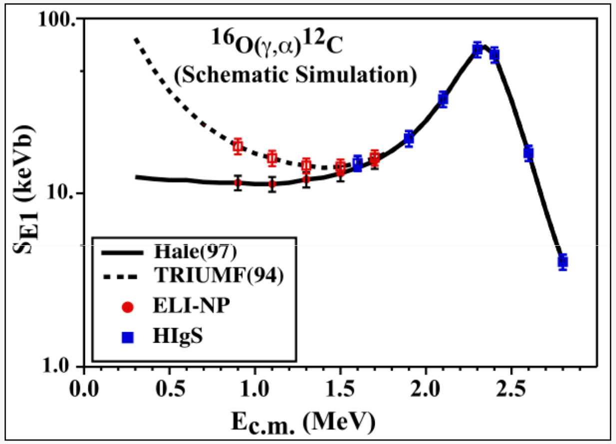
- B_{GT} evaluation is in progress

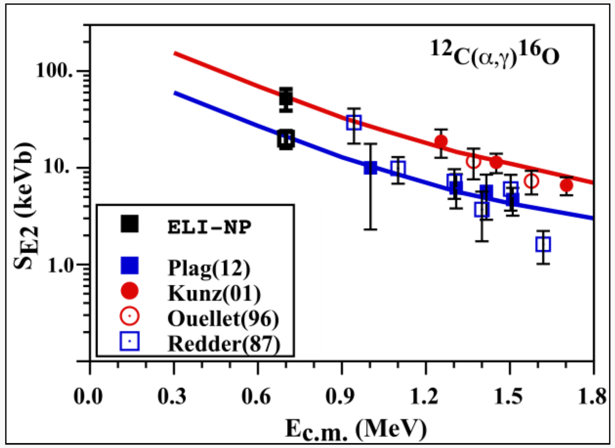
Mianowski, Janas, to be published
Mianowski, PhD thesis

Helium burning problem

- Understanding the $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$ reaction is still one of the key open questions in nuclear astrophysics. It determines the carbon/oxygen ration which determines the fate of massive stars and the light curve of SN I a („standard candles”)



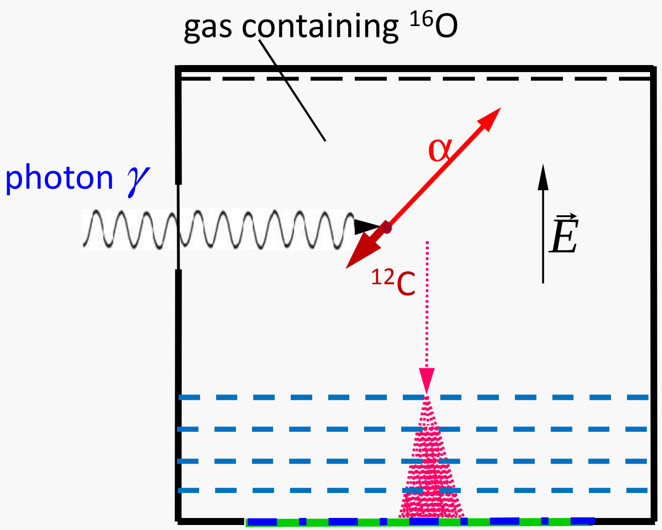




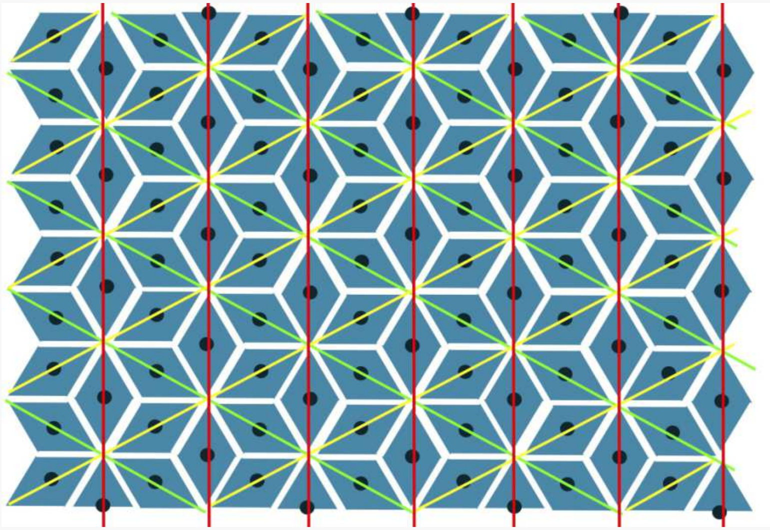
M. Gai, Phys. Rev. C88 (2013) 062801(R)

e-TPC

- The proposed solution is to measure the reverse reaction: $\gamma + {}^{16}\mathrm{O} \rightarrow {}^{12}\mathrm{C} + \alpha$ using photon beams at ELI-NP.
- Advantages: very clean signal, no background issues, angular correlations alows E1/E2 decomposition



- To have the full freedom of gas selection, a new detector with electronic readout is developed at University of Warsaw



- Other reactions planned:

${}^{19}\mathrm{F}(\gamma,p){}^{18}\mathrm{O}$, ${}^{22}\mathrm{Ne}(\gamma,\alpha){}^{18}\mathrm{O}$,
${}^{24}\mathrm{Mg}(\gamma,\alpha){}^{20}\mathrm{Ne}$, ...

See a talk by Jan Bihałowicz on Thursday!

Summary

- The OTPC detector is a very efficient tool to search for very rare multiparticle decays or to investigate particle decays obscured by beta background.
- Can provide precise branching ratios for β-delayed particle channels. Although the energy resolution is worse than for Si detectors, yields complementary data for low-energy particles.
- Non-trivial 3-body character of 2p decay of ^{45}Fe discovered. 2p decay of ^{48}Ni discovered.
- New decay channels, like β3p (^{45}Fe, ^{43}Cr, ^{31}Ar), observed for the first time. β2p emission discovered in ^{46}Fe based on one atom decay!
- Low-energy part of d-spectrum will shed light on the halo structure of ^{6}He
- Strong β-delayed triton emission confirmed for ^{8}He. Will provide the B_{GT} strength for the t-emitting states.
- A new TPC with electronic read-out being developed for ELI-NP to solve the helim burning problem.

Thank you!