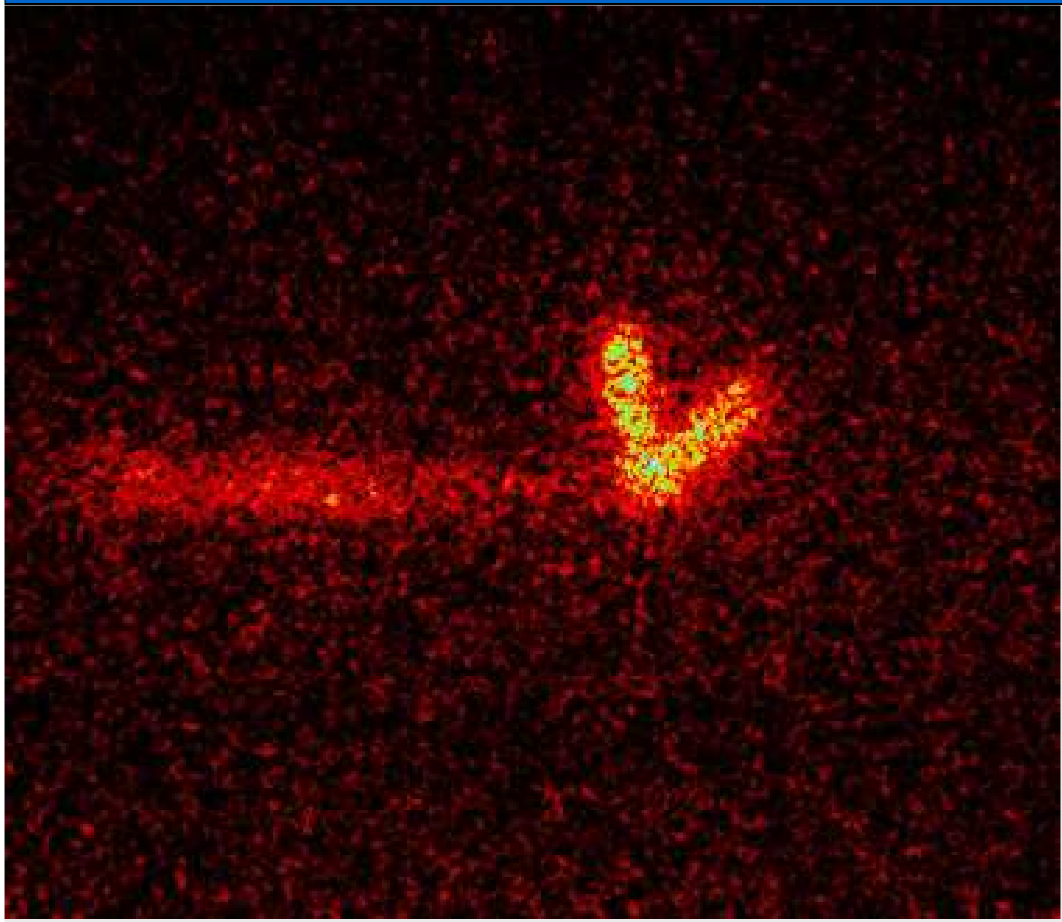
Exotic nuclear decays in digital photography



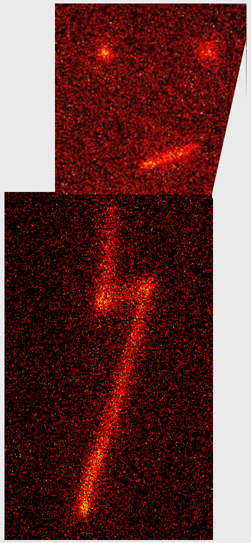
Marek Pfützner

Physics Department

University of Warsaw

CERN - ISOLDE, February 3, 2010

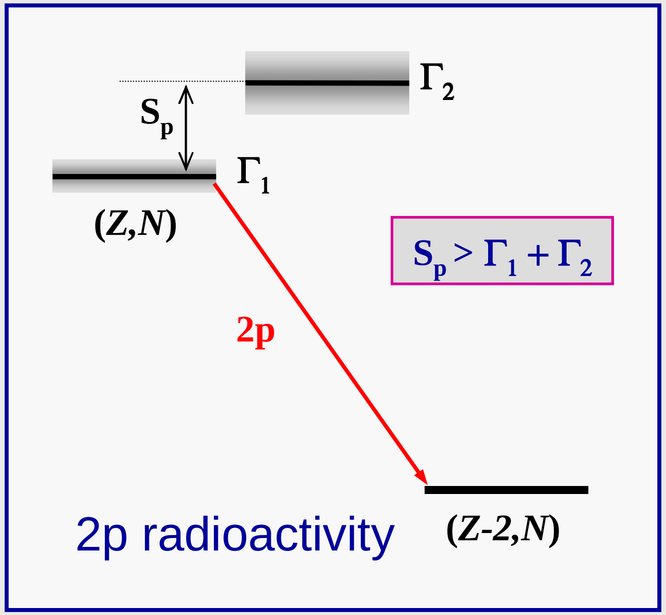
Outline

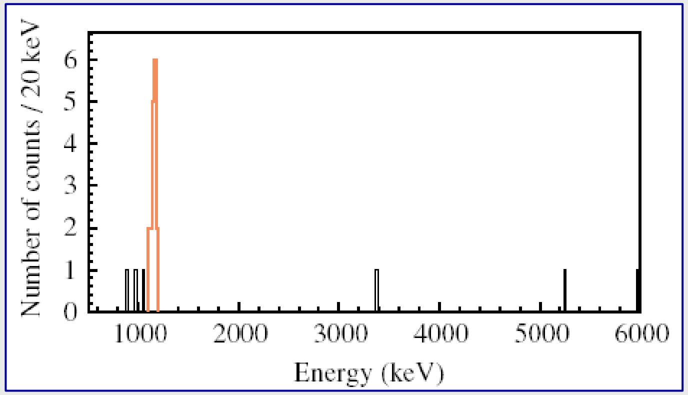


- *2p* radioactivity – the original challenge
- Idea of the optical detection and a prototype
- Tests with *β*-delayed particles
- *p-p* correlations in the decay of ^{45}Fe
- New results for the ^{43}Cr decay
- A new test: ^{8}He – *β*-decay of the halo?

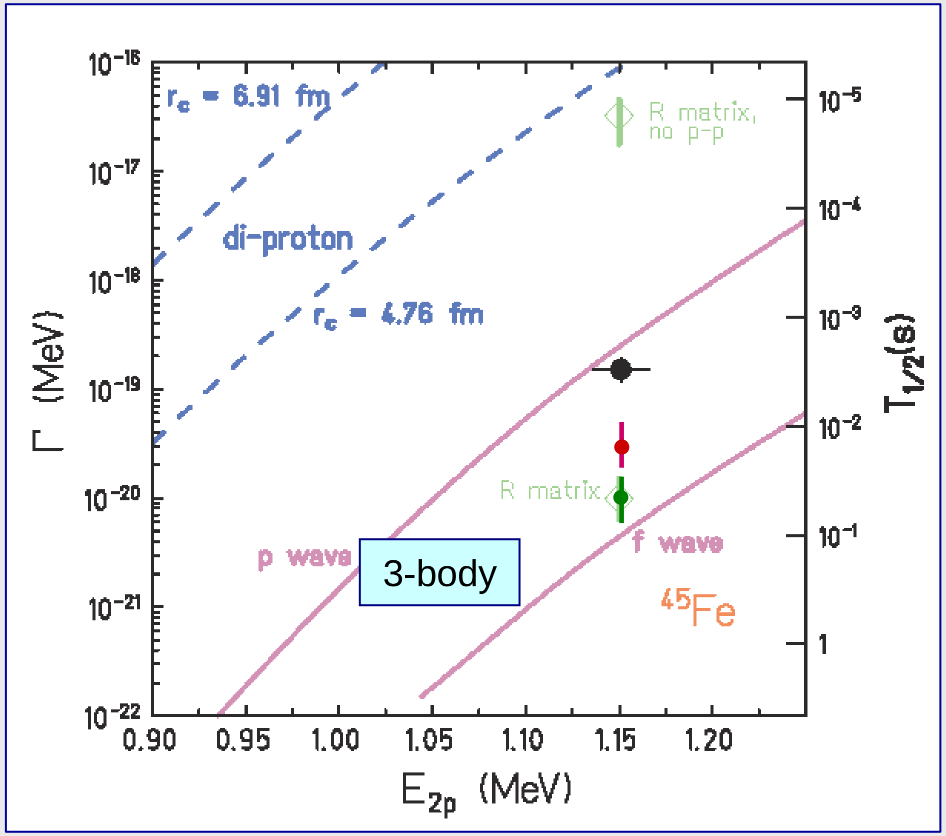
...and all illustrated with photos ☺

2p decay of ^{45}Fe





C. Dossat et al., PRC 72 (2005) 054315
M. P. et al., EPJ A 14 (2002) 279
J. Giovinazzo et al., PRL 89 (2002) 102501



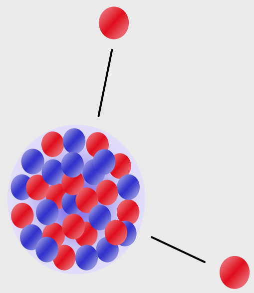
3-body : L.V. Grigorenko, I.G. Mukha, M.V. Zhukov, NP A714 (2003) 425

R-matrix : B.A. Brown, F.C. Barker, PRC 67 (2003) 041304(R)

SMEC : J. Rotureau, J. Okołowicz, M. Płoszajczak, Nucl. Phys. A767 (2006) 13

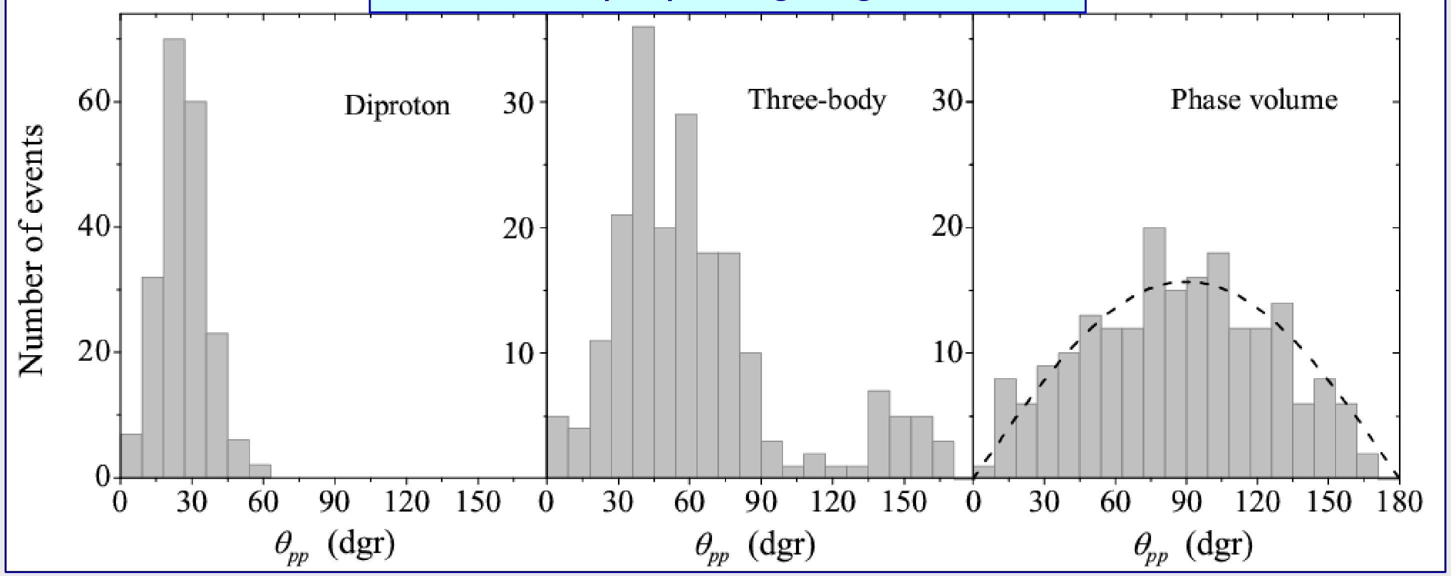
Main goals

- Experimental challenge: in addition to decay energy and half-life, measure momenta of both protons and determine their correlations!



- The questions: can we disentangle the 3-body decay dynamics from the structure of the initial state? Can we learn anything on the latter?

Predicted *2p* opening angle for ^{45}Fe



L. Grigorenko : simulation for 200 events

A great idea

G. Charpak, W. Dominik, J. P. Farbe, J. Gaudaen, F. Sauli, and M. Suzuki,
"Studies of light emission by continuously sensitive avalanche chambers,"
NIM A269 (1988) 142

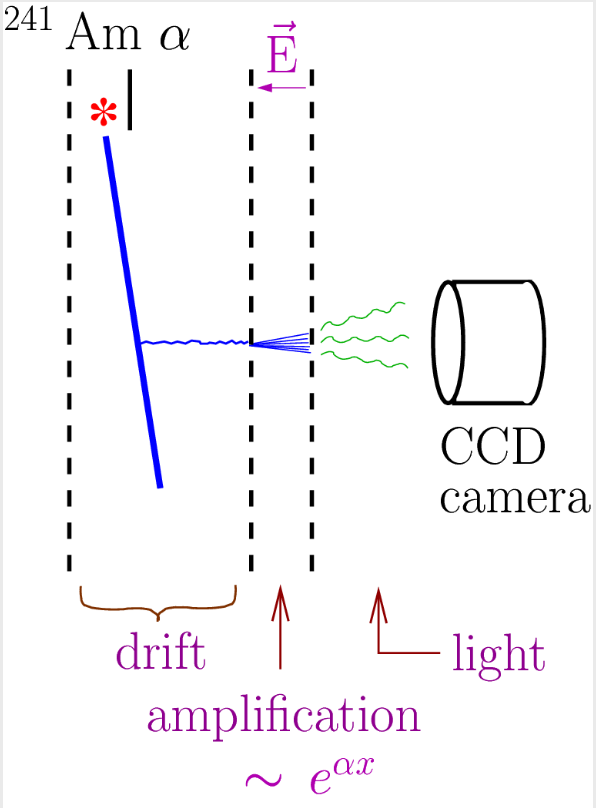
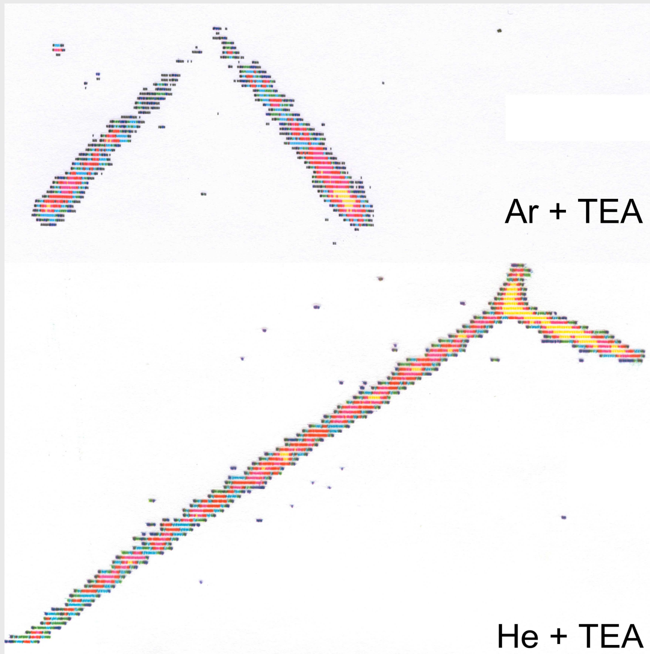
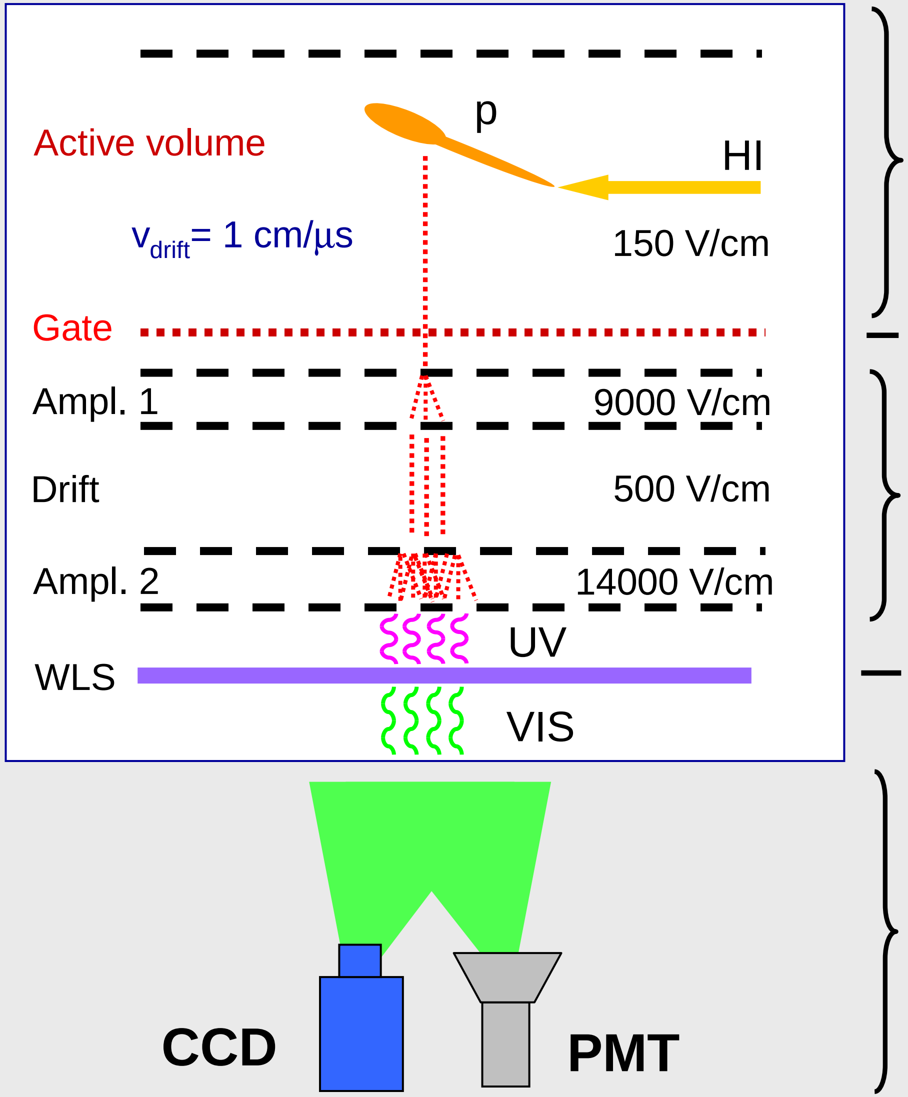


Image examples of α-particle tracks



TEA = Triethylamine $N(C_2H_5)_3$

Optical Time Projection Chamber



Active volume

He + Ar + ≈1%N_2 + ≈ 1%CH_4

Gating electrode

Amplification

UV / VIS conversion

VIS light detection

M. Ćwiok et al., IEEE TNS, 52 (2005) 2895

K. Miernik et al., NIM A581 (2007) 194

The prototype

Chamber active volume:

20 x 20 x 15 cm^3

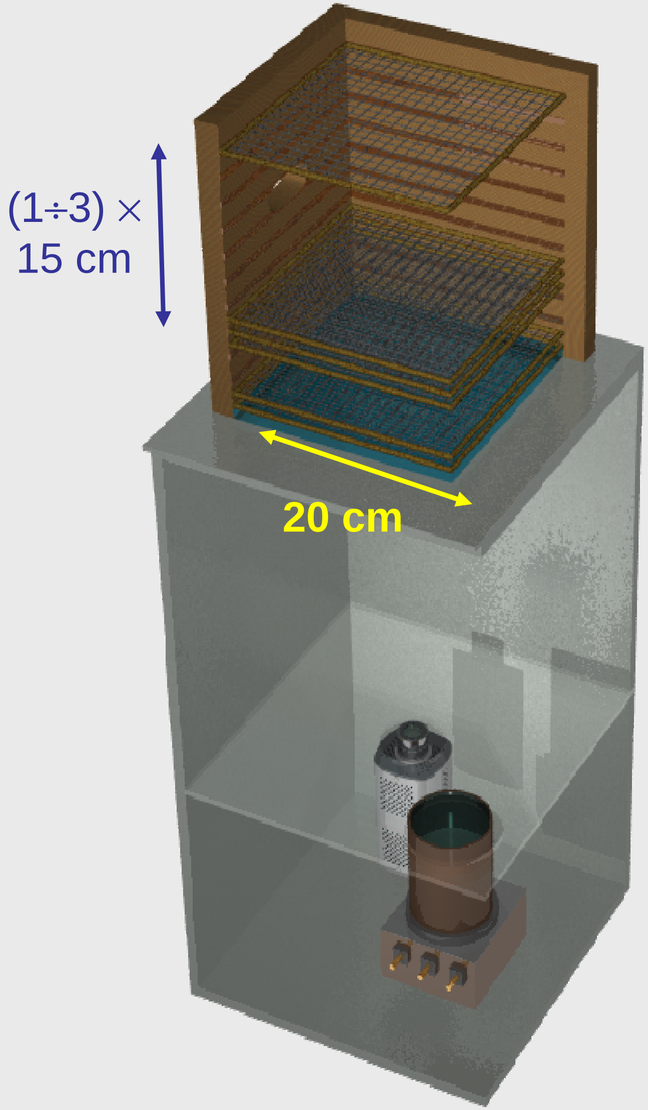
Materials used:

Stesalit fibreglass

PCB plates

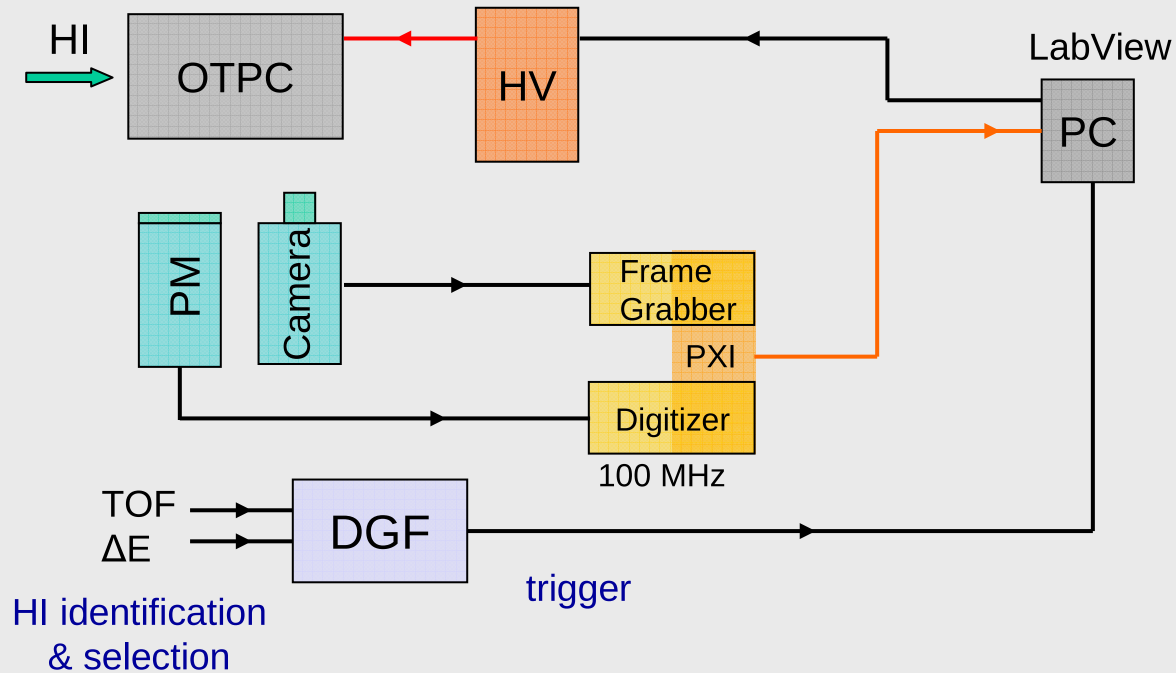
Pyrex optical window

Optical Time Projection Chamber

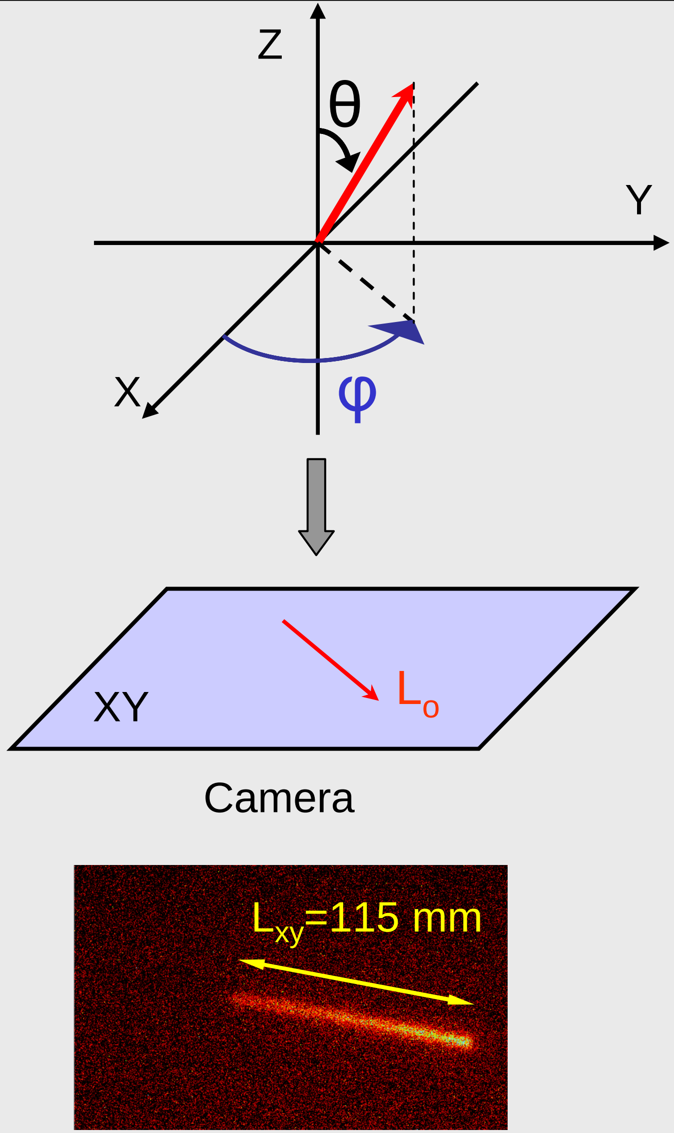


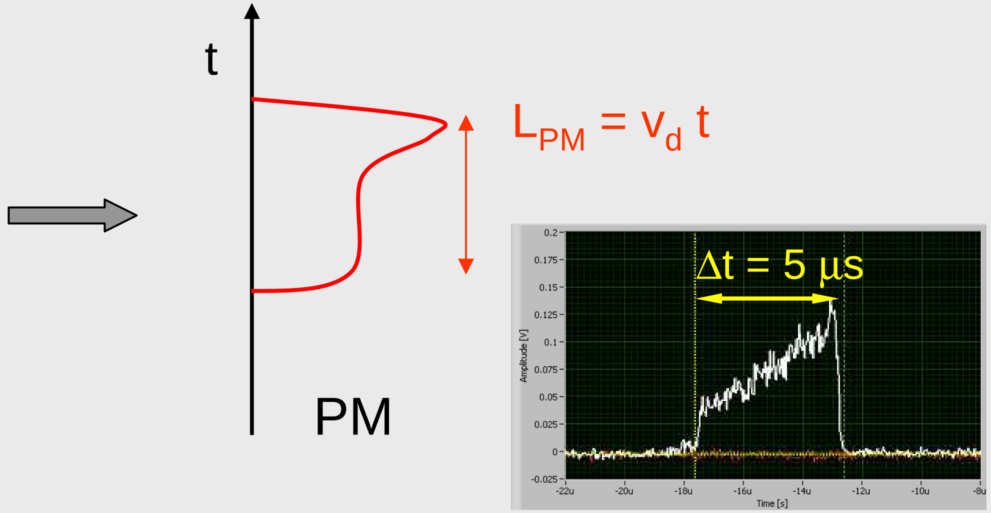
CCD 2/3''

- 1000 × 1000 pix.
- 12-bits
- image ampl. (×2000)



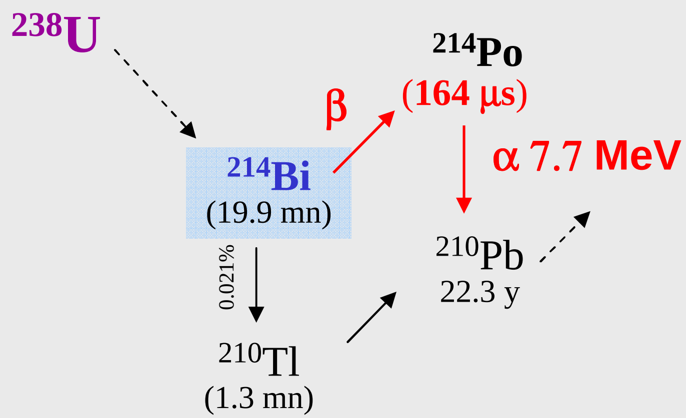
Event reconstruction



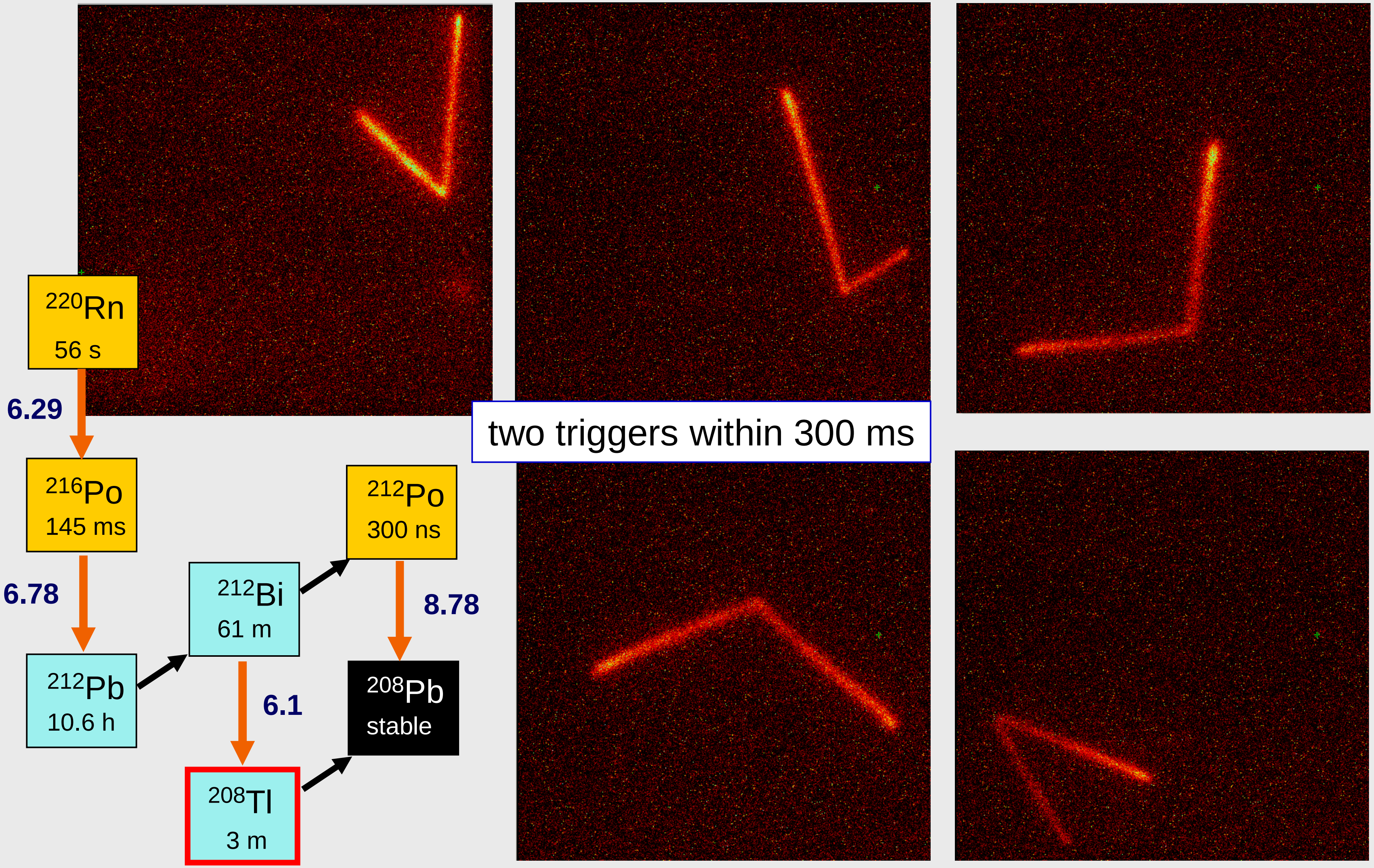


$$L = \sqrt{115^2 + (5 \cdot 10)^2} = 125\,\text{mm}$$
$$\Leftrightarrow \quad E_\alpha = 7.8\,\text{MeV}$$

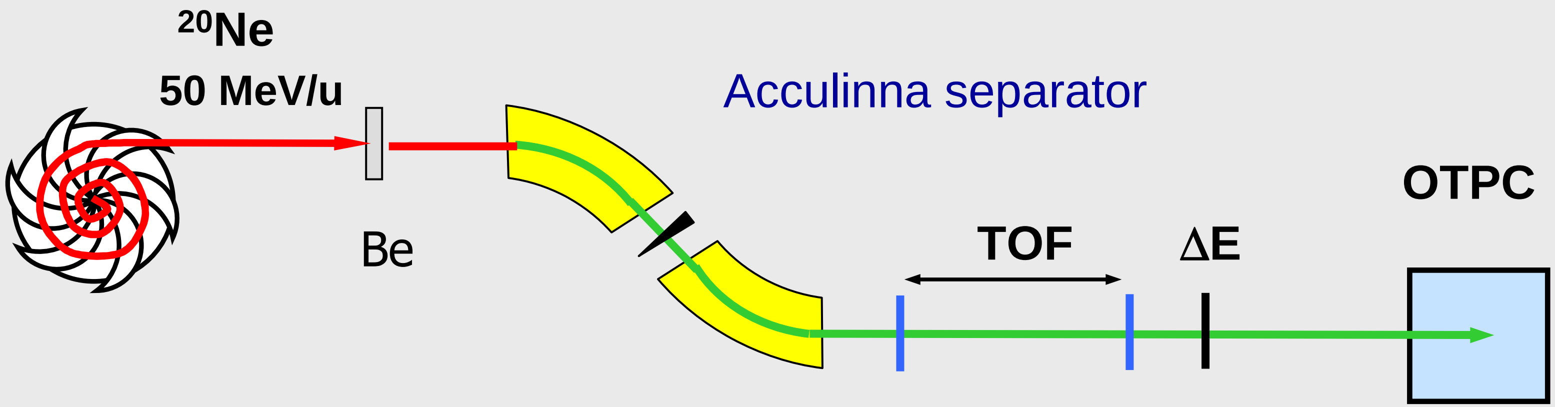
→ ^{214}Po α decay



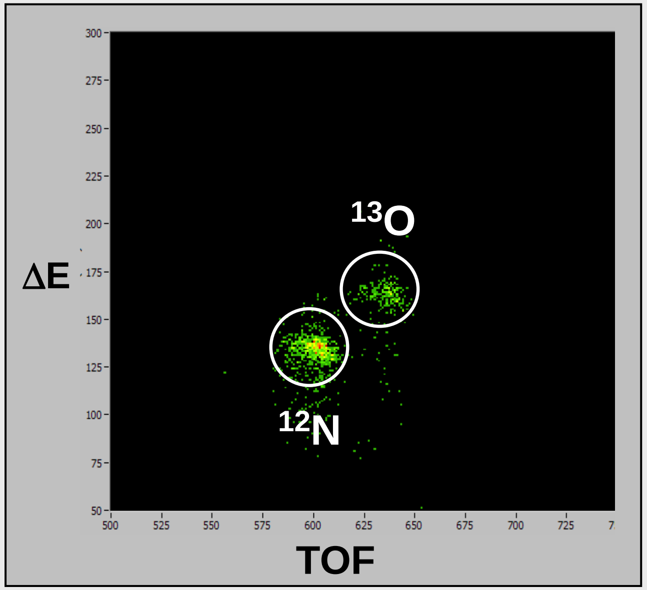
α particles from the Th chain



Test at JINR, Dubna



Ion identification



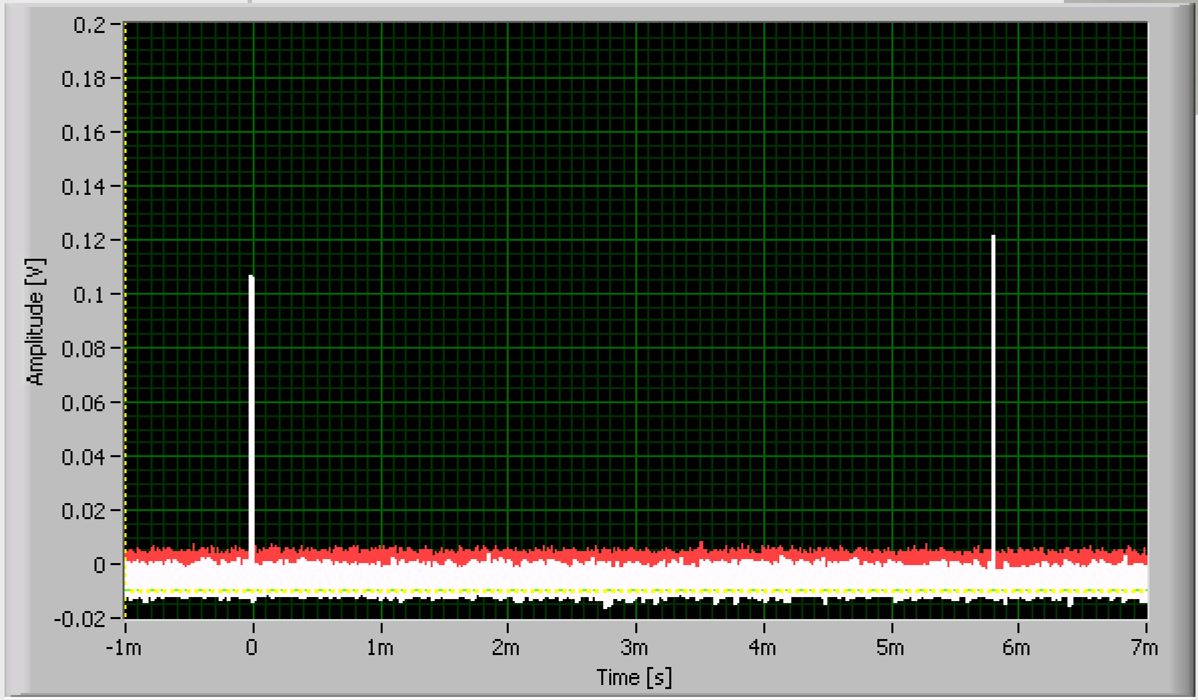
Measurement sequence

BEAM ON

BEAM OFF

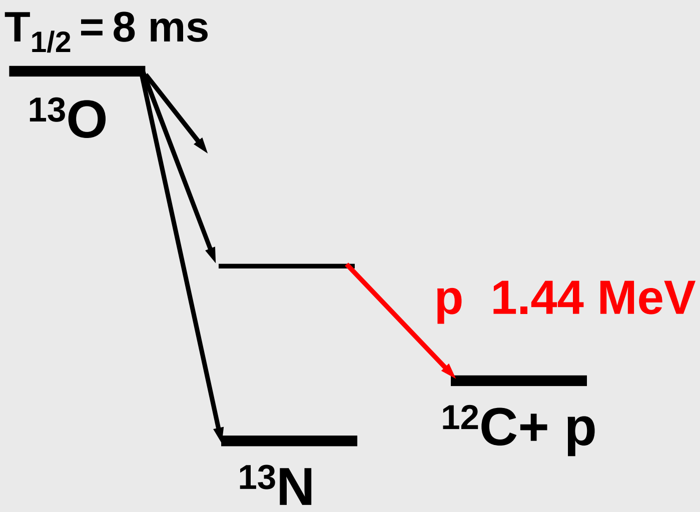
OTPC LOW

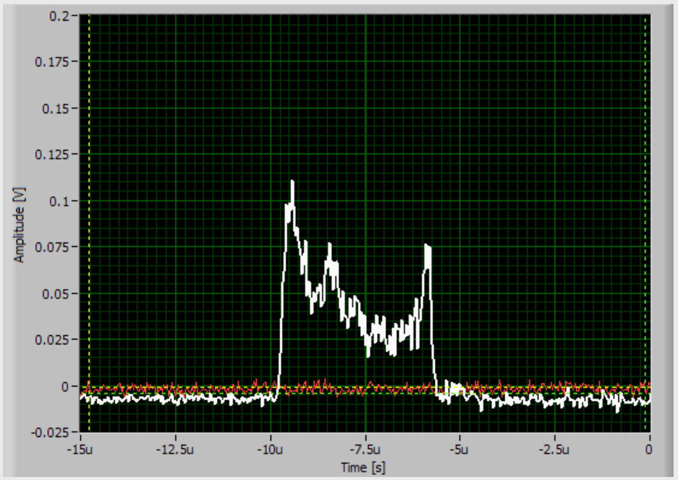
OTPC HIGH

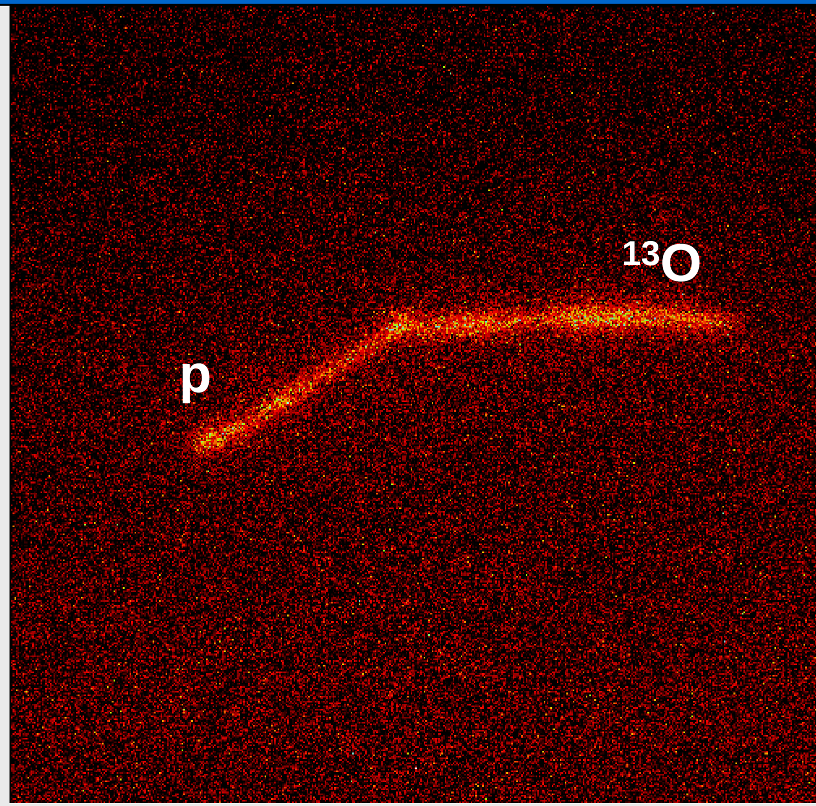


PMT signal

Protons after ^{13}O β decay

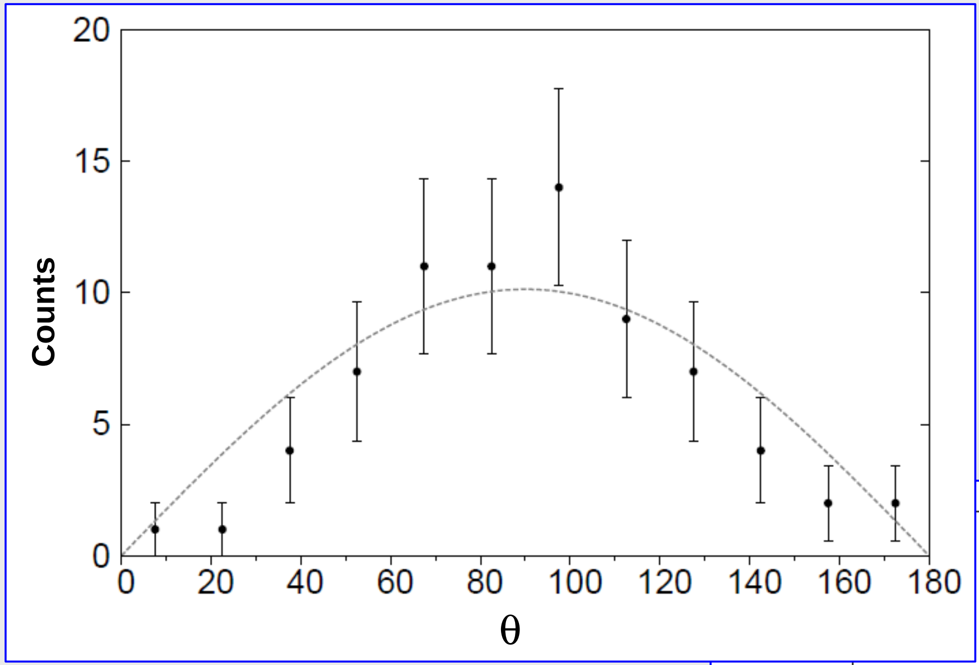




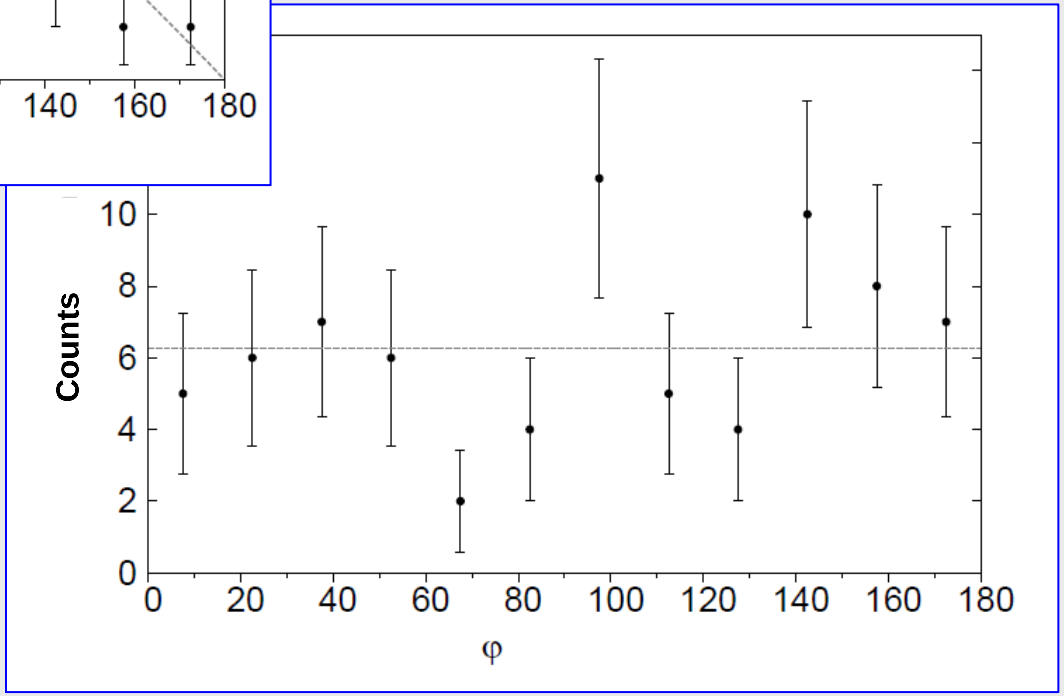


K. Miernik et al., NIM A581 (2007) 194

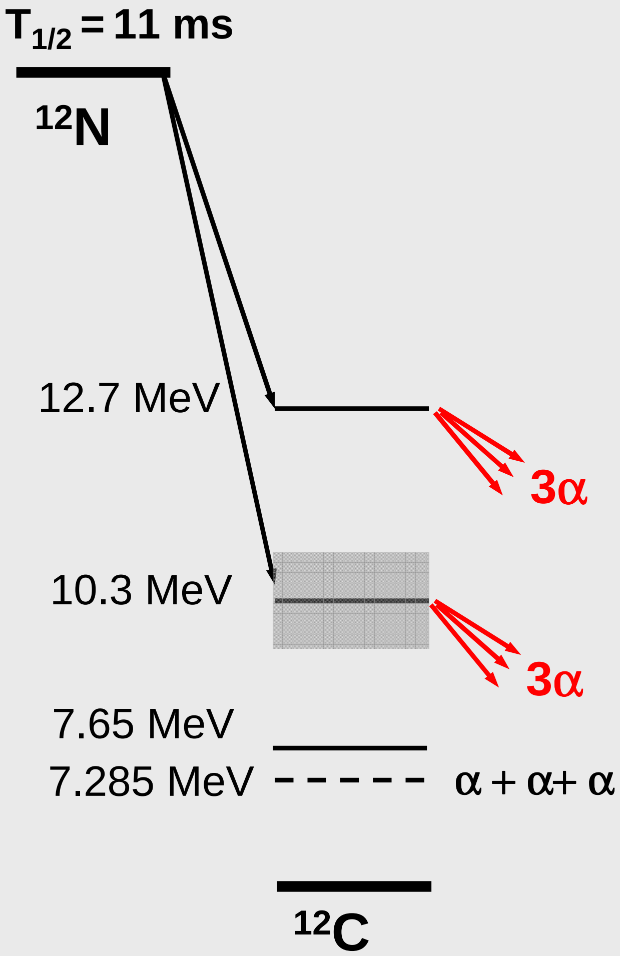
Is one proton emission isotropic?

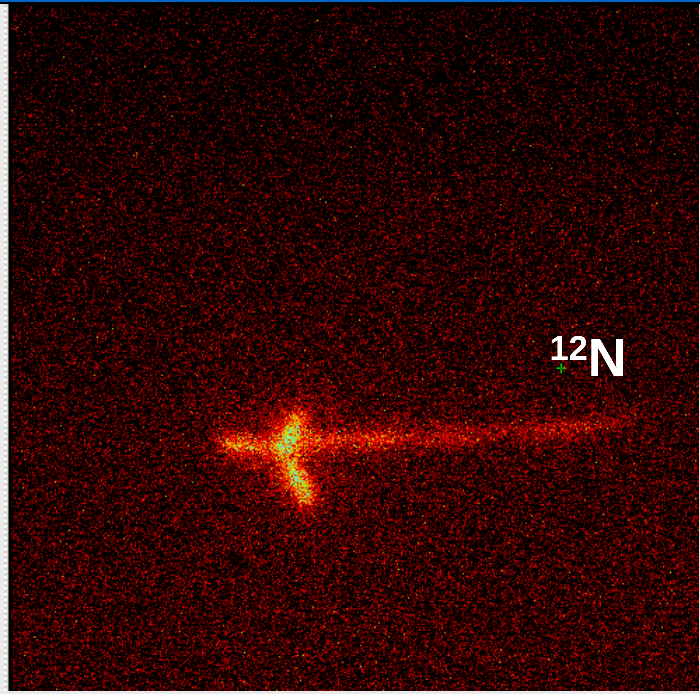


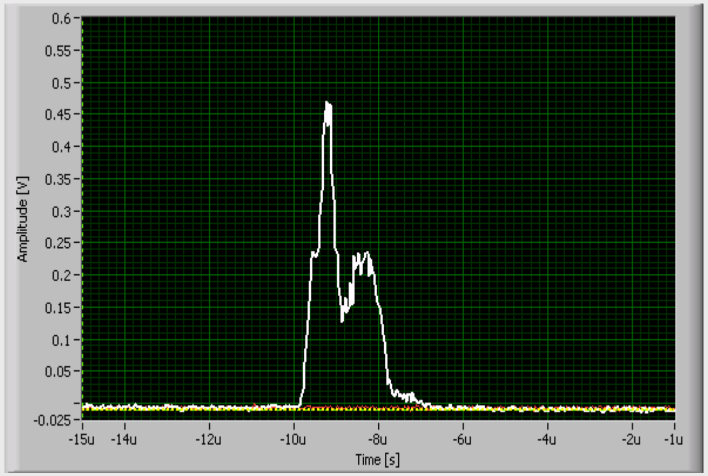
- To check if we do not miss particular directions, we check emission angles for one proton, which should reflect an isotropic distribution



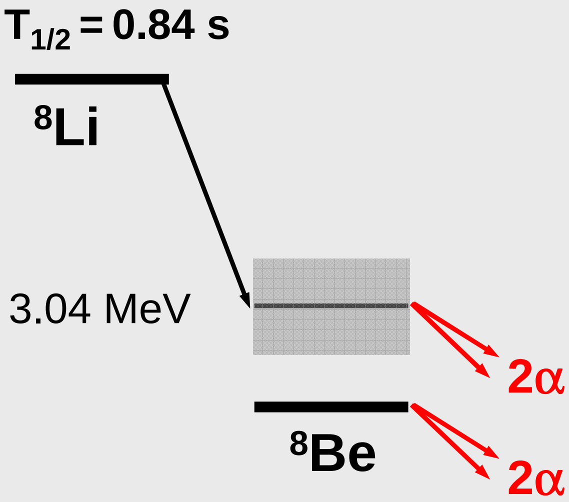
3α decay of $^{12}C^*$

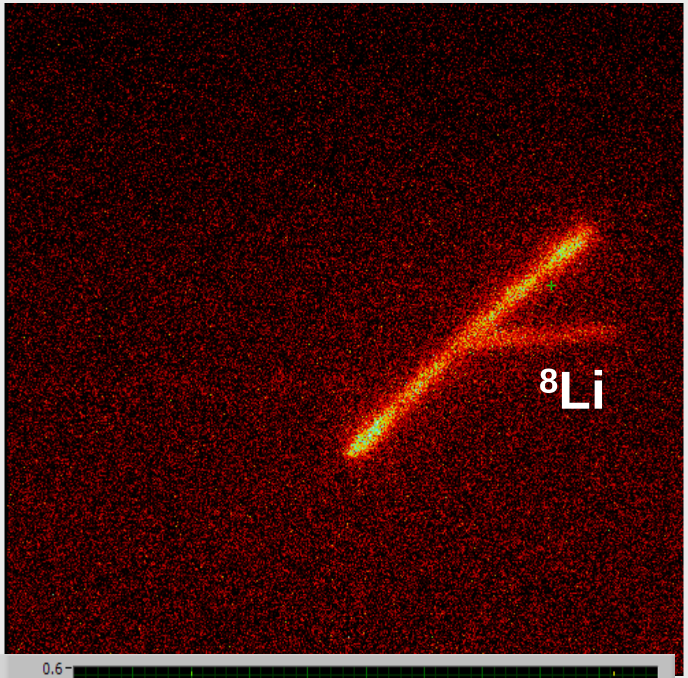


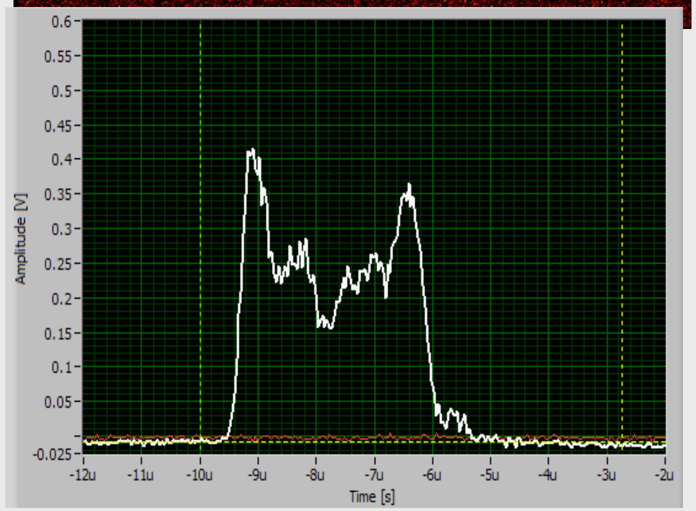




Decay of ^{8}Be

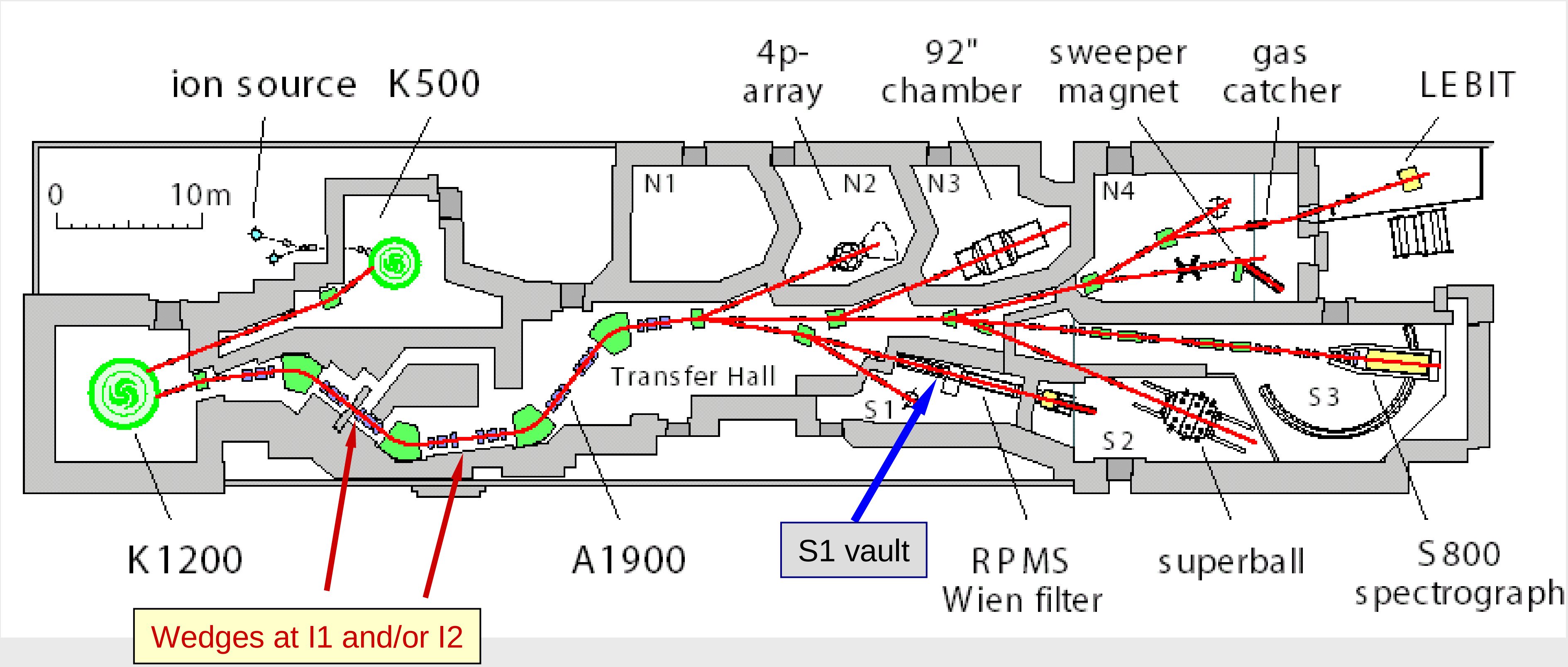

T1/2 = 0.84 s
8Li
3.04 MeV
2α
8Be
2α


8Li


Amplitude [V]
Time [s]
0.6
0.55
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
-0.025
-12u
-11u
-10u
-9u
-8u
-7u
-6u
-5u
-4u
-3u
-2u

Experiment on ^{45}Fe @ NSCL/MSU

February 2007



Reaction: ^{58}Ni at 161 MeV/u + ^{nat}Ni → ^{45}Fe

Ion identification in-flight : ΔE + TOF

The „cannon”

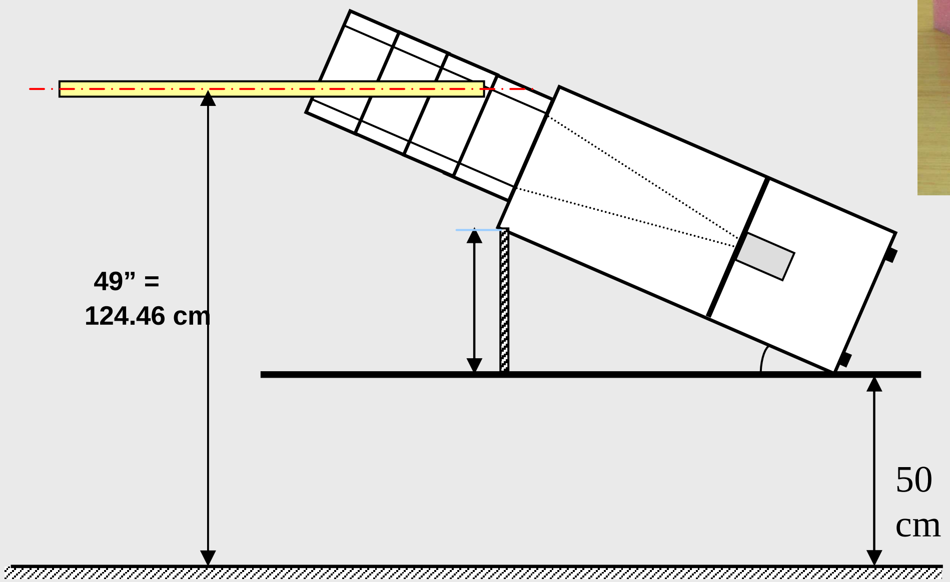
Thin gas:

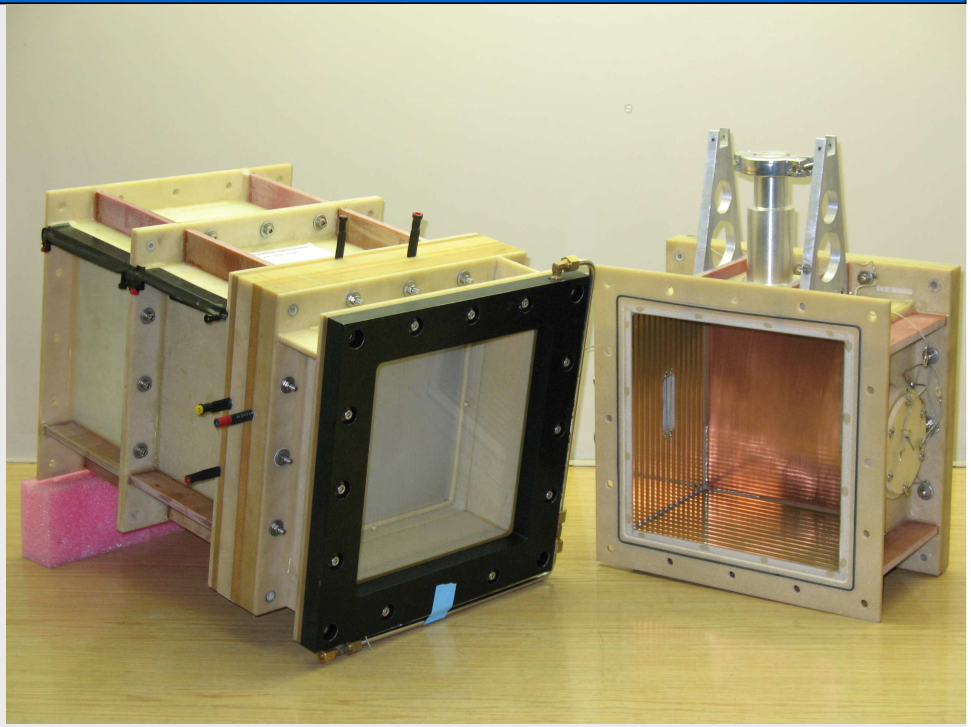
66% He + 32% Ar + 1% N_2 + 1% CH_4

as a compromize for the active length:

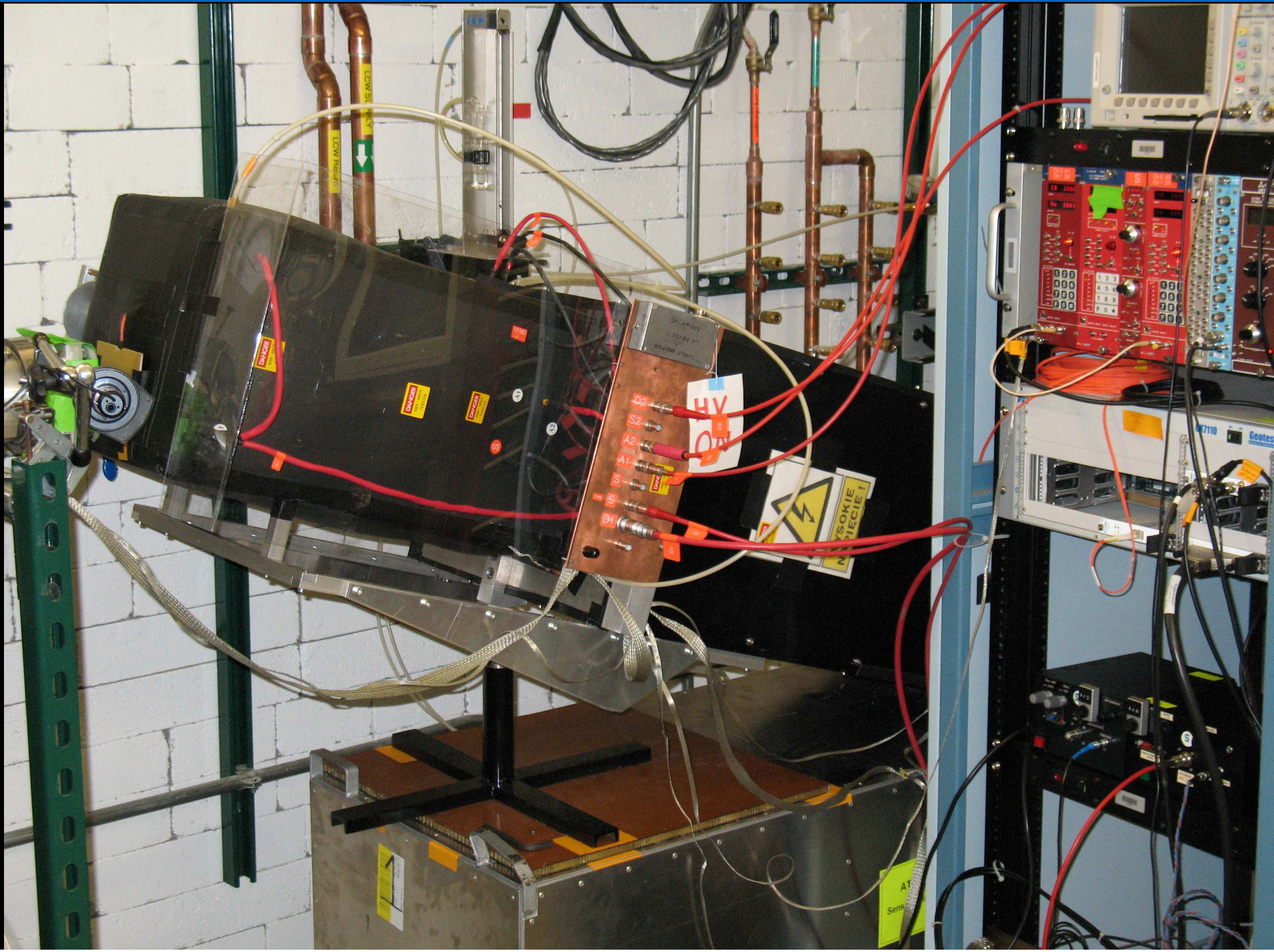
- range of 550 keV proton ≈ 2.3 cm
- range of ^{45}Fe ion ≈ 50 cm

Active volume: 20×20×42 cm^3

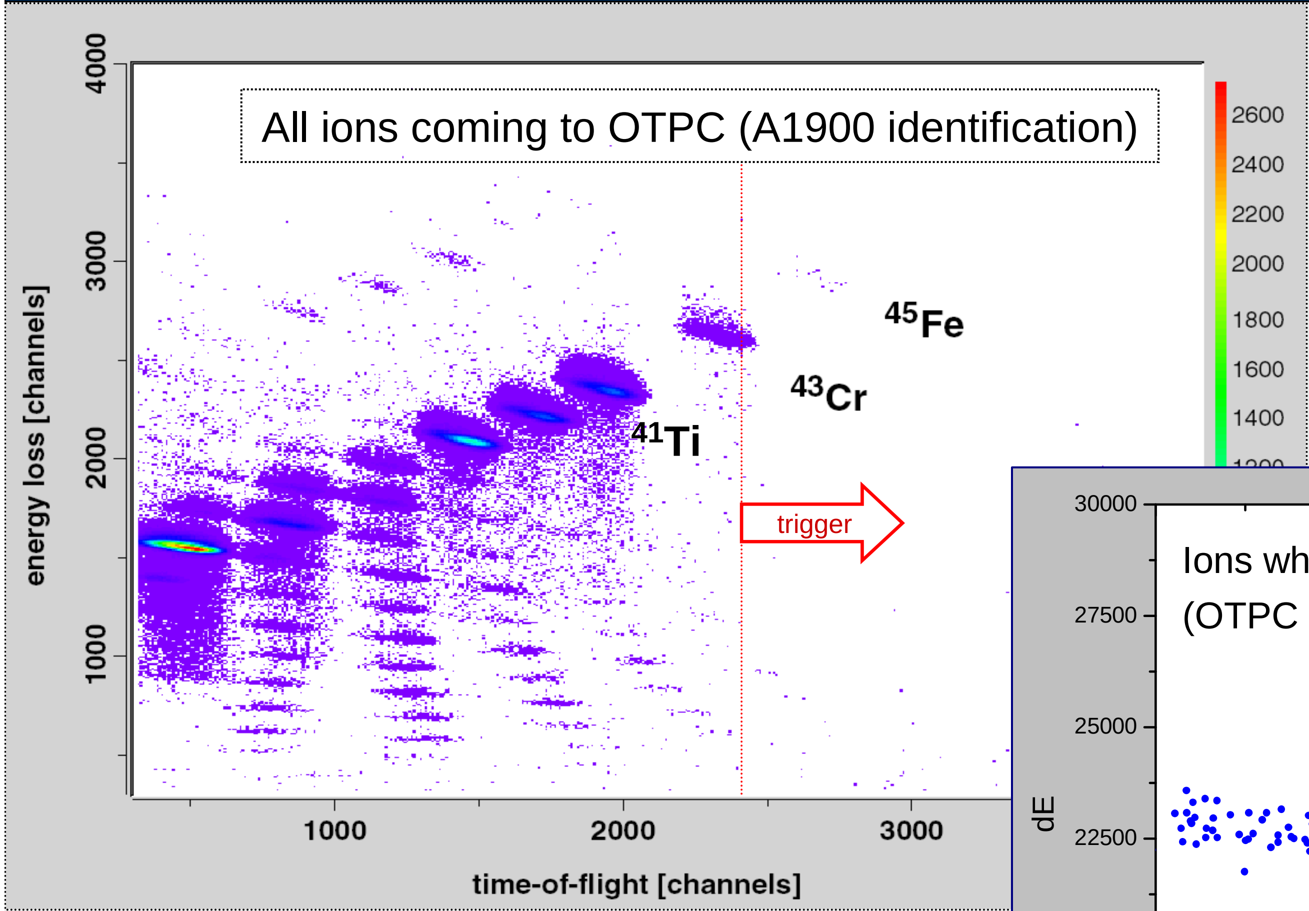




Set-up at the beam line

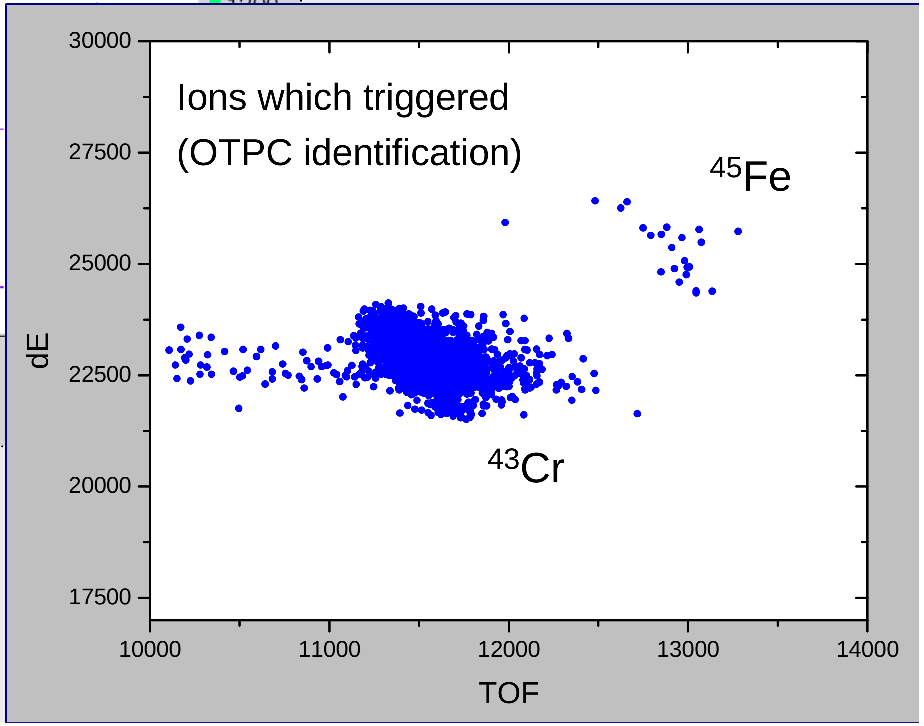


Ion identification

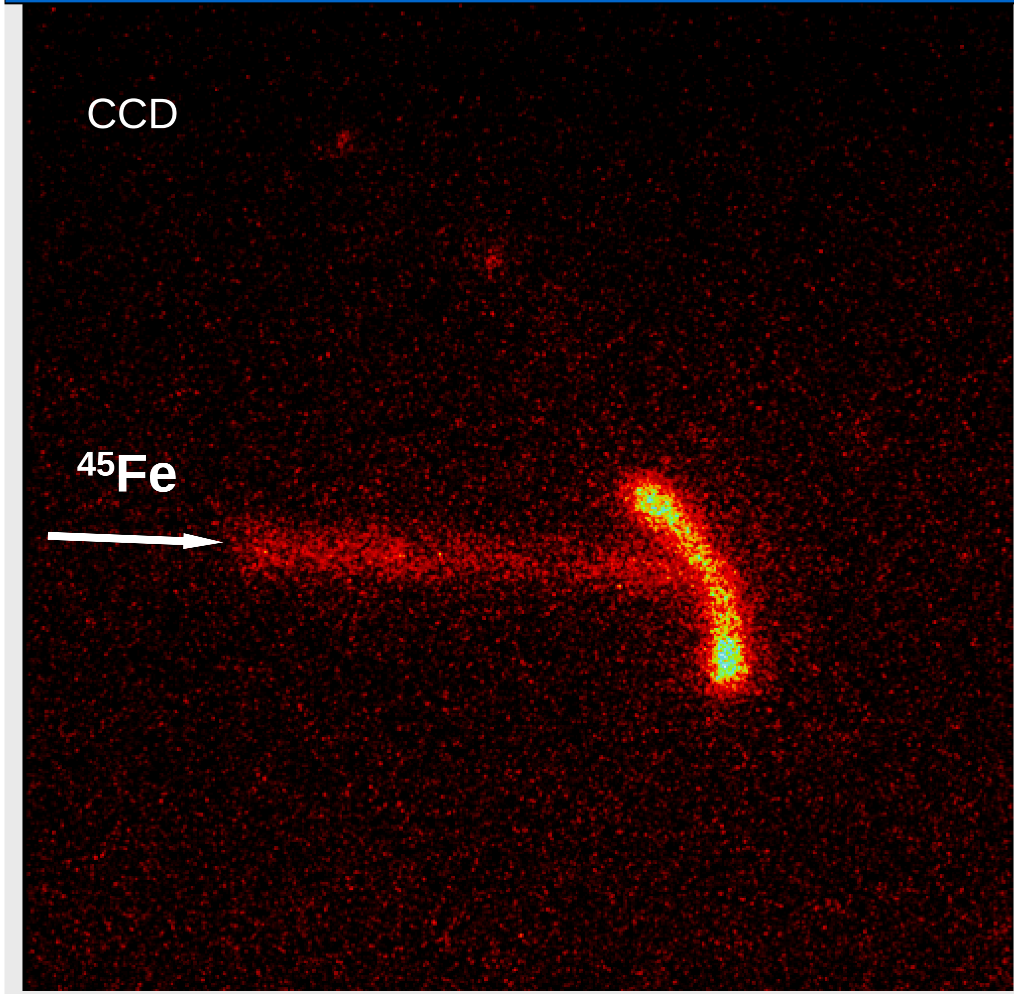


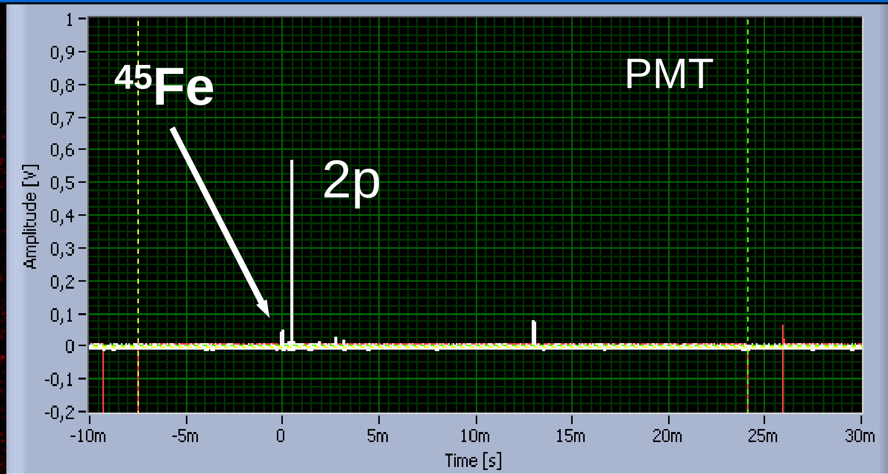
^{45}Fe: 2 /h

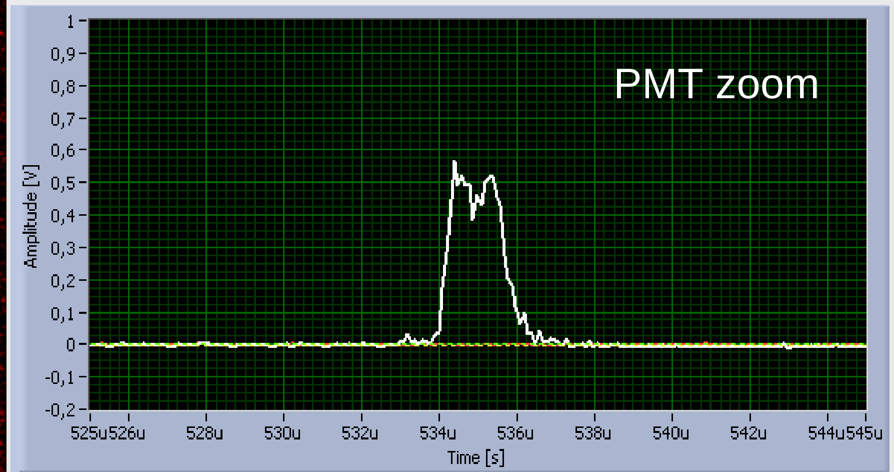
^{43}Cr: 8 /min.



2p event!

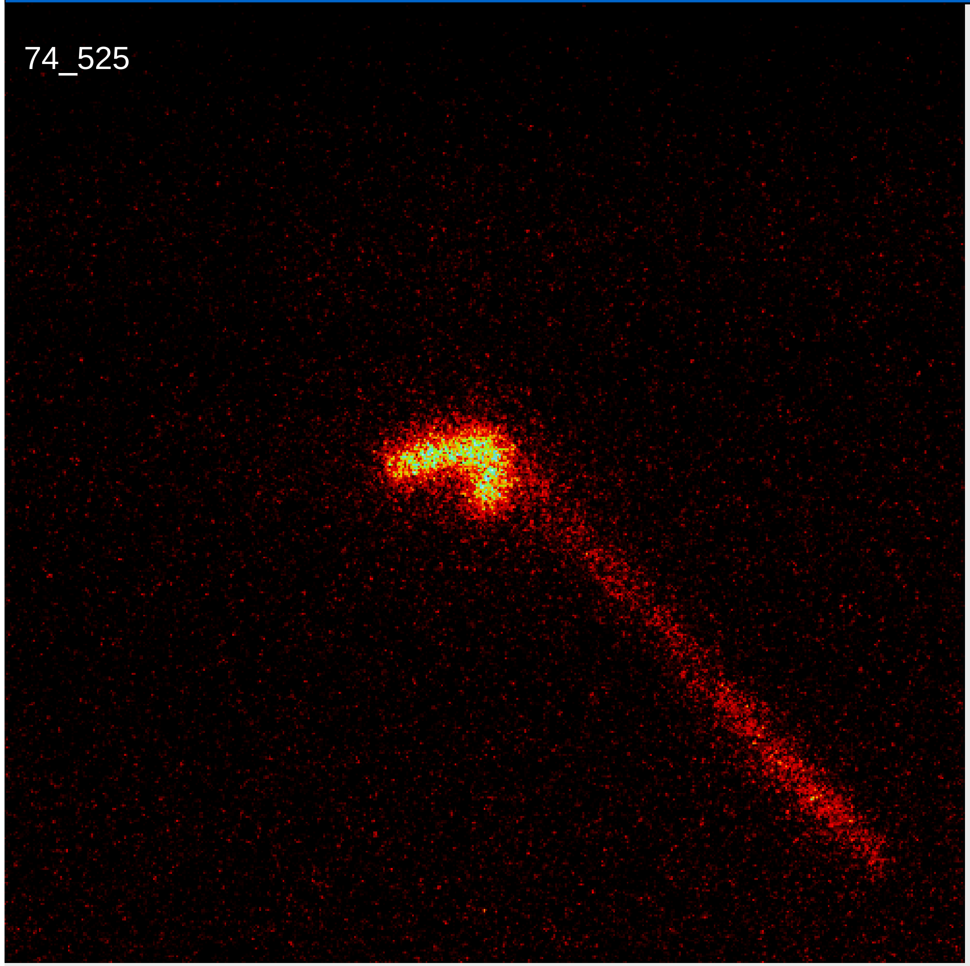


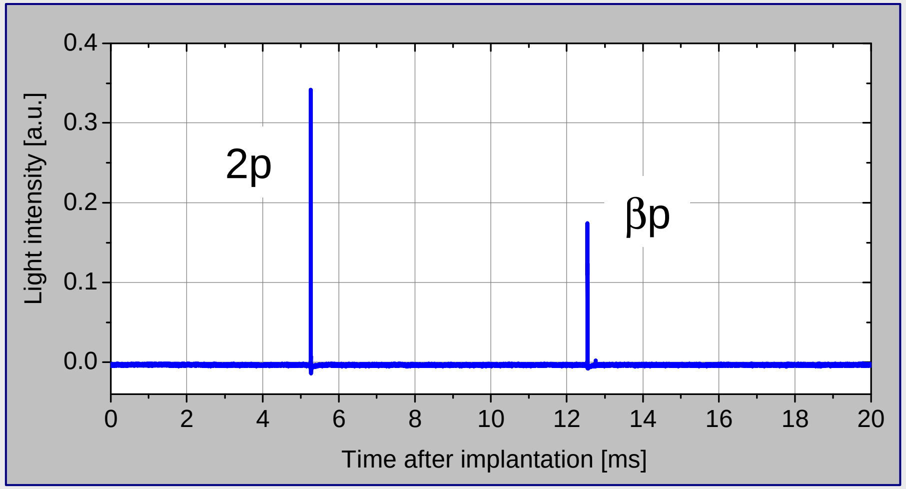




decay 0.53 ms after implantation

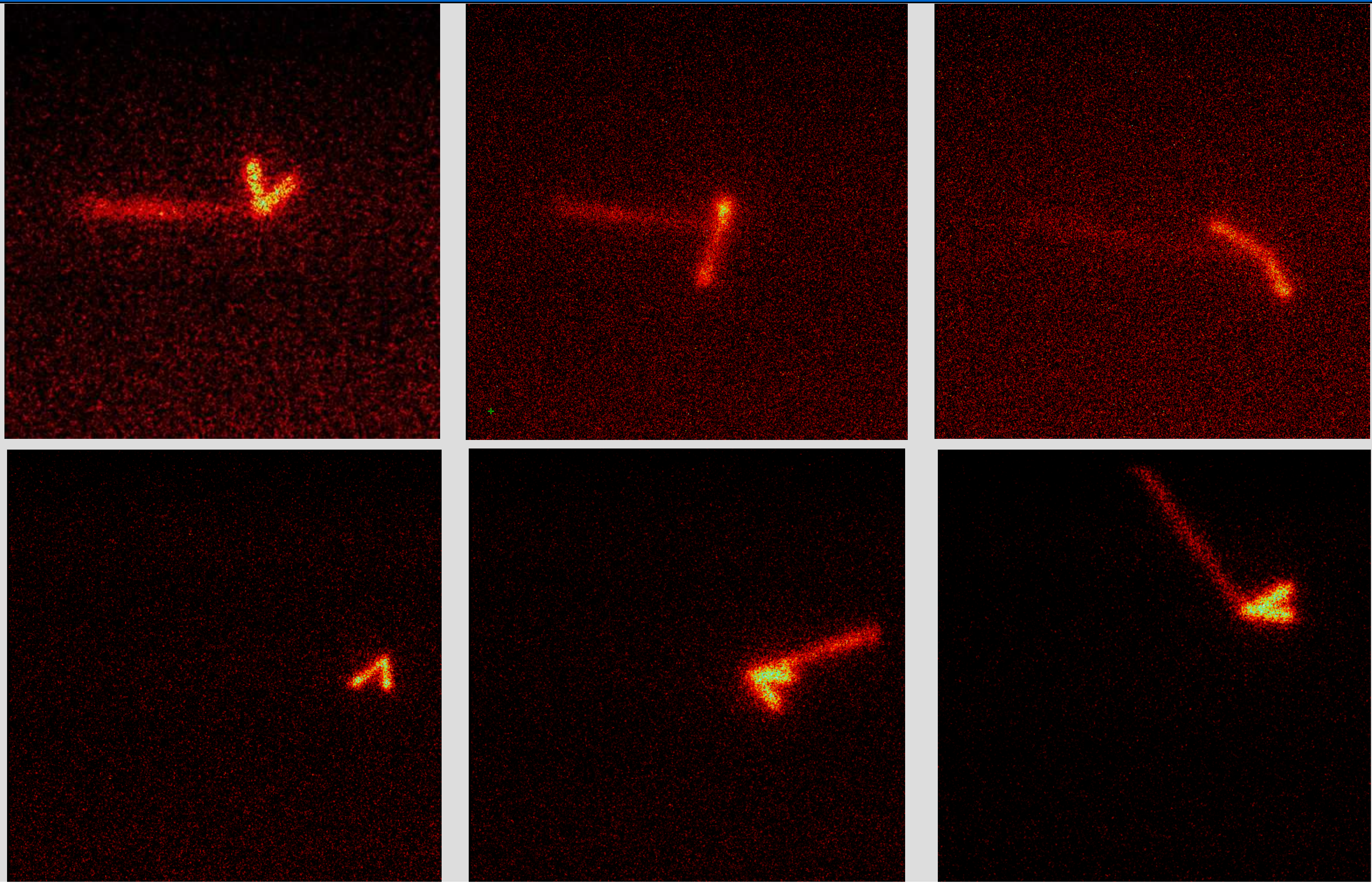
2p followed by β*p*



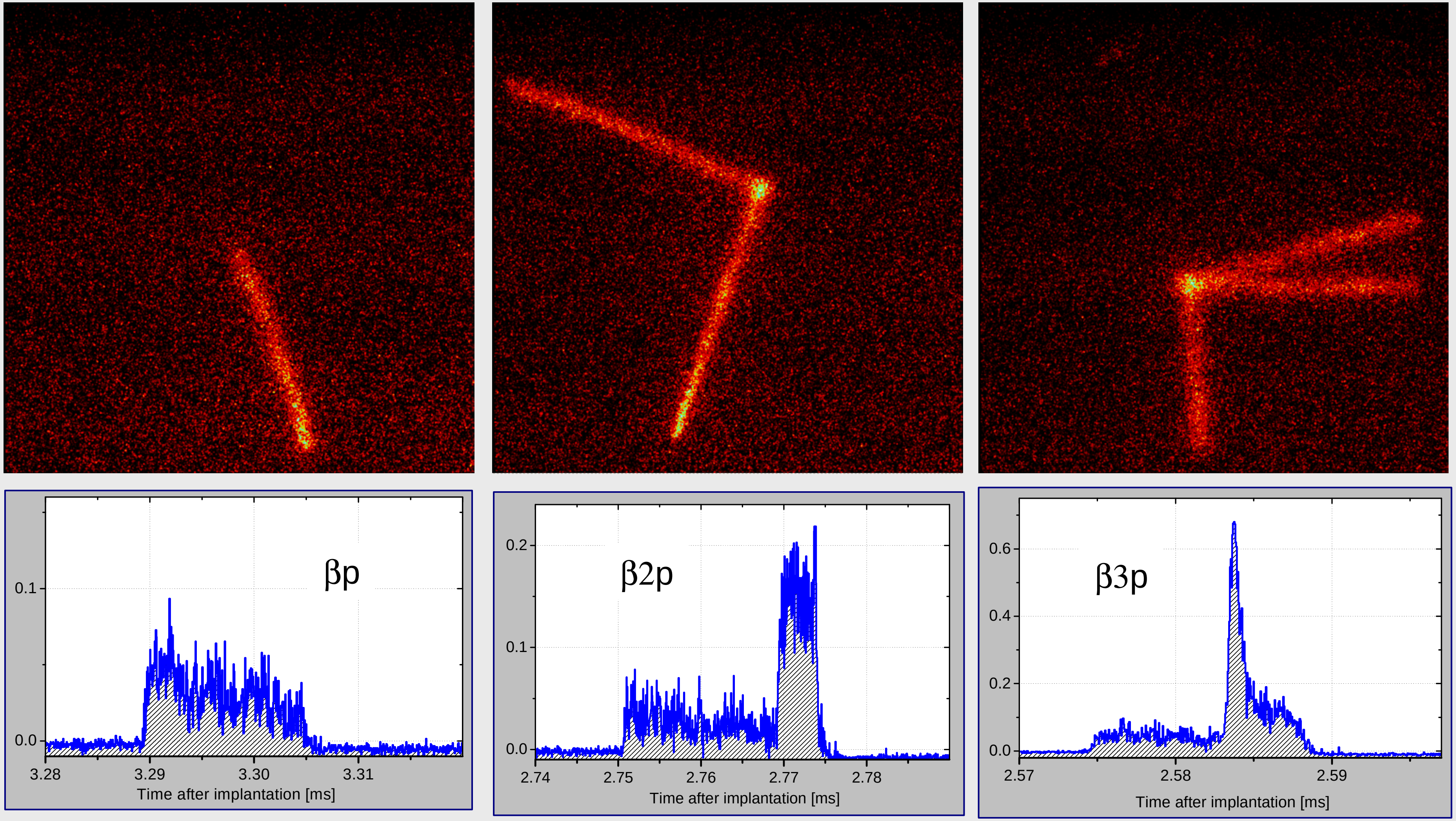


Synchronous mode ⇨ ion track not seen

Selection of *2p* events



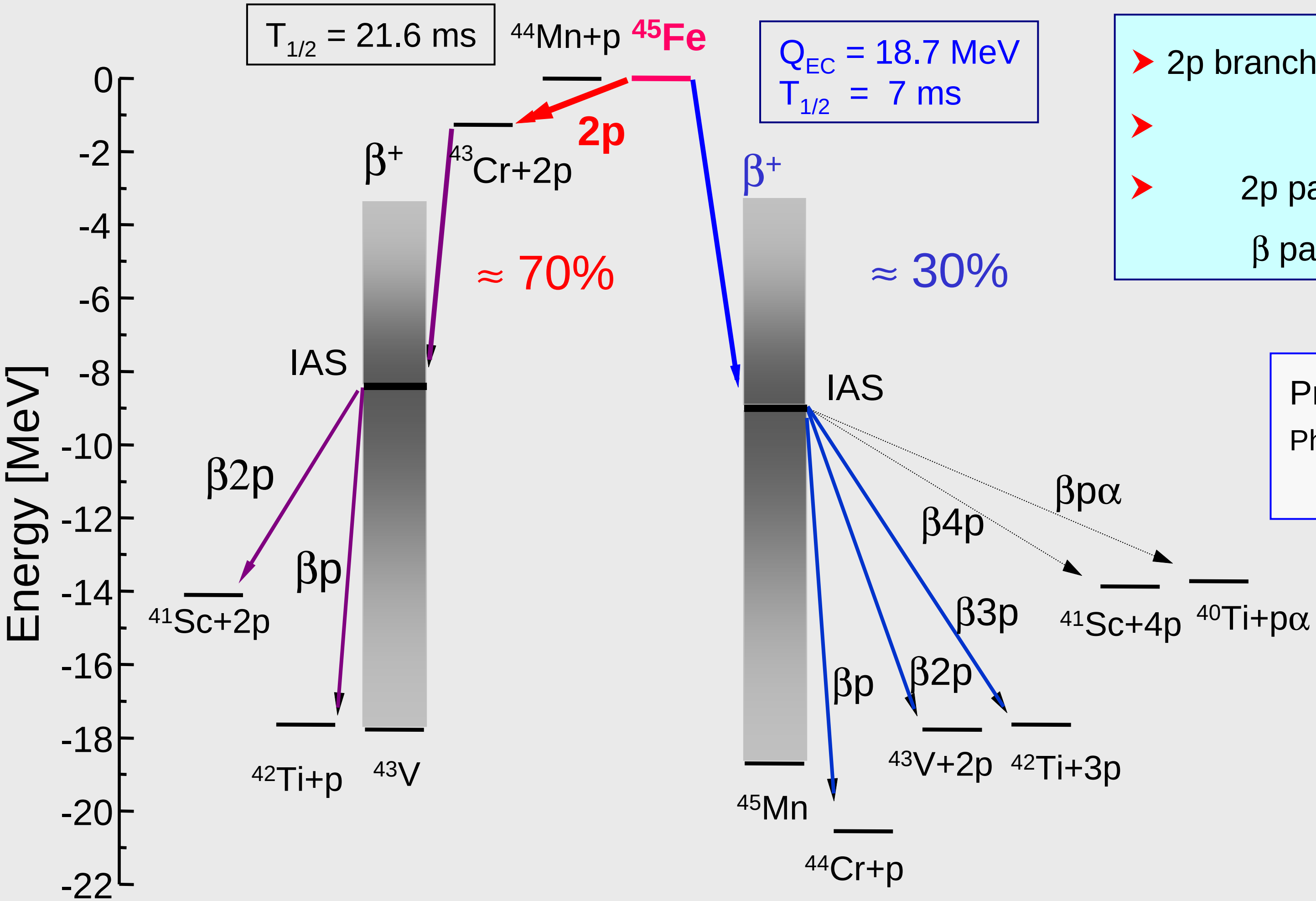
β+ decay of ^{45}Fe



K. Miernik et al., Phys. Rev. C 76 (2007) 041304(R)

Decay channels observed

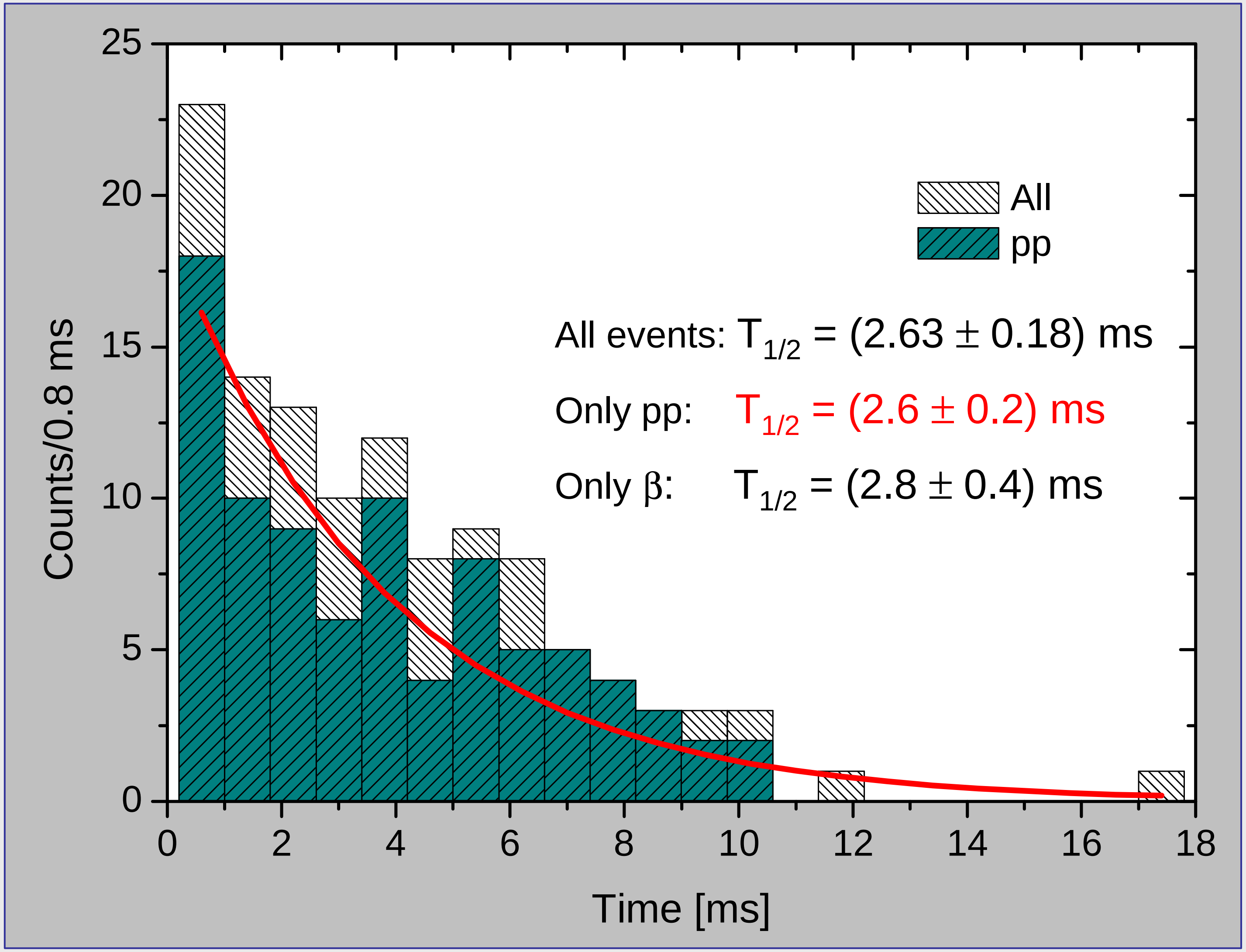
125 decays recorded



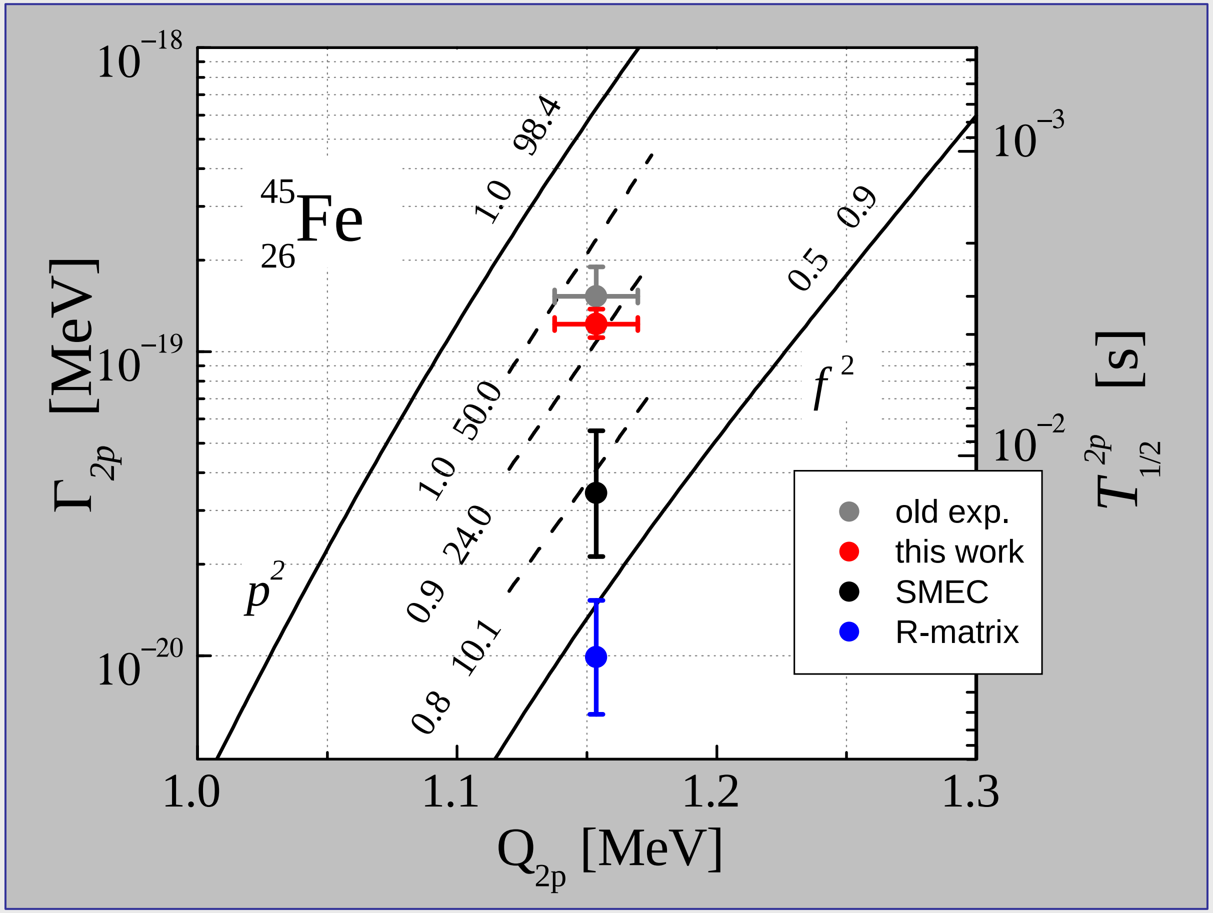
- 2p branching ratio: 0.70 ± 0.04
- half-life: 2.6 ± 0.2 ms
- 2p partial $T_{1/2}$: 3.7 ± 0.4 ms
- β partial $T_{1/2}$: 8.7 ± 1.3 ms

Prediction by E. Ormand
Phys. Rev. C 53 (1996) 214
$T_{1/2}(\beta)$ = 7 ms

Decay time of ^{45}Fe



2p energy vs. half-life

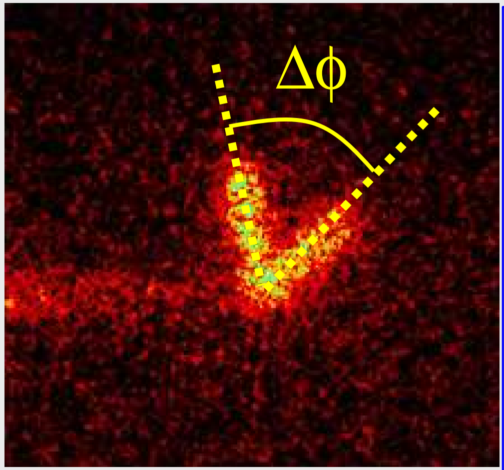


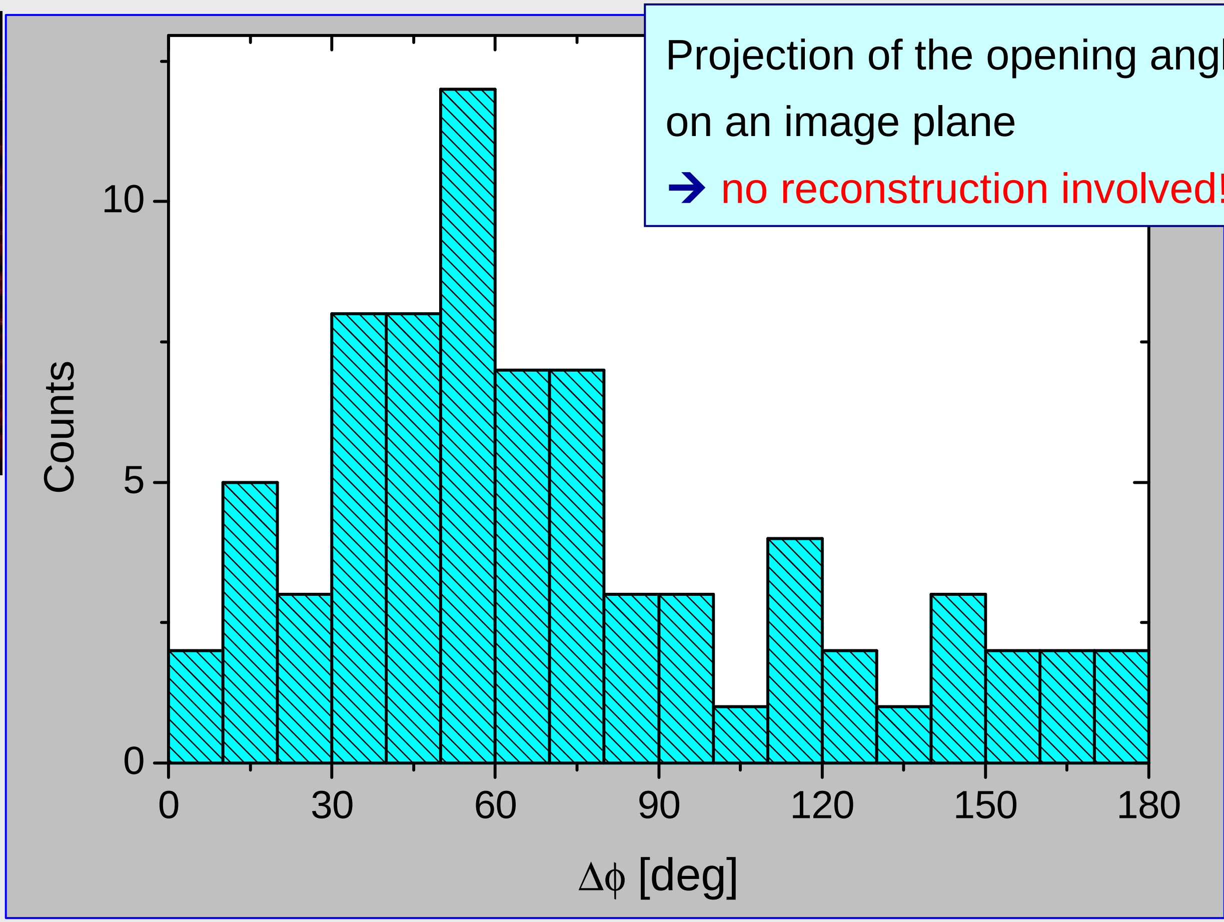
3-body model: L.V. Grigorenko and M.V. Zhukov, PRC 68 (2003) 054005

SMEC: Rotureau, Okołowicz, Płoszajczak, Nucl. Phys. A 767 (2006) 13

R-matrix: Brown, Barker, Phys. Rev. C 67 (2003) 041304

p-*p* opening angle (Δϕ)



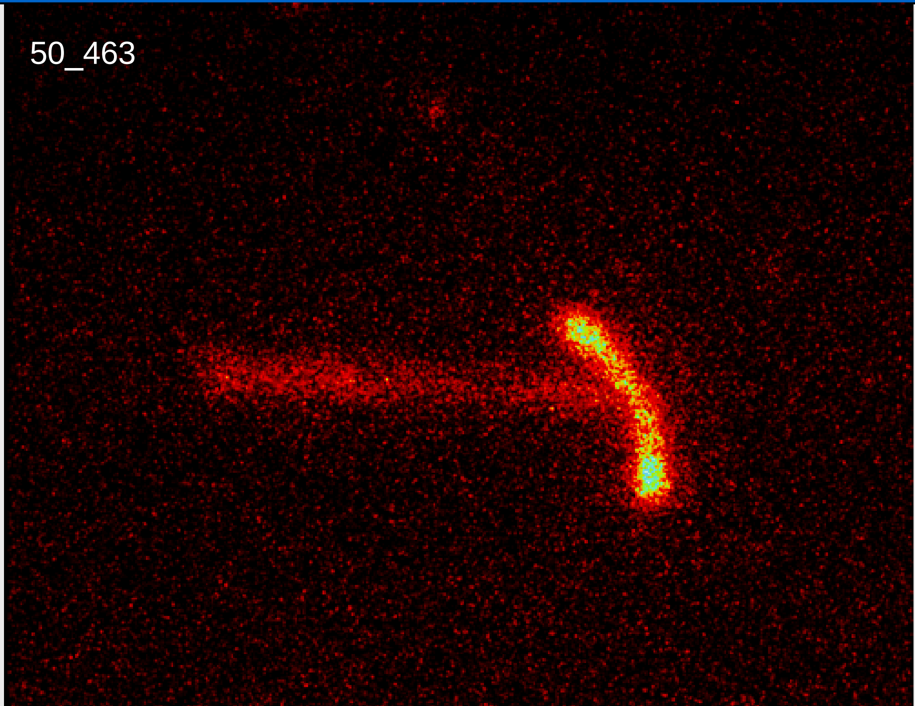


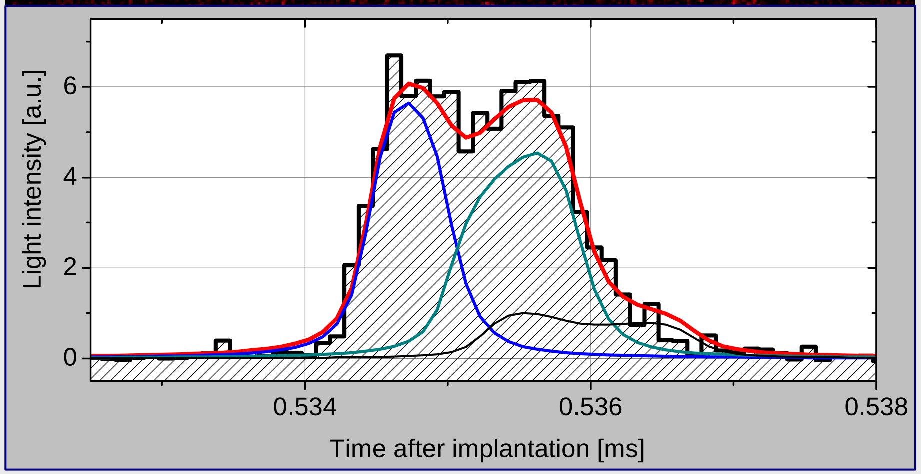
Projection of the opening angle on an image plane

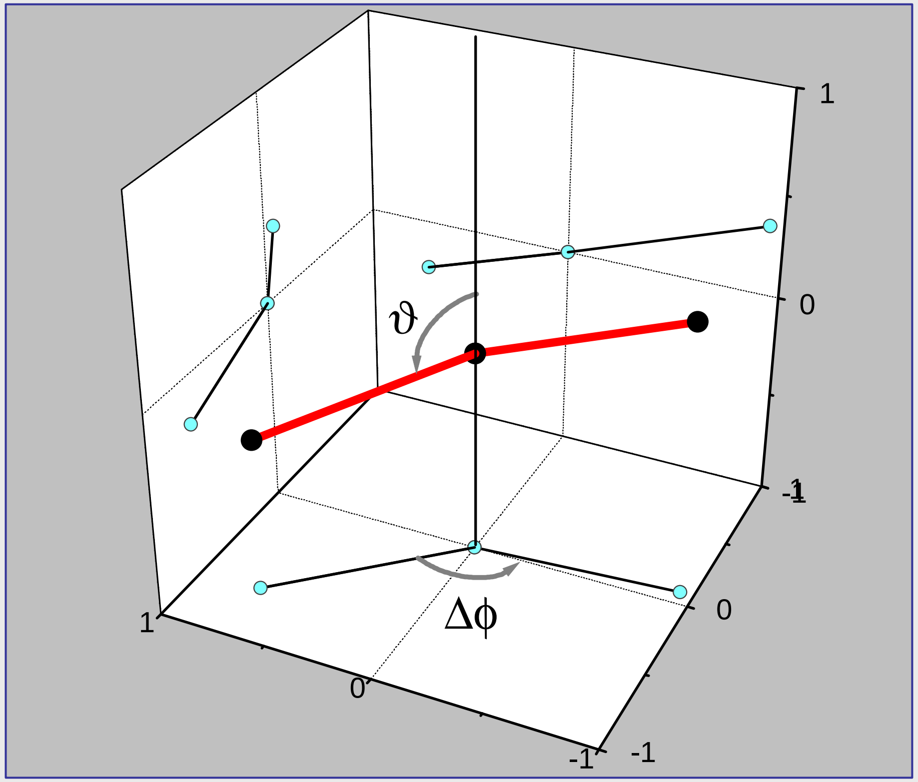
→ no reconstruction involved!

The distribution characteristic for the 3-body mechanism !!!

3D reconstruction



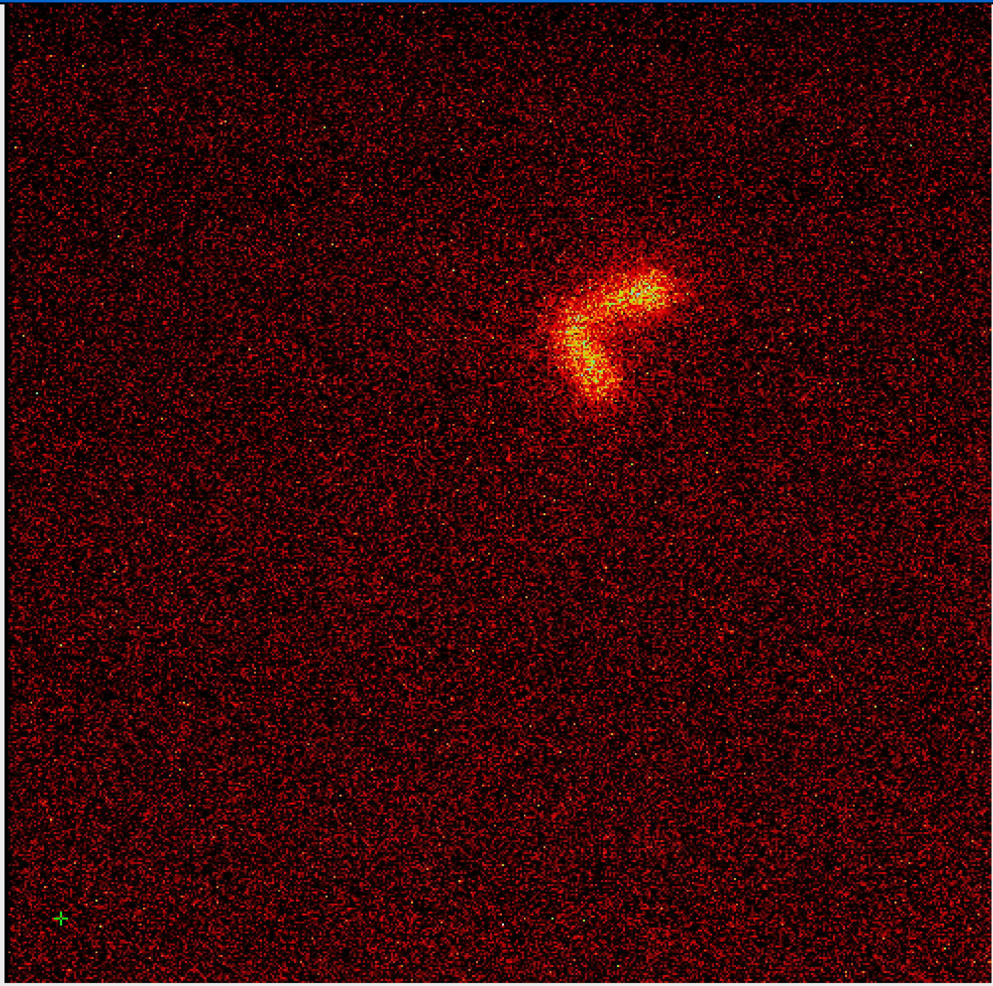


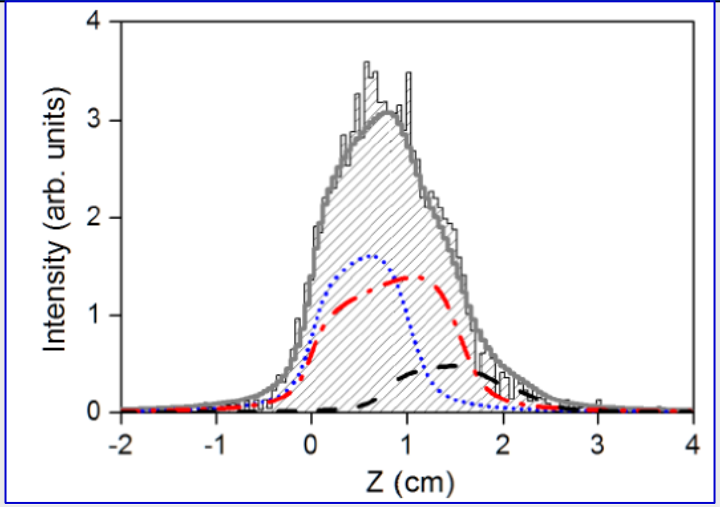


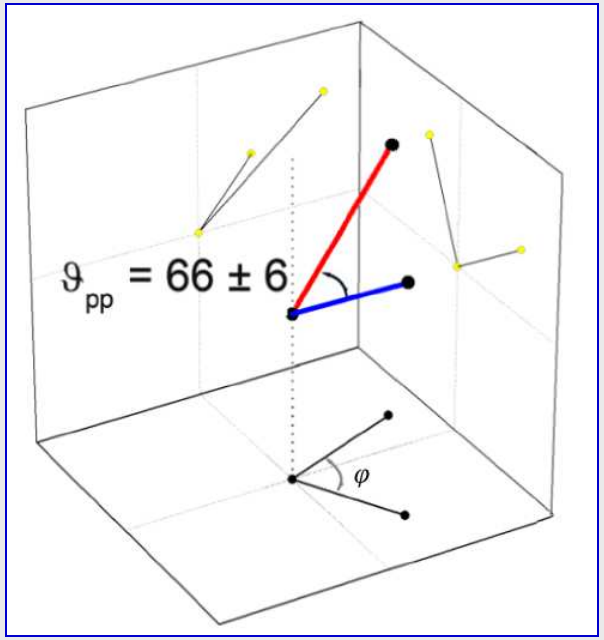
$\vartheta_1 = (104 \pm 2)°$, $\vartheta_1 = (70 \pm 3)°$

$\Delta\phi = (142 \pm 3)^o \rightarrow \theta_{pp} = (143 \pm 5)^o$

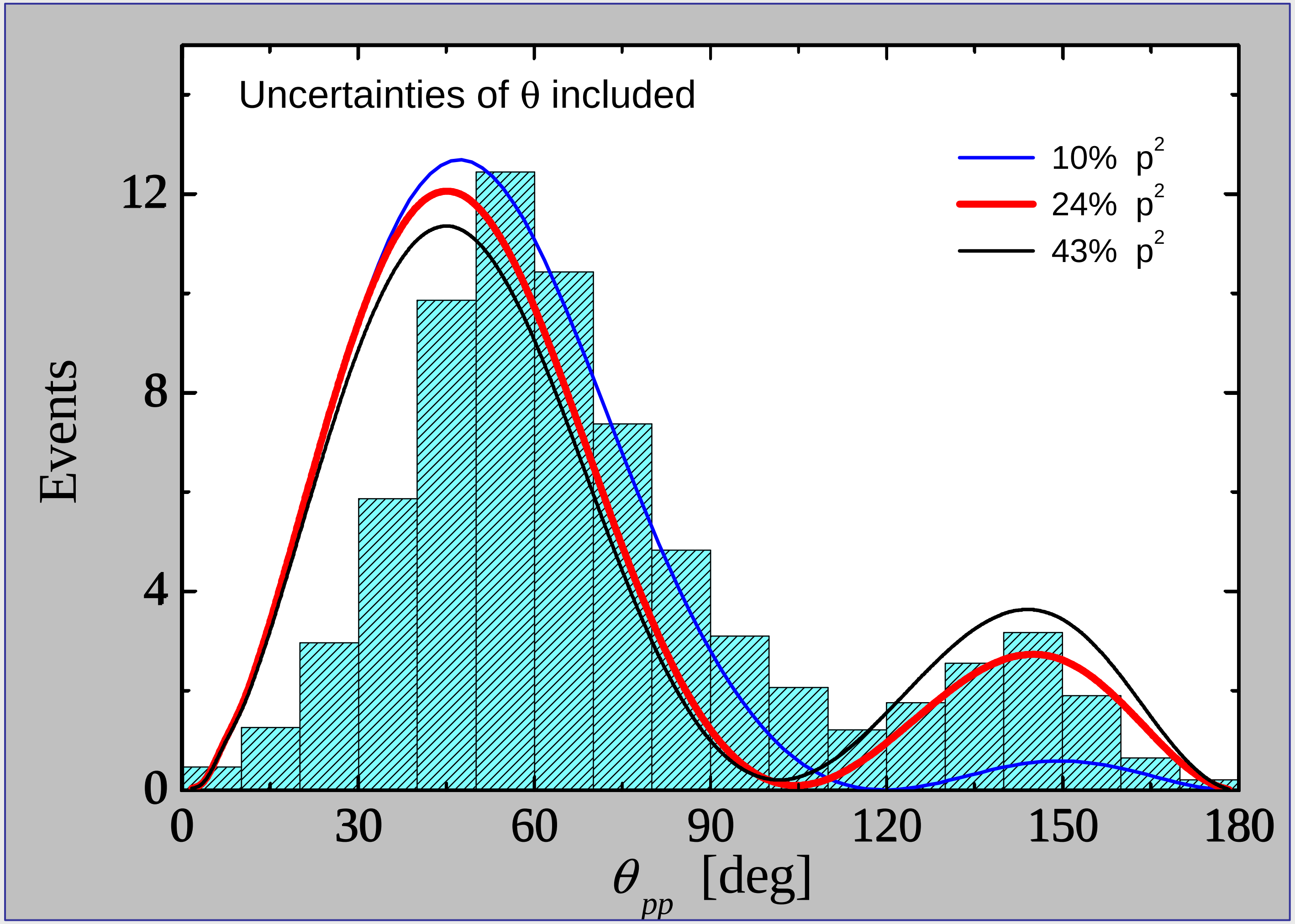
3D reconstruction







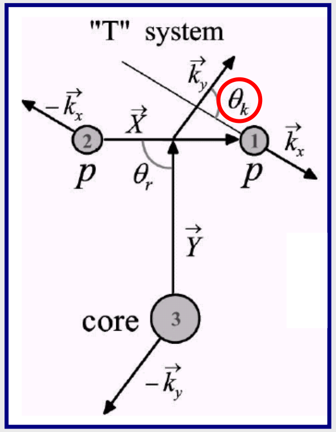
p-p opening angle

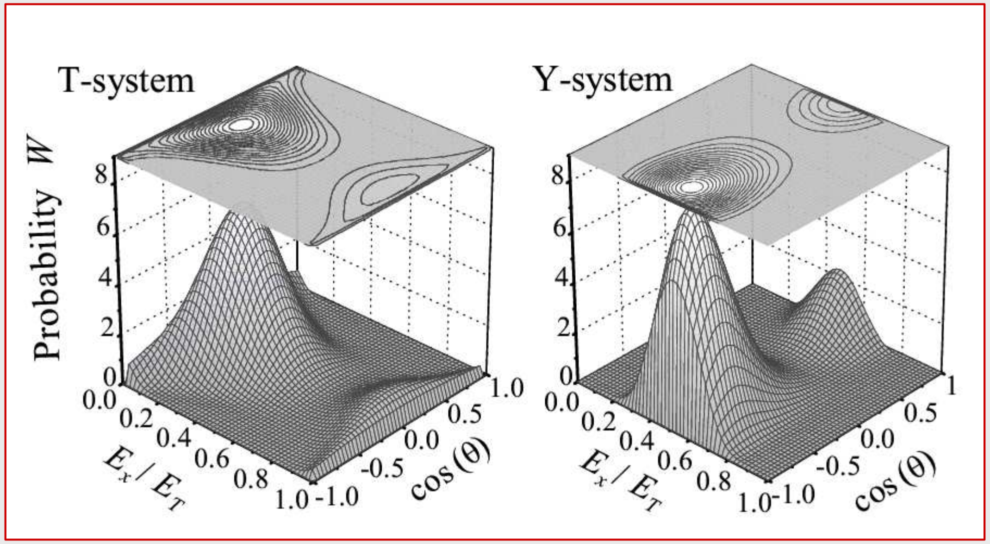


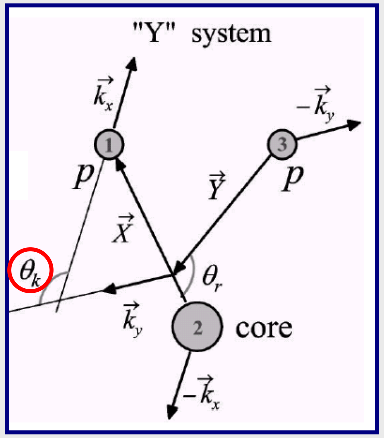
K. Miernik et al., Phys. Rev. Lett. 99, 192501 (2007)

p-*p* correlations in the 3-body model

L.V. Grigorenko and M.V. Zhukov, PRC 68 (2003) 054005



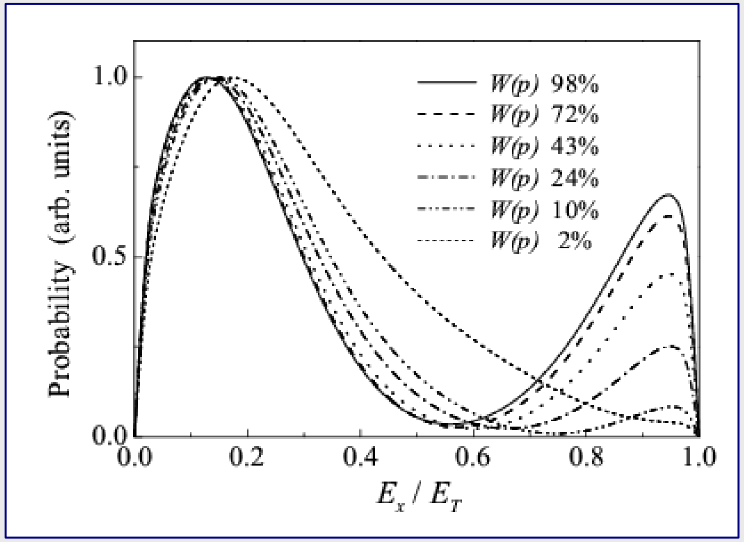




$E_T = E_x + E_y$

$E_x = k_x^2/2M_x$

$M_x = M_1M_2/(M_1+M_2)$

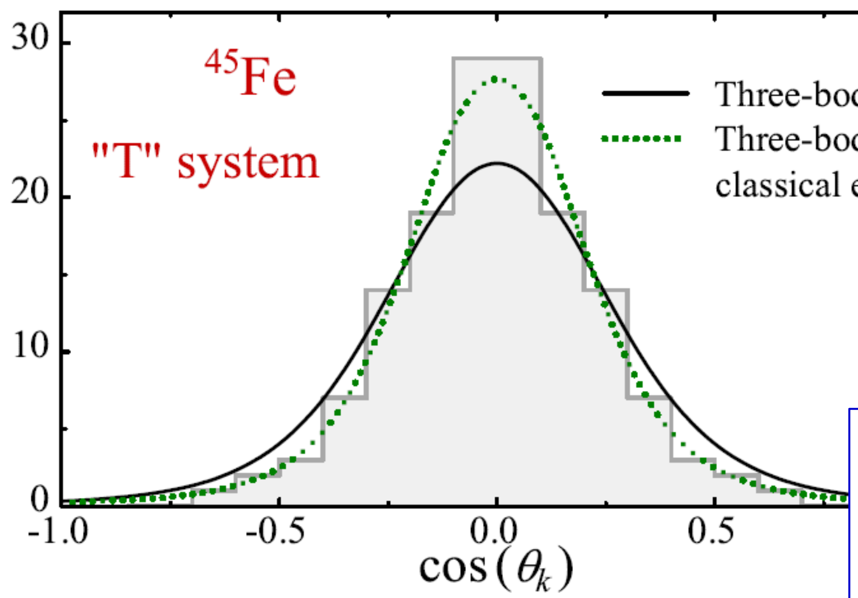


^{45}Fe

p/*f* configurations

≈ 25% p^2 + 75% f^2

p-p correlations in the "T" system

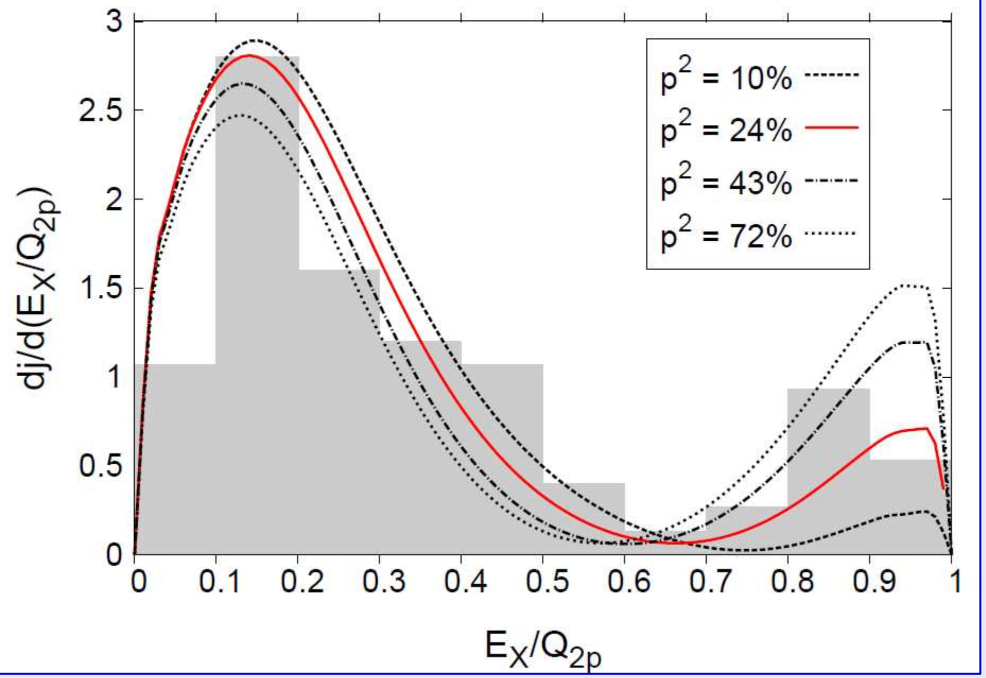


θ_k is the angle between vectors:

$(\vec{k}_1 - \vec{k}_2)$ and $(\vec{k}_1 + \vec{k}_2)$

$\vec{k}_1, \vec{k}_2$ - protons' momenta in CM

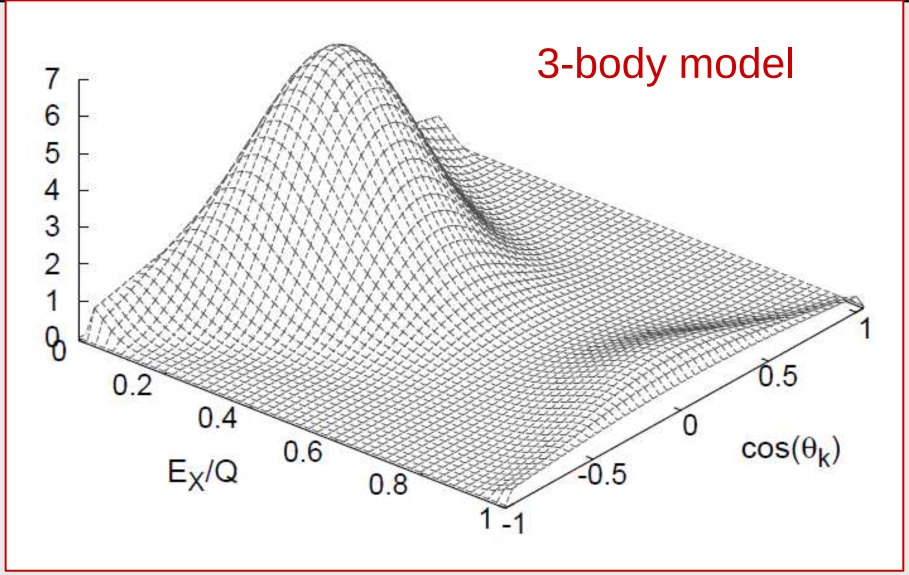
$$E_X = (\vec{k}_1 - \vec{k}_2)^2 / 4m_p$$

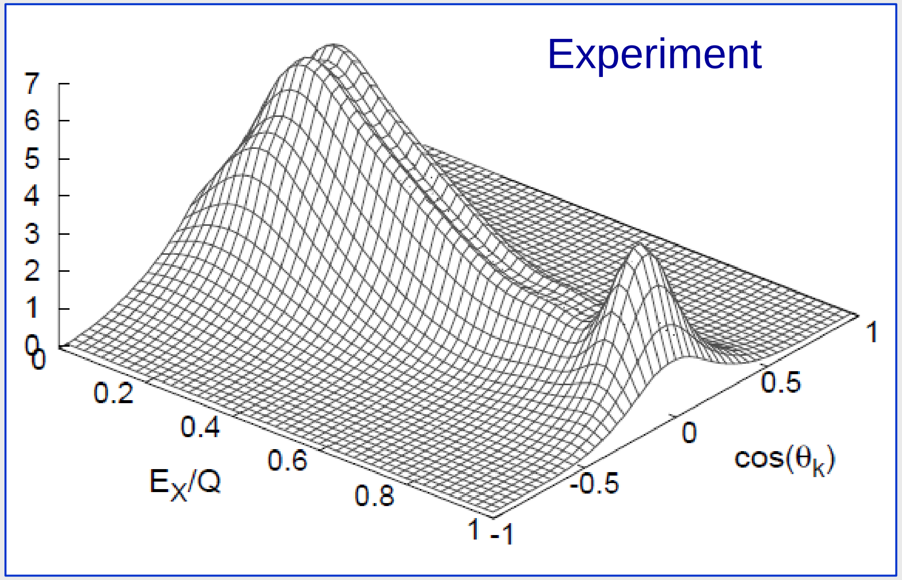


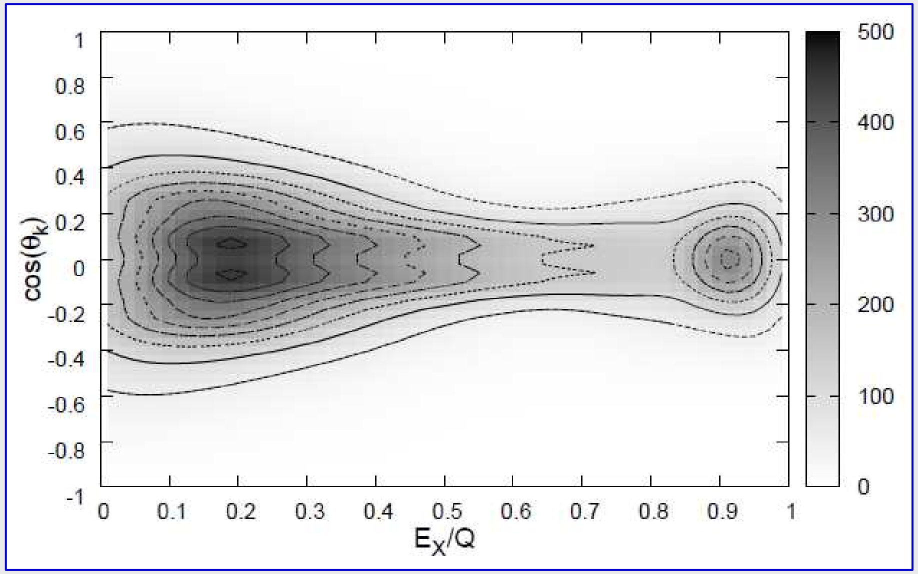
Classical extrapolation:

quantum-mechanical w-f is propagated to a distance of 1000 fm. Further, classical trajectories are followed up to 50 000 fm.

Full picture in the "T" system

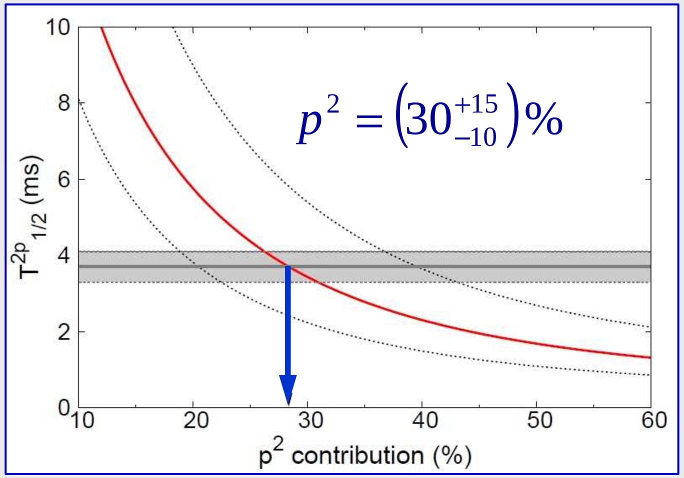


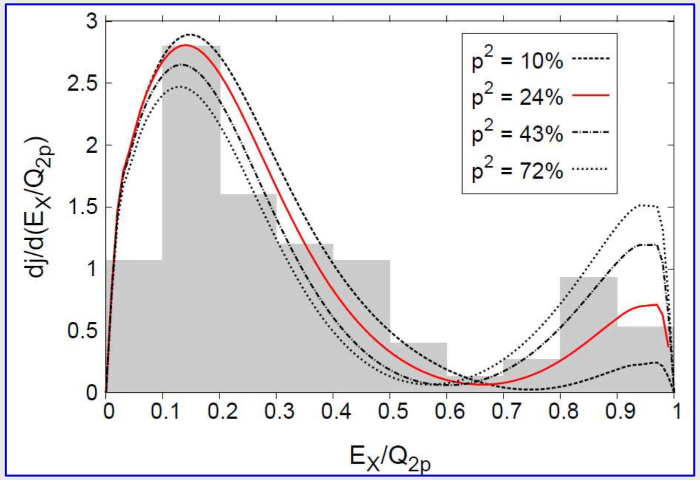




2p decay and nuclear structure

- *2p* radioactivity offers more observables than *1p* emission (correlations!)
  Better test of nuclear models



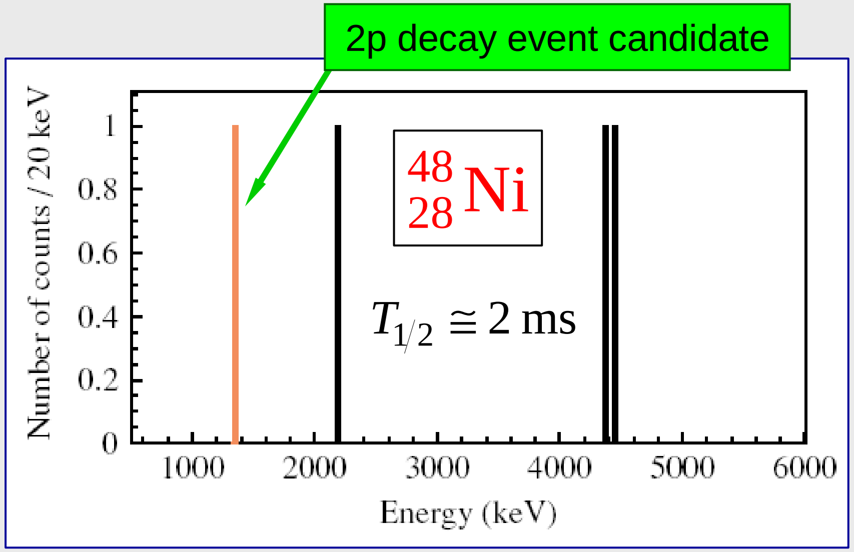


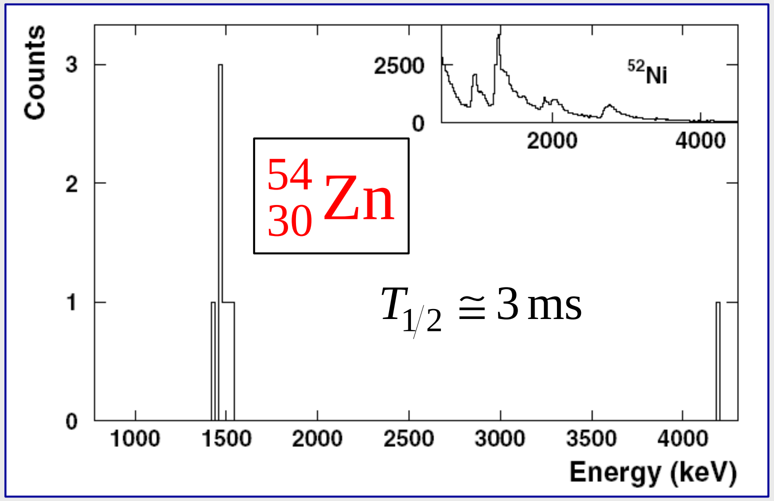
- 3-body model consistently reproduces all observables for ^{45}Fe which evidently depend on the initial state of two protons.

- Perhaps one can separate the 3-body decay dynamics from the correct description of the detailed structure of the decaying nucleus?

probability of *2p* in a state of given *l* → 3-body decay with correct FS and Coulomb interactions

Next *2p* experiments





GANIL: fragmentation of ^{58}Ni beam @ 75 MeV/u

4 ^{48}Ni ions implanted in a Si strip detector

C. Dossat et al., PRC 72 (2005) 054315

- 2p branching possibly small (≈ 25%)
- closed shell!
- good estimate of x-sec.
  6 atoms/day @ 30 pnA

NSCL experiment soon

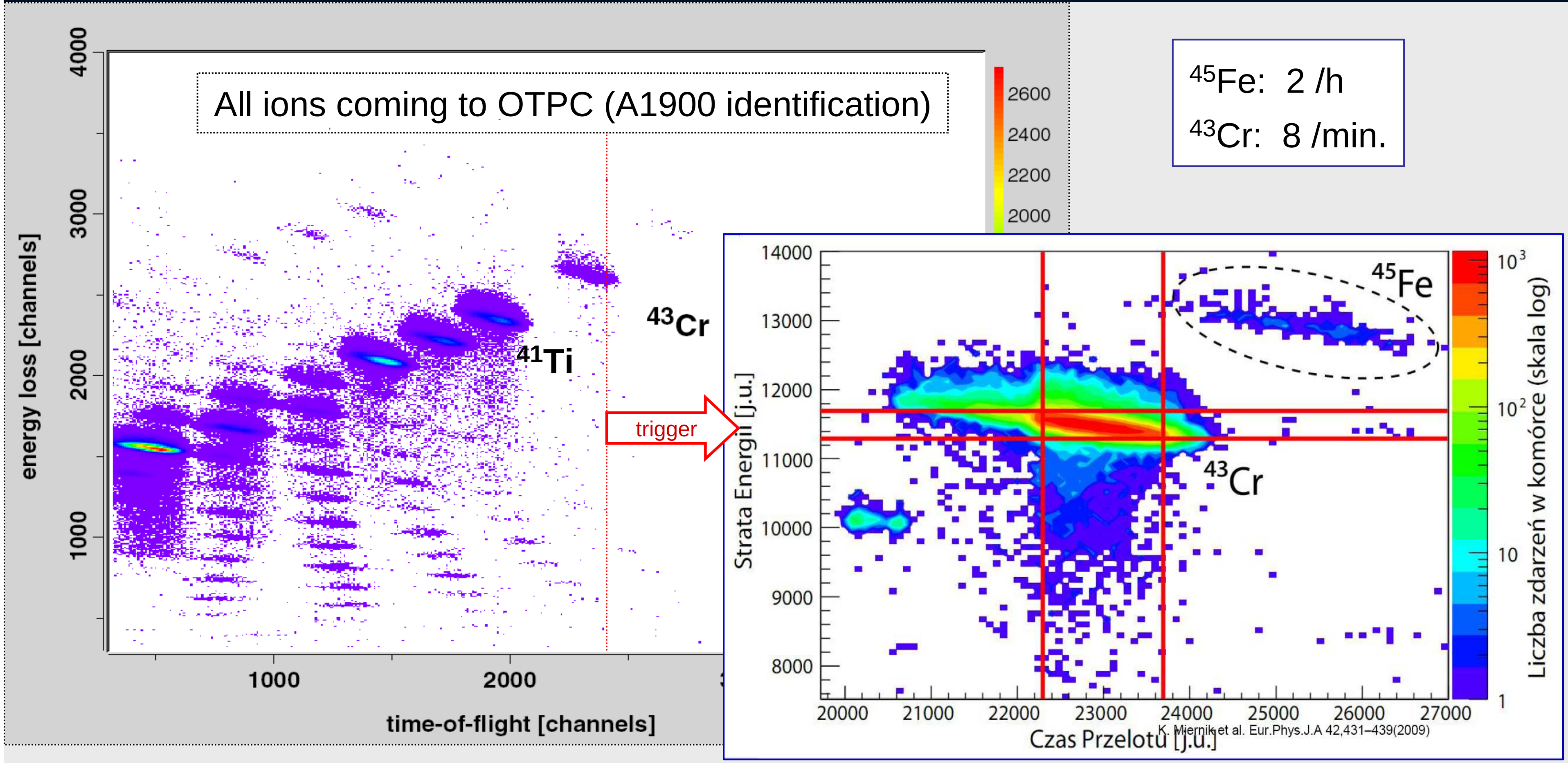
GANIL: fragmentation of ^{58}Ni beam @ 75 MeV/u

8 ^{54}Zn ions implanted in a Si strip detector

B. Blank et al., PRL 94 (2005) 232501

- known to be *2p* emitter (b(*2p*) ≈ 90%)
- probably dominated by p^2

A byproduct: ^{43}Cr

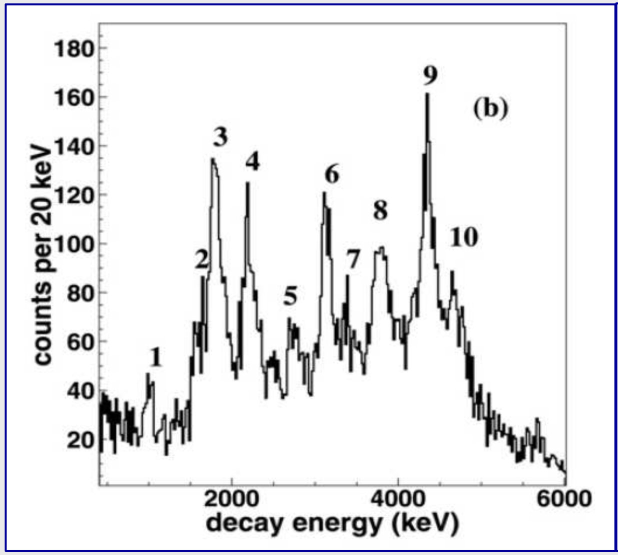


^{45}Fe: 2 /h

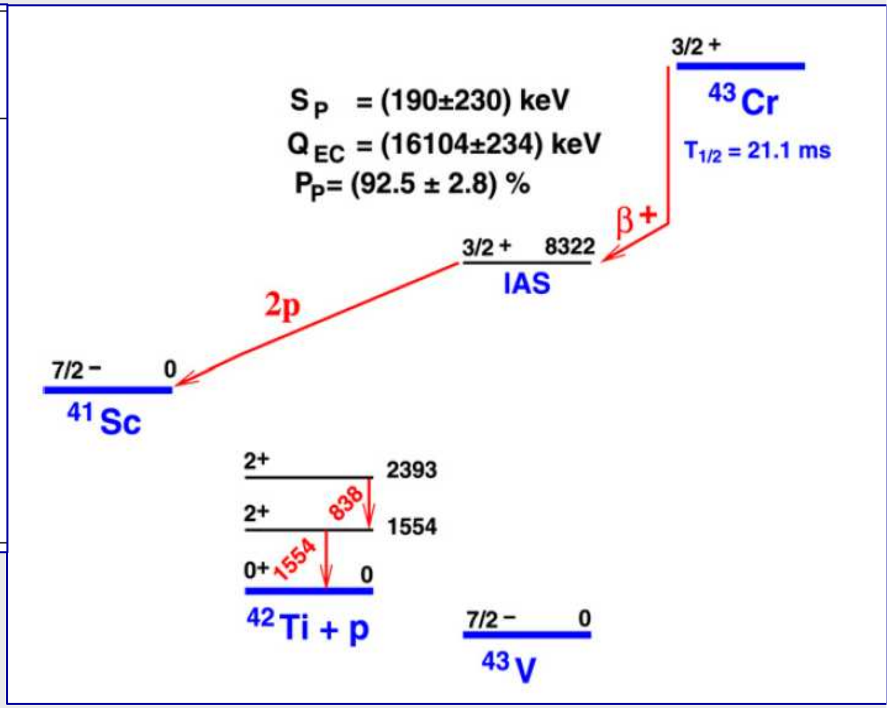
^{43}Cr: 8 /min.

We recorded about 40 000 events of ^{43}Cr

A lot is already known



	Present work	
	E_p (keV)	I_p (%)
1	998(16)	0.6(1)
2	1614(34)	2.1(11)
3	1812(15)	7.1(12)
4	2179(17)	4.7(7)
5	2753(19)	1.2(4)
6	3138(17)	3.4(7)
7	3382(25)	1.0(4)
8	3744(27)	3.0(14)
9	4348(16)	5.6(7)*
10	4671(26)	4.5(8)



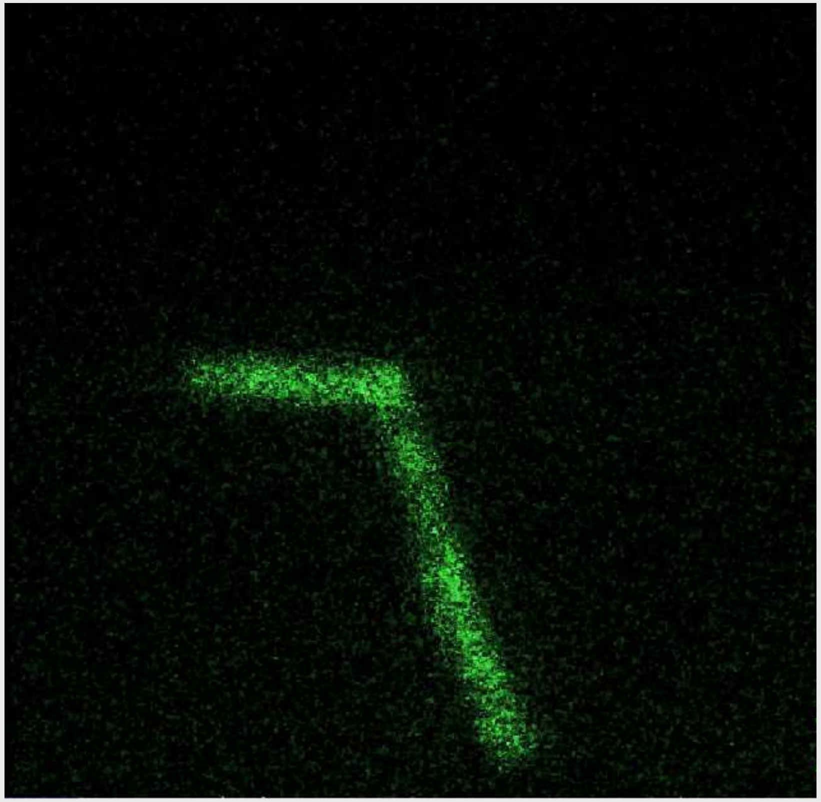
C. Dossat et al., Nucl. Phys. A 792 (2007) 18

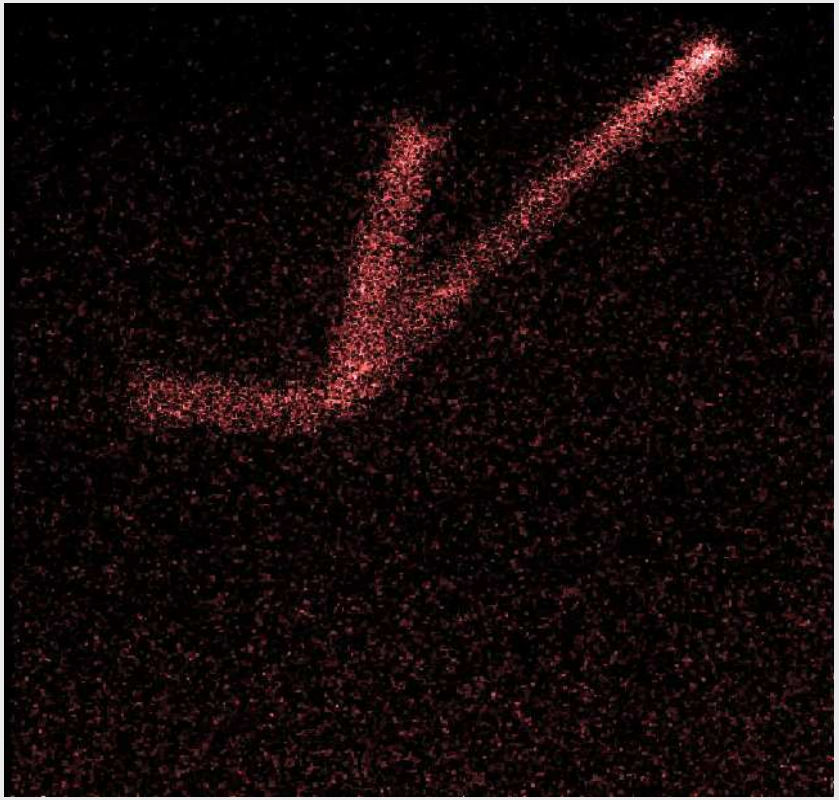
Implantantion method at GANIL

- The branching for *p* emission is determined to be 92.5 %
- Only 33 % is seen in peaks in the *p* spectrum

What new could we possibly add with an OTPC measurement?

βp and $\beta 2p$ events are there

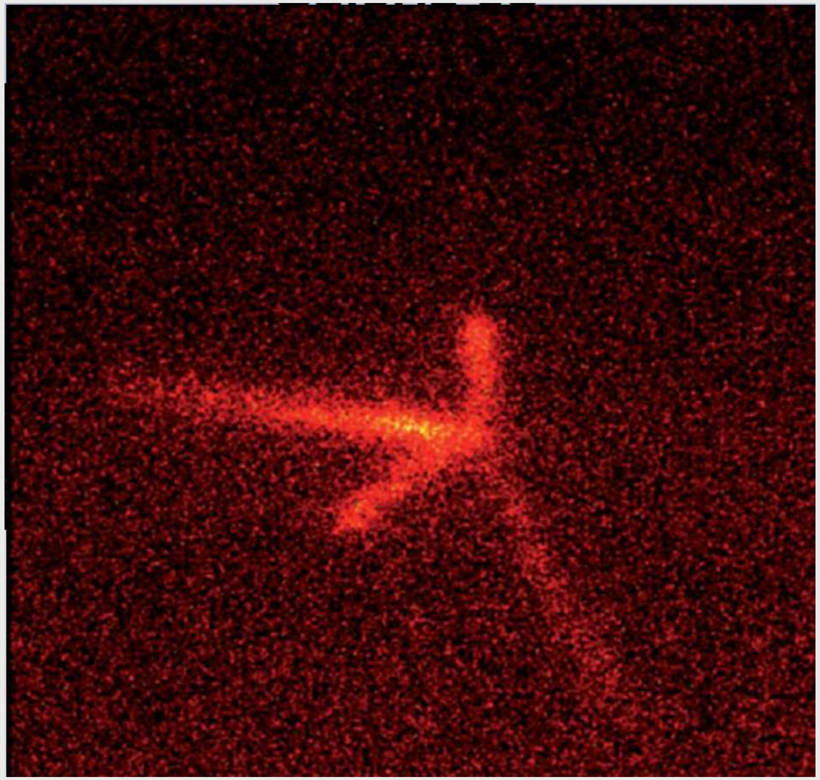




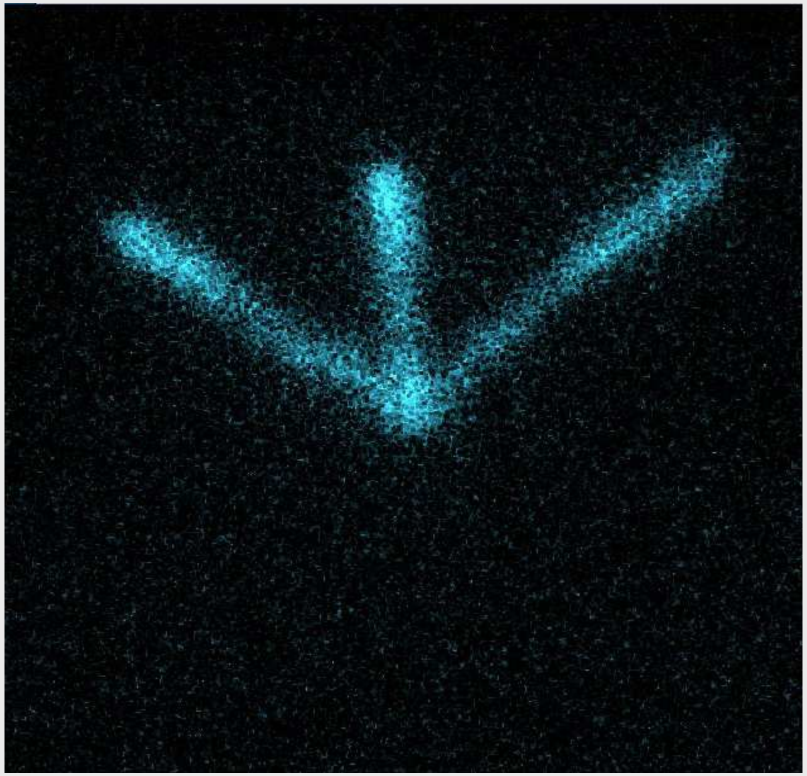
Example events in the asynchronous mode (incoming ^{43}Cr ion visible)

M. Pomorski et al., to be published

But β3*p* are there, too!



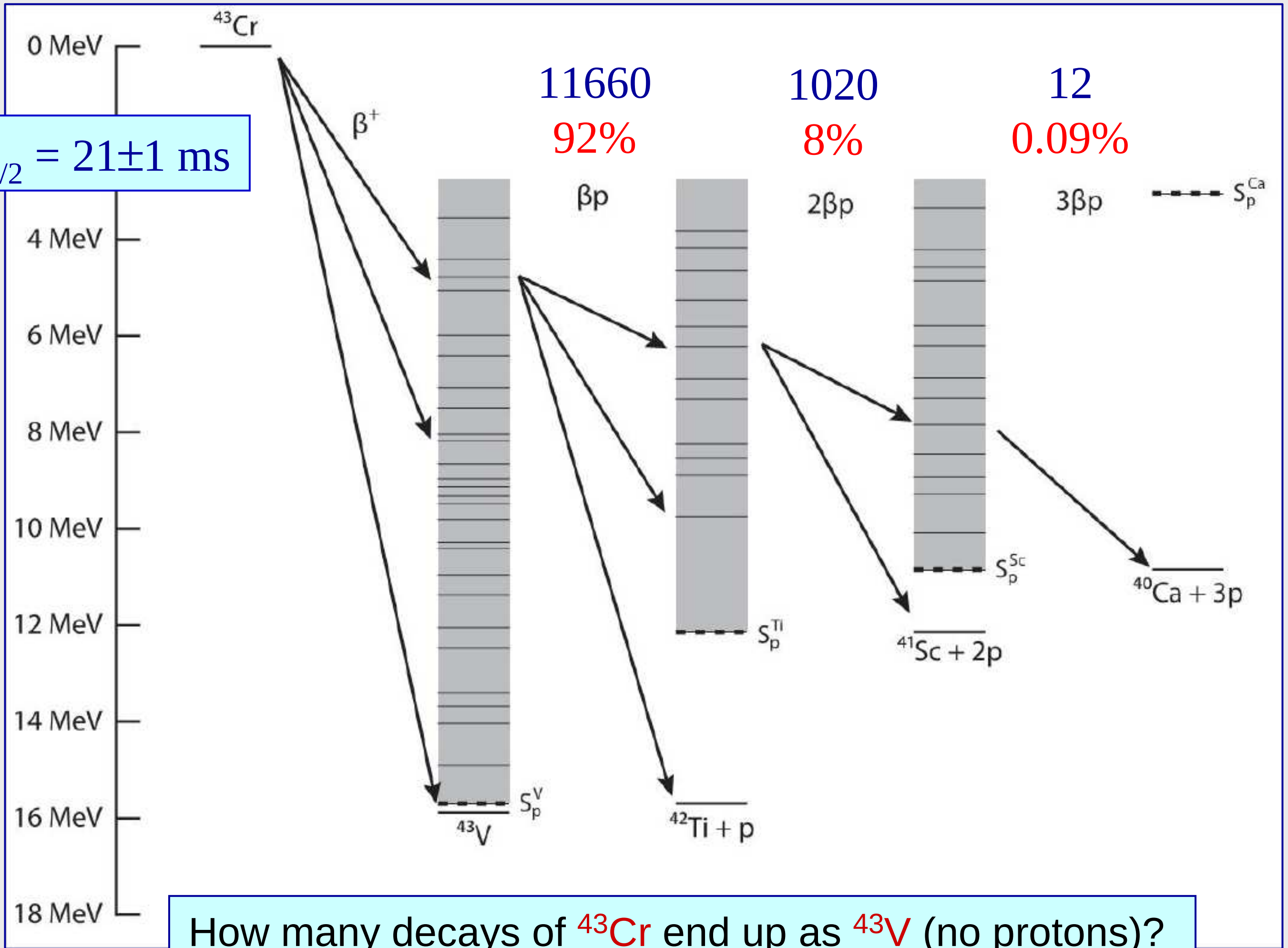
an event in an asynchronous mode



an event in a synchronous mode
(an ion not visible)

- In total 12 such events were observed

Decay channels observed



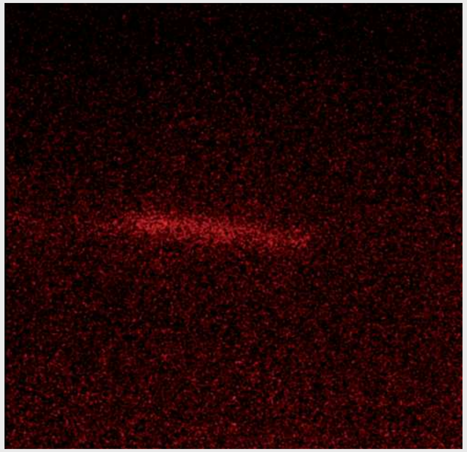
$T_{1/2}$ = 21±1 ms

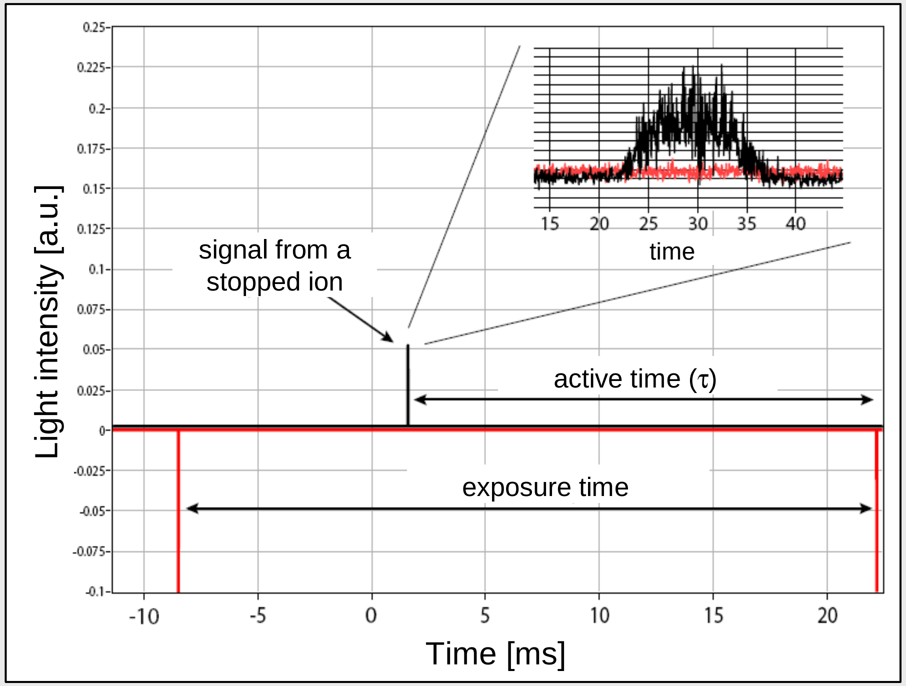
How many decays of ^{43}Cr end up as ^{43}V (no protons)?

→ We cannot see such decays, but we can count them!

Counting invisible

- The key lies in the asynchronous events when ion is seen but it doesn't decay





→ Either the ion decayed after the known active time

or it decayed within this time but with no protons,

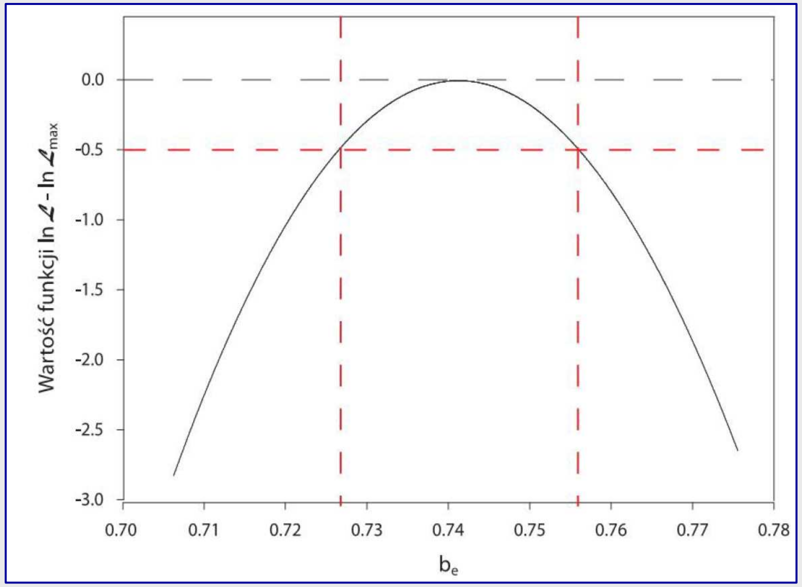
the probability is: $P_{\text{no proton}} = \exp(-\lambda\tau) + (1-b_e)[1-\exp(-\lambda\tau)]$

Absolute branchings

preliminary!

➔ Taking into account many events with and without protons, we build the *likelihood function* and maximize it with respect to the absolute branching.

$$\mathscr{L} = \prod_{i=0}^{N_e} \left\{ b_e \left[1 - \exp\left(-\lambda \tau^i\right) \right] \right\} \prod_{j=0}^{N_{ne}} \left\{ \exp\left(-\lambda \tau^j\right) + (1 - b_e) \left[1 - \exp\left(-\lambda \tau^j\right) \right] \right\}$$



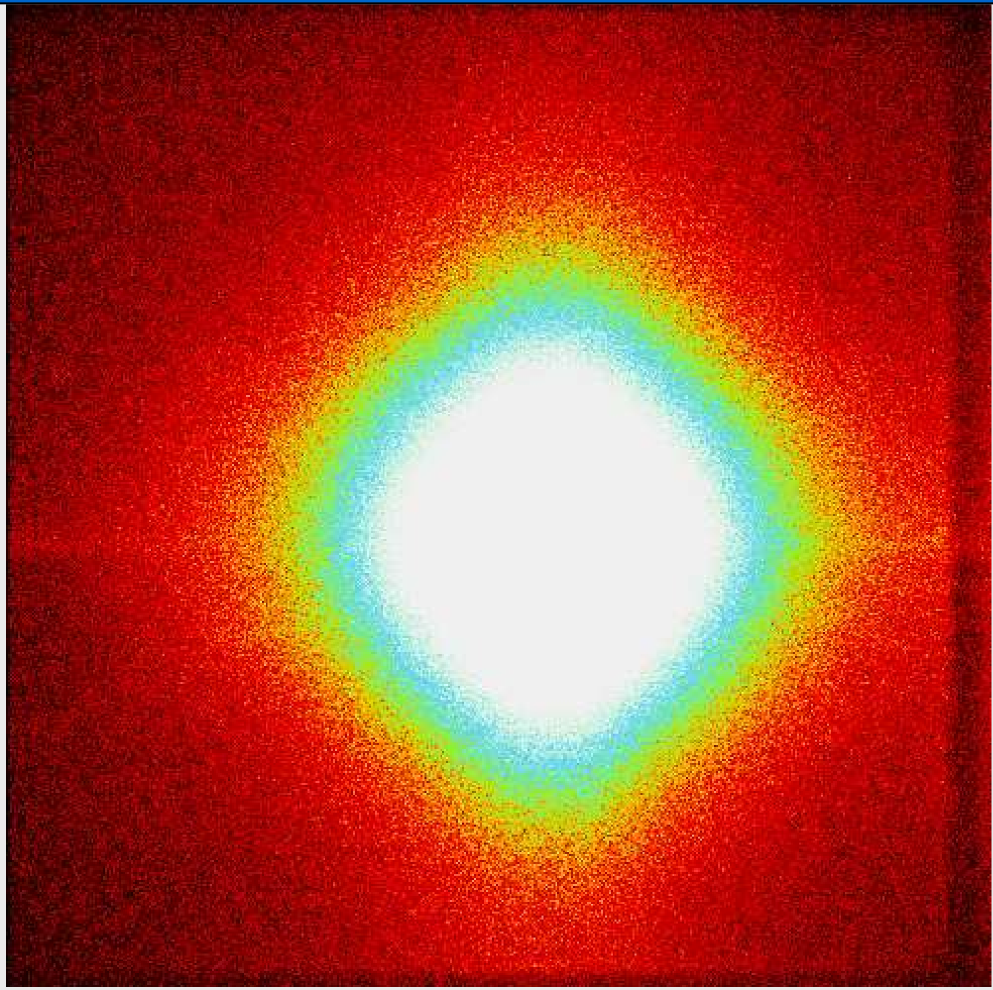
Number of protons	Absolute branching [%]	Dossat et al.
0	26(2)	7.5(3)
1	68(2)	> 28(1)
2	5.9(6)	5.6(7)
3	0.07(2)	-

?

M. Pomorski et al., to be published

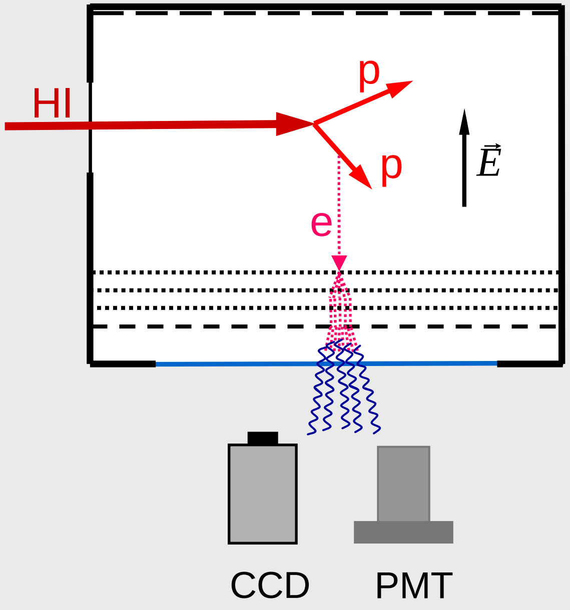
C. Dossat et al., Nucl. Phys. A 792 (2007) 18

A spark ☺

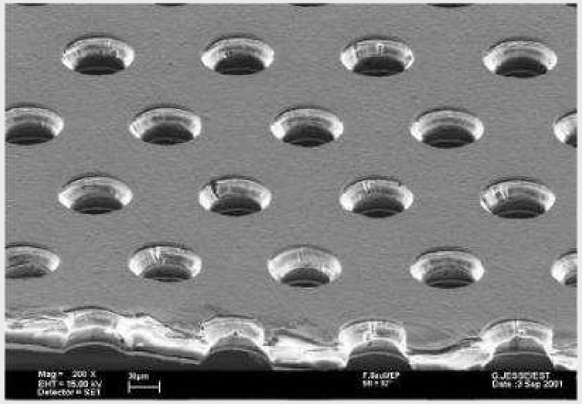


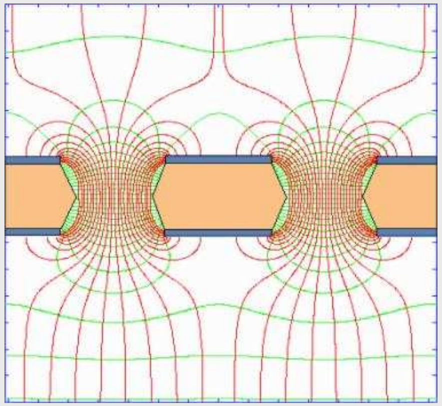
Mini explosions are spectacular but we need to get rid of them!

OTPC development

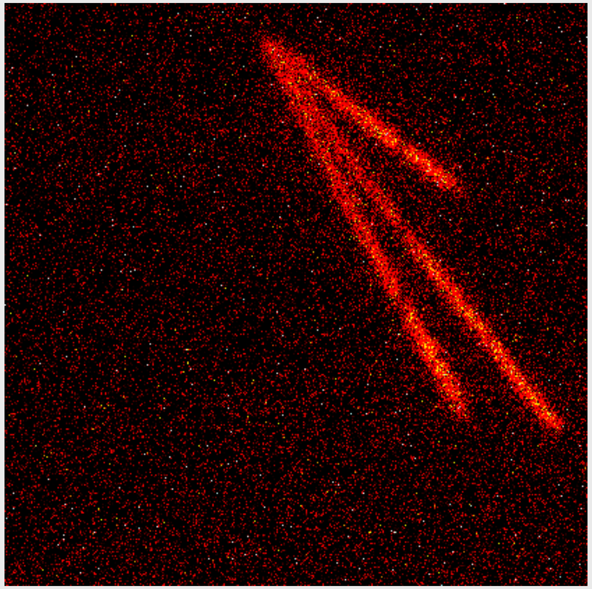


- ‘Natural’ geometry (implantation perpendicular to field lines):
  - → increased efficiency
  - → no ion-induced sparks
  - → no diffusion problem





- First amplification stage replaced by 3 GEM foils:
  - → lower voltages
  - → less sparking
  - → larger amplification
  - → larger dynamic range



α tracks from a source !

Testing new version

- The new OTPC version needs testing with real charged-particle decays.
- An ideal case: combine a test with a real physics experiment

Our choice ⟶ ^{8}He

^{8}He – the most neutron-rich, particle-stable nucleus, attracts lot of interest (NNDC/NSR Data Base shows 225 papers!)

Most recent highlights, all presented at ENAM'08 conference:

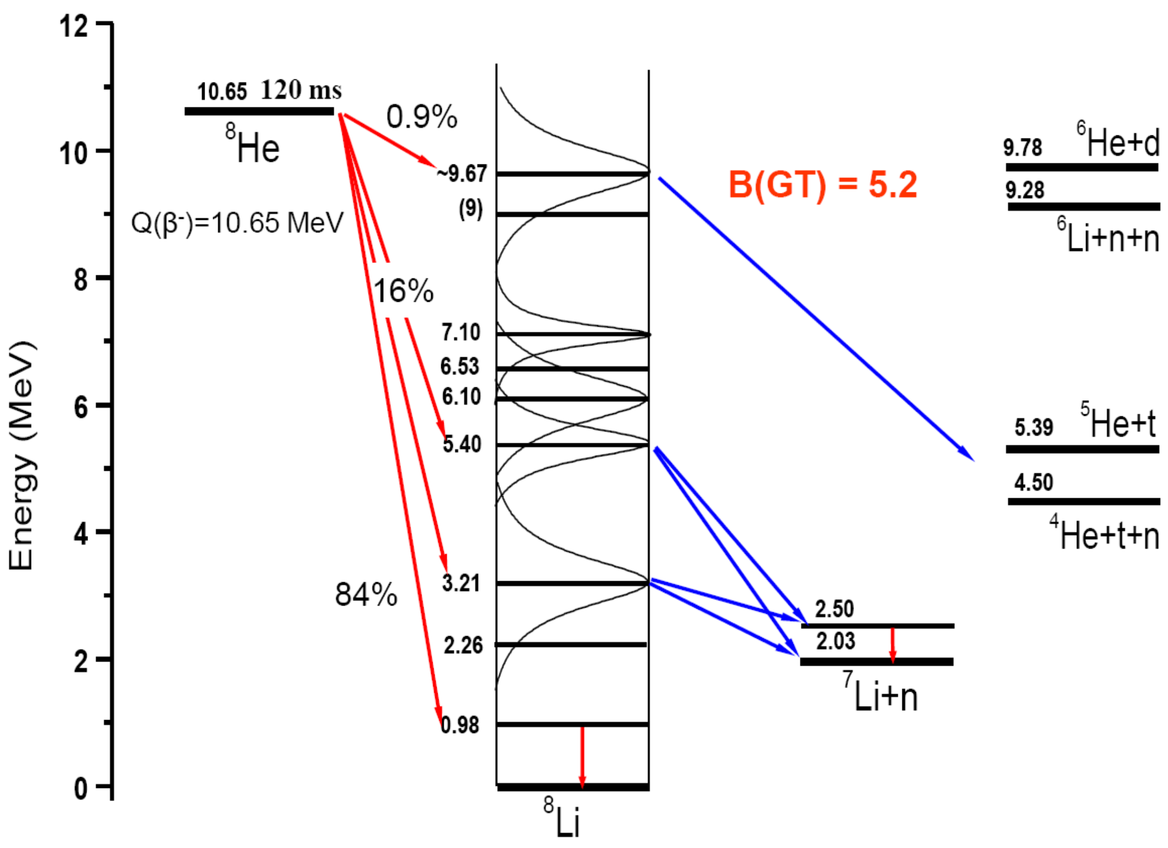
⇨ P. Mueller et al., Phys. Rev. Lett. 99 (2007) 252501 – „Nuclear Charge Radius of ^{8}He"

⇨ V.L. Ryjkov et al., Phys. Rev. Lett. 101 (2008) 012501 – „Direct Mass Measurement of the Four-Neutron Halo Nuclide ^{8}He"

⇨ M.S. Golovkov et al., Phys. Lett. B 672 (2009) 22 – „The ^{8}He and ^{10}He spectra studied in the (t,p) reaction"

➤ Still not all is known in the β- decay of ^{8}He !

β-decay of ^{8}He



D. R. Tilley et. all, Nucl. Phys. A 745 (2004)

The last (?!) experiment on β-decay of ^{8}He:

ISOLDE (1992)

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

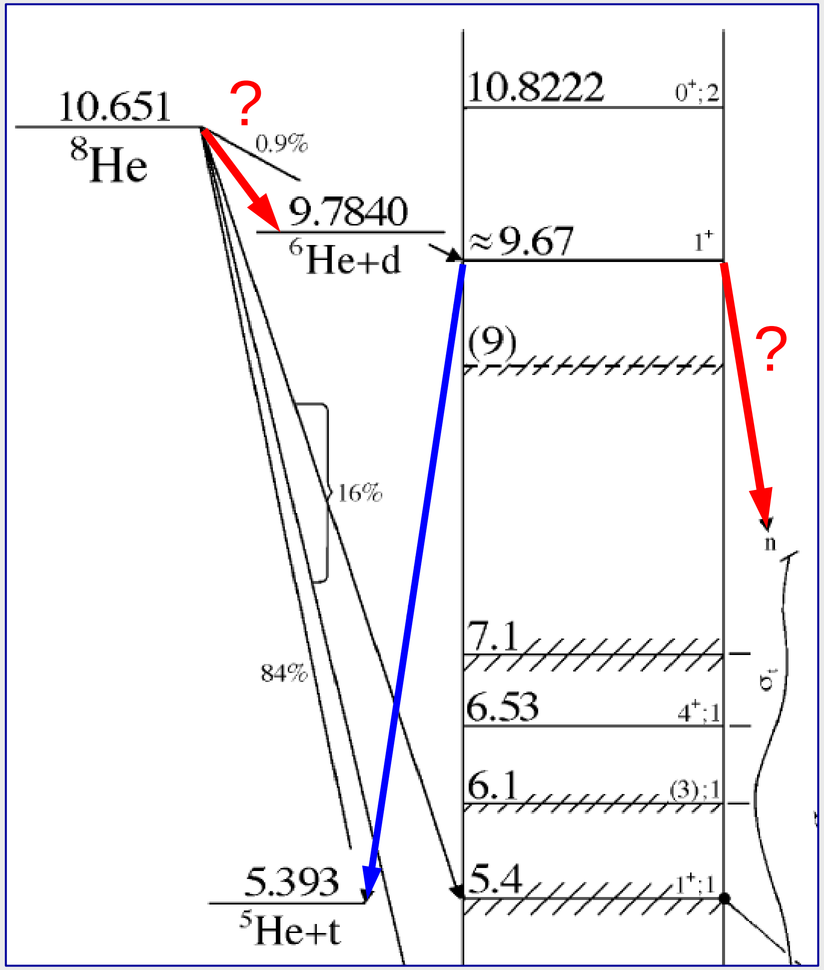
β-delayed t emission measured

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

$$b_t = (8.0 \pm 0.5) \times 10^{-3}$$

➔ $B_{GT} \geq 5.2$, log $ft = 2.9$!

Questions



- What really is the feeding of the 9.67 MeV state?

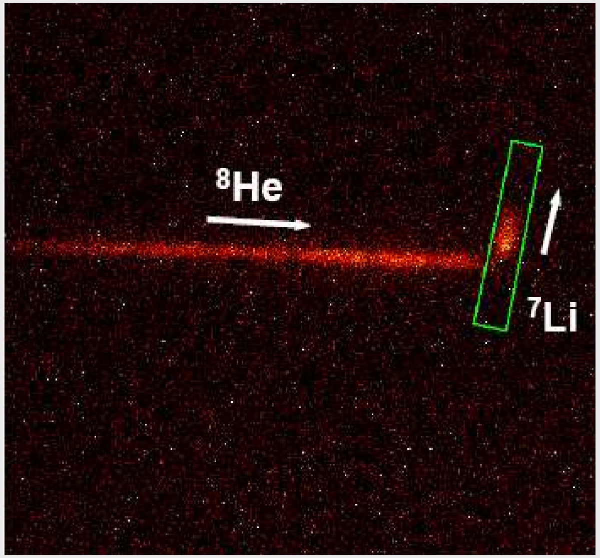
- Is there a strong feeding to a predicted *halo analogue* state?

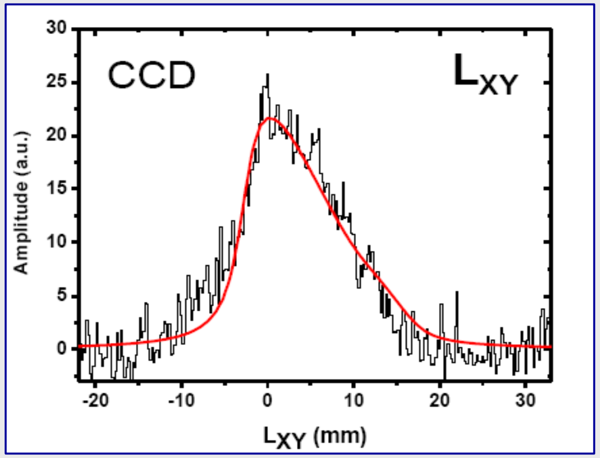
M. Zhukov et al., PRC 52 (1995) 2641
L.V. Grigorenko et al., NP A607 (1996) 277

- Can we see the branch with the deuteron emission?

  If yes, is it sensitive to the halo structure (compare ^{6}He, ^{11}Li)?

A decay event





L = (21 ± 2) mm

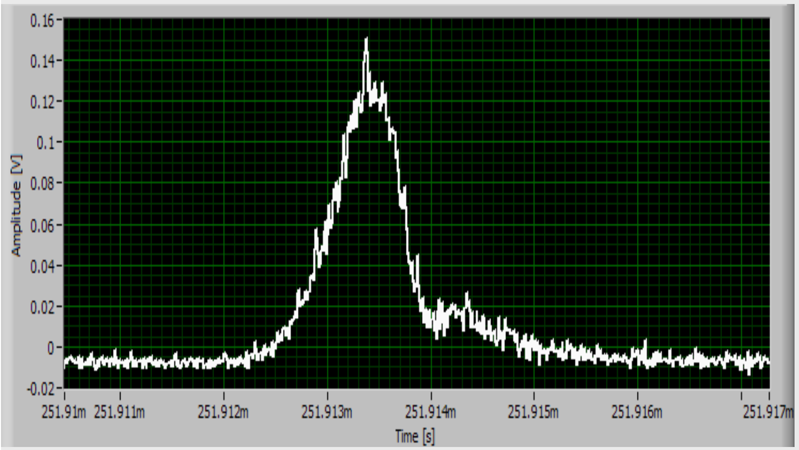
E = (800 ± 50) keV

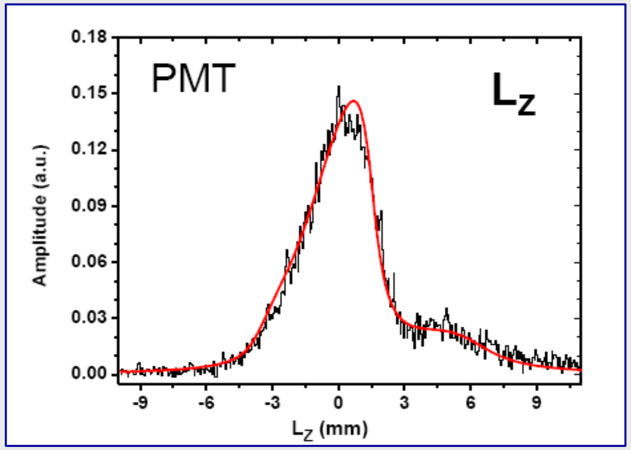
Θ = (105 ± 10)º

f = (83 ± 5)º

$^{8}\mathrm{He} \rightarrow {}^{8}\mathrm{Li}^{**} \rightarrow {}^{7}\mathrm{Li} + \mathrm{n}$

Q = (6.4 ± 0.4) MeV

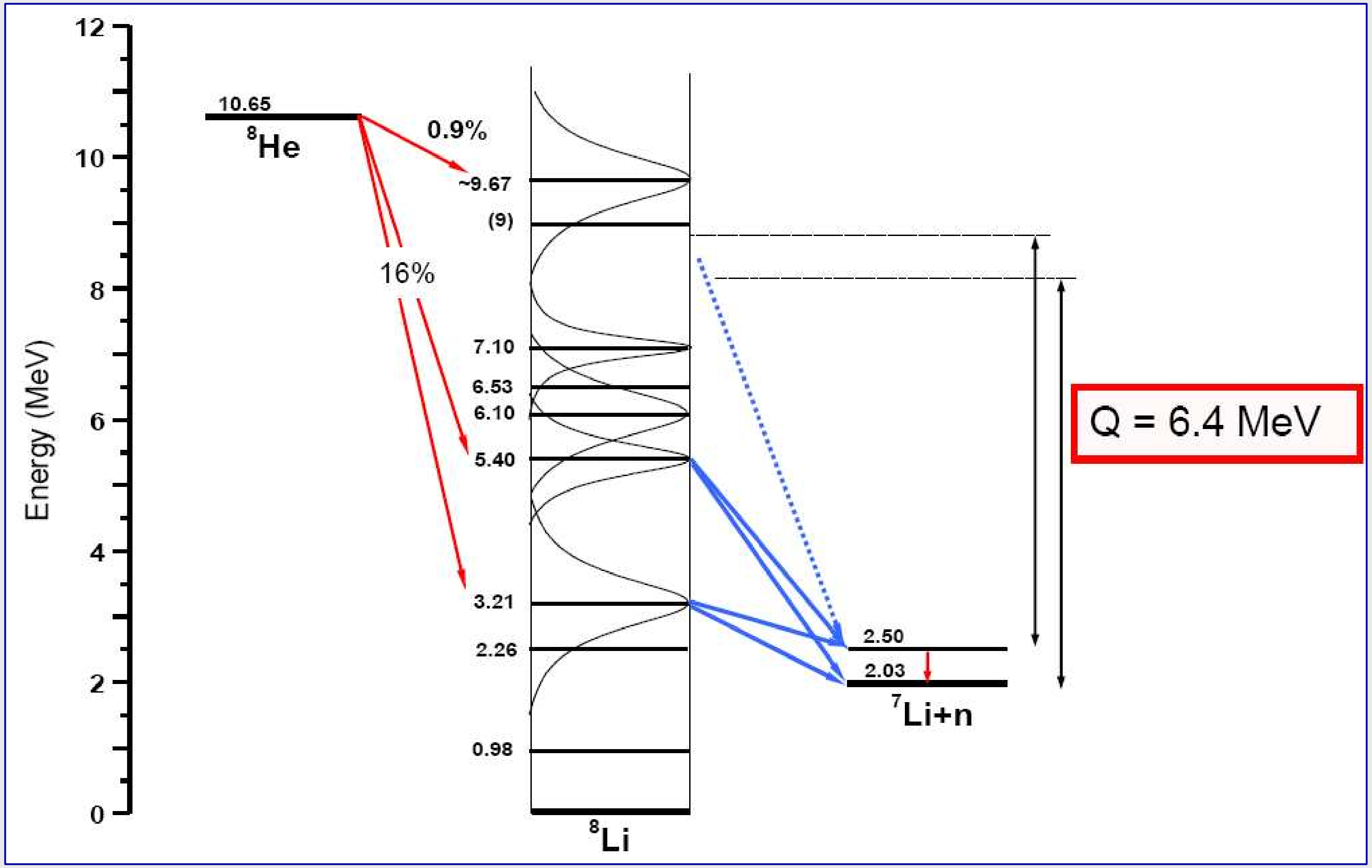




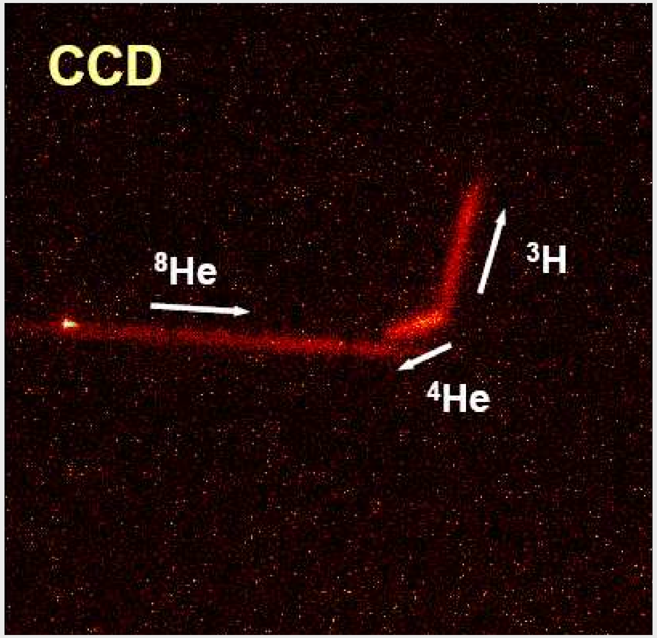
S. Mianowski et al., to be published

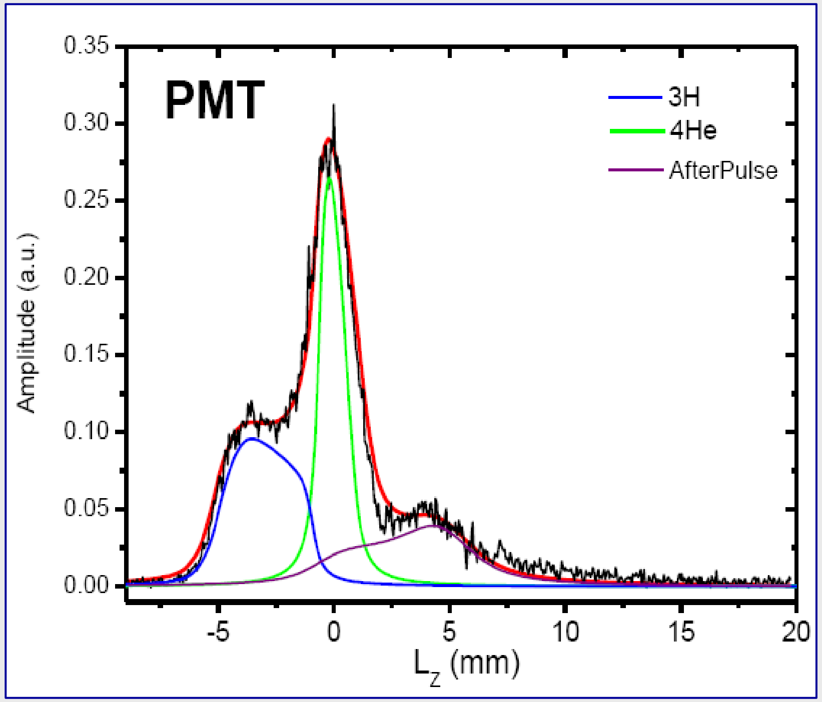
A new decay channel!

preliminary!



Another event





^{4}He:

L = (18 ± 2) mm
E = (700 ± 40) keV
Θ = (85 ± 10)°
φ = (200 ± 5)°

^{3}H:

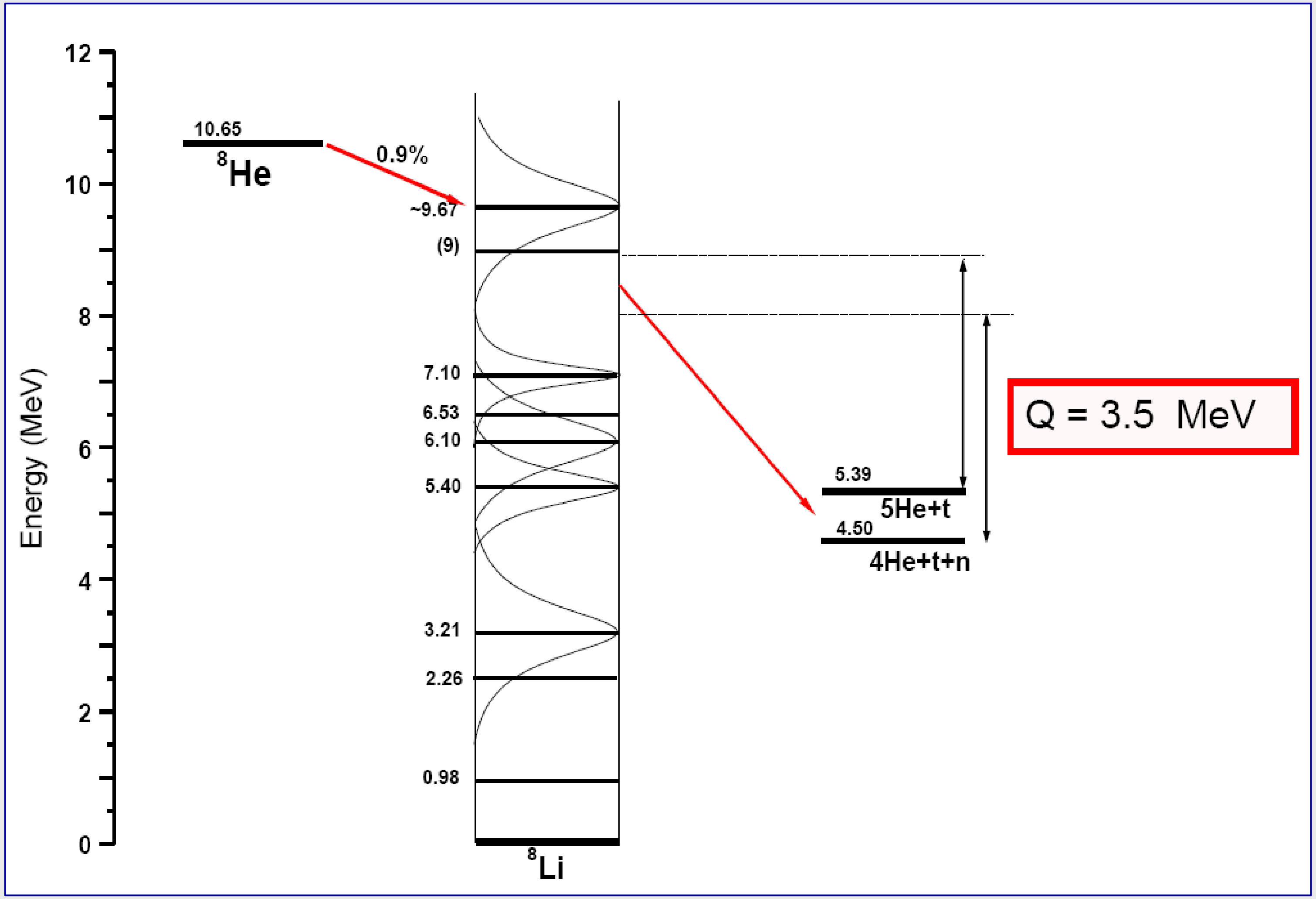
L = (35 ± 3) mm
E = (640 ± 35) keV
Θ = (98 ± 10)°
φ = (77 ± 5)°

n:

E = (2.2 ± 0.3) MeV

Q = (3.5 ± 0.3) MeV

β-delayed triton emission



Summary

- The idea of optical recording of charged particles' tracks does work!
  Return of photographic techniques to nuclear science!

- This idea implemented as OTPC brought new results
  - *p-p* correlations in the decay of ^{45}Fe
  - *β3p* emission in two nuclei
  - possibly a new decay channel of ^{8}He

- Remarkable sensitivity – one good event suffices!

- Much cheaper and simpler than electronic TPC

- Present version has limitations
  - rather slow
  - limited to simple decays (2 tracks can be reconstructed)
  - not sensitive enough to see b particles

- Experiment in Dubna on ^{8}He should start this week

Collaboration

Dubna Experiments:

University of Warsaw

- H. Czyrkowski
- W. Dominik
- Z. Janas
- S. Mianowski
- K. Miernik
- M. P.

Joint Institute for Nuclear Reasearch

- A. Fomichev
- M. Golovkov
- L. Grigorenko
- A. Rodin
- S. Stepantsov
- R. Slepnev
- G. M. Ter-Akopian
- R. Wolski

NSCL Experiment:

University of Warsaw

- H. Czyrkowski
- M. Ćwiok
- W. Dominik
- Z. Janas
- M. Karny
- A. Korgul
- K. Miernik
- M. P.

University of Tennessee

- C. Bingham
- I. Darby
- R. Grzywacz
- S. Liddick
- M. Rajabali

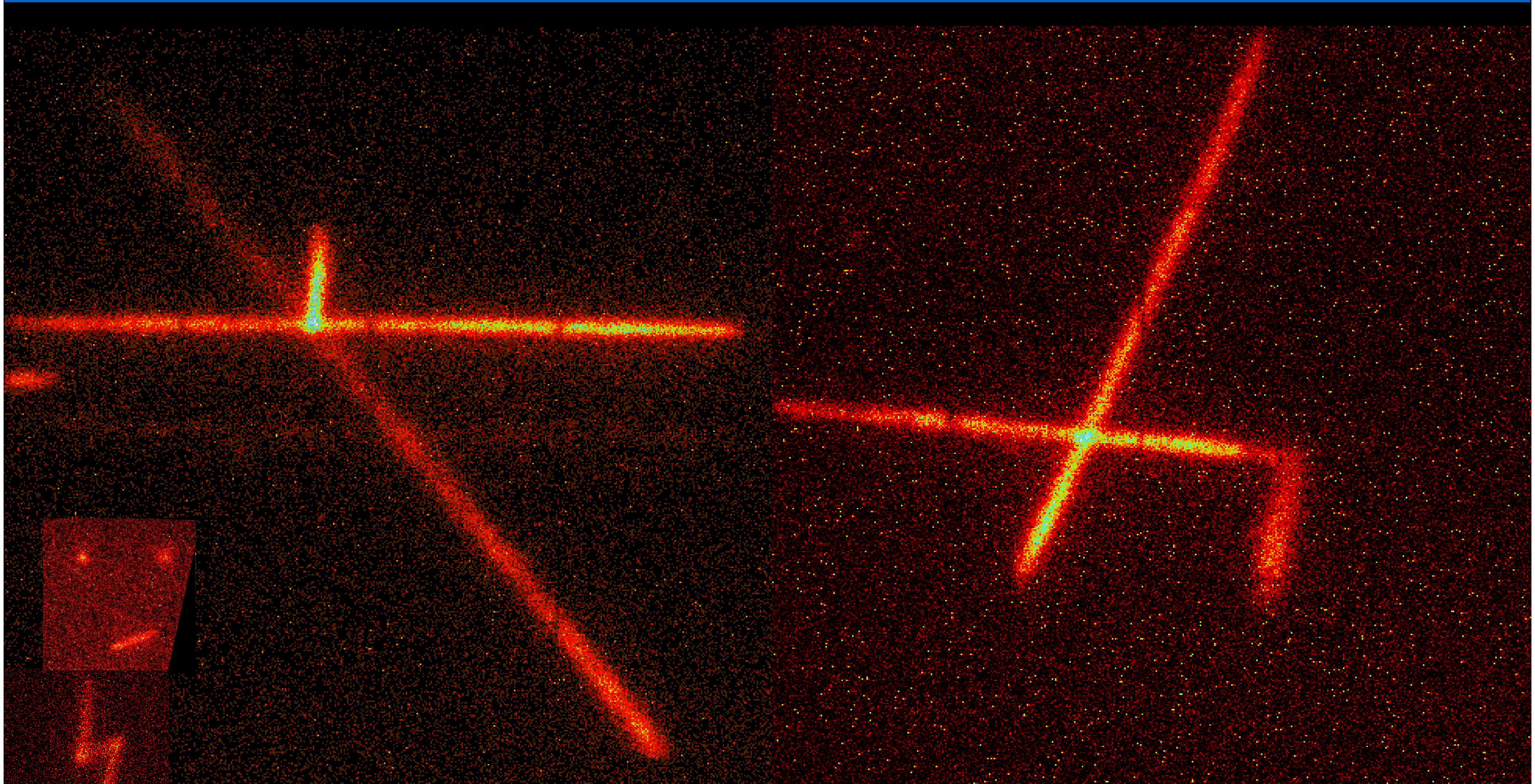
National Superconducting Cyclotron Laboratory

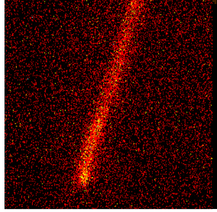
- T. Ginter
- A. Stolz

Oak Ridge National Laboratory

- K. Rykaczewski

And what's that ???





Thank you for attention!